Supply Chain Competencies and Strategies for Resilience: Post-COVID-19 Scenario for a High-Value Manufacturing Industry

Abstract

Purpose – This study identifies and analyses the critical core competencies and strategies required to build supply chain resilience for a high-value manufacturing industry – industrial valve manufacturer.

Design/methodology/approach – Initially, nine core competencies and nine strategies for establishing supply chain resilience during the post-COVID-19 era are identified through literature. A neutrosophic analytical hierarchy process (NAHP) is utilised to evaluate the relative weights of all strategies and competencies. Later, the strategies and competencies are prioritised according to their relative weight to determine the most critical strategies and competencies for the firm under study.

Findings – The findings from the study revealed that to achieve supply chain resilience, "operations & risk management and circular and leagile supply chain" are the essential competencies the firm under study should possess. While "creating resilient supply chain actors/stages and bringing sustailient operations" are the critical strategies the case should adopt under study.

Research Implications – The authors manifest the key role of the core competencies of resilience and the critical strategies required for building resilience in a high-value manufacturer using the case of industrial valve manufacturers.

Originality/value – The novelty of this work is associated with the consideration of the type of industry, i.e. high-value manufacturer. This is the early attempt in the body of knowledge to demonstrate the core competencies and strategies that are required to build supply chain resilience for a high-value manufacturer.

Keywords – Supply chain resilience, Core Competencies, Resilient Strategies, Post-COVID-19 era, Neutrosophic AHP, High-Value Manufacturer

1 Introduction

The COVID-19 pandemic has significantly disrupted global supply chains, exposed their vulnerabilities and highlighted the critical importance of supply chain resilience (Liu *et al.*, 2023; Sharma *et al.*, 2021a; Shih, 2020). Organisations across industries faced unprecedented challenges, such as sudden demand fluctuations, supply shortages, transportation disruptions, labour shortages, and lockdown measures (Dohale, Ambilkar, Gunasekaran and Verma, 2022; Ivanov and Dolgui, 2020; Tröster and Küblböck, 2020). The impact of these challenges repercussed even after the coronavirus pandemic, causing industries to struggle to achieve their desired goals. These disruptions have underscored the need for organisations to enhance their supply chain management competencies and implement robust strategies to navigate future crises effectively by bringing resilience in their SC structure (Dohale, Verma, Gunasekaran and Ambilkar, 2023; Islam *et al.*, 2023; Paul *et al.*, 2023).

In this context, the industrial valve manufacturers, i.e. hydraulic and pneumatic valve manufacturing industry, which plays a crucial role in various sectors like manufacturing, oil and gas, and automotive, have experienced significant disruptions due to the pandemic (Nayak *et al.*, 2022; Raj *et al.*, 2023). Over 60 countries are majorly involved in the industrial oil and gas valve markets (Resolute Research, 2017). Projections indicate that the size of the worldwide Industrial Valves Market could attain USD 99.8 billion by 2028, building upon an estimated valuation of USD 80.4 billion in 2023 at a compounded annual growth rate (CAGR) of 4.4% (Markets and Markets, 2023). Meanwhile, the Indian Industrial Valve market is expected to cross USD 3 billion by 2023 (The Economic Times, 2018). However, the disruption due to the COVID-19 pandemic resulted in a sharp drop in the demand for oil and gas, automotive, industrial equipment, etc., resulting in the overall reduction of the production of industrial valve manufacturers (Research and Markets, 2023). The post-pandemic situations for industrial valve manufacturers are more or less similar, and it took huge efforts for them to revamp again. However, the struggle continues for them till now. The fluctuations in demand and supply led the industrial valve manufacturer to rethink their operations in an entire value chain and highlighted the urgent need for organisations in this industry to enhance their supply chain resilience to effectively navigate future crises (Emenike and Falcone, 2020; Piya *et al.*, 2022).

Supply chain resilience encompasses the integration of various supply chain management competencies and strategies to build a robust and agile supply network capable of withstanding and mitigating the impact of disruptions (Liu *et al.*, 2023; Raj *et al.*, 2022). This study explores the effective supply chain management competencies and strategies to bolster supply chain resilience in the post-COVID-19 era, focusing specifically on the industrial valve manufacturer, i.e. a high-value manufacturing industry. To achieve the aim of the present research work, this study seeks to answer the following research questions:

RQ 1. What are the key supply chain management competencies required for enhancing supply chain resilience in the post-COVID-19 era in industrial valve manufacturers?

RQ 2. What strategies can industrial valve manufacturers employ to enhance supply chain resilience in the face of future disruptions?

RQ 3. How can the identified supply chain resilience strategies and competencies be evaluated to determine critical ones for the industrial valve manufacturing industry?

We formulated a quantitative framework based on Neutrosophic AHP (NAHP) to address the aforementioned research questions. Initially, we determined the core competencies and strategies required for building supply chain resilience through literature. We considered a real-life case of an industrial hydraulic valve manufacturing company from India to illustrate the implementation of the NAHP framework. We analysed the competencies and strategies by evaluating their priority weightage through NAHP using industry experts' feedback to identify the critical strategies and competencies required for supply chain resilience at the firm.

The remainder of this article is organised in the following manner. A review of the relevant literature on supply chain resilience post-pandemic is discussed in Section 2. Section 3 details the proposed research framework and solution methodology – NAHP utilised in this study. An application of the proposed decision-making framework in a real-life case of an industrial valve manufacturer and its results are presented in Section 4. The concluding remarks, limitations, and suggested scope for future work are drawn in Section 5.

2 Literature Review

In the context of today's interconnected and volatile business environment, supply chain resilience has emerged as a critical concept for organisations aiming to ensure continuity and competitiveness. As disruptions become more frequent and impactful, scholars and practitioners alike have turned their attention to understanding and enhancing supply chain resilience strategies. In this context, the following section delves into the significance of supply chain resilience, elucidating its multi-dimensional aspects and profound implications for modern organisations.

2.1 The Changing Landscape: Importance of Supply Chain Resilience

Supply chain resilience involves building a system that can withstand and recover from disruptions, ranging from sudden demand shifts, supply shortages, natural or manmade disasters, geopolitical events, and economic crises to unexpected technological issues (Dohale, Verma, Gunasekaran and Ambilkar, 2023). Different scholars discussed and provided their interpretations and definitions of supply chain resilience. Al-Banna *et al.* (2023) compiled the definitions of supply chain resilience provided in various studies. The commonality of these definitions signifies the interpretation of supply chain resilience as "an organisation's capacity to anticipate, respond to, recover from, and adapt to disruptions, challenges, and uncertainties within its supply chain network while maintaining essential operations, minimising negative impacts, and preserving customer satisfaction" (Pettit *et al.*, 2010a).

Supply chain resilience has gained extensive interest since the attack of the COVID-19 pandemic across the globe that not only resulted in the loss of millions of lives but also halted the entire world (Dohale, Verma, Gunasekaran and Ambilkar, 2023; Remko, 2020). The COVID-19 pandemic has underscored the importance of resilient supply chains that adapt and thrive in unprecedented disruptions (Tröster and Küblböck, 2020). Whereas, in post-COVID-19, the focus should shift from merely resilient supply chains to crafting enduring ones. The enduring nature of a supply chain's survival can be accomplished by integrating supply chain resilience strategies with competencies. Post-COVID-19 era resilient supply chains must evolve into survivable ones (Sarkar *et al.*, 2022). Thus, organisations across industries are reevaluating their supply chain management competencies and strategies to enhance resilience (Islam *et al.*, 2023; Liu *et al.*, 2023; Paul *et al.*, 2023). This involves the dynamic harmonisation, integration, and enhancement of competencies, strategies, resources, and overall capacities (Islam *et al.*, 2023; Liu *et al.*, 2023).

Considering High-value manufacturing (HVM) firms, they typically involve complex, precision-based production processes, low-volume but high-cost products, and high customisation, often operating in tightly regulated markets (Sminia *et al.*, 2019). These characteristics necessitate distinct resilience competencies such as stringent quality assurance, supplier specialisation, and technological maturity. Unlike broader manufacturing, HVM is highly sensitive to disruptions and risks due to its intricate nature, longer lead times to produce precision products and capital intensity. Disruptions at any stage of the supply chain of HVM can collapse an entire value chain of HVM.

Supply chain resilience is paramount in anticipating potential risks, assessing their impact, and implementing effective risk mitigation strategies for maintaining operational continuity during and post-disruptions (Christopher and Peck, 2004; Klöckner *et al.*, 2023; Paul *et al.*, 2023). Many researchers attempted to develop studies on this conjecture. Table 1 enlisted the research conducted on supply chain resilience in post-COVID-19 situations.

Table 1. Existing studies on Supply Chain Resilience in Post-Covid-19 situations

#	Author	Contribution	Method	Sub- method
1	(Spieske *et al.*, 2023)	This study provides empirical evidence to navigate Industry 4.0 applications in supply chain risk management post-COVID-19 by impactfully implementing key areas like technology, data generation, visibility, digital capability, and information sharing to enhance supply chain resilience.	Survey	Delphi
2	(Nikookar and Yanadori, 2022)	This study empirically establishes the supply chain managers' impact and their social capital on enhancing supply chain resilience.	Statistical Model	Regression Model
3	(Remko, 2020)	This study identifies research opportunities in areas like supply chain designing models, sourcing strategies, supplier segmentation, and talent management of supply chain resilience in COVID-19.	Survey	Interviews
4	(Paul *et al.*, 2023)	This study highlights the significance of supply chain resilience and sustainability practices in the post-COVID-19 era and provides strategic formulation to supply chain decision-makers.	Survey	Interviews
5	(Islam *et al.*, 2023)	This study proposes a hierarchical model of critical supply chain competencies to enhance supply chain resilience, particularly in the post-COVID era of the garment industry in Bangladesh.	MCDM	Fuzzy importance and performance analysis + Fuzzy Delphi
6	(Ayyildiz, 2021)	This study provides a set of comprehensive criteria for practitioners and managers to enhance supply chain resilience and sustainability in the post-COVID-19 era.	MCDM	Fuzzy analytic hierarchy process
7	(Cherrafi *et al.*, 2022)	This study identifies key challenges supply chains face during COVID-19 and offers mitigation strategies to enhance supply chain responsiveness and restoration.	Survey	Semi-structured interviews
8	(Sarkar *et al.*, 2022)	This study highlighted the need for designing sustainable, cost-effective, and survivable supply chains to mitigate challenges caused by COVID-19 disruptions and enhance resilient and sustainable supply chains.	Literature review	–
9	(Frederico *et al.*, 2023)	This study highlights the impact of integrating Industry 4.0 technologies and interoperability on the supply chain post-COVID-19 to enhance supply chain resilience.	Statistical Model	Regression Model

10	(Li *et al.*, 2023)	This study uncovers sustainable supply chain resilience strategies and offers budget-constraint solutions to address challenges in the post-COVID-19 landscape.	Questionnaire	Kano model
11	(Graves *et al.*, 2022)	This study identifies challenges and issues encountered across different stages in the supply chain during the COVID-19 pandemic to tackle uncertain demand and supply for the post-pandemic era.	Conceptual	–

2.2 Research gaps

The novel coronavirus has ushered in a swiftly evolving landscape, demanding businesses embrace adaptability, responsiveness, and proactive measures to effectively counter and manage disruptions (Raj *et al.*, 2022). Previous research convincingly highlights resilience as a pivotal dynamic capability that guides organisations to navigate periods of turbulence successfully. Also, researchers did their best to apply scientific approaches and methodologies to enhance supply chain resilience in post-pandemic times, as evident from Table 1. Despite that, the literature is silent in highlighting some promising areas that require attention in the context of supply chain resilience. Following are the research gaps identified through the body of knowledge.

