Journal of Logistics and Digital Supply Chain

Enhancing Supply Chain Resilience: A DEMATEL-Based Framework for Analyzing Performance Metrics

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Abstract

In today's rapidly evolving business landscape, ensuring supply chain resilience is paramount for organizational success. Resilient supply chains withstand disruptions and demonstrate agility by prompt recovery to mitigate adverse operational effects. Analyzing performance metrics for supply chain resilience is essential to understand the relationships between various factors, enabling strategic planning and implementation of preventive measures. This paper introduces a framework focused on analyzing factors related to supply chain resilience through a comprehensive suite of performance metrics. The Decision-Making Trial and Evaluation Laboratory (DEMATEL) method is renowned for analyzing the complex cause-and-effect relationships within systems. This study uses DEMATEL to meticulously delineate the interdependencies among performance metrics, facilitating a nuanced understanding of their relationships. Furthermore, cause-and-effect analysis reveals the insightful influences among diverse performance factors, elucidating how each impacts the overall resilience of the supply chain. To demonstrate the practical application of the proposed framework, we present a numerical example that validates our methodology and illustrates its potential benefits for industry practitioners. In a numerical example, a structured questionnaire was designed to collect primary data from experts in the field. The questionnaire was distributed in April, 2024, targeting professionals with extensive experience in supply chain management and risk assessment. The findings underscore the significance of supply chain collaboration as a critical factor influencing resilience. Other factors, such as flexibility, information sharing, and top management support, also play pivotal roles. The study organizes these factors into cause and effect groups—with collaboration, flexibility, information sharing, and top management support in the cause group, and agility, visibility, trust within partners, and big data in the effect group—thereby offering valuable insights into the interdependencies that shape overall supply chain resilience.

Keywords: Performance metrics; Supply chain resilience; Decision-Making Trial and Evaluation Laboratory (DEMATEL)

Received: August 30, 2024; Revised: September 19, 2024; Accepted: September 23, 2024

1. INTRODUCTION

In an era of escalating global uncertainties, supply chain disruptions have become more frequent and severe, driven by events such as natural disasters, economic instability, and global pandemics. For example, the COVID-19 pandemic in particular highlighted the fragility of global supply chains, prompting organizations to reevaluate their resilience plan (Hafner & Tagliapietra, 2020).Such planning enables organizations and stakeholders to adapt to the unpredictable dynamics of the global market and maintain competitive advantage (Nikookar et al., 2024).

Supply chain resilience significantly influences an organization's ability to respond to disruptions swiftly and effectively, thereby minimizing downtime and financial losses. This concept is about enduring disruptions and demonstrating agility by promptly recovering to mitigate adverse effects on operations. Such agility enables the continuation of operations with minimal impact on production, transportation, and overall customer satisfaction. It ensures that the organization can maintain operational continuity, adapt quickly to unforeseen challenges, and sustain its market position despite external pressures.

However, achieving true resilience involves complex processes and requires collaboration among various stakeholders, making the measurement and assessment of performance characteristically challenging. Traditional performance measurements may not always be applicable due to their different focus; resilience metrics require a unique approach that encompasses the complicated nature of supply chain dynamics and the collaborative efforts needed to maintain and enhance resilience. This complexity necessitates developing specific tools and methods that can accurately reflect the resilience capacity of the supply chain in response to various types of disruptions. Additionally, it's important to consider how resilience-related performance factors can influence each other. For instance, enhancing flexibility in the supply chain might increase costs, while improving visibility could impact process-related factors. Understanding these interrelationships is necessary, as they play a significant role in the overall efficacy and sustainability of resilience strategies. Therefore, focusing on these dynamics and their interdependencies should be a priority in the development and implementation of resilience measures.

Hence, the study aims at enhancing the understanding and resilience of supply chains by identifying and analyzing the interrelationships among key performance factors. There are two steps. The first step involves identifying key performance factors essential for evaluating and enhancing supply chain resilience, which is informed by an extensive review of literature and expert consultations. The subsequent step employs the DEMATEL method to assess the interdependencies among these factors. To illustrate the application of this framework, an example is provided using primary factors and numerical data. The expected results and the analysis methodology are also detailed.

