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Identifying and Analyzing Critical Success Factors for Pharmaceutical Supply Chain Resilience in Bangladesh: A BWM–ISM–MICMAC Approach

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Abstract

Supply chains are the core of almost any economic environment. However, disruptions in supply chains have become increasingly frequent as economic environments grow more dynamic. The COVID-19 pandemic exposed vulnerabilities across many industries, and pharmaceutical supply chains (PSCs) were particularly affected in developing countries such as Bangladesh. During the crisis, Bangladesh experienced a critical shortage of active pharmaceutical ingredients (APIs). This situation highlights the need to strengthen PSCs so that they can absorb sudden shocks and recover rapidly. Accordingly, this study applies an established framework combining the Best–Worst Method (BWM), Interpretive Structural Modeling (ISM), and MICMAC (Matrice d'Impacts Croisés Multiplication Appliqués à un Classement) analysis to identify, prioritize, and structurally model the critical success factors (CSFs) required for PSC resilience in Bangladesh. Fourteen CSFs are identified through a literature review and expert consultation. The BWM is applied to determine the comparative importance of the CSFs, ISM is used to develop their hierarchical relationships, and MICMAC analysis is employed to classify them according to their driving and dependence power. The results provide a Bangladesh-specific resilience structure in which digital integration, supplier support, and diversified sourcing emerge as important driver factors, while flexibility is positioned within the resulting hierarchy. Thus, the contribution of the study lies primarily in the contextual application and interpretation of an established methodological framework for a pharmaceutical supply chain characterized by high API import dependence, regulatory requirements, and cold-chain constraints.

Keywords: Supply chain resilience; Pharmaceutical supply chain; Critical success factors; Best–Worst Method; ISM–MICMAC; Bangladesh.

Research highlights:

The contribution of this study includes the following:

(i) Identification of most influential critical success factors (CSFs) based on extensive literature review and expert opinions.

(ii) Evaluating and ranking the CSFs using the Best–Worst Method (BWM).

(iii) Unraveling the underlying relationships among the CSFs through a combined ISM–MICMAC approach.

(iv) Providing managers and policymakers with effective actions to further strengthen the resilience of pharmaceutical supply chains (PSCs).

1. Introduction

Supply chains have now spread across the national borders and are vastly interconnected. Companies have shifted their target towards cost efficiency, specialization, and globalization. The cost of supply chain imbalance, unanticipated shocks and failure is catastrophic due to interconnected global economy. Shocks can be caused by various events such as pandemics, natural disasters, local and international political unrest, geopolitical conflicts, cyber wars, and fluctuations in demand [1]. Local disruptive events like floods in one region, like recently in China and India, can also cause disruptions in the global supply chain, create economic instability, and hamper global public welfare. As a result, making smart and effective decisions to mitigate these effects and make the supply chain resilient and responsive have become particularly important for practitioners and policy makers.

Supply chain management is not limited to commercial activities nowadays; it is widely connected to non-commercial activities too. It includes humanitarian relief, healthcare, and non-profit operations [2]. Like commercial supply chains, non-commercial supply chains are also

vulnerable to sudden disruptions. Bangladesh experienced a critical medicine shortage during the COVID-19 pandemic because the country is heavily dependent on imported active pharmaceutical ingredients (APIs) from China, India, and South Korea [3,11]. A major shock to the supply chain can result in reduced service quality, retail price increment, and reduction in competitive advantages. But more importantly, it can threaten precious human lives. Therefore, it has become necessary to build a more resilient supply chain, a supply chain that can absorb sudden disruptions and recover quickly.

The concept of resilience is common in a lot of fields including ecology [4], psychology [5], engineering [6], and organizational studies [7]. The context might be different, but resilience carries a similar concept across all fields. It refers to the ability of an element to quickly return to a normal state of operation after experiencing disruption. In supply chain management (SCM), resilience is commonly known as a proactive strategy that allows businesses to minimize risks and quickly recover from sudden disruptions [8]. Resilience is also known as the ability to maintain the normal flow of operations at desired levels of connectivity and control in a business environment [9]. Resilient supply chains are also characterized by their ability to quickly detect risks, reduce impacts, and recover swiftly from disruptions [10].

Pharmaceutical supply chains (PSCs) are unique and critical because they are paired with life-saving medicines. They also face strict regulatory requirements, cold chain constraints and volatile demand. PSCs experience increased vulnerability in emerging economic setup in developing countries like Bangladesh. The pharmaceutical industry in Bangladesh is one of the largest contributors to its foreign exchange earnings. 98% of the local medicine demand is met through domestic production but 95% of the active pharmaceutical ingredients (APIs) used in these productions are imported from India, China, and South Korea [3, 11].

Despite growing research interest in supply chain resilience, there is limited empirical work on critical factors of PSCs and their interconnections. To reduce this research gap, more quantitative exploration is required in this field. The knowledge extracted from this kind of exploration should prove to be invaluable to ensure uninterrupted access to life-saving medicines.

Based on that, this study attempts to answer the following research questions:

RQ1: Which critical success factors (CSFs) are the most influential to a pharmaceutical supply chain (PSC) in Bangladesh?

RQ2: How can we distinguish and rank the identified CSFs based on their relative importance?

RQ3: What kind of structural and causal relationship exists among the identified CSFs?
RQ4: How can the information about their relationship help us build more resilient pharmaceutical supply chains (PSCs)?

To answer the above-mentioned questions, this study focuses on the following four research objectives:

RO1: Identify the most influential CSFs associated with pharmaceutical supply chains through a comprehensive literature review and consultation with experts.

RO2: Rank and prioritize the identified CSFs based on their relative impact on the overall resilience of PSCs.

RO3: Develop a hierarchical and causal relationship framework that quantifies the relationship among the identified CSFs.

RO4: Create an effective guideline for managers for making more efficient decisions.

At first, an integrated multi-criteria decision-making framework is explored. The BWM is used to calculate the relative weights of the identified CSFs. ISM is then used to build hierarchical relationships among the CSFs. After that, MICMAC analysis is employed to classify the CSFs based on their calculated driving and dependence power. This approach will allow us to identify and rank the most influential CSFs and give us a concrete understanding about their relationships.

1.1 Related studies, research gaps, and Bangladesh Context

From previous research on supply chain resilience (SCR), we can get the concepts of resilience in SCM, resilience enablers, barriers, strategies, and performance indicators using both quantitative and qualitative approaches such as AHP, DEMATEL, TOPSIS, fuzzy logic, and system dynamics. For example, the importance of resilience for the sustainability of supply chain and the associated challenges of measuring and managing resilience were highlighted in [12]. A thorough literature review on enablers of supply chain resilience is presented in [13]. The study also mentions the quantitative research gap in this field. A comprehensive literature review of 151 studies on strategies to enhance supply chain resilience is available in [14] that also paves the way for future research directions. Yang et al. [15] draw a similar conclusion about the growing need for detailed quantitative research on supply chain resilience. Beyond conceptual research, there are a few quantitative studies on resilience enablers in specific sectors. A multi-criteria decision-making framework for identifying enablers in healthcare supply chain has been explored in [16]. The study found that redundancy, collaboration, and robustness were the most influential enablers for the healthcare supply chain. Liu *et al.* [17] identified redundancy planning, freight rate stability, and service continuity as the most influential resilience enablers. Zhang *et al.* [18] employed an integrated AHP–TOPSIS approach to evaluate cross-border e-commerce supply chain resilience. Furthermore, researchers also used Interpretive Structural Modeling (ISM) to build a theoretical

model to determine the drivers of resilience in Indian manufacturing firms [19] . This model has also been validated using confirmatory factor analysis. In addition, the BWM was used to evaluate resilience in the manufacturing industry, and the findings revealed that reconfigurability is the most effective driver of supply chain resilience [20] .

Some early works on barriers to supply chain resilience (SCR) can be found in [21]. Through a systematic and comprehensive literature review, the study found that complexity, financial weakness, lack of capacity, collaboration, integration, flexibility, visibility, trust, and long lead time are the major barriers to resilience. The study portrayed the barriers as opposites of enablers and suggested that effective management of enablers can strengthen supply chain resilience. But the focus of the study was concentrated only on procurement.

Rajesh [22] proposed a comprehensive classification of 30 different barriers to SCR using the VIKOR method. In [23], the authors used structural equation modeling to analyze the internal and external barriers faced by small and medium-sized enterprises (SMEs). The study identifies resource constraints, cultural resistance, market conditions, and institutional limitations to being the most critical barriers. In [24], the authors identified barriers to supply chain resilience in the Indian MSME sector in the post-COVID-19 context. They then employed a grey-based DEMATEL approach to quantify the interrelationships among the identified barriers. The study considered 16 barriers and found that lack of flexibility was the most critical causal barrier. Other key barriers included lack of planned resource management, collaboration, supply chain design, and technical capability. In [25], critical barriers to supply chain resilience (SCR) in Vietnamese SMEs were identified and prioritized using a fuzzy VIKOR approach based on literature review and expert input. Fifteen barriers were classified into resilience phase, strategy resilience, and competency-related groups; the most critical were lack of financial resources and alternative

supply sources, shortage of skilled workforce, and delays in government support and policies. In [26], resilience capabilities for Industry 4.0 manufacturing supply chains were prioritized using a hybrid AHP–fuzzy TOPSIS approach, where barriers served as evaluation criteria. Five categories of barriers - strategic, technological, cultural, individual, and organizational—along with 23 sub criteria were considered, and six resilience capabilities were ranked, with planning capability emerging as the most important, followed by collaborative capability, agility, supply chain design modification capability, interoperability, and supply flexibility. Barriers to building resilient supply chain networks in India in the post-COVID-19 context were identified and prioritized using the AHP method [27]. Drawing on literature review, surveys, and consultations with supply chain managers, the study evaluated barriers experienced during pandemics and suggested strategic actions to enhance resilience and support recovery from future crises.