RG 1. There is a scarcity of literature delving into supply chain resilience within the realm of high-value manufacturing in the post-COVID era.

RG 2. The existing body of knowledge lacks in determining and assessing the core competencies that the high-value manufacturing industry must possess to achieve supply chain resilience.

RG 3. The pertinent literature lacks in identifying pivotal strategies that the high-value manufacturing industry should embrace to realise a state of supply chain resilience.

Against this backdrop of research gaps and the transformative challenges posed during the post-COVID-19 situations, creating a resilient supply chain is strategically imperative for all types of industries, including a high-value manufacturing industry. This work lays the foundation for comprehending the intrinsic significance of supply chain resilience and its implications for the high-value manufacturing industry's trajectory in a post-pandemic era. This study offers novel insights in terms of competencies and strategies that help build a resilient supply chain for a high-value manufacturer, i.e. industrial valve manufacturing industry.

2.3 Competencies and Strategies for Supply Chain Resilience

The profound implications of supply chain disruptions on customer satisfaction and loyalty necessitate a resilient approach (Liu *et al.*, 2023). Companies bolster customer loyalty and maintain satisfaction by ensuring timely order fulfilment even during disruptions. Studies on supply chain disruption underscore that disruptions in supply chains can lead to customer dissatisfaction and erosion of trust (Ketchen and Craighead, 2020; Pettit *et al.*, 2010b). This situation emphasises the critical role of resilience in preserving positive customer relationships. In order to develop and maintain supply chain resilience, several key competencies and strategies are crucial.

The supply chain resilience competencies (SCRC) encompass a wide range of skills, tactics, and practices that enable an organisation to navigate uncertainties and disruptions to create a resilient environment (Islam *et al.*, 2023). The competencies form a robust toolkit for an organisation to tackle the disruption within a complex supply chain network and enable swift response and effective supply chain management.

On the other hand, supply chain resilience strategies (SCRS) are measures adopted to enhance an organisation's ability to withstand and recover from disruptions that can impact the flow of goods, services, and information within its supply chain and reduce vulnerability (Liu *et al.*, 2023; Norrman and Wieland, 2020; Sharma *et al.*, 2021b; Virmani *et al.*, 2022). These strategies aim to minimise the negative impact of disruptions, maintain operational continuity, and ensure the organisation's ability to meet customer demands (Dohale, Ambilkar, Gunasekaran and Verma, 2022). Resilience strategies demonstrate a role in upholding regulatory compliance of material supply even during disruptions (Zhang *et al.*, 2021).

Scholars have highlighted various competencies and strategies for fostering and strengthening supply chain resilience in the existing body of knowledge to prepare, react, and recuperate from disruptive events like the COVID-19 pandemic. Figures 1 and 2 highlight the core competencies and strategies for supply chain resilience, respectively. A detailed description of all supply chain resilience competencies and strategies is provided in Tables A1 and A2 in the supplementary file. Further, the relevance of these competencies and strategies in HVM is highlighted in Appendices 1 and 2.

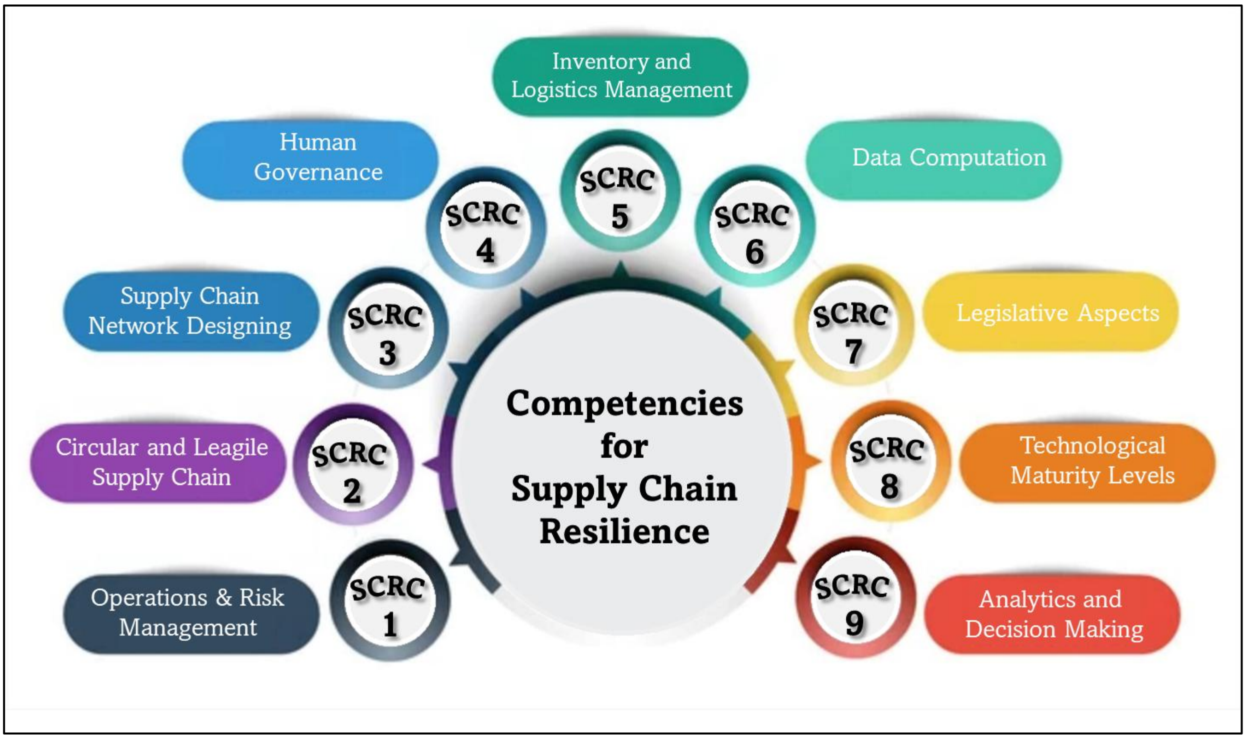

Figure 1. Supply Chain Resilience Competencies (SCRC) (Source: (Cherrafi *et al.*, 2022; Derwik and Hellström, 2017; Fernando and Wulansari, 2021; Islam *et al.*, 2023; Li *et al.*, 2023; Sharma *et al.*, 2021b; Tseng *et al.*, 2023; Yuan *et al.*, 2023))

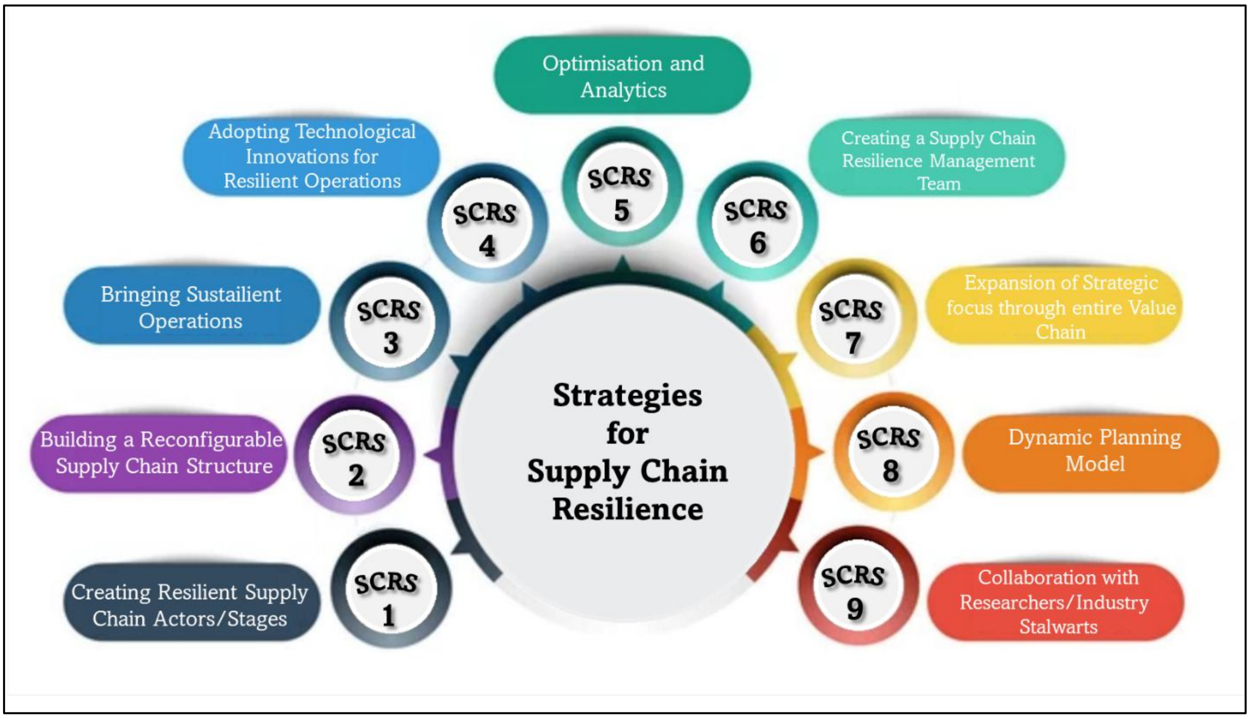

Figure 2. Supply Chain Resilience Strategies (SCRS) (Source: (Butt, 2021; Derwik and Hellström, 2017; Liu *et al.*, 2023; Paul *et al.*, 2023; Raj *et al.*, 2022; Sharma *et al.*, 2021b; Yuan *et al.*, 2023))

3 Research Methodology

In this study, we considered a real-life case of a high-value manufacturing organisation, i.e., the industrial valve manufacturing industry, to evaluate the competencies and strategies of supply chain resilience provided in Figures 1 and 2. We utilised the neutrosophic analytical hierarchy process (NAHP) to determine the most critical competencies and strategies that can aid in creating and enhancing supply chain resilience during the post-COVID-19 scenario for the organisation. The detailed methodology to conduct the research work is presented in Figure 3. Further, the details of NAHP are as follows.