2. LITERATURE REVIEW

2.1 Performance metrics in supply chain resilience

The uncertain and intensified competitive landscape in today's global market presents a multitude of disruptions to supply chains. The first widespread study of supply chain resilience began in the United Kingdom following transportation disruptions caused by fuel protests in 2000 and the outbreak of Foot and Mouth Disease in early 2001 (Britain, 2003; Pettit, 2008). After then, the COVID-19 pandemic in 2020 further underscored the importance of supply chain resilience on a global scale. It exposed critical weaknesses in supply chains worldwide, as many industries faced unprecedented disruptions due to lockdowns, travel restrictions, and fluctuating demand. Supply chain resilience refers to the ability of a supply chain to prepare for unexpected disruptions, respond to disruptions while maintaining continuity of operations at desired levels of connectedness and control over structure and function, and recover from them by regaining a desired state of connectedness and control (Ali & Gölgeci, 2019; Ke et al., 2023).

Supply chain resilience fundamentally depends on several critical performance factors that enable organizations to respond effectively to disruptions and maintain operational continuity. These factors not only aid in identifying vulnerabilities within the supply chain but also facilitate the development of strategies to mitigate risks effectively. Among these, collaboration is pivotal, as it fosters strong relationships between suppliers, manufacturers, and distributors, facilitating rapid responses to supply chain challenges (Ali & Gölgeci, 2019; Jain et al., 2017; Kamalahmadi & Parast, 2016). Similarly, flexibility in the supply chain allows companies to adapt their operations dynamically to changing conditions, such as demand fluctuations or supply interruptions(Ali & Gölgeci, 2019; Hosseini et al., 2019). This adaptability is supported by agility, which refers to the speed at which a supply chain can respond to external changes and recover from disruptions (Kamalahmadi & Parast, 2016; Yadav & Samuel, 2022). Agility helps in quickly rerouting supplies, altering production schedules, or finding alternative resources, minimizing the impact on service levels and customer satisfaction(Chowdhury & Quaddus, 2016; Yadav & Samuel, 2022).

Enhanced visibility across the supply chain is another essential factor that contributes to resilience by providing all stakeholders with timely and accurate information about inventory levels, shipment statuses, and production schedules (Hosseini et al., 2019; Kochan & Nowicki, 2018; Qureshi et al., 2023). This transparency is critical during disruptions, enabling more informed decision-making and better risk management. Complementing visibility and information sharing among supply chain partners plays a crucial role. Effective communication mechanisms ensure that all relevant data concerning potential threats or opportunities are shared in real-time (Liu et al., 2021; Yazdanparast et al., 2021). This facilitates a unified approach to managing risks and harnessing opportunities, thereby strengthening the overall resilience of the supply chain.

In this research, we will initially focus on these five performance factors; collaboration, flexibility, visibility, agility, and information sharing; as the primary framework. This selection is based on their demonstrated impact on enhancing supply chain resilience. By analyzing and improving these core factors, the study aims to comprehensively understand how they interact and contribute to supply chain resilience, providing valuable insights for further strategic developments.

2.2 DEMATEL

The DEMATEL method, developed by Gabus and Fontela, effectively resolves complex system challenges by utilizing a matrix to analyze interrelationships among system elements through causal diagrams (Zolfani & Ghadikolaei, 2013). This approach excels in addressing problems characterized by feedback loops and interdependencies within systems (Hung et al., 2012). The method is widely used to identify related factors across various fields, such as the manufacturing industry (Singh et al., 2021), sustainable supply chain management (Lin et al., 2018), business strategy (Acuña-Carvajal et al., 2019), and construction sites (Seker & Zavadskas, 2017). He et al. (2021) who applied DEMATEL to determine the risk factors in sustainability supply chains, highlighting the method's utility in deciphering the interrelationships and providing a roadmap for mitigating risks in a more strategic and informed manner. Hatem et al. (2019) used DEMATEL to assess the significance of vulnerability factors and build causal relationships between the most critical factors for better targeting and implementation of resilience and increased efficiency. By identifying key factors and clarifying their directional influences, DEMATEL equips supply chain managers with crucial insights to enhance resilience, responsiveness, and efficiency. The method not only aids in strategic decision-making but also improves understanding of system dynamics, helping managers optimize operations and improve overall performance.

