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Evaluating Supply Resilience Performance of an Automotive Industry during Operational Shocks: A Pythagorean Fuzzy AHP-VIKOR-Based Approach

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Abstract: An integral aspect of global businesses and economic activities is the supply chain networks. Importantly, the coronavirus (COVID-19) pandemic scenario has further shown that the outbreak of diseases can create a global network-scale disruption to supply chain or logistics, thereby damaging several aspects of economic activities and business life. Hence, this study aims to assess the resilient supplier selection (RSS) process in the wake of the COVID-19 outbreak. A two-stage hybrid decision model using Pythagorean fuzzy sets was proposed as a case study from the automotive industry to deal with RSS during the COVID-19 outbreak. In the first stage, significant criteria and their corresponding sub-criteria were determined through a vast review of the literature and nominal group technique, while the relative weights for RSS were obtained through the Pythagorean Fuzzy Analytic Hierarchy Process (PFAHP) method. In the second stage, nine suppliers were evaluated with Pythagorean Fuzzy VIKOR (PFVIKOR) method. The results of the hybrid approach revealed that flexibility is the most important criterion among resilience criteria that constitute the most significant dimensions for RSS. In many studies, strategic criteria such as quality, cost, and delivery are found to be the most important criteria in supplier selection, however, in the wake of the COVID-19 outbreak, the opinions of decision-makers were significantly changed as the present study reveals that flexibility is the most important criterion to improve the operations of the supply chain for RSS. Next to flexibility is process capabilities, while quality (Q), and cost (C) existed as the first and second in the category of influential criteria for strategic supplier selection criteria, respectively. The managerial and practical implication is that, in the wake of COVID-19 disruptions, suppliers need to be re-evaluated based on resilience-related indicators.

Keywords: automotive industry; coronavirus pandemic; Pythagorean Fuzzy Analytic Hierarchy Process (PFAHP); Pythagorean Fuzzy VIKOR (PFVIKOR); resilient supplier selection (RSS)



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1. Introduction

In recent years, supply chain networks have been confronted with unexpected incidents such as epidemics, climate change, and various natural disasters [1]. For instance, when the SARS epidemic hit China in 2003, China's domestic trade suffered a reduction in its growth from 11.1% to 9.1% in the first quarter of the year [2,3]. Aside from epidemics, cases of natural disasters such as Iceland's volcano eruption in March 2010, the Japan earthquake and tsunami in March 2011, and the flood in Thailand in August 2011 have

also caused diverse degrees of disruptions in business activities and various companies' supply chains. As a result of these events, companies are increasingly recognizing the need for effective supply chain risk management to find new ways in the face of uncertainty and changes [4]. The impacts of these developments are thus far limited, and there is no doubt that the evolving uncertainties that come with the coronavirus (COVID-19) outbreak are still destabilizing the global economy with respect to the known status quo of the pre-pandemic era [5,6]. Therefore, it is expected that companies aim to minimize the negative effects of disruptions by creating resilient supply chain networks.

When searching for suppliers, companies might wish to consider flexibility as one of the selection factors. If companies need to make modifications to customers' orders in the future, the supplier's flexibility in responding to companies' shifting demands may become very helpful. The most crucial weapon to combat and manage risks and uncertainties in today's unpredictable markets is supply chain flexibility [7]. It may also be viewed as developing tactics to outperform rivals and remain in an advantageous position in the market. In this regard, the overall profit can be raised, overall quantities can be optimized, and unanticipated occurrences can be responded to more swiftly with the help of cooperating flexible providers. The substantial correlations between sourcing flexibility, delivery performance, and product financial performance highlight the need for supply chain managers to pay attention to sourcing flexibility when choosing suppliers and making purchases [8]. A flexible supply chain is an indicator of how quickly, easily, inexpensively, or poorly a system can change or respond by adjusting to shifts in demand or supply [9]. A resilient supply chain describes a supply chain system's adaptive ability to react and respond to unanticipated circumstances with the appropriate measures, to respond to risks and disruptions, and to recover from them by sustaining and managing the operations at the desired level [10]. Thus, high cooperation levels and flexibility with suppliers are the driving forces of resilience [11].