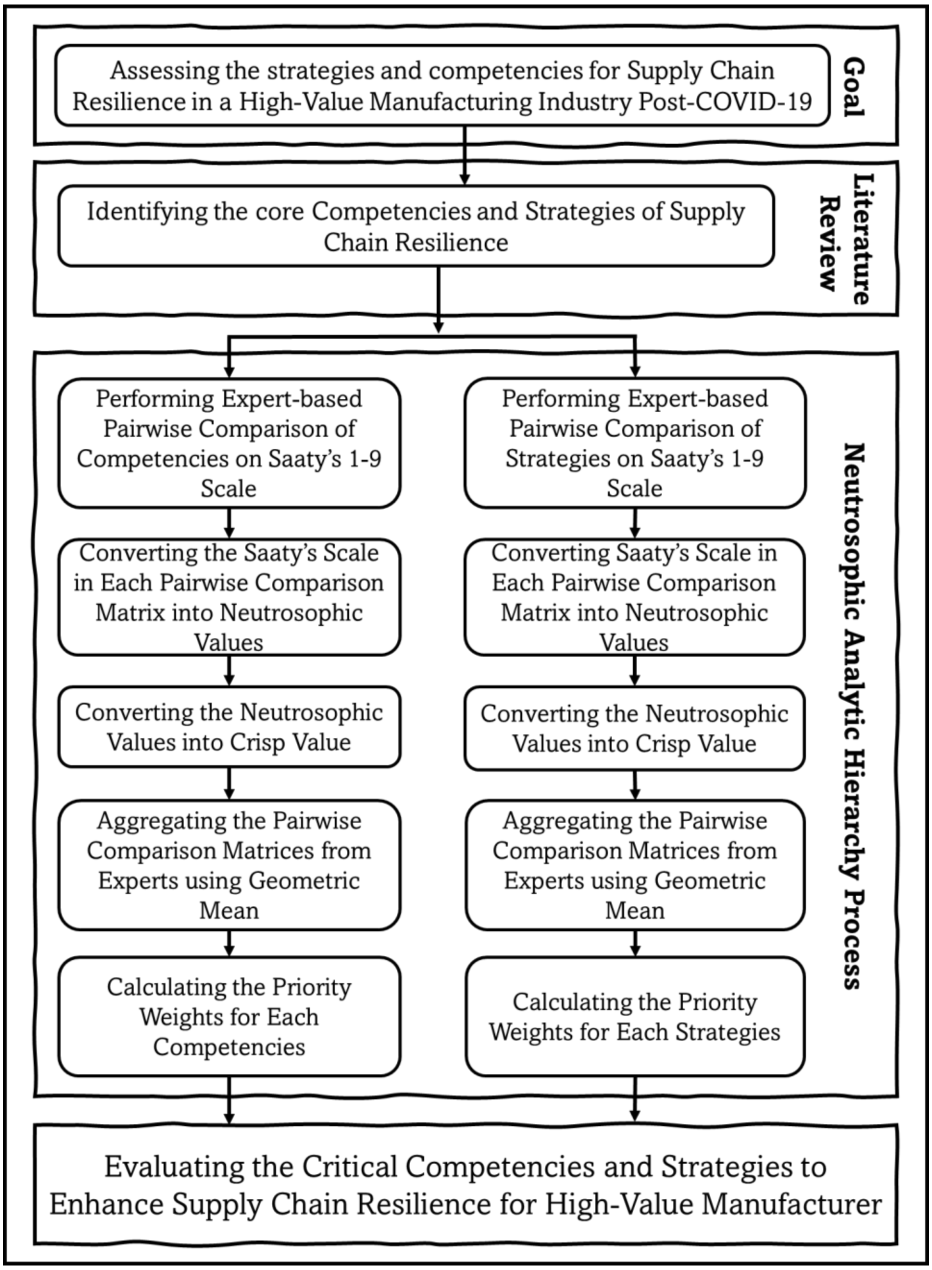

Figure 3. Methodological Approach for Conducting Present Research Work (Source: Author's Own)

3.1 Neutrosophic Analytical Hierarchy Process (NAHP)

AHP is a globally recognised and widely utilised multi-criteria decision-making (MCDM) technique created by Prof. Thomas L. Saaty in 1980 (Mardani *et al.*, 2015; Saaty, 1980). This technique helps break down complex decisions into smaller parts and creates a hierarchy to analyse them (Dohale, Akarte, *et al.*, 2021a; Dohale, Ambilkar, Gunasekaran and Bilolikar, 2022). AHP involves pairwise comparison of different evaluation criteria using a scale from 1 to 9 (Saaty, 2008; Vieira *et al.*, 2017). While AHP is helpful, it has some issues because it uses a crisp scale, which can be vague and subjective for solving complex problems. Different versions of AHP were developed, like Fuzzy AHP, Grey AHP, Intuitionistic AHP, and Voting AHP, to overcome these issues (Mardani *et al.*, 2015).

Abdel-Basset *et al.* (2017) coined an advanced version of AHP by combining it with the neutrosophic approach, called Neutrosophic AHP. They utilised neutrosophic sets to convert the 1-9 scale to neutrosophic numbers (Nabeeh *et al.*, 2019). This helps deal with uncertainties and disagreements in decision-making (Nabeeh *et al.*, 2021). The neutrosophic theory works well for cases where things are intricate and comprise unclear or little information, unlike fuzzy and intuitionistic fuzzy sets (Abdel-Baset *et al.*, 2019; Ambilkar *et al.*, 2023). It uses a special scale to measure the uncertainty within the decision-makers' opinions. These advantages are the solid reasons to utilise NAHP in this research. The NAHP procedure is explained next.

3.2 NAHP Computation Process:

In this part, we'll explain the key stages of conducting a neutrosophic AHP framework for calculating the criteria weights. The steps are as follows:

3.2.1 Expert Selection

The choice of experts for conducting any MCDM method is the crucial factor based on which the authenticity of results relies. Thus, the expert selection is extremely crucial in carrying out MCDM evaluation. Generally, the traditional AHP requires 3 to 11 experts to conduct the evaluation process (Ahsan and Rahman, 2016). Whereas neutrosophic AHP (NAHP) studies utilised 2 to 4 experts to gather data (Nabeeh *et al.*, 2021). The experts are then guided to perform a pairwise comparison between the proposed criteria (here in this study – competencies and strategies) using a linguistic scale (1-9 scale) developed by Saaty (1980), as shown in Table 2.

3.2.2 Consistency Ratio

We evaluated the consistency ratio (CR) of each pairwise comparison matrix to measure any inconsistency within the judgments (Saaty, 1980, 2008). The CR value is considered satisfactory if it's less than or equal to 10%, which helps ensure the reliability of the comparisons (Dohale, Akarte, *et al.*, 2021b; Saaty, 2008). The consistency ratio is measured using the guidelines provided by Saaty (2008).

3.2.3 Forming a Neutrosophic Decision Matrix

Once the pairwise decision matrix is developed based on Saaty’s nine-point scale, with each numerical entry in the matrix given by experts, the crisp value of Saaty’s scale is converted into a respective triangular neutrosophic number. The neutrosophic AHP scale, as depicted in Table 2, serves as the framework for this decision-making process.

Table 2. Triangular Neutrosophic Number for Saaty's AHP scale (Source: Nabeeh *et al.*, 2019)

Saaty Scale	**Linguistic Terms**	**Neutrosophic Triangular Number**
1	Equally important	$\langle\langle 1,1,1\rangle; 0.50, 0.50, 0.50\rangle$
3	Slightly important	$\langle\langle 2,3,4\rangle; 0.30, 0.75, 0.70\rangle$
5	Strongly important	$\langle\langle 4,5,6\rangle; 0.80, 0.15, 0.20\rangle$
7	Very strongly important	$\langle\langle 6,7,8\rangle; 0.90, 0.10, 0.10\rangle$
9	Absolutely important	$\langle\langle 9,9,0\rangle; 1.00, 0.00, 0.00\rangle$
2	Values in-between two close scales	$\langle\langle 1,2,3\rangle; 0.40, 0.65, 0.60\rangle$
4		$\langle\langle 3,4,5\rangle; 0.35, 0.60, 0.65\rangle$
6		$\langle\langle 5,6,7\rangle; 0.70, 0.25, 0.30\rangle$
8		$\langle\langle 7,8,9\rangle; 0.85, 0.10, 0.15\rangle$

The adjusted pairwise comparison matrix can be represented using equation 1.

$$P^k = \begin{bmatrix} d_{11}^k & \cdots & d_{1n}^k \\ \vdots & \ddots & \vdots \\ d_{m1}^k & \cdots & d_{mn}^k \end{bmatrix} \ldots\ldots (1)$$

where d_{ij}^k signifies the neutrosophic value given by the k^{th} expert to represent the preference relationship between the i^{th} criteria over j^{th}criteria. The triangular neutrosophic number $d_{ij}^k = \langle (a_{ij}^k, b_{ij}^k, c_{ij}^k);\ T_{ij}^k, I_{ij}^k, F_{ij}^k\rangle$. Where, $a_{ij}^k, b_{ij}^k, c_{ij}^k$ denotes lower, medium, and upper bounds of the neutrosophic number, while $T_{ij}^k, I_{ij}^k, F_{ij}^k$ stand for truth-membership, indeterminacy-membership, and falsity-membership functions, respectively. Once the neutrosophic pairwise comparison matrix for each expert is obtained, the next step involves determining the weights for each criterion from their respective pairwise comparison matrices.