The concept of critical success factors (CSFs) originates from early work in [28] and was later refined in [29]. In [28], it was argued that information systems should concentrate on a small set of "success factors," with most industries typically having three to six areas in which firms must excel to achieve success. Subsequently, CSFs were defined in [29] as key performance factors that should be the primary focus of managerial attention. Several studies in different fields have tried to identify and model CSFs in building resilient supply chains. For example, a sequential mixed-methods framework integrating fuzzy DEMATEL and ISM was proposed to identify and structure critical success factors (CSFs) for supply chain resilience in sustainable construction. Seventeen CSFs were classified into cause–effect groups, with safety measures and guidelines having the highest driving power and skilled human resources and standardized materials/equipment identified as highly dependent factors [30]. In [31] 21 blockchain-enabled critical success factors (CSFs) for supply chain resilience and sustainability were identified and

analyzed using a Grey-DEMATEL approach. The results showed that internal integration is the most influential causal factor, while standardized data management and smart ordering are the most significant effect factors. It depicts blockchain's potential to enhance adaptiveness and responsiveness of supply chains. Critical success factors (CSFs) for resilient, sustainable, and intelligent supply chains in the context of Industry 5.0 and AIoE were identified and prioritized using a fuzzy hierarchical analysis approach in [32] . The results showed that technical infrastructure and hardware availability represent the highest-priority enablers for successful implementation of smart supply chain systems.

PSC is more complex than other industries [33]. Although SCR is an emerging research direction, the current literature shows the scarcity of empirical evidence on critical success factors of resilience for pharmaceuticals industry. Recently, the role of knowledge management in enhancing pharmaceutical supply chain resilience in the Middle East was examined using semi-structured interviews with industry professionals [34].The study found that effective knowledge sharing improves agility, adaptability, response capability, and innovation, thereby supporting organizational and supply chain resilience. However, the work does not identify specific critical success factors (CSFs) for knowledge-driven resilience, nor does it model interdependence among resilience enablers; in addition, the qualitative design and region-specific focus limit generalizability and lack quantitative validation. In [35], critical success factors and traceability technologies for establishing a safe pharmaceutical supply chain were reviewed, and a conceptual framework was proposed linking traceability tools, barriers, and success factors to combat counterfeit drugs. However, the study does not empirically identify or prioritize CSFs, nor model interdependencies among them, and the framework remains purely conceptual without quantitative validation. A bibliometric review of 41 publications on pharmaceutical supply chain resilience

synthesized thematic trends such as risk management, collaboration, and digitalization in the post-COVID-19 era in [36]. However, the review maps keywords and publication patterns without deeply integrating theoretical lenses or explaining how identified themes translate into measurable resilience capabilities. Eighteen critical success factors for implementing drug traceability systems in pharmaceutical supply chains were identified and prioritized using the TOE framework and AHP with expert judgment, with top management involvement and information-quality-related factors emerging as influential [37]. Talapatra et al. [38] employed fuzzy-TOPSIS to rank resilience strategies for the Bangladeshi pharmaceutical supply chain and identified agility, visibility, and collaboration as high-priority strategies. However, that approach provides a flat ranking and does not establish hierarchical relationships or distinguish driving from dependent factors. The present study therefore builds on the Bangladesh-specific literature by applying an established integrated framework to identify and prioritize CSFs and, importantly, to examine their structural interdependence in a pharmaceutical context characterized by high API import dependence, regulatory requirements, and cold-chain constraints.

Despite extensive research on supply chain resilience enablers, barriers, and strategies across multiple sectors, there remains a need for empirical studies that identify and structurally model the critical success factors (CSFs) of resilience in pharmaceutical supply chains in emerging economies. Much of the existing work focuses on manufacturing, construction, or humanitarian settings, and commonly employs MCDM techniques to produce flat rankings without examining hierarchical structure or causal interdependence. The Bangladesh pharmaceutical context is distinctive because of strict regulatory controls, heavy import dependency for APIs, product criticality, quality-assurance requirements, and cold-chain restrictions. These characteristics limit

the direct transferability of findings from other industries and contexts. In Bangladesh, existing research has emphasized risk identification, strategy lists, and qualitative assessments, while the structural relationships among resilience-enabling CSFs remain less explored. Accordingly, the contribution of this study is not a new decision-making methodology; rather, it is the rigorous application of an established BWM–ISM–MICMAC framework to this specific context and the interpretation of the resulting priorities and relationships for Bangladesh's pharmaceutical supply chain. This provides a structured resilience perspective beyond an isolated ranking of factors.

The rest of the paper is organized as follows: Details on the materials and methods are provided in Section 2. The study's results are presented in Section 3, and its managerial implication is discussed in Section 4. Section 5 concludes the study and provides future research direction**.**

2. Methods2

The overall research methodology has been divided into ten steps. A recommended flow chart of the proposed methodology can be found in Figure 1. The methodology is organized in such a manner that it can reliably identify, prioritize, and structure critical success factors (CSFs) for pharmaceutical supply chains.

Step1: Defining research goals

The study starts by defining the four research goals as mentioned at the beginning. This step clarifies the entire scope of the work and guides all subsequent methodological choices.

Step 2: Literature review

A comprehensive literature review on pharmaceutical supply chain and supply chain resilience is conducted to identify the initial pool of critical success factor (CSFs). This

comprehensive literature review also sets the theoretical foundation of this study and defends our research questions. Additionally, this step ensures that we are headed in the right direction.

Step 3: Finalizing CSF list

In step 3, the initial pool of CSFs is presented to the expert panel. The expert panel reviews each CSF based on relevance, clarity, and mutual agreement. A final list of CSFs is crafted through this process and used in the following steps. Any overlapping CSFs are merged; vague ones are clarified and missing one are added to the list.

Step 4: Development of questionnaire for CSF analysis

In this step, a structured questionnaire is prepared to complies the expert opinions on individual CSFs. The questionnaire is prepared in compliance with the requirements of the best-worst method (BWM) and subsequent structural modeling. The goal is to use this information for ranking the CSFs, calculate pairwise preference ratings, and note any additional qualitative comments from the experts.

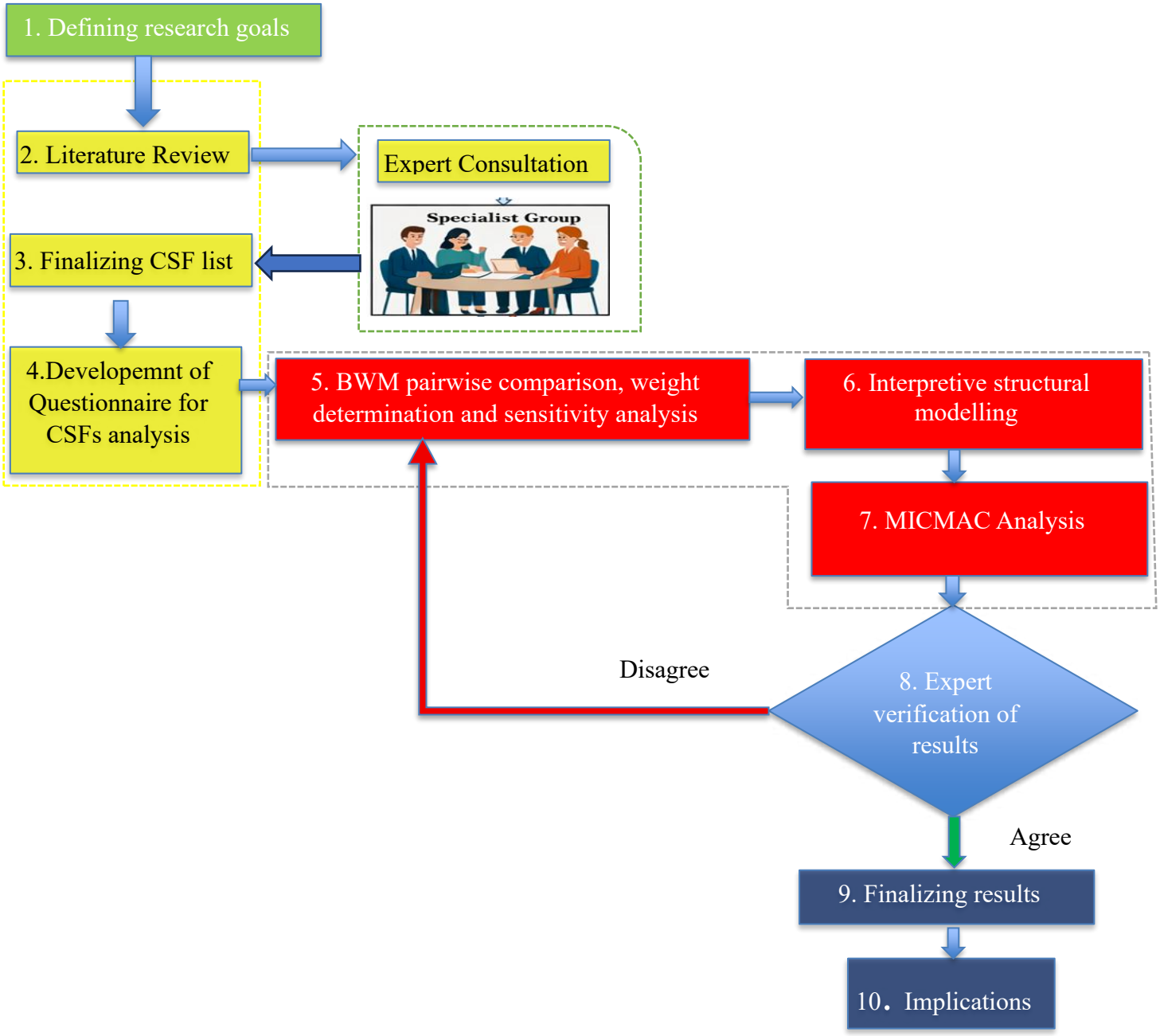


Figure 1: Methodological framework of the study

Step 5: BWM pairwise comparisons, weight determination, and sensitivity analysis

In Step 5, the Best–Worst Method (BWM) is applied to rank the identified CSFs. Each member of the expert panel identifies the most important (best) and least important (worst) CSF from the finalized list. The experts then provide pairwise preference ratings in two ways: (i) the preference of the best CSF over each of the other CSFs and (ii) the preference of each CSF over the worst CSF. The individual judgments from the second-round BWM respondents are aggregated by taking the arithmetic means of the corresponding ratings to form group-level best-to-others and others-to-worst comparison vectors. These aggregated vectors are then used as inputs to the BWM optimization model, from which the final CSF weights are obtained. To further assess the stability of the resulting weights, a sensitivity analysis is carried out by varying the relevant expert-assessment weights within reasonable ranges and examining the effects on the results.