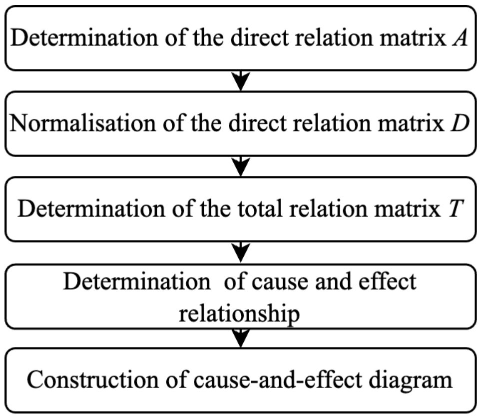

Figure 1 DEMATEL steps

The DEMATEL method's procedural steps are organized as shown in Figure 1. Initially, the relationship of each performance factor is evaluated through a questionnaire that utilizes a Likert scale ranging from 0 (no influence) to 4 (most influence). This questionnaire is distributed to field experts who assess the importance of each factor. The collected data are then averaged and compiled into the direct relation matrix A, as detailed in equation (1) in Table 1. Following this, matrix A is normalized to create the normalized direct relation matrix D, according to equation (2) in Table 1. Subsequently, the total relation matrix T is derived from matrix D using equation (3) in Table 1. The next step involves calculating the sums of the rows (Di) and columns (Rj) within matrix T to determine the importance and prominence of each factor as either a cause or an effect. The importance of the factors is determined by the value of Di + Rj, i=j; a higher number indicates greater importance. The prominence of each factor is determined by Di - Rj, i=j. If Di - Rj > 0, factor i is identified as a cause factor. Conversely, if Di - Rj < 0, factor i is identified as an effect factor. Finally, the cause-and-effect diagram is constructed, visually representing these relationships, and facilitating the prioritization and categorization of the performance factors based on their influence and impact.

Table 1 Description of matrixes in DEMATEL

Matrix	**Formula**	**Equation**
The direct relation matrix *(A)*	$a_{ij} = \frac{1}{k}\sum_{k=1}^{k} x_{ij}$	(1)
The normalized direct relationship matrix *(D)*	$D = \frac{1}{max \prec i \prec n \sum_{j=1}^{n} a_{ij}} A$	(2)
The total relation matrix *(T)*	$T = D(I - D)^{-1}$	(3)
The sum of the rows of the total relation matrix	$D = (D_i)_{n*1} = \left[\sum_{j=1}^{n} a_{ij}\right]_{n*1}$	(4)
The sum of the columns of the total relation matrix	$R = (R_i)_{n*1} = \left[\sum_{j=1}^{n} a_{ij}\right]_{1*n}$	(5)

Where:

A: $[a_{ij}]$ indicates the crisp direct impact value of factor i on factor j;

k: number of experts;

x_{ij}: the experts' assessments concerning the influence of factor i on factor j on each matrix;

D_i: the sum of i^{th} row in total influence matrix T, then D_i aggregating both direct and indirect effects given by factor i to the other factors;

R_j: the sum of j^{th} column in total influence matrix T, then R_j shows both direct and indirect effects by factor j from the other factors.

3. METHODOLOGY

To conduct the proposed framework, the methodology is shown in Figure 2.