3.2.4 Developing a Deneutrified Matrix

The conversion of the neutrosophic pairwise comparison matrix to a deneutrified matrix is done to determine the weight of each criterion. In doing so, the respective triangular neutrosophic numbers from the neutrosophic pairwise comparison matrix are converted to a crisp number by deneutrifying them using the following equations as –

Let, $\tilde{d}_{ij} = (a_1, b_1, c_1), T_1, I_1, F_1$ be a single-valued triangular neutrosophic number, then the conversion is achieved through the application of the following equations:

$$s(d_{ij}^{k}) = \left| \left(a_{ij}^{k} \times b_{ij}^{k} \times c_{ij}^{k}\right)^{\left(T_{ij}^{k}+I_{ij}^{k}+F_{ij}^{k}\right)/9} \right| \ldots\ldots (2)$$

3.2.5 Aggregating the Experts' Opinions

A geometric mean method is used to aggregate the decision-makers' perceptions. The geometric mean of each ($s(d_{ij}^{k})$) is computed. Further, a final aggregated pairwise comparison matrix P^{a} is created consisting of d_{ij} elements.

3.2.6 Computing the priority weights

The aggregated pairwise comparison matrix is used for evaluating the priority weights. It can be computed using the following equations.

- Calculate the Geometric Mean of each row in aggregated pairwise comparison matrix.

$$GM = \sqrt[n]{\prod_{j=1}^{n} d_{ij}} \ldots.\ldots\ldots where\ i = 1\ to\ m \ldots\ldots (5)$$

- Normalise GM to get the priority weights of all the PCC

$$w_i = \frac{GM}{\sum GM} \ldots\ldots (7)$$

4 The Case and Results

This section provides the details of the case under study and the results obtained by utilising the 5-step NAHP approach for evaluating the priority weights of competencies and strategies of supply chain resilience.

4.1 Case Description

We have considered the case of an industrial valve, i.e. hydraulic and pneumatics valve manufacturing firm, which is a high-value manufacturer. A high-value manufacturer is defined as – an organisation with a manufacturing function *"involving a process of understanding and managing the full cycle consisting of identifying the markets through R&D, product design, production, distribution, and services within an economic and social context*" (Dohale, Gunasekaran, *et al.*, 2021; Livesey, 2006). There are typically four types of high-value manufacturers – Service Lead Producers, Product Manufacturers, Service Manufacturers, and System Integrators.

The company belongs to the category of high-value product manufacturers. These manufacturers excel in delivering products that offer substantial benefits across economic, environmental, and social dimensions (Livesey, 2006). Considering the economic dimension, the firm stands as one of the top revenue generators within its industry segment. Moreover, it plays a pivotal role in the local community by providing employment opportunities, thus establishing strong social ties and contributing to its social value. By embracing the practice of recycling waste materials, the company demonstrates a keen environmental consciousness, actively working towards achieving environmental value. These facts justify that the current firm is a high-value manufacturer, as per the Livesey (2006) definition.

The firm is situated in Pune, India, and holds a prominent position within the industrial valve manufacturing sector. Established in 1844, this company has achieved market prowess by consistently delivering products of superior quality at competitive prices. The company boasts a workforce of over 820 employees. In the year 2018-2019, the firm's annual revenue reached ₹641 Million, and in 2019-2020, it touched ₹827 Million. However, during the COVID-19 hit in 2020 (Since March in India), the overall production of the firm dropped by 39% owing to the global lockdowns. Somehow, the firm earns through the selling of valves required for health equipment, but the margin was very low. Considering the post-pandemic conditions, the shortages of skilled labour, constant churn out of workers, frequent work from home, which is unhealthy for the manufacturing industry, and demand fluctuations caused the firm to rethink its operations and supply chain and create a resilient supply chain network structure. These challenges necessitated competencies in Human Governance (SCRC4) and strategies such as Creating Resilient Supply Chain Actors (SCRS1). Similarly, the disruption caused by remote work highlighted the need for enhanced Analytics and Decision Making (SCRC9), and dynamic planning frameworks (SCRS8), which allowed the firm to maintain oversight and responsiveness. Thus, an attempt is made through this study to aid the firm in understanding the competencies and strategies they should follow to overcome these challenges.

4.2 NAHP Results

As discussed earlier, the NAHP is applied to evaluate the priority weight of strategies and competencies for the firm to identify the most critical ones that a firm should focus on and implement to alleviate the challenges posed by post-COVID-19 situations. We utilised the 5-step procedure discussed in sections 3.2.1 to 3.2.5. Initially, we contacted the experts to conduct the assessments. We considered the following experts selection criteria to decide the right experts with adequate expertise – 1) possessing a minimum of ten years of experience and expertise in the subject under investigation; 2) currently holding a position within the company; and 3) expressing both availability and a keen interest in taking part in the study (Dohale, Gunasekaran, *et al.*, 2021; Dohale, Verma, Gunasekaran and Akarte, 2023). As the expert sample varies between 3 – 11, we contacted 10 experts from the firm with adequate expertise. The profile of the experts is provided in Table 3.

Table 3. Detailed Profile of Experts

#Expert	Designation	Year of Experience	Department
1	Operations Head (Pan India)	29+	Operations
2	Logistics Head (Pan India)	31+	Logistics
3	Vice President	26+	Operations and Supply Chain
4	Associate Vice President	28+	Service & Logistics
5	General Manager	28+	Operations
6	Senior Manager	21+	Operations
7	Senior Manager	23+	Logistics
8	Junior Manager	16+	Operations
9	Junior Manager	16+	Logistics
10	Associate Manager	19+	Logistics

All the experts are requested to provide their opinions to conduct NAHP for supply chain resilience competencies (SCRC) and strategies (SCRS). For each expert, an individual pairwise matrix for SCRCs and SCRSs is created. A sample matrices for pairwise comparison for SCRC and SCRS corresponding to expert 1 are provided in Table 4 and Table 5, respectively.

Table 4. Pairwise Comparison Matrix of SCRC - Expert 1

Competencies	SCRC1	SCRC2	SCRC3	SCRC4	SCRC5	SCRC6	SCRC7	SCRC8	SCRC9
SCRC1	1	2	4	9	8	5	7	3	6
SCRC2	1/2	1	3	8	9	5	8	4	5
SCRC3	1/4	1/3	1	9	7	2	3	1/2	1
SCRC4	1/9	1/8	1/9	1	1/2	1/4	1/3	1/6	1/3
SCRC5	1/8	1/9	1/7	2	1	1/3	1/2	1/4	1/2
SCRC6	1/5	1/5	1/2	4	3	1	1/5	1/2	2
SCRC7	1/7	1/8	1/3	3	2	5	1	1/4	1/2
SCRC8	1/3	1/4	2	6	4	2	4	1	4
SCRC9	1/6	1/5	1	3	2	1/2	2	1/4	1
								CR	**8.7%**

After getting the initial pairwise comparison matrix, Saaty's scale is replaced by the neutrosophic number. Table 6 and Table 7 provide the neutrosophic pairwise comparison matrix for Expert 1.

Table 5. Pairwise Comparison Matrix of SCRS - Expert 1

Strategies	SCRS1	SCRS2	SCRS3	SCRS4	SCRS5	SCRS6	SCRS7	SCRS8	SCRS9
SCRS1	1	5	1/2	1	3	4	6	7	2
SCRS2	1/5	1	1/7	1/4	1/3	1/2	2	2	4
SCRS3	2	7	1	3	5	6	8	9	4
SCRS4	1	4	1/3	1	2	3	5	6	1
SCRS5	1/3	3	1/5	1/2	1	1	3	4	1/2
SCRS6	1/4	2	1/6	1/3	1	1	2	3	1/3
SCRS7	1/6	1/2	1/8	1/5	1/3	1/2	1	1	1/5
SCRS8	1/7	1/2	1/9	1/6	1/4	1/3	1	1	1/6
SCRS9	1/2	1/4	1/4	1	2	3	5	6	1
								CR	**9%**

After converting into a neutrosophic pairwise comparison matrix, the deneutrification of the values is carried out using equation (2). This results in obtaining a crisp-valued deneutrified pairwise comparison matrix. A sample of the deneutrified matrices of supply chain resilience strategies and competencies are provided in Table 8 and Table 9.

As discussed earlier, once all the deneutrified matrices corresponding to each expert are obtained, the final aggregation is carried out using a geometric mean method. The final aggregated matrix is utilised to compute the priority weights using the procedure mentioned in Section 3.2.5. Tables 10 and 11 highlight the aggregated matrix for competencies and strategies, respectively. We have provided all the pairwise comparison matrices, neutrosophic pairwise comparison matrices, deneutrified matrices corresponding to all the 10 experts and the final aggregated matrix in the supplementary file (Appendices 2, 3, and 4).