The Best–Worst Method, originally proposed by Rezaei [39], is a relatively recent multi-criteria decision-making (MCDM) approach. Compared to traditional methods such as the Analytic Hierarchy Process (AHP), BWM requires substantially fewer pairwise comparisons because only the best–to–others and others–to–worst comparisons are needed instead of a full comparison matrix. This reduces the cognitive burden on experts and decreases inconsistency in responses. As a result, BWM is considered efficient and practical, and it has been widely adopted in various application domains [40, 41]. Its simplicity also makes the data collection process faster for researchers while also minimizing time requirements for decision makers.

The procedure of BWM consists of the following phases:

Phase 1: Identify decision criteria.

A final list of CSFs is obtained from literature and expert consultation.

Phase 2: **Experts' assessments**

- Selection of the most important criterion (Best, B) by the experts
- Selection of the least important criterion (Worst, W) by the experts

Phase 3: **Best-to-others comparisons**

Experts rate their preference of B over each criterion, j, using a rating scale from 1 to 9:

$$A_B = (a_{B1}, a_{B2}, \ldots\ldots, a_{Bn},)$$

Where a_{Bj}, indicates the preference of the best criterion B over criteria j.

Phase 4: Others-to-worst comparisons

Experts rate their preference of each criterion, j, over W , using a rating scale from 1 to 9:

$$A_w = (a_{w1}, a_{w2}, \ldots\ldots, a_{wn},)^T$$

Phase 5: **Formulation of optimization model**

Weights $(w_1, \ldots, w_n)$ for each criterion is determined such that:

$$|W_B^m - a_{Bj}^m W_j^m| \quad , \quad |W_j^m - a_{jw}^m W_W^m|$$

are minimized subjected to the following constraints:

$$\sum_j w_j^m = 1$$

$$W_j^m \geq 0 \text{ for all j}$$

This optimization problem can be solved by converting it into the following linear programming problem model.

$$\text{Min } \zeta^{\text{L}}$$

Subject to,

$$|W_B^m - a_{Bj}^m W_j^m| \leq \zeta^{\text{L}}$$

$$|W_j^m - a_{jw}^m W_W^m| \leq \zeta^{\text{L}}$$

$$\textstyle\sum_j w_j^m = 1 \qquad (1)$$

$$W_i^m \geq 0 \text{ for all j}$$

Phase 6: Obtaining final weights:

Normalized weights of CSFs are obtained by solving the linear programming model that minimizes the maximum deviation (ζ^L) between the weight ratios and expert pairwise comparisons, subject to the constraint that all weights sum to 1.

Phase 7: **Consistency check**

lower ζ= higher consistency

$\zeta < 1$ indicates acceptable consistency.

Phase 8: Sensitivity analysis

Sensitivity analysis is performed by varying the weight of the highest-ranked cluster from 0.1 to 0.9 and observing the resulting changes in CSF rankings.

Step 6: **Interpretive structural modelling**

A Structural Self-Interaction Matrix (SSIM) is first constructed based on the judgments of a group of experts with relevant experience in pharmaceutical supply chain management. The experts assess the direction of contextual relationships among the selected CSFs using the symbols V (i influences j), A (j influences i), X (mutual influence), and O (no influence). The individual judgments are consolidated to construct the SSIM, which is then converted to an Initial Reachability Matrix (IRM) by replacing the four symbols with their corresponding binary values. This matrix is further converted to a Final Reachability Matrix (FRM) by applying the principles of transitivity. The FRM captures both direct and indirect (transitive) relationships among the CSFs. The driving power of a CSF is the number of CSFs it reaches, including itself (its row sum in the FRM). Its dependence power is the number of CSFs that reach it, including itself (its column sum)[43].

Step 7: **MICMAC Analysis**

the MICMAC analysis is performed on the CSFs to strengthen their classification and interpretation. The MICMAC analysis categorizes the CSFs into four groups using the driving and dependence power of each CSF [44]. MICMAC analysis is particularly suitable in our research as the causal relationship among the CSFs is fundamental to the proposed approach. Other analytical techniques such as the principal component analysis (PCA) [45], is not very suitable here as it mainly focuses on dimensionality reduction. Based on the driving and dependence power, the CSFs are plotted on a MICMAC grid and classified into four groups:

(i) Autonomous factors (low driving power, low dependence power)

(ii) Dependent factors (low driving power, high dependence power)

(iii) Linking factors (high driving power, high dependence power)

(iv) Driving factors (high driving power, low dependence power)

With the help of the classification of CSFs, decision makers can make more efficient decisions that will increase the resilience of PSCs. CSFs with high driving power should be prioritized for resource investment as they can trigger a system-wide effect.

Step 8: Expert verification of results

The results so far are presented in front of the experts once again. They can review the derived weights, the hierarchical structure, and the classification of CSFs to access if they are consistent with practical experience. If there appears to be a non-negligible amount of discrepancies, feedback from the experts is fed into prior steps. The entire analysis up to now is then revised until an acceptable level of agreement on outcomes vs practical experience is reached.

Steps 9-10: Finalizing results and implications.

In the last two steps, the final results are obtained through multiple iterations of prior steps through the incorporation of expert opinions on results. The findings are interpreted from a pharmaceutical supply chain resilience point of view. In this step, the managerial recommendations and policy implications are derived. These recommendations possess the potential power to guide decision makers towards building more resilient pharmaceutical supply chains. At this point, we can draw conclusions, highlight the key contributions, limitations, and directions of future research.

Use of large language models (LLMs)

An LLM (Claude, developed by Anthropic) was used to generate Python (Matplotlib) code to redraw the MICMAC diagram (Figure 4) and the ISM structural model (Figure 5) from the authors' own results. The LLM was not used to generate the study design, data, analysis, results, or interpretation. The authors checked the redrawn figures against their original results and take full responsibility for the final content of the manuscript.

3. Results

A questionnaire-based survey has been conducted among the industry experts. These questions are framed in a way that they can be used in identifying the most critical success factors (CSFs) in the pharmaceutical supply chain. Primarily, 20 industry experts have been interviewed (profile shown in Appendix I) through emails and one to one meeting. All experts have more than 10 years of experience in the pharmaceutical supply chain. Their feedback has been used to refine and finalize the list of CSFs.

Initially, 11 CSFs were identified from the literature and given to the experts for review. Based on their suggestions, three additional CSFs were added: (i) Supplier support after disruptive events,

(ii) TQM and Six Sigma Practices, and (iii) Continuous and new technological innovation. Table 1 presents the final set of CSFs consolidated from both literature review and expert opinion.

Following the identification of CSFs, a second round of interviews was conducted with experts having more than 15 years of experience in pharmaceutical supply chains. Inputs from these experts were used to build the best-to-others and others-to-worst comparison matrix using a rating scale from 1 to 9, required for BWM analysis. They also proposed grouping the CSFs into three clusters: (i) CSFs related to production process practices, (ii) CSFs related to organizational culture, and (iii) CSFs related to technology and collaboration. The clustered CSFs are shown in Table 2.

Table 1: Final List of CSFs identified from literature and Expert Feedback

CSF's	Definition	Source
Flexibility in aligning different parts of the production process	Ability to overcome disruptions and continually transform itself to meet the changing needs and expectations of its customers, shareholders and other stakeholders	[1], [46] , [47]
Lean production with JIT delivery and low inventory	Practice of minimizing waste and continuous improvement to lessen product development cycle after disruptive events to ensure quick recovery.	[46]
Existence of multiple viable sourcing options	Practice of using multiple sources for resource gathering reduces disruption risk.	[48], [49]
Continuous and new technological innovations	New and advanced technology can forecast disruptive events and increase capability to restore performance.	Expert feedback

Practicing risk Management strategies in regular operations	Well-informed and trained employees can make quick decisions to recover from the disruptive state.	[1], [50]
Increased re-engineering trend in the pharmaceutical sector	Restructuring of supply chain after experiencing a disruption under the assumption that the future would be much like the past	[1], [48]
Collaboration with other relevant research and development entities	Ability to work effectively with other entities, to share risks and to be able to forecast in a proper manner.	[1], [46], [51]
Digital Integration	The capability to link internal and external digital platforms across the pharmaceutical supply chain to ensure seamless information flow, collaborative decision-making, and timely prediction and response to disruptions.	[52]
Rapid response and built -in Process Integration	Rapid response involves using standard processes having built-in interoperability involving interchangeable processes so that people familiar with operation at one location are comfortable at other location.	[53]
Information sharing among different departments	Central process through which team members collectively utilize their available informational resources.	[1], [46],[[48]
Awareness on corporate social responsibility (CSR) to protect customers and environmental interests	Intangible resources derived from firm's interorganizational relationships as external resources do not act themselves	[48], [54], [55]
TQM and Six Sigma practices	Managers of Industries which follow six sigma practices have knowledge of all the possible errors in their production system and act accordingly in times of risk.	Expert Feedback