As indicated by many researchers, supplier selection is a Multi-criteria decision-making (MCDM) problem [12,13] and a lack of knowledge of decision-makers or insufficient information about suppliers can expose the supplier selection decision-making process to a high degree of uncertainty, as noted by [14]. In the resilient supplier selection (RSS) problem, most researchers use MCDM methods based on ordinary fuzzy sets to determine weights of criteria and rank suppliers. However, extensions of fuzzy sets could be considered a stronger tool for handling higher uncertainty. For example, [10] investigated RSS using linguistic neutrosophic numbers. To our knowledge, no one has applied Pythagorean fuzzy sets (PFSs) in the RSS problem. PFSs, which are an extension of Intuitionistic Fuzzy Sets, capture the uncertainty and vagueness in a better way through more flexibility while revealing decision-makers judgments [15–17]. PFSs have generated a great deal of interest by providing more freedom to decision-makers in their assessment of MCDM problems.

Automobile sales, which dropped to 64 million worldwide in 2020, had a downward trend with the emergence of the coronavirus outbreak [18]. The coronavirus outbreak was observed to have led to cuts in China's parts exports, large-scale production cuts across Europe, and the closure of assembly facilities in the United States. Furthermore, suppliers facing liquidity issues can cause a disruption in the global automotive supply chain and potentially create catastrophic consequences [19]. The automotive industry in Turkey, besides comprising the first three largest sectors, has a vast 60 years of history, and Turkey ranks fifth in Europe's automotive production list [18]. However, despite being a prominent industry for Turkey, automotive production and exports decreased by 11% and 27%, respectively, year-on-year in 2020 [18]. Therefore, there is a need to examine the resilience of the Turkish automotive industry, especially in times of global disruption, as is the case for the novel coronavirus COVID-19 pandemic.

Generally, it has been reported that there are two main issues in supplier selection, namely determining appropriate criteria and corresponding sub-criteria, and developing an accurate model to rank the suppliers [20]. In many studies, resilience criteria were considered stand-alone, and the RSS under a uncertainty environment has not been adequately

addressed by researchers [10,21]. Hence, in this study, we propose a novel hybrid approach based on Pythagorean fuzzy numbers (PFNs) while intending to investigate the following important research questions.

- (i) What are the most important criteria and sub-criteria that affect the resilience performance of suppliers during the COVID-19 outbreak?
- (ii) How can the importance levels of the resilience criteria be obtained under the Pythagorean fuzzy environment?
- (iii) How can the performances of the suppliers be evaluated under the Pythagorean fuzzy environment with the resilience criteria?

The review of extant studies on RSS in the automotive industry showed that the case of Turkey is rarely addressed, especially with respect to the resilience performance of suppliers using a multi-criteria approach. Hence, given the outbreak of COVID-19, the current study examines whether RSS has gained importance in overcoming disruptions, and to further examine how the evaluation process can deal with uncertainties, thereby facilitating experts' judgments and comparisons. In specific terms, the study fills research gaps in the literature by: (i) specifying and providing detailed assessment criteria and their corresponding sub-criteria, (ii) developing a novel hybrid approach using PFNs, (iii) calculating weights of the criteria according to the decision-makers opinions using PFAHP, (iv) evaluating the resilience performance of suppliers by PFVIKOR, (v) performing a comprehensive sensitivity analysis, and (vi) presenting detailed theoretical and managerial implications.

The remainder of this study is provided as follows. The literature review is presented in Section 2. The necessary materials and methods are explained in Section 3. The case study and results are presented in Sections 4 and 5, respectively, while the conclusions, alongside the policy implications and limitations of the study, are captured in Section 6.

2. Literature Review

We provide a systematic review of the relevant literature regarding RSS and the used methods in this section. This section is organized into three parts. The first part details RSS studies (see Table 1) and their findings, the second section focuses on the review of PFAHP and PFVIKOR (see Table 2), while the third part essentially highlights the research gaps.