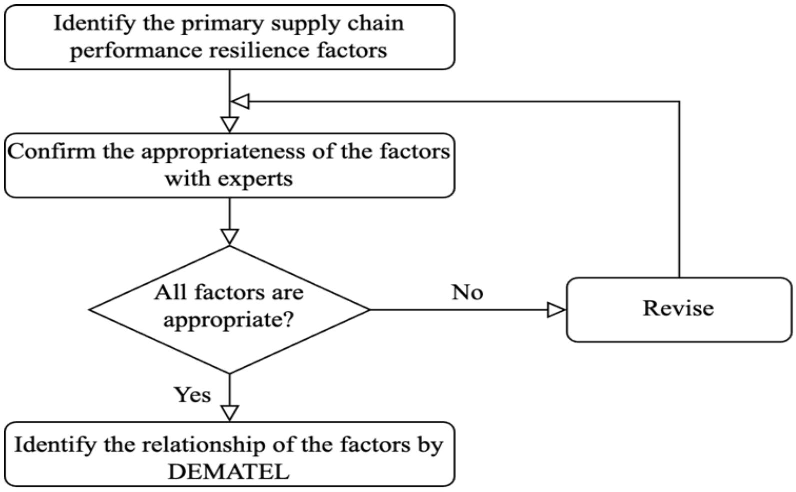

Fig. 2. The flow of methodology

The literature review initially identified the primary supply chain performance resilience factors. The performance metrics were identified through an exhaustive review of the literature, concentrating on prior research within the domains of supply chain management. In this paper, the review covered publications from the period 2010 to 2023, employing keywords like "performance metrics," "supply chain resilience," "performance factors". These factors are then reviewed with experts to confirm their appropriateness for assessing and enhancing resilience in the supply chain. If all factors are deemed appropriate, the process moves forward; if not, the factors are revised based on expert feedback. Once the factors are finalized, the DEMATEL method is employed to identify and analyze the relationships among these factors. This step is imperative as it helps to understand how different factors influence each other, thereby providing insights into key leverage points for improving resilience.

4. PRIMARY PERFORMANCE FACTORS AND A NUMERICAL EXAMPLE

This section presents the results and a numerical example. The initial step involves identifying primary supply chain performance resilience factors. This paper identifies eight primary factors commonly referenced in the literature, as outlined in Table 2. The table comprises three columns detailing the factors, their definitions, and the corresponding references, providing a structured overview of the foundational elements considered in this study.

Table 2 Primary Performance Factors

Performance Factors	Symbols	Definition	References
Supply chain collaboration	PF 1	The cooperative capability of supply chain members to achieve common goals and respond promptly to supply chain interruptions.	(Chowdhury & Quaddus, 2017; Han et al., 2020; Hohenstein et al., 2015; Jain et al., 2017; Kamalahmadi & Parast, 2016; Razmi et al., 2017; Sarker et al., 2023)

Table 3 (*continued*)

Performance Factors	Symbols	Definition	References
Supply chain flexibility	PF 2	The adaptability of the supply chain to swiftly meet the demands of its stakeholders and environmental conditions.	(Ali & Gölgeci, 2019; Chen & Huang, 2022; Hosseini et al., 2019; Kamalahmadi & Parast, 2016; Kochan & Nowicki, 2018; Qureshi et al., 2023; Razmi et al., 2017)
Supply chain agility	PF 3	The responsiveness to economic changes.	(Chowdhury & Quaddus, 2017; Kamalahmadi & Parast, 2016; Pettit et al., 2010; Razmi et al., 2017; Sarker et al., 2023; Yadav & Samuel, 2022)
Supply chain visibility	PF 4	The transparency of upstream and downstream inventory, demand, supply conditions, and production and procurement plans.	(Ali & Gölgeci, 2019; Hosseini et al., 2019; Jain et al., 2017; Kochan & Nowicki, 2018; Qureshi et al., 2023; Razmi et al., 2017; Stone & Rahimifard, 2018)
Information sharing	PF 5	The real-time exchange of critical data concerning potential threats to mitigate disruptions and their impacts.	(Ali & Gölgeci, 2019; Hosseini et al., 2019; Jain et al., 2017; Kamalahmadi & Parast, 2016; Naghshineh & Lotfi, 2019; Siagian et al., 2021).
Trust within partners	PF 6	The effective sharing of information on planning, production, and distribution by partners to mitigate the bullwhip effect.	(Chowdhury & Quaddus, 2016; Jain et al., 2017; Liu et al., 2021; Razmi et al., 2017; Yazdanparast et al., 2021)
Top management support	PF 7	The explicit support and involvement from organizational top leadership.	(Ali & Gölgeci, 2019; Das et al., 2022; Han et al., 2020; Qureshi et al., 2023).
Big data	PF 8	The extensive generation of structured and unstructured data across the supply chain, providing insights for enhanced decision-making and performance improvement.	(Dubey et al., 2020; Papadopoulos et al., 2017; Zhang et al., 2023)
Market position	PF 9	The relative position and status of a business or product compared to competitors in a specific market.	(Ali & Gölgeci, 2019; Han et al., 2020; Hosseini et al., 2019; Singh et al., 2019; Yazdanparast et al., 2021)