Supplier support after the disruptive event	The willingness and capability of suppliers, especially API and raw-material suppliers, to prioritize orders, share capacity and information, and offer flexible terms so that the focal firm can resume production quickly after a disruption.	Expert Feedback
Legislation compliance in new drug development	Adherence to national and international regulatory requirements, such as DGDA (Bangladesh's drug regulator) approvals, GMP and registration standards, throughout new drug development.	[52]

Table 2: Final List of CSF with Clustering

Cluster	CSF's
CSFs related to production process practices	Lean production with JIT delivery and low inventory (CSF1)
	TQM and Six Sigma Practices (CSF2)
	Flexibility in aligning different parts of the production process (CSF3)
	Rapid response and built -in Process Integration (CSF4)
CSFs related to organization's culture	Practicing Risk Management strategies in regular operations (CSF5)
	Supplier support after the disruptive event (CSF6)
	Digital Integration (CSF7)
	Existence of multiple viable sourcing options (CSF8)
	Increased re-engineering to reduce the downtime in the production lines (CSF9)
	Continuous and new technological innovations (CSF10)

CSFs related to Technology and Collaboration	Information Sharing among different departments (CSF11)
	Collaboration with other relevant research and development entities (CSF12)
	Awareness on the corporate social responsibility (CSR) to protect customer and environmental interests (CSF13)
	Legislation Compliance in New Drug Development (CSF14)

3.1 BWM Results

After the group-level BWM comparison vectors were obtained from the second-round expert responses, the BWM analysis was carried out following the sequential steps described in the methodology section. The resulting weights of the CSFs are presented in Table 3.

Table 3: Weights of the Clusters and CSFs

Main Criteria	Main Criteria Weights	Sub Criteria	Sub Criteria weights	Global weight	Rank
Production Process	0.2857	CSF1	0.101604	0.0290	10
		CSF2	0.064171	0.0183	12
		CSF3	0.529412	0.1512	2
		CSF4	0.304813	0.0870	5
Organization Culture	0.5714	CSF5	0.211538	0.1208	4
		CSF6	0.141026	0.0805	6
		CSF7	0.371795	0.2125	1
		CSF8	0.064103	0.0366	8
		CSF9	0.211538	0.1208	3
Technology and Collaboration	0.1428	CSF10	0.242775	0.0347	9
		CSF11	0.416185	0.0594	7
		CSF12	0.16185	0.0231	11
		CSF13	0.057803	0.0082	14
		CSF14	0.121387	0.0173	13

In multi-criteria decision making (MCDM), conducting sensitivity analysis is essential to evaluate the robustness of the final rankings of the selected CSFs. In this study, sensitivity analysis was first performed at the cluster level by varying the weight of the highest-ranked cluster within the range of 0.1 to 0.9 and examining the resulting changes in the rankings of the remaining CSFs. After completing the cluster-level analysis, a similar procedure was applied at the CSF level, where the weight of the highest-ranked CSF was varied within the same range and the effects on the rankings of the other CSFs were observed. Substantial variations were observed when the weight of the top-ranked cluster was perturbed, whereas only minor changes were detected when the weight of the top-ranked CSF was altered. The detailed results of the sensitivity analyses are reported in Tables 4–7. First, Table 4 presents the changes in the weights of the different clusters across the sensitivity analysis runs, providing an overview of how the relative importance of the clusters changes as the sensitivity parameter varies. The sensitivity analysis of the highest-weighted cluster is presented in Table 5. The results show how the weights of the individual critical success factors (CSFs) within the highest-weighted cluster change across the sensitivity analysis runs. In particular, CSF3 and CSF4 exhibit a decreasing trend in their weights, whereas CSF5, CSF6, CSF7, CSF8, and CSF9 generally increase as the sensitivity parameter changes.

Table 4. Weights of Various Clusters During Sensitivity Analysis

Main Cluster Normalize weights		**Modified weights of all CSFs when modifying Organization Culture Cluster from 0.1 to 0.9**								
Production Process	0.2857	0.5405	0.4545	0.3921	0.3448	0.3076	0.2777	0.2531	0.2325	0.2150
Organization Culture	0.5714	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Technology and Collaboration	0.1428	0.2702	0.2272	0.1960	0.17241	0.1538	0.1051	0.1265	0.1162	0.0814

Table 5: Weights of various CSFs through sensitivity analysis of highest weighted Cluster

	Run 0.1	Run 0.2	Run 0.3	Run 0.4	Run5	Run6	Run7	Run8	Run9
CSF1	0.0549	0.0461	0.0398	0.0350	0.0312	0.0282	0.0257	0.0236	0.0218
CSF2	0.0346	0.0291	0.0251	0.0221	0.0197	0.0178	0.0162	0.0149	0.0138
CSF3	0.2861	0.2406	0.2076	0.1825	0.1628	0.1470	0.1340	0.1231	0.1138
CSF4	0.1647	0.1385	0.1195	0.1051	0.0937	0.0846	0.0771	0.0708	0.0655
CSF5	0.0400	0.0673	0.0871	0.1021	0.1139	0.1233	0.1312	0.1377	0.1433
CSF6	0.0266	0.0448	0.0580	0.0680	0.0759	0.0822	0.0874	0.0918	0.0955
CSF7	0.0703	0.1183	0.1531	0.1795	0.2002	0.2169	0.2306	0.2420	0.2518
CSF8	0.0121	0.0204	0.0264	0.0300	0.0345	0.0373	0.0397	0.0417	0.0434
CSF9	0.0400	0.0673	0.0871	0.1021	0.1139	0.1233	0.1312	0.1377	0.1433
CSF10	0.0656	0.0551	0.0476	0.0418	0.0373	0.0337	0.0307	0.0282	0.0261
CSF11	0.1124	0.0945	0.0816	0.0717	0.0640	0.0578	0.0526	0.0483	0.0447
CSF12	0.0437	0.0367	0.0317	0.0279	0.0249	0.0224	0.0204	0.0188	0.0174
CSF13	0.0156	0.0131	0.0113	0.0099	0.0088	0.0080	0.0073	0.0067	0.0062
CSF14	0.0328	0.0275	0.0238	0.0209	0.0186	0.0168	0.0153	0.0141	0.0130

Table 6 presents the ranking of the CSFs across the sensitivity analysis runs. The results indicate that the relative ranking of several CSFs changes as the sensitivity parameter varies. In particular, CSF3 and CSF7 remain among the highest-ranked factors, while CSF13 and CSF14 consistently remain among the lowest-ranked factors.

Table 6: Ranking of CSFs during Sensitivity analysis of Cluster.

	Run 1	Run 2	Run 3	Run 4	Run5	Run6	Run7	Run8	Run9
CSFs1	6	8	9	9	10	10	10	10	10
CSFs2	10	11	12	12	12	12	12	12	12
CSFs3	1	1	1	1	2	2	2	4	4
CSFs4	2	2	3	3	5	5	6	6	6
CSFs5	9	6	5	5	4	4	4	3	3
CSFs6	12	9	7	7	6	6	5	5	5
CSFs7	4	3	2	2	1	1	1	1	1
CSFs8	14	13	11	10	9	8	8	8	8
CSFs9	8	5	4	4	3	3	3	2	2
CSFs10	5	7	8	8	8	9	9	9	9
CSFs11	3	4	6	6	7	7	7	7	7
CSFs12	7	10	10	11	11	11	11	11	11
CSFs13	13	14	14	14	14	14	14	14	14
CSFs14	11	12	13	13	13	13	13	13	13

Table 7 presents the normalized weights of the CSFs and their corresponding changes across the sensitivity analysis runs. These results provide a basis for examining whether the relative importance of the CSFs remains stable when the underlying cluster weights are perturbed.

Table 7: Weights of the CSFs during the sensitivity analysis of the top ranked CSF.

	Normalize	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
CSFs1	0.0549	0.0327	0.029	0.0266	0.0244	0.022	0.0209	0.01951	0.0182	0.017
CSFs2	0.0346	0.0206	0.0185	0.0168	0.0244	0.014	0.0132	0.012	0.0115	0.010
CSFs3	0.2861	0.1704	0.1531	0.1390	0.1273	0.117	0.109	0.1016	0.0952	0.08
CSFs4	0.1647	0.0981	0.0881	0.0800	0.0733	0.0676	0.0627	0.0585	0.0548	0.051
CSFs5	0.0400	0.1361	0.1224	0.1111	0.1017	0.0938	0.087	0.0812	0.0761	0.07
CSFs6	0.0266	0.0907	0.0816	0.0740	0.0678	0.062	0.0580	0.054	0.0507	0.047
CSFs7	0.0703	0.1126	0.2025	0.2758	0.3368	0.388	0.4324	0.470	0.50392	0.533
CSFs8	0.0121	0.0412	0.0370	0.0336	0.0308	0.028	0.026	0.0246	0.0230	0.021
CSFs9	0.0400	0.1361	0.1224	0.1111	0.1017	0.093	0.087	0.0812	0.0761	0.071
CSFs10	0.0656	0.0390	0.0351	0.0318	0.0292	0.0269	0.024	0.0233	0.0218	0.020
CSFs11	0.1124	0.0669	0.0602	0.0546	0.0500	0.0461	0.0428	0.0399	0.03745	0.035
CSFs12	0.0437	0.0260	0.023413	0.0212	0.0194	0.0179	0.016	0.0155	0.01456	0.013
CSFs13	0.0156	0.0093	0.008362	0.0075	0.0069	0.0064	0.005	0.0055	0.00520	0.004
CSFs14	0.0328	0.0195	0.01756	0.0159	0.0146	0.0134	0.0124	0.01165	0.01095	0.0102

Finally, Table 8 presents the rankings of the CSFs across the sensitivity analysis runs. The results indicate that the rankings remain largely stable across the runs, with only minor changes observed for CSF3, CSF5, CSF7, and CSF9. In particular, CSF7 remains the highest-ranked CSF in most runs, while CSF13 and CSF14 consistently remain among the lowest-ranked CSFs.