Contribution to Literature

The COVID-19 outbreak has hit several aspects of business life and its undesirable impacts have spread across various industries, including the automotive industry. Since suppliers are critical parts of supply chain management, addressing RSS appears to be an important topic during and in the aftermath of the COVID-19 outbreak. However, the selection of resilient supplier can be considered a difficult decision-making problem due to the identified challenges of COVID-19, as well as periodic and sectoral differentiating factors.

Although many MCDM methods have been used for RSS, as seen in the literature review tables, no study has attempted to combine resilience and supplier selection during the COVID-19 outbreak. In addition, different MCDM methods were discussed in most of the previous studies, however, PFNs were not evaluated. Here, PFNs are evaluated, as they provide a better opportunity to cope with the uncertainty in the evaluations of decision-makers in the problem of RSS. Furthermore, although different MCDM methods were discussed in most of the previous studies, the automotive industry was not discussed in RSS. Therefore, in addition to having a new MCDM approach, this study also contributes to the literature by researching RSS in the automotive industry during the COVID-19 outbreak. As such, the study suggested theoretical and managerial implications of the proposed approach for the automotive sector to increase the resilience of suppliers.

Table 1. RSS studies.

Author(s)	Aim	Resilience Criteria	Other Criteria	Method(s)	Fuzzy Environment	Application
[22]	To investigate resiliency and greenness in supply chain context and suggest a new resilient supplier assessment model	Development, agility, robustness, sensing, flexibility	Traditional criteria, green criteria, and related sub-criteria	DEMATEL and VIKOR	-	A chemical manufacturing company
[23]	To examine RSS problem	Pollution control initiatives, investment in capacity buffers, responsiveness, capacity for holding strategic inventory stocks for crises	Green criteria, and related sub-criteria	DEA, entropy, and principal components analysis	Interval type-2 fuzzy sets	Usage of secondary data from the previous study by Sen et al. (2016)
[24]	To develop a global performance measurement MCDM model	Strategic resilient criteria: Supply chain flexibility, adaptability, agility Information resilient criteria: Inconsistent data and information formats, inadequate stream of information, unreliability and unwillingness, inaccessibility, information sharing External resilient criteria Natural disasters, rapid development of technology, transportation network problem	General critical criteria, most critical criteria, and related sub-criteria	Fuzzy entropy, Fuzzy AHP Fuzzy additive ratio assessment	Type-1 fuzzy sets	An automotive original equipment manufacturer
[25]	To discuss the sustainable RSS problem	Robustness, responsiveness, cooperation, agility, visibility, risk reduction, surplus inventory, restorative capacity	General, sustainable, and related sub-criteria	FDEMATEL, FBWM, FANP, and fuzzy inference system	Type-1 fuzzy sets	A company in palm oil industry
[10]	To offer a decision-making structure for RSS	Top management support, reputation, corporate strategy, and commitment, customer/community pressures, economic stability, logistics-optimized infrastructure, environmental conservation, vulnerability and collaboration in risk reduction, supplier's sustainability, SC velocity, supplier responsiveness and training		PW model and MABAC	Neutrosophic fuzzy sets	A construction company

Table 1. Cont.

Author(s)	Aim	Resilience Criteria	Other Criteria	Method(s)	Fuzzy Environment	Application
[26]	To develop a supplier selection and order allocation model	Quality, delivery, technology, environmental competency, and continuity, and related sub-criteria		Fuzzy DEMATEL, ANP, and fuzzy multi-objective mixed integer programming	Type-1 fuzzy sets	A wood products manufacturer
[27]	RSS	Responsiveness, backup supplier contracts, restoration, risk of losing information and communication, service and support, innovation and technology, and product quality		TOPSIS	-	An electronic components manufacturer
[28]	RSS	Absorptive capacity: Surplus inventory, location separation, interdependency, robustness, reliability Adaptive capacity: Rerouting, reorganization Restorative capacity: Repair/restoration	Traditional criteria, and related sub-criteria	Logistic regression, CART, neural network, and AHP	-	A reputed plastic pipe manufacturer
[29]	RSS	Resilience criteria: Supply chain density, supply chain complexity, responsiveness, number of critical nodes, and re-engineering Critical criteria: Buffer capacity, supplier's resource flexibility, and lead time	General criteria, and related sub-criteria	AHP, QFD, and TOPSIS	-	A manufacturing company
[30]	RSS	Benefits: Delivery, flexibility, quality, and culture Opportunity: Joint growth, supplier's technology, and relationship building. Cost: Cost of product and cost of relationship	-	FANP and Grey VIKOR	Type-1 fuzzy sets	An example from the wood and paper industry

Table 1. Cont.