Table 4 (*continued*)

Performance Factors	Symbols	Definition	References
Artificial intelligence	PF 10	The focus on making computer systems perform tasks that typically require human intelligence.	(Belhadi et al., 2021; Gupta et al., 2021; Priyadarshini et al., 2022; Wang et al., 2023; Zhang et al., 2023)

In this study, all identified factors will undergo validation by experts across various related disciplines. To validate factors, a Likert scale (ranging from 1, signifying 'least significant,' to 5, indicating 'absolutely most significant') is employed within the questionnaires. These questionnaires are scattered among field experts who provided their assessments regarding the significance of various performance factors. Table 3 details the experts who participated in this study. A response rate of 70% or above indicates high positivity among experts (Fowler Jr, 2013; Sumsion, 1998; Zhang et al., 2022). five experts give their opinion on the importance level of the performance factors. The response rate is 100%, which is enough for further analysis. A mean value greater than 3 indicates significant performance factors (Koo & Li, 2016). For example, for PF 1, the scores of five experts are 4, 5, 5, 5, and 5. Subsequently, the mean and standard deviation are calculated to be 4.80 and 0.447, respectively. Given that the mean exceeds 3, this factor is considered significant for the performance assessment. In this study, it is posited that only eight factors, designated as PF 1 through PF 8, are deemed necessary for further analysis as shown in Table 4.

Table 3 The details of the experts who participated in this study

Experts	Years of work experience	Educational level	Academic position	Focus on field
A	25 years or more	Ph.D	Professor	Supply chain management and logistics
B	10-15years	MS	Associate professor	Supply chain management and logistics
C	10-15years	Ph.D	Associate professor	Supply chain management and logistics
D	10-15years	MS	Lecturer	Supply chain management and logistics
E	3- 5-years	Ph.D	Lecturer	Supply chain management and logistics

Table 4 The mean value and standard deviation for validating the performance factors

Performance factors	Mean	Standard Deviation	Significant result
PF 1	4.800	0.447	Yes
PF 2	4.600	0.548	Yes
PF 3	4.000	1.732	Yes
PF 4	3.600	1.140	Yes
PF 5	4.400	0.548	Yes
PF 6	4.600	0.548	Yes
PF 7	3.400	1.140	Yes
PF 8	4.000	1.000	Yes
PF 9	2.750	0.477	No
PF 10	2.980	0.548	No

Utilizing Equation (1), the direct-relation matrix (A) that consists of aij, is presented in Table 5. For example, considering the relationship between PF 1 and 2, five experts provided scores of 3, 4, 4, 4, and 3. These scores are then averaged to calculate a12, which is highlighted in grey in Table 5. The element a12 is calculated as follows:

$$a_{12} = \frac{3+4+4+4+3}{5}$$
$$= 3.6$$

All other elements a_{ij} in the matrix are calculated in the same manner. Subsequently, the normalized initial direct relation matrix (D) is derived using Equation 2, as illustrated in **Table 6**. The total influence matrix (T) is then calculated employing Equation 3, and its details are depicted in Table 7. The summation of the elements within each row of the total relation matrix (D_i) and the summation of the components across the columns of the total relation matrix (R_j) are computed utilizing Equation (4). Then the importance and prominence of each factor are determined and demonstrated in **Table** . Finally, a cause-and-effect diagram is constructed, as displayed in Figure 2.