Table 8: Rank of the CSFs during the sensitivity analysis of the top ranked CSF.

	Normal	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
CSFs1	10	10	10	10	10	10	10	10	10	10
CSFs2	12	12	12	12	12	12	12	12	12	12
CSFs3	2	1	2	2	2	2	2	2	2	2
CSFs4	5	5	5	5	5	5	5	5	5	5
CSFs5	4	3	4	4	4	4	4	4	4	4
CSFs6	6	6	6	6	6	6	6	6	6	6
CSFs7	1	4	1	1	1	1	1	1	1	1
CSFs8	8	8	8	8	8	8	8	8	8	8
CSFs9	3	2	3	3	3	3	3	3	3	3
CSFs10	9	9	9	9	9	9	9	9	9	9
CSFs11	7	7	7	7	7	7	7	7	7	7
CSFs12	11	11	11	11	11	11	11	11	11	11
CSFs13	14	14	14	14	14	14	14	14	14	14
CSFs14	13	13	13	13	13	13	13	13	13	13

The changes in the relative rankings of the CSFs across the sensitivity analysis runs are illustrated in Figures 2 and 3. Figure 2 shows the variation in the ranking of each CSF across the sensitivity runs, while Figure 3 provides a complementary visualization of the ranking patterns across the different runs. Overall, the figures demonstrate that the relative ranking of most CSFs remains stable despite changes in the sensitivity parameter.

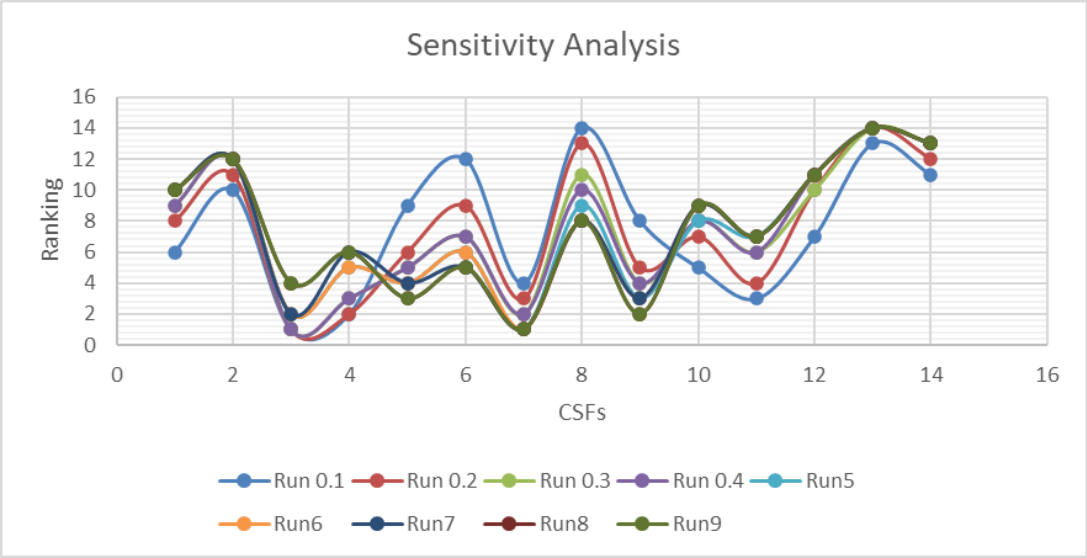


Figure 2: Ranking of the CSFs during sensitivity analysis of the top ranked cluster

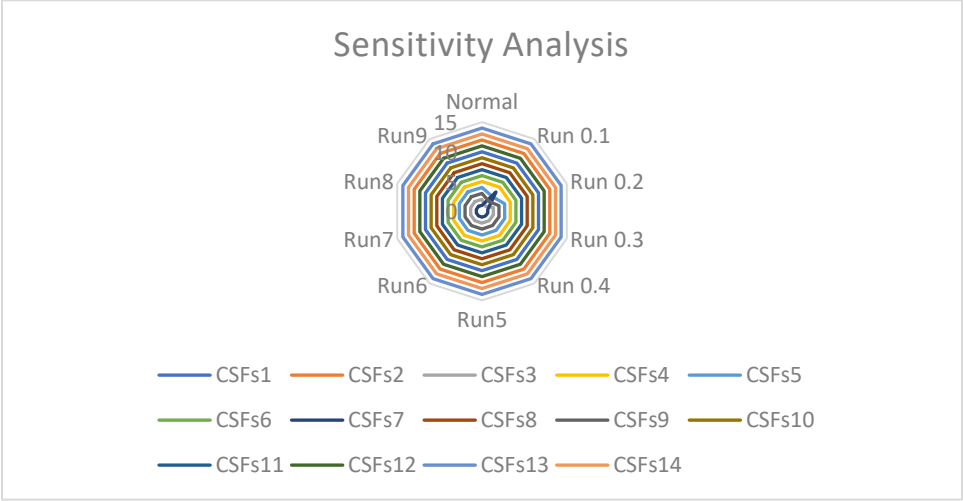


Figure 3: Ranking of CSFs while CSFs level analysis

3.2 ISM and MICMAC

Although the sensitivity analysis showed that the rankings respond to changes in cluster weights, the top-ranked CSFs (CSF7, CSF3, CSF9, and CSF5) remained among the highest-ranked factors across the runs, and only minor changes occurred when the weight of the top-ranked CSF

was varied. The eleven highest-ranked CSFs were then selected for structural analysis using ISM. Together, these eleven CSFs account for 95.6% of the total BWM weight, whereas the three excluded CSFs (CSF2, CSF14, and CSF13) jointly account for less than 5%. Limiting the ISM analysis to these CSFs also keeps the number of pairwise judgments (55 pairs) manageable for the expert panel. The selected CSFs and their corresponding rankings are presented in Table 9. CSF7 (Digital Integration) was ranked first, followed by CSF3 (Flexibility in aligning different parts of the production process) and CSF9 (Increased re-engineering to reduce downtime in the production lines). The SSIM for the selected CSFs was developed based on the judgments of 10 experts drawn from the second-round panel (Appendix : Table A1). Each expert independently assessed the contextual relationship between every pair of CSFs, and the individual judgments were consolidated using the majority rule, with ties resolved through follow-up discussion with the experts. The experts assessed the contextual relationships among the selected CSFs using the symbols V, A, X, and O. Their judgments were consolidated to construct the SSIM, which is presented in Table 10. The resulting SSIM was then converted into the initial and final reachability matrices following the procedure described in the methodology section. The level partitioning results are presented in Table 11, while the final reachability matrix and the corresponding driving and dependence powers of the selected CSFs are presented in Table 12.

From the final reachability matrix, the driving and dependence power of each CSF was calculated and further used in the MICMAC analysis. The resulting classification of CSFs based on their driving and dependence power is illustrated in Figure 4. Level partitioning was then performed by examining the reachability, antecedent, and intersection sets. A CSF that appears in both its reachability set and antecedent set is assigned to the first level and positioned at the highest level in the ISM hierarchy. After assigning first-level CSFs, they are removed from further

analysis, and the next levels are obtained in an iterative manner until all CSFs are classified. Finally, the BWM weights, the ISM hierarchy, and the MICMAC classification were presented to experts from the panel for verification. The experts considered the results consistent with their practical experience of pharmaceutical supply chains in Bangladesh. No revisions to the analysis were required. The final ISM-based hierarchical structure obtained from this entire process is shown in Figure 5.

Table 9: Finally Selected CSFs for ISM-MICMAC

	Finally Selected CSFs	**Rank**
CSF7	Digital Integration	1
CSF3	Flexibility in aligning different parts of the production process	2
CSF9	Increased re-engineering to reduce the downtime in the production Lines	3
CSF5	Practicing Risk Management strategies in regular operations	4
CSF4	Rapid response and built -in Process Integration	5
CSF6	Supplier Support after the disruptive event	6
CSF11	Information Sharing among different departments	7
CSF8	Existence of multiple viable sourcing options	8
CSF10	Continuous and new technological innovations	9
CSF1	Lean production with JIT delivery and low inventory	10
CSF12	Collaboration with other relevant research and development entities	11

Table 10: Structural Self-Interaction Matrix (SSIM)

	CSF7	**CSF3**	**CSF9**	**CSF5**	**CSF4**	**CSF6**	**CSF11**	**CSF8**	**CSF10**	**CSF1**	**CSF12**
CSF7	x	V	V	V	V	V	O	V	V	V	V
CSF3		x	O	O	A	O	O	A	A	A	O
CSF9			x	X	V	O	A	O	X	X	O
CSF5				x	O	O	O	O	O	O	O
CSF4					x	A	A	A	A	O	A
CSF6						x	O	A	O	V	V
CSF11							x	O	X	O	V
CSF8								x	O	O	V
CSF10									x	V	O
CSF1										x	O
CSF12											x