Table 6. Neutrosophic Pairwise Comparison Matrix of SCRC - Expert 1

Competencies	SCRC1	SCRC2	SCRC3	SCRC4	SCRC5	SCRC6	SCRC7	SCRC8	SCRC9
SCRC1	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <1,2,3> ; <0.40, 0.65, 0.60> >	< <3,4,5> ; <0.35, 0.60, 0.65> >	< <9,9,9> ; <1.00, 0.00, 0.00> >	< <7,8,9> ; <0.85, 0.10, 0.15> >	< <4,5,6> ; <0.80, 0.15, 0.20> >	< <6,7,8> ; <0.90, 0.10, 0.10> >	< <2,3,4> ; <0.30, 0.75, 0.70> >	< <5,6,7> ; <0.70, 0.25, 0.30> >
SCRC2	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <2,3,4> ; <0.30, 0.75, 0.70> >	< <7,8,9> ; <0.85, 0.10, 0.15> >	< <9,9,9> ; <1.00, 0.00, 0.00> >	< <4,5,6> ; <0.80, 0.15, 0.20> >	< <7,8,9> ; <0.85, 0.10, 0.15> >	< <3,4,5> ; <0.35, 0.60, 0.65> >	< <4,5,6> ; <0.80, 0.15, 0.20> >
SCRC3	< <1/5, 1/4, 1/3> ; <0.35, 0.60, 0.65> >	< <1/4, 1/3, 1/2> ; <0.30, 0.75, 0.70> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <9,9,9> ; <1.00, 0.00, 0.00> >	< <6,7,8> ; <0.90, 0.10, 0.10> >	< <1,2,3> ; <0.40, 0.65, 0.60> >	< <2,3,4> ; <0.30, 0.75, 0.70> >	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >	< <1,1,1> ; <0.50, 0.50, 0.50> >
SCRC4	< <1/9, 1/9, 1/9> ; <1.00, 0.00, 0.00> >	< <1/9, 1/8, 1/7> ; <0.85, 0.10, 0.15> >	< <1/9, 1/9, 1/9> ; <1.00, 0.00, 0.00> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >	< <1/5, 1/4, 1/3> ; <0.35, 0.60, 0.65> >	< <1/4, 1/3, 1/2> ; <0.30, 0.75, 0.70> >	< <1/7, 1/6, 1/5> ; <0.70, 0.25, 0.30> >	< <1/4, 1/3, 1/2> ; <0.30, 0.75, 0.70> >
SCRC5	< <1/9, 1/8, 1/7> ; <0.85, 0.10, 0.15> >	< <1/9, 1/9, 1/9> ; <1.00, 0.00, 0.00> >	< <1/8, 1/7, 1/6,> ; <0.90, 0.10, 0.10> >	< <1,2,3> ; <0.40, 0.65, 0.60> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <1/4, 1/3, 1/2> ; <0.30, 0.75, 0.70> >	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >	< <1/5, 1/4, 1/3> ; <0.35, 0.60, 0.65> >	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >
SCRC6	< <1/6, 1/5, 1/6> ; <0.80, 0.15, 0.20> >	< <1/6, 1/5, 1/6> ; <0.80, 0.15, 0.20> >	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >	< <3,4,5> ; <0.35, 0.60, 0.65> >	< <2,3,4> ; <0.30, 0.75, 0.70> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <1/6, 1/5, 1/6> ; <0.80, 0.15, 0.20> >	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >	< <1,2,3> ; <0.40, 0.65, 0.60> >
SCRC7	< <1/8, 1/7, 1/6,> ; <0.90, 0.10, 0.10> >	< <1/9, 1/8, 1/7> ; <0.85, 0.10, 0.15> >	< <1/4, 1/3, 1/2> ; <0.30, 0.75, 0.70> >	< <2,3,4> ; <0.30, 0.75, 0.70> >	< <1,2,3> ; <0.40, 0.65, 0.60> >	< <4,5,6> ; <0.80, 0.15, 0.20> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <1/5, 1/4, 1/3> ; <0.35, 0.60, 0.65> >	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >
SCRC8	< <1/4, 1/3, 1/2> ; <0.30, 0.75, 0.70> >	< <1/5, 1/4, 1/3> ; <0.35, 0.60, 0.65> >	< <1,2,3> ; <0.40, 0.65, 0.60> >	< <5,6,7> ; <0.70, 0.25, 0.30> >	< <3,4,5> ; <0.35, 0.60, 0.65> >	< <1,2,3> ; <0.40, 0.65, 0.60> >	< <3,4,5> ; <0.35, 0.60, 0.65> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <3,4,5> ; <0.35, 0.60, 0.65> >
SCRC9	< <1/7, 1/6, 1/5> ; <0.70, 0.25, 0.30> >	< <1/6, 1/5, 1/6> ; <0.80, 0.15, 0.20> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <2,3,4> ; <0.30, 0.75, 0.70> >	< <1,2,3> ; <0.40, 0.65, 0.60> >	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >	< <1,2,3> ; <0.40, 0.65, 0.60> >	< <1/5, 1/4, 1/3> ; <0.35, 0.60, 0.65> >	< <1,1,1> ; <0.50, 0.50, 0.50> >

Table 7. Neutrosophic Pairwise Comparison Matrix of Supply Chain Resilience Strategies – Expert 1

Strategies	**SCRS1**	**SCRS2**	**SCRS3**	**SCRS4**	**SCRS5**	**SCRS6**	**SCRS7**	**SCRS8**	**SCRS9**
SCRS1	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <4,5,6> ; <0.80, 0.15, 0.20> >	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <2,3,4> ; <0.30, 0.75, 0.70> >	< <3,4,5> ; <0.35, 0.60, 0.65> >	< <5,6,7> ; <0.70, 0.25, 0.30> >	< <6,7,8> ; <0.90, 0.10, 0.10> >	< <1,2,3> ; <0.40, 0.65, 0.60> >
SCRS2	< <1/6, 1/5, 1/6> ; <0.80, 0.15, 0.20> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <1/8, 1/7, 1/6,> ; <0.90, 0.10, 0.10> >	< <1/5, 1/4, 1/3> ; <0.35, 0.60, 0.65> >	< <1/4, 1/3, 1/2> ; <0.30, 0.75, 0.70> >	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >	< <1,2,3> ; <0.40, 0.65, 0.60> >	< <1,2,3> ; <0.40, 0.65, 0.60> >	< <3,4,5> ; <0.35, 0.60, 0.65> >
SCRS3	< <1,2,3> ; <0.40, 0.65, 0.60> >	< <6,7,8> ; <0.90, 0.10, 0.10> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <2,3,4> ; <0.30, 0.75, 0.70> >	< <4,5,6> ; <0.80, 0.15, 0.20> >	< <5,6,7> ; <0.70, 0.25, 0.30> >	< <7,8,9> ; <0.85, 0.10, 0.15> >	< <9,9,9> ; <1.00, 0.00, 0.00> >	< <3,4,5> ; <0.35, 0.60, 0.65> >
SCRS4	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <3,4,5> ; <0.35, 0.60, 0.65> >	< <1/4, 1/3, 1/2> ; <0.30, 0.75, 0.70> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <1,2,3> ; <0.40, 0.65, 0.60> >	< <2,3,4> ; <0.30, 0.75, 0.70> >	< <4,5,6> ; <0.80, 0.15, 0.20> >	< <5,6,7> ; <0.70, 0.25, 0.30> >	< <1,1,1> ; <0.50, 0.50, 0.50> >
SCRS5	< <1/4, 1/3, 1/2> ; <0.30, 0.75, 0.70> >	< <2,3,4> ; <0.30, 0.75, 0.70> >	< <1/6, 1/5, 1/6> ; <0.80, 0.15, 0.20> >	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <2,3,4> ; <0.30, 0.75, 0.70> >	< <3,4,5> ; <0.35, 0.60, 0.65> >	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >
SCRS6	< <1/5, 1/4, 1/3> ; <0.35, 0.60, 0.65> >	< <1,2,3> ; <0.40, 0.65, 0.60> >	< <1/7, 1/6, 1/5> ; <0.70, 0.25, 0.30> >	< <1/4, 1/3, 1/2> ; <0.30, 0.75, 0.70> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <1,2,3> ; <0.40, 0.65, 0.60> >	< <2,3,4> ; <0.30, 0.75, 0.70> >	< <1/4, 1/3, 1/2> ; <0.30, 0.75, 0.70> >
SCRS7	< <1/7, 1/6, 1/5> ; <0.70, 0.25, 0.30> >	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >	< <1/9, 1/8, 1/7> ; <0.85, 0.10, 0.15> >	< <1/6, 1/5, 1/6> ; <0.80, 0.15, 0.20> >	< <1/4, 1/3, 1/2> ; <0.30, 0.75, 0.70> >	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <1/6, 1/5, 1/6> ; <0.80, 0.15, 0.20> >
SCRS8	< <1/8, 1/7, 1/6,> ; <0.90, 0.10, 0.10> >	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >	< <1/9, 1/9, 1/9> ; <1.00, 0.00, 0.00> >	< <1/7, 1/6, 1/5> ; <0.70, 0.25, 0.30> >	< <1/5, 1/4, 1/3> ; <0.35, 0.60, 0.65> >	< <1/4, 1/3, 1/2> ; <0.30, 0.75, 0.70> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <1/7, 1/6, 1/5> ; <0.70, 0.25, 0.30> >
SCRS9	< <1/3, 1/2, 1> ; <0.40, 0.65, 0.60> >	< <1/5, 1/4, 1/3> ; <0.35, 0.60, 0.65> >	< <1/5, 1/4, 1/3> ; <0.35, 0.60, 0.65> >	< <1,1,1> ; <0.50, 0.50, 0.50> >	< <1,2,3> ; <0.40, 0.65, 0.60> >	< <2,3,4> ; <0.30, 0.75, 0.70> >	< <4,5,6> ; <0.80, 0.15, 0.20> >	< <5,6,7> ; <0.70, 0.25, 0.30> >	< <1,1,1> ; <0.50, 0.50, 0.50> >

Table 8. Deneutrified Pairwise Comparison Matrix of SCRC - Expert 1

Competencies	SCRC1	SCRC2	SCRC3	SCRC4	SCRC5	SCRC6	SCRC7	SCRC8	SCRC9
SCRC1	1.0000	1.3889	2.0707	1.6295	2.1394	1.8436	2.0360	1.8551	2.1015
SCRC2	0.7200	1.0000	1.8551	2.1394	1.6295	1.8436	2.1394	2.0707	1.8436
SCRC3	0.4829	0.5390	1.0000	1.6295	2.0360	1.3889	1.8551	0.7200	1.0000
SCRC4	0.6137	0.4674	0.6137	1.0000	0.7200	0.4829	0.5390	0.4758	0.5390
SCRC5	0.4674	0.6137	0.4912	1.3889	1.0000	0.5390	0.7200	0.4829	0.7200
SCRC6	0.5424	0.5424	0.7200	2.0707	1.8551	1.0000	0.5424	0.7200	1.3889
SCRC7	0.4912	0.4674	0.5390	1.8551	1.3889	1.8436	1.0000	0.4829	0.7200
SCRC8	0.5390	0.4829	1.3889	2.1015	2.0707	1.3889	2.0707	1.0000	2.0707
SCRC9	0.4758	0.5424	1.0000	1.8551	1.3889	0.7200	1.3889	0.4829	1.0000