Table 5 The direct-relation matrix (A)

PF	PF 1	PF 2	PF 3	PF 4	PF 5	PF 6	PF 7	PF 8
PF 1	0.000	3.600	3.600	3.000	3.200	2.600	3.000	3.400
PF 2	3.200	0.000	3.600	3.400	3.600	3.000	2.800	3.000
PF 3	3.400	3.000	0.000	3.000	3.200	3.200	2.200	2.800
PF 4	2.800	2.400	2.400	0.000	3.400	2.400	2.000	2.800
PF 5	2.800	2.600	2.600	2.600	0.000	3.800	3.200	3.000
PF 6	2.800	2.800	3.000	3.200	2.800	0.000	1.800	2.600
PF 7	3.000	2.800	2.800	3.000	2.400	2.800	0.000	3.400
PF 8	2.600	2.400	3.000	2.200	2.600	2.600	2.800	0.000

Table 6 The normalized the initial direct relation matrix (D)

PF	PF 1	PF 2	PF 3	PF 4	PF 5	PF 6	PF 7	PF 8
PF 1	0.000	0.159	0.159	0.133	0.142	0.115	0.133	0.150
PF 2	0.141	0.000	0.159	0.150	0.159	0.133	0.124	0.133
PF 3	0.150	0.133	0.000	0.133	0.142	0.142	0.097	0.124
PF 4	0.124	0.106	0.106	0.000	0.150	0.106	0.088	0.124
PF 5	0.124	0.115	0.115	0.115	0.000	0.168	0.142	0.133
PF 6	0.124	0.124	0.133	0.142	0.124	0.000	0.080	0.115
PF 7	0.133	0.124	0.124	0.133	0.106	0.124	0.000	0.150
PF 8	0.115	0.106	0.133	0.097	0.115	0.115	0.124	0.000

Table 7 The total relation matrix (T)

PF	PF 1	PF 2	PF 3	PF 4	PF 5	PF 6	PF 7	PF 8	D_i
PF 1	1.084	1.175	1.241	1.190	1.239	1.180	1.070	1.232	9.411
PF 2	1.214	1.043	1.246	1.210	1.259	1.201	1.068	1.224	9.466
PF 3	1.145	1.088	1.032	1.121	1.167	1.132	0.981	1.140	8.807
PF 4	1.008	0.956	1.010	0.889	1.055	0.990	0.873	1.023	7.804
PF 5	1.110	1.061	1.121	1.094	1.027	1.139	1.003	1.133	8.688
PF 6	1.044	1.004	1.067	1.049	1.071	0.928	0.895	1.051	8.109
PF 7	1.101	1.052	1.112	1.091	1.108	1.087	0.865	1.131	8.545
PF 8	1.003	0.958	1.033	0.980	1.028	0.997	0.901	0.914	7.813
R_j	8.709	8.337	8.862	8.622	8.954	8.654	7.656	8.848	

Table 8 The cause-and-effect groups of performance factors

Performance factor	D_i	R_j	D_i+R_j	D_i-R_j	CAUSE OR EFFECT
PF 1	9.411	8.709	18.120	0.701	CAUSE
PF 2	9.466	8.337	17.803	1.129	CAUSE
PF 3	8.807	8.862	17.669	-0.055	EFFECT
PF 4	7.804	8.622	16.426	-0.818	EFFECT
PF 5	8.688	8.954	17.642	-0.266	EFFECT
PF 6	8.109	8.654	16.763	-0.545	EFFECT
PF 7	8.545	7.656	16.201	0.890	CAUSE
PF 8	7.813	8.848	16.661	-1.035	EFFECT