Table 11: Level Partitioning of the Selected CSFs

Elements (Mi)	**Reachability Set R(Mi)**	**Antecedent Set A(Mi)**	**Intersection Set R(Mi)∩A(Mi)**	**Level**
CSF7	CSF7	CSF7	CSF7	7
CSF3	CSF3	CSF7, CSF3, CSF9, CSF5, CSF4, CSF6, CSF11, CSF8, CSF10, CSF1, CSF12	CSF3	1
CSF9	CSF9, CSF5, CSF11, CSF10, CSF1	CSF7, CSF9, CSF5, CSF6, CSF11, CSF8, CSF10, CSF1	CSF9, CSF5, CSF11, CSF10, CSF1	4
CSF5	CSF9, CSF5, CSF11, CSF10, CSF1	CSF7, CSF9, CSF5, CSF6, CSF11, CSF8, CSF10, CSF1	CSF9, CSF5, CSF11, CSF10, CSF1	4
CSF4	CSF4	CSF7, CSF9, CSF5, CSF4, CSF6, CSF11, CSF8, CSF10, CSF1, CSF12	CSF4	2
CSF6	CSF6	CSF7, CSF6, CSF8	CSF6	5

CSF11	CSF9, CSF5, CSF11, CSF10, CSF1	CSF7, CSF9, CSF5, CSF6, CSF11, CSF8, CSF10, CSF1	CSF9, CSF5, CSF11, CSF10, CSF1	4
CSF8	CSF8	CSF7, CSF8	CSF8	6
CSF10	CSF9, CSF5, CSF11, CSF10, CSF1	CSF7, CSF9, CSF5, CSF6, CSF11, CSF8, CSF10, CSF1	CSF9, CSF5, CSF11, CSF10, CSF1	4
CSF1	CSF9, CSF5, CSF11, CSF10, CSF1	CSF7, CSF9, CSF5, CSF6, CSF11, CSF8, CSF10, CSF1	CSF9, CSF5, CSF11, CSF10, CSF1	4
CSF12	CSF12	CSF7, CSF9, CSF5, CSF6, CSF11, CSF8, CSF10, CSF1, CSF12	CSF12	3

Table 12: Final Reachability Matrix and Driving and Dependence Power of the Selected CSFs

	CSF7	**CSF3**	**CSF9**	**CSF5**	**CSF4**	**CSF6**	**CSF11**	**CSF8**	**CSF10**	**CSF1**	**CSF12**	**Driving Power**
CSF7	1	1	1	1	1	1	1*	1	1	1	1	11
CSF3	0	1	0	0	0	0	0	0	0	0	0	1
CSF9	0	1*	1	1	1	0	1*	0	1	1	1*	8
CSF5	0	1*	1	1	1*	0	1*	0	1*	1*	1*	8
CSF4	0	1	0	0	1	0	0	0	0	0	0	2
CSF6	0	1*	1*	1*	1	1	1*	0	1*	1	1	9
CSF11	0	1*	1	1*	1	0	1	0	1	1*	1	8
CSF8	0	1	1*	1*	1	1	1*	1	1*	1*	1	10
CSF10	0	1	1	1*	1	0	1	0	1	1	1*	8
CSF1	0	1	1	1*	1*	0	1*	0	1*	1	1*	8
CSF12	0	1*	0	0	1	0	0	0	0	0	1	3
Dependence Power	1	11	8	8	10	3	8	2	8	8	9	

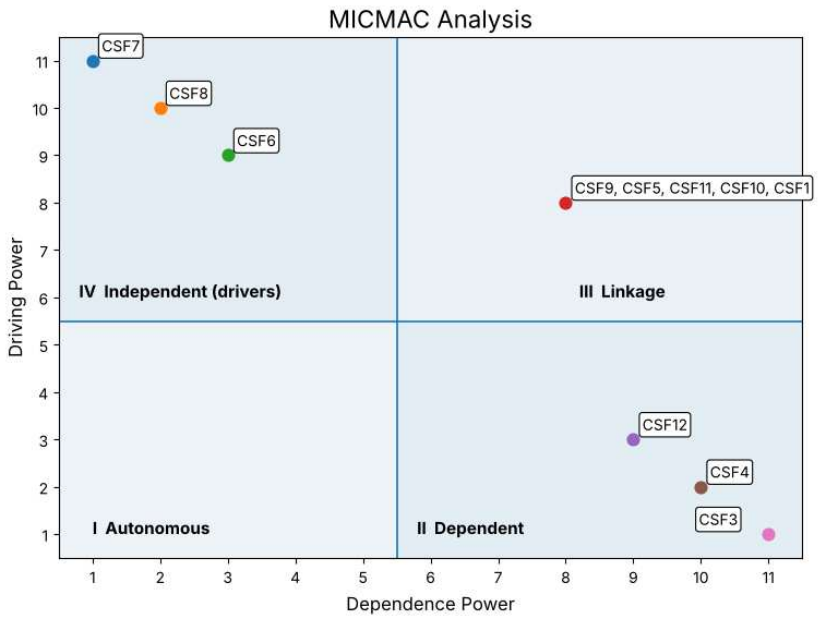


Figure 4: MICMAC Analysis

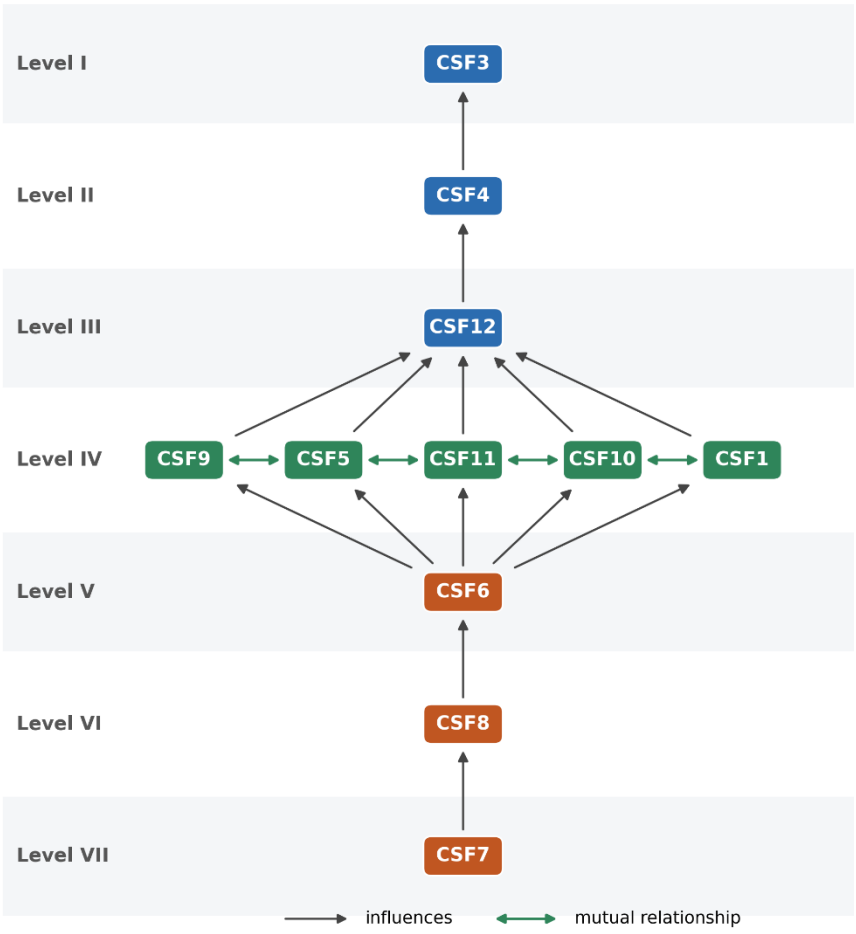


Figure 5: Structural Model to implement resilient supply chain

The results of this study show that CSF7(Digital Integration) obtained the highest global weight, followed by CSF3(Flexibility in production processes) and CSF9 (Increased re-engineering to reduce downtime). It suggests that CSF7, CSF3, and CSF9 are the most influential critical success factors (CSF) of the resilience of pharmaceutical supply chains.

The ISM hierarchy shows that CSFs with high driving power and low dependence power are positioned at the lower levels of the hierarchy. These CSFs work as foundational drivers of other associated CSFs. On the other hand, CSFs with high dependence power and low driving power are

positioned at the upper levels of the hierarchy. They are passively driven by the CSFs at lower levels.

The initial findings are reinforced by the MICMAC analysis. The MICMAC analysis identified CSF7, CSF8, and CSF6 as independent (driver) CSFs. These three CSFs have high driving power and low dependence power. They play a foundational role in influencing other CSFs. Decision makers should focus on them first. On the other hand, CSF3 CSF4, and CSF12 are identified as dependent (driven) CSFs. They heavily depend on other CSFs and have little driving power of their own. Notably, CSF3(Flexibility in production process) has the highest dependence power and lowest driving power. It means that flexibility in the production process is just a passive outcome of improvements in other driver CSFs. Change in one CSF will bring change to the others, whether positive or negative. It shows the interconnected nature of all the critical success factors (CSFs) of resilience in pharmaceutical supply chains.

Overall, the results obtained from the combined BWM-ISM-MICMAC approach suggest that building resilience requires a bottom-up view. Driver CSFs should be improved, and the driven CSFs will follow. Digital integration, supplier support, and diversified sourcing are driving factors of resilience in pharmaceutical supply chains. On the other hand, Flexibility in production process and collaboration are the results of improving the driver CSFs. Using these findings, a structured roadmap can be crafted to determine which CSF to prioritize in terms of resource allocation.