Table 9. Deneutrified Pairwise Comparison Matrix of SCRC – Expert 1

Strategies	SCRS1	SCRS2	SCRS3	SCRS4	SCRS5	SCRS6	SCRS7	SCRS8	SCRS9
SCRS1	1.0000	1.8436	0.7200	1.0000	1.8551	2.0707	2.1015	2.0360	1.3889
SCRS2	0.5424	1.0000	0.4912	0.4829	0.5390	0.7200	1.3889	1.3889	2.0707
SCRS3	1.3889	2.0360	1.0000	1.8551	1.8436	2.1015	2.1394	1.6295	2.0707
SCRS4	1.0000	2.0707	0.5390	1.0000	1.3889	1.8551	1.8436	2.1015	1.0000
SCRS5	0.5390	1.8551	0.5424	0.7200	1.0000	1.0000	1.8551	2.0707	0.7200
SCRS6	0.4829	1.3889	0.4758	0.5390	1.0000	1.0000	1.3889	1.8551	0.5390
SCRS7	0.4758	0.7200	0.4674	0.5424	0.5390	0.7200	1.0000	1.0000	0.5424
SCRS8	0.4912	0.7200	0.6137	0.4758	0.4829	0.5390	1.0000	1.0000	0.4758
SCRS9	0.7200	0.4829	0.4829	1.0000	1.3889	1.8551	1.8436	2.1015	1.0000

Table 10. Aggregated Pairwise Comparison Matrix of SCRC

Competencies	SCRC1	SCRC2	SCRC3	SCRC4	SCRC5	SCRC6	SCRC7	SCRC8	SCRC9	Priority Weights	Rank
SCRC1	1.0000	1.5149	1.8283	1.8671	1.8579	1.9683	2.0591	1.9251	2.0546	0.1834	1
SCRC2	0.6601	1.0000	1.7701	1.9522	1.7207	1.8925	2.0160	2.0010	1.9175	0.1644	2
SCRC3	0.5469	0.5649	1.0000	1.7207	2.0461	1.7701	1.8964	0.7022	0.8519	0.1143	4
SCRC4	0.5356	0.5122	0.5812	1.0000	0.6230	0.5109	0.5752	0.5080	0.7000	0.0631	9
SCRC5	0.5382	0.5812	0.4887	1.6052	1.0000	0.5712	0.6605	0.4991	0.5649	0.0699	8
SCRC6	0.5080	0.5284	0.5649	1.9575	1.7508	1.0000	0.5993	0.7022	1.3283	0.0914	6
SCRC7	0.4856	0.4960	0.5273	1.7386	1.5139	1.6687	1.0000	0.5951	0.7228	0.0894	7
SCRC8	0.5195	0.4997	1.4241	1.9683	2.0035	1.4241	1.6804	1.0000	1.8084	0.1286	3
SCRC9	0.4867	0.5215	1.1739	1.4286	1.7701	0.7528	1.3835	0.5530	1.0000	0.0955	5

Table 11. Aggregated Pairwise Comparison Matrix of SCRS

Strategies	SCRS1	SCRS2	SCRS3	SCRS4	SCRS5	SCRS6	SCRS7	SCRS8	SCRS9	Priority Weights	Rank
SCRS1	1.0000	1.9563	0.6795	1.1036	1.8756	2.0010	2.0949	2.0424	1.5594	0.1565	2
SCRS2	0.5112	1.0000	0.4796	0.5162	0.6230	0.7441	1.3440	1.4297	1.9679	0.0887	7
SCRS3	1.4716	2.0852	1.0000	1.9385	1.8870	2.0854	2.0260	1.6295	1.9551	0.1831	1
SCRS4	0.9062	1.9373	0.5159	1.0000	1.5594	1.8221	1.9534	2.0517	1.2675	0.1395	3
SCRS5	0.5332	1.6052	0.5300	0.6413	1.0000	1.2179	1.8295	2.0010	0.6413	0.1027	5
SCRS6	0.4997	1.3440	0.4795	0.5488	0.8211	1.0000	1.5090	1.8423	0.5986	0.0896	6
SCRS7	0.4774	0.7441	0.4936	0.5119	0.5466	0.6627	1.0000	1.2585	0.5109	0.0682	8
SCRS8	0.4896	0.6995	0.6137	0.4874	0.4997	0.5428	0.7946	1.0000	0.5318	0.0640	9
SCRS9	0.6413	0.5082	0.5115	0.7890	1.5594	1.6706	1.9575	1.8805	1.0000	0.1076	4

4.3 Discussions of the Findings

The results from the computation provided in Table 10 revealed that, in terms of competencies, operations & risk management (SCRC1), circular and leagile supply chain (SCRC2), and technological maturity levels (SCRC8) are the critical competencies. The firm provides essential components in various industries, including oil and gas, power generation, chemical, water treatment, healthcare equipment, etc. Thus, any disruption can cause delayed production, which, in turn, leads to customer dissatisfaction (Pettit *et al.*, 2010b; Spieske *et al.*, 2023). The supply chain resilience competencies can create a significant hold in the firm to overcome these challenges. The most critical competency identified through analysis is efficient operations and risk management capabilities. This competency can help the firm develop risk management tactics to prepare for disruptive events and streamline operations (Hussain *et al.*, 2022; Paul *et al.*, 2023; Sharma *et al.*, 2021b).

Secondly, circular and leagile supply chain competency can help the firm manage its environmental consciousness along with a flexible and efficient supply chain that can handle both stable and unpredictable demand scenarios. This competency combines the power of both circular and leagile supply chain properties to – 1) design the products for circularity (using recycled materials, and easily recyclable components) while also applying leagile principles to efficiently manage products with stable and volatile demand patterns.; and 2) quickly adapting to changing demand patterns while also incorporating circular practices like material recycling and refurbishment of returned products during the disruptive events (Drake *et al.*, 2013; Islam *et al.*, 2023; Tseng *et al.*, 2023).

Apart from these two, the technological maturity levels of the firm can act as a critical competency to alleviate the challenges posed post-disruption, viz. post-COVID-19 situations (Islam *et al.*, 2023; Spieske *et al.*, 2023; Yuan *et al.*, 2023). It deals with the extent to which an organisation's supply chain operations are integrated with and utilise cutting-edge technologies such as – the Internet of Things (ToT), big data, artificial intelligence, etc. As stated by one plant manager, 'Technological maturity was not just about tools, but about training our workforce to use them during crises' – highlighting the operational need for aligning SCRC8 with human governance (SCRC4).

An efficient manufacturing strategy for implementing these technologies in the firm can help boost the organisation's capability to quickly determine, respond, and recover from the disruption impacts (Dohale, Verma, Gunasekaran and Akarte, 2023; Islam *et al.*, 2023; Paul *et al.*, 2023). The results of our study are in line with and support the findings of the existing study by Islam *et al.* (2023).

Considering the supply chain resilience strategies (SCRS), the results from Table 11 depict that – bringing sustailient operations (SCRS3), creating resilient supply chain actors/stages (SCRS1), and adopting technological innovations for resilient operations (SCRS4) are the critical strategies the firm must adopt to create a more resilient supply chain while achieving environmentally responsible performance. Firstly, bringing sustailient operations in industrial valve manufacturing firms can lead to cater the advantages of both sustainable and resilient supply chains (Ambilkar *et al.*, 2023). By embedding sustainability and resilience into supply chain operations, organisations can proactively evade disruptions, swiftly recover from challenges, and create a robust foundation for future growth (Liu *et al.*, 2023; Paul *et al.*, 2023). Besides this, sustainable operations can help usher towards circularity (Dohale *et al.*, 2024; Walker *et al.*, 2022), which helps achieve SCRC 2. At the same time, the sustainable operations, when integrated with resilience strategies, help mitigate disruption risks while supporting environmental goals (Park and Broder, 2023). Secondly, creating resilient supply chain actors is imperative to triumph over post-COVID-19 challenges. The firm understudy and industrial valve manufacturers must foster adaptability, embracing technology and diversification in terms of both – supplier base expansion and operational flexibility, i.e. strategies critical for risk mitigation in high-value manufacturing. Robust supplier networks, agile logistics, and data-driven insights across the supply chain from suppliers and manufacturers to distributors and even customers help fortify against disruptions (Paul *et al.*, 2023). Enhanced collaboration between supply chain stages, contingency planning, and risk management ensures readiness for the unpredictable. Thus, by nurturing resilient capabilities, supply chain actors can navigate uncertainties, minimise future shocks, and ensure seamless operations in adversity (Dohale, Verma, Gunasekaran and Ambilkar, 2023; Paul *et al.*, 2023). Lastly, adopting technological innovations for resilient operations has been computed as the third critical SCRS in this study, which helps improve the competency related to technological maturity level (SCRC 8). Technological innovations are reshaping supply chains for heightened resilience (Al-Banna *et al.*, 2023; Spieske *et al.*, 2023). Internet of Things (IoT) devices offer real-time tracking, improving visibility and response to disruptions. Artificial Intelligence (AI) and data analytics enhance demand forecasting accuracy and risk assessment. Blockchain ensures transparent and secure transactions, reducing fraud risks (Spieske and Birkel, 2021). Thus, digital transformation has emerged as a critical enabler in this process, offering new possibilities for optimising operations, mitigating risks, and ensuring continuity by improving supply chain resilience (He et al., 2023; Klöckner et al., 2023a; Yuan et al., 2023a). These findings are supported by the recent studies by Paul *et al.* (2023), Cherrafi *et al.* (2022), and Spieske *et al.* (2023).

To enhance the practical relevance of our results, we present a real-life case example from Siemens AG, a leading high-value manufacturing firm that has successfully implemented advanced technologies to enhance supply chain resilience (AIX, 2023; Siemens, 2024). Siemens integrated IoT and AI into their supply chain operations, allowing for real-time monitoring and predictive maintenance. This adoption of advanced data analytics enabled Siemens to foresee potential disruptions and swiftly reconfigure their supply chain to mitigate risks. As a result, Siemens minimised downtime, improved operational efficiency, and demonstrated how advanced technologies can achieve a resilient supply chain in the high-value manufacturing sector. Apart from this, Siemens' adoption of digital twin technology and modular manufacturing systems illustrates how HVM firms are integrating technological maturity (SCRC8) and reconfigurable structures (SCRS2) to foster resilience post-COVID-19. This case illustrates the practical application of our identified strategies and competencies, demonstrating how high-value manufacturing firms can achieve supply chain resilience and operational excellence. By adopting similar technologies and strategies, other high-value manufacturing firms can enhance their supply chain resilience, validating our findings and providing actionable guidance for industry practitioners.