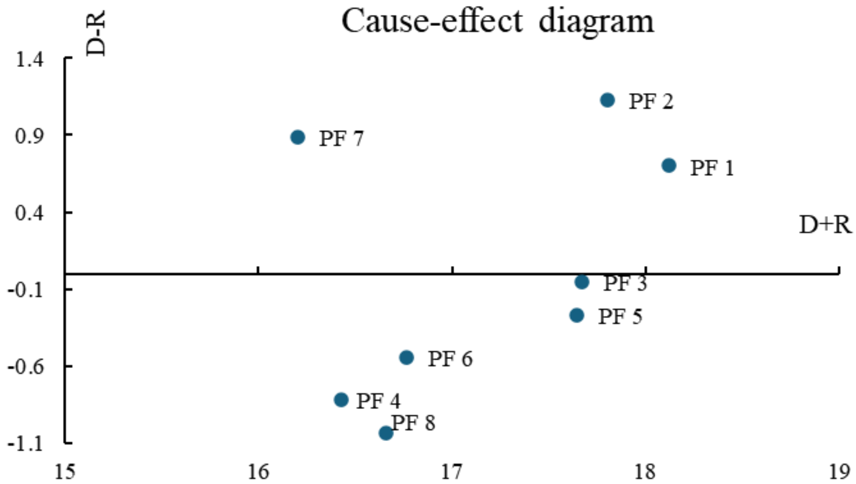

Figure 2 The cause-and-effect diagram

5. RESULTS AND DISCUSSION

As illustrated in Table , the importance ratings of the performance factors are shown in column 4, with supply chain collaboration (PF 1) receiving the highest rating of 18.120, indicating greater importance than the other factors. The order of importance is as follows: PF 1, PF 2, PF 3, PF 5, PF 6, PF 8, PF 4, and PF 7. The prominence of each factor, indicated by the values of Di-Rj, is displayed in columns 5 and 6. PF 1, PF 2, PF 5, and PF 7, having positive Di-Rj values, are categorized into a cause group. Among these, PF 1 exhibits the highest value, emphasizing its significant influence in facilitating inter-organizational cooperation and coordination (Scholten & Schilder, 2015). This positioning enhances an organization's ability to manage and respond to both external and internal pressures, thus improving overall responsiveness and stability (Sarker et al., 2023). This factor should be prioritized for further development or continued support to maintain or enhance its positive impact. Conversely, PF 3, PF 4, PF 5, PF 6, and PF 8, with negative values of Di-Rj (-0.055, -0.818, -0.266, -0.545, -1.035, respectively), belong to the effect group. Within this group, PF 8, PF 4, and PF 6 are more influenced by other factors than they affect others. Notably, PF 8, with the lowest score of -1.035, plays a critical role within the framework of supply chain resilience, highlighting both opportunities and challenges in enhancing the responsiveness of supply chain operations.

This analysis not only underscores the importance of each performance metric but also guides strategic interventions. For metrics in the cause group, efforts should focus on enhancing their influential capacity. For those in the effect group, strategies should aim to bolster resilience and mitigate vulnerabilities, thus enhancing the overall efficacy and adaptability of the supply chain system.

6. CONCLUSION

The complex structure of supply chain resilience complicates its performance evaluation system. Providing a clearer view of performance to all stakeholders involved is necessary for effective management and improvement efforts. This research has introduced a method to identify the importance and interrelationships of each performance factor by employing an expert system coupled with the DEMATEL method. A step-by-step approach and a numerical example have been presented to ensure a clear understanding of the process. The proposed framework facilitates straightforward application within actual systems, allowing users to integrate and apply these methodologies in real-world scenarios easily. However, as with any research, this study has several limitations. The primary focus of the analysis was on key performance factors, without delving deeply into secondary or less apparent factors that may also impact supply chain resilience. While the focus on primary factors provides valuable insights, the exclusion of these secondary factors may limit the comprehensiveness of the framework. Supply chain resilience is a complex and multi-dimensional concept, and overlooking potentially influential yet less prominent factors could result in an incomplete evaluation.

Additionally, it is important to recognize that the impact of performance factors on supply chain resilience may vary significantly across different industries and supply chains. The factors identified as primary in this study may not hold the same level of importance in other contexts, and their relative influence may fluctuate based on the unique characteristics of each supply chain. This variability highlights another limitation of the framework—while it provides a useful general overview, it may not fully capture the nuances specific to different industries or supply chain structures.

The results of this study were obtained through a methodology that serves as a valuable starting point for understanding the dynamics of supply chain resilience. However, future research should aim to address these limitations by incorporating a broader range of performance factors, including secondary ones, and by applying the framework to more diverse supply chain environments. By doing so, the analysis will become more robust and better equipped to offer tailored recommendations for enhancing resilience across various industries.

In conclusion, while the proposed DEMATEL-based framework offers a practical tool for assessing supply chain resilience, its focus on primary performance factors and the use of hypothetical numerical examples for illustration call for further exploration. Future work should expand the scope of the analysis to include a more comprehensive set of factors and test the framework across different supply chain contexts to improve its generalizability and applicability.

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