4. Managerial implications

Pharmaceutical supply chains cause more sufferings during sudden disruptions than other supply chains. So, it's important for managers to try their best to enhance the resilience of PSCs. The main challenge for managers is not identifying the CSFs but ranking them properly. Proper ranking ensures timely and efficient allocation of limited resources. In our study, Digital Integration (CSF7) received the highest global weight (0.2125), indicating that digital integration was the highest-priority CSF in the BWM results. For managers, this finding points specifically to the importance of real-time information flows, inventory visibility, supply-and-demand forecasting, and timely access to regulatory information. The MICMAC analysis additionally classified Digital Integration (CSF7), Existence of multiple viable sourcing options (CSF8), and Supplier Support after the disruptive event (CSF6) as driver CSFs. These results suggest that managers should consider digital integration, sourcing diversification, and supplier support as foundational capabilities when allocating resilience-related resources.

Increased re-engineering to reduce downtime (CSF9) and flexibility in production processes (CSF3) were also highly ranked in the BWM results; however, the MICMAC results indicate that CSF3 is a dependent factor. Thus, flexibility should be interpreted as an outcome that can be strengthened through improvements in the underlying driver CSFs rather than as an isolated intervention.

These implications are particularly relevant to the Bangladesh pharmaceutical context, where high dependence on imported APIs can transmit international disruptions into domestic pharmaceutical production and distribution. Strengthening information integration, maintaining alternative sourcing options, and developing supplier-support arrangements can therefore address

vulnerabilities identified in this context. The framework can provide a structured basis for managers to discuss resource allocation, but the specific implementation priorities should be interpreted considering firm-level capabilities and supply-chain conditions.

5. Conclusion

In today's uncertain global environment, supply chain disruptions are common. Pharmaceutical supply chains are particularly critical because disruption in medicine supply can affect public health and patient care. This study applies a structured BWM–ISM–MICMAC framework to identify, prioritize, and model the relationships among critical success factors (CSFs) for pharmaceutical supply chain resilience in Bangladesh. The study's contribution lies in applying an established methodological framework to a context characterized by high API import dependence, strict regulatory requirements, and pharmaceutical product criticality, and in translating the resulting structure into context-specific managerial implications.

Fourteen CSFs were identified: 11 from the literature and three additional CSFs from expert consultation. The combined BWM–ISM–MICMAC approach was then used to prioritize the CSFs and examine their structural interrelationships. Digital Integration (CSF7) received the highest global BWM weight (0.2125), followed by Flexibility in aligning different parts of the production process (CSF3) and Increased re-engineering to reduce downtime in the production lines (CSF9). The MICMAC analysis classified Digital Integration (CSF7), Existence of multiple viable sourcing options (CSF8), and Supplier Support after the disruptive event (CSF6) as driver CSFs. These findings provide the basis for the following Bangladesh-specific implications:

i) Digital integration should receive particular attention because CSF7 obtained the highest global BWM weight and was also classified as a driver in the MICMAC analysis. Relevant

actions include improving real-time information flows, inventory visibility, supply-and-demand forecasting, and access to regulatory information.

ii) Information sharing among departments should be strengthened to support coordinated decisions during disruptions, consistent with the role of CSF11 in the resulting structural model.

iii) Managers should develop adaptive and re-engineering capabilities, particularly because CSF9 ranked third in the BWM results and appears within the interconnected structure identified by the ISM analysis. At the same time, the dependence of CSF3 on other factors indicates that production flexibility should be supported through improvements in the underlying driver CSFs.

The combined BWM–ISM–MICMAC framework can therefore serve as a decision-support tool for structuring discussions about resilience-related resource allocation in the Bangladesh pharmaceutical supply chain. Its value is in showing both the relative importance of the CSFs and the relationships among them, rather than providing only a flat ranking.

This study has several limitations. First, although the SSIM was developed based on the judgments of a group of experts with relevant supply chain expertise, the structural assessment remains dependent on expert judgment. Therefore, the resulting ISM hierarchy and MICMAC classification should be interpreted as an expert-informed structural representation rather than as a universally generalizable causal structure. Second, the BWM comparison judgments from the 13 second-round experts were aggregated using arithmetic means, which provides a group-level representation but may mask heterogeneity among individual judgments. Future research could examine alternative aggregation procedures and assess the sensitivity of the results to expert

heterogeneity. Finally, the findings are based on expert judgment within the Bangladesh pharmaceutical context and could be further validated using empirical operational data or additional industry settings.

List of abbreviations

AHP: Analytic Hierarchy Process

API: Active pharmaceutical ingredient

BWM: Best–Worst Method

COVID-19: Coronavirus disease 2019

CSF: Critical success factor

ISM: Interpretive Structural Modeling

MCDM: Multi-criteria decision-making

MICMAC: Matrice d'Impacts Croisés Multiplication Appliqués à un Classement

PSC: Pharmaceutical supply chain

SCM: Supply chain management

SCR: Supply chain resilience

SMEs: Small and medium-sized enterprises

SSIM: Structural Self-Interaction Matrix

Declarations

Ethics approval and consent to participate

Data were collected in Bangladesh through anonymous opinion surveys of pharmaceutical supply chain professionals regarding organizational practices. The study involved no clinical

procedures, patient data, or collection of personal or sensitive information, and therefore did not require formal ethics committee approval under the applicable national and institutional guidelines. Participation was voluntary, and all experts provided informed consent.

Consent for publication

Not Applicable

Availability of data and material

The data and materials used in this study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

Funding

The authors received no specific funding for this research.

Authors' contributions

Faisal Mahmud conceived the research idea, developed the methodology, and performed all calculations.

Md. Tanvir Ahmmed Fahim contributed to manuscript writing, analysis, and revision.

Both authors read and approved the final manuscript.

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References

[1] I. Ali and I. Gölgeci, "Where is supply chain resilience research heading? A systematic and co-occurrence analysis," *Int. J. Phys. Distrib. Logist. Manag.*, vol. 49, no. 8, pp. 793–815, 2019.

[2] A. Charles, M. Lauras, L. N. Van Wassenhove, and L. Dupont, "Designing an efficient humanitarian supply network," *J. Oper. Manag.*, vol. 47, pp. 58–70, 2016.

[3] J. U. Haroon, "Pharma industry growth halves in 2020," *The Financial Express*, Jan. 09, 2021. [Online]. Available: https://thefinancialexpress.com.bd/trade/pharma-industry-growth-halves-in-2020-1610159516

[4] B. Walker *et al.*, "Resilience management in social-ecological systems: a working hypothesis for a participatory approach," *Conserv. Ecol.*, vol. 6, no. 1, 2002.

[5] C. K. Barnett and M. G. Pratt, "From threat-rigidity to flexibility-Toward a learning model of autogenic crisis in organizations," *J. Organ. Chang. Manag.*, vol. 13, no. 1, pp. 74–88, 2000.

[6] E. Hollnagel, D. D. Woods, and N. Leveson, *Resilience engineering: Concepts and precepts*. Ashgate Publishing, Ltd., 2006.

[7] G. Hamel and L. Valikangas, "The quest for resilience," *icade. Rev. la Fac. Derecho*, no. 62, pp. 355–358, 2004.

[8] J. Fiksel and J. R. Fiksel, *Resilient by design: Creating businesses that adapt and flourish in a changing world*. Island Press, 2015.

[9] S. Y. Ponomarov and M. C. Holcomb, "Understanding the concept of supply chain resilience," *Int. J. Logist. Manag.*, vol. 20, no. 1, pp. 124–143, 2009.

[10] N. P. Singh and S. Singh, "Building supply chain risk resilience: Role of big data analytics in supply chain disruption mitigation," *Benchmarking An Int. J.*, vol. 26, no. 7, pp. 2318–2342, 2019.

[11] M. Haque *et al.*, "Availability and price changes of potential medicines and equipment for the prevention and treatment of COVID-19 among pharmacy and drug stores in Bangladesh; findings and implications," *Bangladesh J. Med. Sci.*, vol. 19, pp. S36–S50, 2020.

[12] M. Reeves and K. Whitaker, "A guide to building a more resilient business," *Harv. Bus. Rev.*, pp. 2–8, 2020.

[13] I. Falagara Sigala and A. Maghsoudi, "Overview of the enablers of humanitarian supply chain resilience," in *Supply Chain Resilience: Insights from Theory and Practice*, Springer, 2022, pp. 325–336.

[14] T. Rahman, S. K. Paul, N. Shukla, R. Agarwal, and F. Taghikhah, "Supply chain resilience initiatives and strategies: A systematic review," *Comput. Ind. Eng.*, vol. 170, p. 108317, 2022.

[15] C. Yang, K. Tian, and X. Gao, "Supply chain resilience: Measure, risk assessment and

strategies," *Fundam. Res.*, vol. 5, no. 2, pp. 433–436, 2025.

[16] C. Zamiela, N. U. I. Hossain, and R. Jaradat, "Enablers of resilience in the healthcare supply chain: A case study of US healthcare industry during COVID-19 pandemic," *Res. Transp. Econ.*, vol. 93, p. 101174, 2022.

[17] J. Liu, B. Gu, and J. Chen, "Enablers for maritime supply chain resilience during pandemic: An integrated MCDM approach," *Transp. Res. Part A Policy Pract.*, vol. 175, p. 103777, 2023.

[18] H. Zhang, F. Jia, and J.-X. You, "Striking a balance between supply chain resilience and supply chain vulnerability in the cross-border e-commerce supply chain," *Int. J. Logist. Res. Appl.*, vol. 26, no. 3, pp. 320–344, 2023.

[19] M. S. Narassima, S. P. Anbuudayasankar, K. Mathiyazhagan, K. Ganesh, and T.-R. Lee, "Supply chain resilience: conceptual model building and validation," *Int. J. Logist. Res. Appl.*, vol. 27, no. 5, pp. 781–813, 2024.