4.4 Sensitivity analysis

Sensitivity analysis is a important tool in decision-making processes, particularly for evaluating the robustness and reliability of prioritisations in models or systems (Ambilkar *et al.*, 2023; Latunde and Bamigbola, 2018; Saaty, 2013). It involves systematically varying input parameters within a certain range and observing how these changes impact the outputs. In the context of high-value manufacturing, sensitivity analysis helps decision-makers understand how variations in expert judgments affect the priority weights of critical competencies and strategies. By examining the impact of adjustments ranging from -20% to +20%, decision-makers can identify which competencies and strategies are most sensitive to changes and ensure their evaluations are robust and reliable.

The sensitivity analysis performed on the priority weights of competencies in high-value manufacturing reveals significant insights into the decision-making process. For example, SCRC1 (Operations & Risk Management) and SCRC2 (Circular and Leagile Supply Chain) showed considerable sensitivity to variations, indicating that these competencies are crucial and require precise assessments. On the other hand, competencies like SCRC8 (Technological Maturity) displayed moderate sensitivity, suggesting stable prioritisation under different scenarios. The sensitivity analysis results revealed that changes in the highest weight criterion did not significantly affect the importance of the alternatives. Consequently, the overall ranking of the final outcome remained consistent with the ranking graphically represented in Figure 4 and 5. These findings enable decision-makers to allocate resources effectively, focus on critical areas, and enhance consensus-building among experts. Overall, sensitivity analysis provides valuable insights, ensuring that strategies and competencies for achieving supply chain resilience in high-value manufacturing are robust, adaptable, and informed by comprehensive evaluations of potential variations. By exploring the impact of weight variations, decision-makers can enhance their understanding of the decision-making process and make more informed and reliable choices.

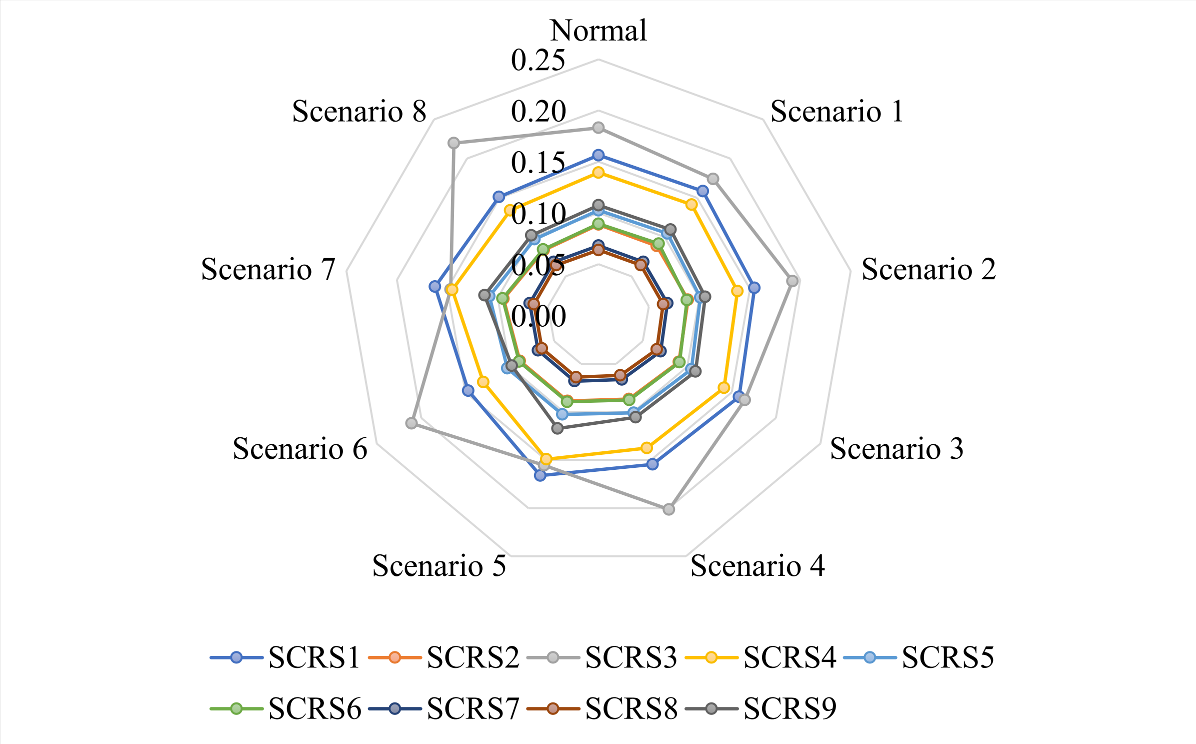

Figure 4. Radar Plot of SCRSs Sensitivity Analysis (Source: Author's Own)

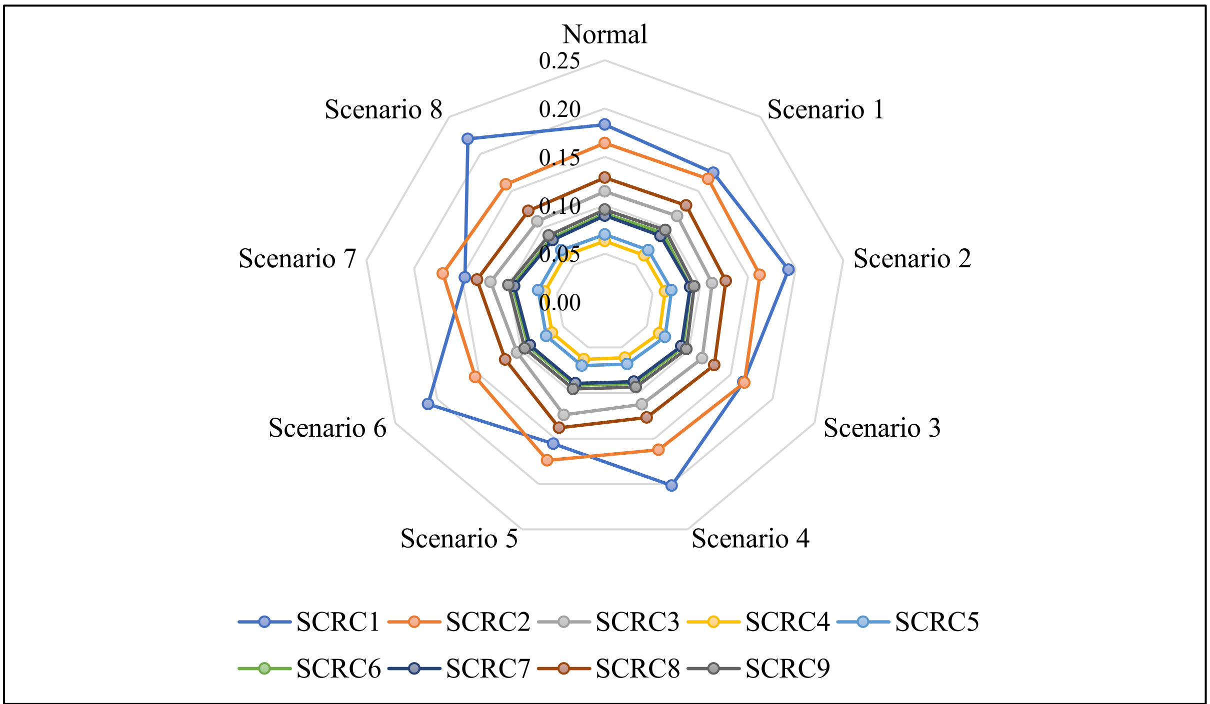

Figure 5. Radar Plot of SCRCs Sensitivity Analysis (Source: Author's Own)

4.5 Strategies and Competencies in the Context of HVM

The prioritised supply chain competencies and resilience strategies identified in this study are not only applicable at a generic level but also demonstrate strong alignment with the unique requirements and challenges of high-value manufacturing (HVM) firms. This sector is characterised by high customisation, complex product designs, precision engineering, capital-intensive operations, and a strong dependency on skilled labour and technological capabilities. Below, we outline how each top-ranked competency and strategy aligns with and supports the distinctive needs of HVM:

4.5.1 Competency-Level Mapping:

- **SCRC8: Technological Maturity Levels** – High-value manufacturing firms rely extensively on sophisticated and digitally integrated machinery, tools, and systems for precision operations. The ability to adopt and integrate technologies such as IoT, predictive analytics, and cloud-based platforms is essential to ensure resilience in dynamic environments. This competency enables seamless operation, predictive maintenance, and remote diagnostics, which became even more vital during the COVID-19 disruptions.
- **SCRC2: Circular and Leagile Supply Chain** – HVM firms deal with both make-to-order and engineer-to-order products, often balancing stable product lines with high-variability custom demands. A leagile supply chain allows for responsiveness while maintaining efficiency. The incorporation of circularity further adds to resource efficiency and regulatory compliance, especially important in sectors dealing with high-value materials.
- **SCRC3: Supply Chain Network Designing** – Given the complexity of component sourcing and specialized supplier relationships in HVM, optimal network design is critical. A flexible and well-structured network allows firms to adapt quickly to supplier disruptions and logistics constraints, as observed during the pandemic.
- **SCRC6: Data Computation** – Precision manufacturing requires data-driven decisions across design, quality control, procurement, and logistics. Strong computational capabilities enable real-time visibility and forecasting accuracy, which are key to managing both complexity and responsiveness.
- **SCRC5: Inventory and Logistics Management** – HVM firms typically operate with high inventory costs and long lead times. Advanced logistics planning and inventory optimisation ensure uninterrupted production while reducing excess costs and minimising waste, especially for critical and expensive components.

4.5.2 Strategy-Level Mapping:

- **SCRS2: Building a Reconfigurable Supply Chain Structure** – Flexibility and modularity are vital in HVM, where customer specifications and product configurations frequently change. Reconfigurable structures allow for rapid adjustment in production and sourcing strategies without extensive downtime or reengineering.