[20] M. A. Moktadir, S. K. Paul, A. Kumar, S. Luthra, S. M. Ali, and R. Sultana, "Strategic drivers to overcome the impacts of the COVID-19 pandemic: implications for ensuring resilience in supply chains," *Oper. Manag. Res.*, vol. 16, no. 1, pp. 466–488, 2023.

[21] I. Ali, S. Nagalingam, and B. Gurd, "Building resilience in SMEs of perishable product supply chains: enablers, barriers and risks," *Prod. Plan. Control*, vol. 28, no. 15, pp. 1236–1250, 2017.

[22] R. Rajesh, "Measuring the barriers to resilience in manufacturing supply chains using Grey Clustering and VIKOR approaches," *Measurement*, vol. 126, pp. 259–273, 2018.

[23] G. Halkos, A. Skouloudis, C. Malesios, and K. Evangelinos, "Bouncing back from extreme weather events: Some preliminary findings on resilience barriers facing small and medium-sized enterprises," *Bus. Strateg. Environ.*, vol. 27, no. 4, pp. 547–559, 2018.

[24] T. Banerjee, A. Trivedi, G. M. Sharma, M. Gharib, and S. S. Hameed, "Analyzing organizational barriers towards building postpandemic supply chain resilience in Indian MSMEs: a grey-DEMATEL approach," *Benchmarking An Int. J.*, vol. 30, no. 6, pp. 1966–1992, 2023.

[25] V.-D.-V. Phan, Y.-F. Huang, T.-T. Hoang, and M.-H. Do, "Evaluating barriers to supply chain resilience in Vietnamese SMEs: The fuzzy VIKOR approach," *Systems*, vol. 11, no. 3, p. 121, 2023.

[26] N. Agarwal, N. Seth, and A. Agarwal, "Selecting capabilities to mitigate supply chain resilience barriers for an Industry 4.0 manufacturing company: An AHP-Fuzzy Topsis approach," *J. Adv. Manuf. Syst.*, vol. 21, no. 01, pp. 55–83, 2022.

[27] K. K. Dadsena, K. Mathiyazhagan, and A. Taghipour, "Analysis of barriers for the build the resilient supply chain networks post-COVID-19," in *Managing Supply Chain Risk and Disruptions: Post COVID-19*, Springer, 2021, pp. 79–89.

[28] D. R. Daniel, "Management information crisis," *Harv. Bus. Rev.*, pp. 111–121, 1961.

[29] J. Rockart, “The change of the information systems executive: A critical factor perspective,” *Sloan Sch. Manag.*, pp. 1–44, 1982.

[30] N. Singh, A. Dixit, and D. K. Ashish, “Modelling of critical success factors to improve the supply chain resilience for sustainable construction sector,” *Smart Sustain. Built Environ.*, vol. 14, no. 6, pp. 1846–1878, 2025.

[31] A. K. Pandey, Y. Daultani, and S. Pratap, “Blockchain technology enabled critical success factors for supply chain resilience and sustainability,” *Bus. Strateg. Environ.*, vol. 33, no. 2, pp. 1533–1554, 2024.

[32] H. Nozari, R. Tavakkoli-Moghaddam, and A. Dolgui, “Analysis of Critical Success Factors of Sustainable and Resilient Aioe-based Supply Chain in Industry 5.0,” in *IFIP International Conference on Advances in Production Management Systems*, Springer, 2024, pp. 76–90.

[33] B. Zahiri, J. Zhuang, and M. Mohammadi, “Toward an integrated sustainable-resilient supply chain: A pharmaceutical case study,” *Transp. Res. part e Logist. Transp. Rev.*, vol. 103, pp. 109–142, 2017.

[34] S. Zighan, N. Y. Dwaikat, Z. Alkalha, and M. Abualqumboz, “Knowledge management for supply chain resilience in pharmaceutical industry: evidence from the Middle East region,” *Int. J. Logist. Manag.*, vol. 35, no. 4, pp. 1142–1167, 2024.

[35] M. Haji, L. Kerbache, K. M. M. Sheriff, and T. Al-Ansari, “Critical success factors and traceability technologies for establishing a safe pharmaceutical supply chain,” *Methods Protoc.*, vol. 4, no. 4, p. 85, 2021.

[36] B. B. Dienes, D. Qorri, and J. Felföldi, “PHARMA SUPPLY CHAIN RESILIENCE. A SYSTEMATIC REVIEW,” *Appl. Stud. Agribus. Commer.*, vol. 18, no. 1, 2024.

[37] R. B. da Silva and C. A. de Mattos, “Critical success factors of a drug traceability system for creating value in a pharmaceutical supply chain (PSC),” *Int. J. Environ. Res. Public Health*, vol. 16, no. 11, p. 1972, 2019.

[38] S. Talapatra, M. H. Mashuk, H. U. Zaman, and M. J. Nayin, “Evaluating Supply Chain Resiliency Strategies in the Context of Bangladeshi Pharmaceutical Supply Chain: FUZZY-TOPSIS Approach”.

[39] J. Rezaei, “Best-worst multi-criteria decision-making method,” *Omega*, vol. 53, pp. 49–57, 2015.

[40] M. Mollaoglu and M. Gul, “A critical review of best–worst method applications in the transportation and logistics industry,” *LogForum*, vol. 21, no. 1, pp. 13–33, 2025, doi: 10.17270/J.LOG.001132.

[41] F. Ecer, “A state-of-the-art review of the BWM method and future research agenda,” *Technol. Econ. Dev. Econ.*, vol. 30, no. 4, pp. 1165–1204, 2024, doi: 10.3846/tede.2024.20761.

[42] F. Talib, Z. Rahman, and M. Qureshi, “Analysis of interaction among the barriers to total quality management implementation using interpretive structural modeling approach,”

Benchmarking, vol. 18, no. 4, pp. 563–587, 2011, doi: 10.1108/14635771111147641.

[43] S. Kadam and P. K. Bandyopadhyay, "Modelling passenger interaction process (PIP) framework using ISM and MICMAC approach," *J. Rail Transp. Plan. Manag.*, vol. 14, no. April 2019, 2020, doi: 10.1016/j.jrtpm.2019.100171.

[44] N. Mkedder and M. Das, "Metaverse integration challenges: An in-depth ISM and MICMAC analysis," *J. Retail. Consum. Serv.*, vol. 77, no. December 2023, p. 103684, 2024, doi: 10.1016/j.jretconser.2023.103684.

[45] N. Trendafilov and M. Gallo, *Multivariate data analysis on matrix manifolds*. 2021. [Online]. Available: https://link.springer.com/10.1007/978-3-030-76974-1

[46] S. Sorooshian, M. Tavana, and S. Ribeiro-Navarrete, "From classical interpretive structural modeling to total interpretive structural modeling and beyond: A half-century of business research," *J. Bus. Res.*, vol. 157, no. July 2022, p. 113642, 2023, doi: 10.1016/j.jbusres.2022.113642.

[47] K. Scholten, P. Sharkey Scott, and B. Fynes, "Building routines for non-routine events: supply chain resilience learning mechanisms and their antecedents," *Supply Chain Manag.*, vol. 24, no. 3, pp. 430–442, 2019, doi: 10.1108/SCM-05-2018-0186.

[48] M. Christopher, R. Lowson, and H. Peck, "Creating agile supply chains in the fashion industry," *Int. J. Retail Distrib. Manag.*, vol. 32, no. 8, pp. 367–376, 2004, doi: 10.1108/09590550410546188.

[49] R. R. Levary, "Ranking foreign suppliers based on supply risk," *Supply Chain Manag.*, vol. 12, no. 6, pp. 392–394, 2007, doi: 10.1108/13598540710826317.

[50] S. Aggarwal and M. K. Srivastava, "A grey-based DEMATEL model for building collaborative resilience in supply chain," *Int. J. Qual. Reliab. Manag.*, vol. 36, no. 8, pp. 1409–1437, 2019, doi: 10.1108/IJQRM-03-2018-0059.

[51] S. Kumar and R. Anbanandam, "An integrated Delphi – fuzzy logic approach for measuring supply chain resilience: an illustrative case from manufacturing industry," *Meas. Bus. Excell.*, vol. 23, no. 3, pp. 350–375, 2019, doi: 10.1108/MBE-01-2019-0001.

[52] Cynthia A. Challener, "Building Resilient Pharma Supply Chains in an Uncertain World," *pharmas almanac*, Mar. 31, 2025. [Online]. Available: https://www.pharmasalmanac.com/articles/building-resilient-pharma-supply-chains-in-an-uncertain-world

[53] Y. Sheffi and J. B. Rice, "A supply chain view of the resilient enterprise," *MIT Sloan Manag. Rev.*, vol. 47, no. 1, 2005.

[54] I. Gölgeci and O. Kuivalainen, "Does social capital matter for supply chain resilience? The role of absorptive capacity and marketing-supply chain management alignment," *Ind. Mark. Manag.*, vol. 84, no. May 2019, pp. 63–74, 2020, doi: 10.1016/j.indmarman.2019.05.006.

[55] M. Polyviou, K. L. Croxton, and A. M. Knemeyer, "Resilience of medium-sized firms to supply chain disruptions: the role of internal social capital," *Int. J. Oper. Prod. Manag.*,

vol. 40, no. 1, pp. 68–91, 2020, doi: 10.1108/IJOPM-09-2017-0530.

Appendix I:

Expert Profile

Role	Experience	Number of People
National Sales Manager	25+	02
Director of Healthcare Strategy	20+	03
Professor	23+	03
Deputy Country Director	15+	02
Senior manager (Quality Control)	15+	03
Supply Chain Analysts	12+	03
Assistant Manager, Supply Chain Management	10+	04
	Total	20