- **SCRS4: Adopting Technological Innovations for Resilient Operations** – Innovation adoption, particularly digital tools and automation, supports resilience by enabling remote monitoring, enhanced traceability, and streamlined communication—critical in high-precision and regulation-intensive environments.
- **SCRS3: Bringing Sustailient Operations** – The integration of sustainable and resilient practices ('sustailience') directly supports HVM firms in meeting industry standards, environmental regulations, and stakeholder expectations. Examples include energy-efficient production systems and localized sourcing models that reduce carbon footprint and vulnerability.
- **SCRS7: Expansion of Strategic Focus through the Entire Value Chain** – HVM firms often operate in global, multi-tier supply chains. A broad strategic focus ensures visibility and alignment from raw material suppliers to end customers, which is essential for managing disruptions, especially in sectors with long product development cycles.
- **SCRS1: Creating Resilient Supply Chain Actors/Stages** – Strengthening each node of the supply chain—from component suppliers to final assembly units—is crucial in HVM to ensure continuity. This includes diversification of suppliers, developing local supplier capabilities, and improving coordination across tiers.

5 Research Implications

The present study offers significant contributions to the academic fraternity by advancing the theoretical underpinning of supply chain resilience. The implications of this study to the theory are discussed next.

Firstly, this study made an early attempt to consolidate the core competencies and key strategies required to build a resilient supply chain in organisations, particularly within the high-value manufacturing sector. The consideration of a high-value manufacturing industry, an industrial valve manufacturer, is very distinctive. This context has its own unicity and novelty in the literature. As a high-value manufacturer has an impact-footprint on economic, environmental, and social dimensions. Any disruption results in a saddled supply chain. This study put forth a guideline in the existing literature on supply chain resilience on the critical strategies and competencies required for high-value manufacturers to create a resilient supply chain structure. Secondly, applying neutrosophic AHP is worth highlighting as a methodological contribution to a scholarly domain. The utilisation of NAHP for evaluating critical supply chain resilience competencies and strategies contributes to the advancement of methodological approaches in the field of supply chain management.

As the application of the present work is demonstrated through a case study, it promises noteworthy managerial implications and insights for the practitioners. The practitioners and managers can understand the know-how about the possible challenges organisations may face during post-COVID-19 times. The findings suggest that to attain a resilient supply chain, high-value manufacturers, particularly industrial valve manufacturers, must focus on the key competencies, namely - operations & risk management, circular and leagile supply chain, and technological maturity levels. At the same time, practitioners should adopt critical strategies - bringing sustailient operations, creating resilient supply chain actors/stages, and adopting technological innovations for resilient operations. Bringing sustailient operations, i.e., adopting sustainable and resilient practices, can help industrial valve manufacturers reduce their exposure to supply chain disruptions while aligning with environmental and circular economy goals.

Furthermore, supply chain managers and organisations can use the information from our study to make informed decisions by leveraging the prioritised strategies and competencies tailored for high-value manufacturing firms. By understanding which strategies – such as building resilient supply chains, adopting technological innovations, and optimising operations are most critical, managers can allocate resources more effectively, focus on initiatives that enhance resilience and efficiency, and implement best practices specific to their sector.

Further, by adopting cutting-edge innovative technologies, like IoT, artificial intelligence, blockchain, etc., industrial valve manufacturers can improve their capability to quickly recover from the disruption, which results in the overall improvement of the resilience performance of the firm. Thus, the identified strategies have emerged as critical enablers in this process, offering new possibilities for optimising operations, mitigating risks, and ensuring continuity by improving supply chain resilience. The practitioners from industrial valve manufacturers and other high-value manufacturing industries (where the situation matches) shall try to strengthen the suggested strategies and competencies to create a resilient supply chain. Apart from these implications, strategists and practitioners from other industries can extend the procedure and findings of this study to check the most critical competencies and strategies relevant to their specific contexts. This comprehensive approach ensures that our findings are not only theoretically robust but also practically applicable, providing valuable insights for enhancing supply chain resilience across various sectors.

6 Conclusion

The COVID-19 pandemic catalysed significant shifts within the industrial valve industry, affecting various facets of its operations. The pandemic created an immense impact on the industry's growth. It posed challenges such as labour constraints and financial uncertainties, causing massive supply chain disruptions within the industrial valve manufacturing industry. These persisting issues, even in post-COVID-19 situations, made the valve manufacturers pursue supply chain resilience. Resilience isn't just recovery; it's the ability to thrive amidst change, securing a stronger, more interconnected global supply chain in the aftermath of the pandemic. However, in order to build a resilient supply chain, industries must adopt the necessary competencies and strategies. This study is developed at the outset to determine the most critical strategies and competencies for building and enhancing supply chain resilience for industrial valve manufacturing industries, a high-value manufacturer.

In doing so, we attempt to answer the three prime research questions mentioned in section 1 using a real-life case of an industrial valve manufacturer from India. For answering the RQ1 and RQ2, we conducted a comprehensive review of the literature. We identified 9 core competencies and 9 key strategies for building supply chain resilience. Further, we answered RQ 3 by assessing the identified competencies and strategies to determine the most critical ones in the context of industrial valve manufacturers. We utilised an advanced form of AHP, i.e. Neutrosophic AHP, to conduct the evaluation procedure. Utilising the 5-steps of NAHP, we determined that *"operations & risk management, circular and leagile supply chain, and technological maturity levels"* are the critical competencies, and *"bringing sustailient operations, creating resilient supply chain actors/stages, and adopting technological innovations for resilient operations"* are the critical strategies the firm under study must adopt to create a resilient supply chain. By focusing on the most critical strategies and competencies, stakeholders can streamline their efforts toward impactful areas such as enhancing supply chain visibility, adopting advanced digital technologies, building agile supplier relationships, and improving inventory responsiveness—all of which collectively contribute to strengthening overall supply chain resilience. This prioritisation allows for more effective resource allocation, reduces vulnerability to disruptions, and enhances the overall agility and responsiveness of the supply chain. For instance, by prioritising resilience-building measures (such as – multisourcing, predictive analytics deployment, supplier segmentation, and buffer stock maintenance) and technological innovations, stakeholders can better anticipate and mitigate risks, ensure continuity of operations during disruptions, and maintain competitive advantage. This approach improves the robustness of the supply chain and also fosters a proactive, strategic mindset among supply chain managers and organisations, leading to sustained operational excellence and long-term success.

Although the present study has notable implications, it possesses certain shortcomings. Since the current study consists of industrial vale manufacturers as context, the results may be confined to this type of industry. Also, the firm under study is a product-type high-value manufacturer. It could be possible that the results may vary for the other three types of high-value manufacturers. The limitations of the study open doors for future research endeavours in the realm of supply chain resilience. Researchers may explore the criticality levels of the identified competencies and strategies in other industries, viz. apparel, automobile, agricultural, healthcare, food, etc. The other forms of high-value industries can be further considered to check the relevance of the findings of the present study. Future research may consider a multiple case study approach to understand the commonalities and differences between the results obtained for different cases to gather meaningful insights for practitioners. As an appropriate strategy could help industries achieve desired competencies, future studies can build a DEMATEL model to determine the causal relationship between the identified strategies and competencies. This will help determine the right strategy for retaining the desired competencies. It would be of interest for prospective academicians and researchers to investigate and evaluate sub-strategies and sub-competencies falling under the primary 9 strategies and competencies to decipher new insights for building a resilient supply chain. Future studies could investigate the integration of neutrosophic AHP with other multi-criteria decision-making (MCDM) methods – such as TOPSIS, DEMATEL, or fuzzy AHP, to compare and validate the prioritisation of resilience strategies in different sectors beyond industrial valve manufacturing. Furthermore, researchers can explore practical implementation challenges, such as data availability, expert bias, and contextual constraints in real-world industrial settings, when deploying these methods.

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Appendix 1. Relevance of SCRC to HVM

#SCRC	Competencies	Relevance to High-Value Manufacturing (HVM)
SCRC1	Operations & Risk Management	Risk-sensitive environments like HVM need strong process control and contingency planning to prevent operational downtimes.
SCRC2	Circular and Leagile Supply Chain	HVM benefits from leanness (for cost) and agility (for flexibility); circularity supports waste reduction in precision-oriented production.
SCRC3	Supply Chain Network Designing	Customized, well-mapped networks reduce lead time and ensure component compatibility critical to HVM quality standards.
SCRC4	Human Governance	Skilled workforce management is vital in HVM, where technical knowledge and institutional experience are hard to replace.
SCRC5	Inventory and Logistics Management	HVM requires precise inventory handling (often JIT or low-volume high-cost items) and reliable logistics for specialized goods.
SCRC6	Data Computation	Enables real-time monitoring and smart manufacturing practices required in digitally advanced HVM environments.
SCRC7	Legislative Aspects	Compliance with sector-specific and export/import regulations is essential for HVM firms dealing with sensitive technologies or markets.
SCRC8	Technological Maturity Levels	A high degree of maturity (automation, IoT, AI) is often a competitive necessity in HVM sectors like aerospace or medical devices.
SCRC9	Analytics and Decision Making	Supports strategic forecasting, risk identification, and customized production planning—a staple for competitive advantage in HVM.

Appendix 2. Relevance of SCRS to HVM

#SCRS	Strategies	Relevance to High-Value Manufacturing (HVM)
SCRS1	Creating Resilient Supply Chain Actors/Stages	HVM firms often rely on specialized suppliers and precision components; resilience at each stage mitigates risk of disruption in critical areas.
SCRS2	Building a Reconfigurable Supply Chain Structure	Allows flexible response to demand variability and technological changes—a necessity in HVM where agility is crucial.
SCRS3	Bringing Sustailient Operations	Combines sustainability and resilience—key for HVM firms under regulatory and stakeholder pressure for responsible operations and robust systems.

SCRS4	Adopting Technological Innovations for Resilient Operations	HVM is inherently technology-intensive; innovation enables predictive maintenance, automation, and disruption resistance.
SCRS5	Optimisation and Analytics	Data-driven optimisation supports high precision and cost-efficiency required in HVM settings.
SCRS6	Creating a Supply Chain Resilience Management Team	Dedicated teams ensure quick response and strategic planning in HVM environments where even small delays can be costly.
SCRS7	Expansion of Strategic Focus through Entire Value Chain	In HVM, end-to-end alignment—from R&D to delivery—ensures quality, traceability, and innovation diffusion.
SCRS8	Dynamic Planning Model	Essential for responding to volatile, low-volume/high-value demand patterns typical of HVM sectors.
SCRS9	Collaboration with Researchers/Industry Stalwarts	HVM thrives on advanced research and niche expertise—collaborations enable access to latest methods and tech.