Author(s)	Aim	Resilience Criteria	Other Criteria	Method(s)	Fuzzy Environment	Application
[31]	RSS	Flexibility: Time flexibility, product flexibility, quantity flexibility Enterprise capacity, R&D, green abilities, and related sub-criteria	Primary performance factors and related sub-criteria	AHP and grey relational analysis	-	A two-story complex construction project
[32]	RSS	Enhancers of supplier resiliency, reducers of supplier resiliency, and related sub-criteria		Grey DEMATEL and Grey simple additive weighting		An example from the wood and paper industry
[33]	RSS	Investment in capacity buffers, responsiveness, and capacity for holding strategic inventory stocks for crises	Product quality, reliability of a product, functionality of product, customer satisfaction, and cost of the product	COPRAS and WASPAS	Interval-valued intuitionistic fuzzy sets	Two case studies from the literature
[34]	RSS	Investment in capacity buffers, responsiveness, and capacity for holding strategic inventory stocks for crises	Quality, reliability of the product, functionality of the product, customer satisfaction, and cost of the product	Fuzzy TOPSIS and Aggregate Fuzzy Weight	Type-1 fuzzy sets	An automobile manufacturer
[35]	RSS	Investment in capacity buffers, responsiveness, capacity for holding strategic inventory stocks for crises	Product quality, reliability of the product, functionality of the product, extent of customer satisfaction, and product price	Fuzzy VIKOR	Type-1 fuzzy sets	Empirical research
[36]	RSS	Buffer capacity, number of critical nodes, responsiveness, re-engineering, and adaptive capability	Quality, delivery, reliability, processing time, and profit margin	AHP, QFD, TOPSIS	Type-1 fuzzy sets	Empirical research

Table 2. Review of recent studies using PFAHP and/or PFVIKOR methods.

Author(s)	Aim	Method(s) Used	Application
[37]	Investigation of risk for the hazards of excavation process	Pythagorean fuzzy proportional risk assessment, Fine Kinney and PFAHP	Excavation process in a construction yard
[38]	Proposal of risk assessment approach	PFAHP and fuzzy VIKOR	A gun and rifle production facility
[39]	A comparative analysis in occupational health and safety risk assessment	PFAHP and FTOPSIS	An underground copper and zinc mine
[40]	Site selection for electric vehicle charging stations	PFVIKOR	An example in China
[16]	Selection of renewable energy technologies	PFVIKOR	An example in India
[17]	Development a new model for regional performance	PFAHP	26 NUTS-2 regions of Turkey
[41]	Evaluation process to assess digital supply chains partners	PFAHP and PF COPRAS	A case study from Turkey
[42]	Presenting a novel model for landfill site selection problem	PFAHP	The city of Istanbul in Turkey
[43]	Suggestion of a risk assessment approach	FMEA, PFAHP, and PFMOORA	A concrete coating process of natural gas pipeline project
[44]	Evaluation of internet banking website quality	TODIM and PFVIKOR	A simulated example of ranking Internet banking websites
[45]	Forming a decision support system for occupational risk assessment	PFVIKOR	A natural gas pipeline construction
[46]	Propose a risk assessment approach	PFVIKOR	An underground copper and zinc mine
[47]	Performing a risk assessment model	PFAHP	A hydroelectric power plan
[48]	Identification of sustainable supply chain innovation enablers	PFAHP	An Indian manufacturing industry
[49]	Building a hazard evaluation approach	PFAHP	A company operating in Istanbul
[15]	Green supplier selection problem with industry 4.0 drivers	PFAHP and PFTOPSIS	An agricultural tool and machinery company
[50]	Construction of an ecological landslide prevention model	PFAHP	The specific tropical rainforest area China
[51]	Evaluating the hospital service quality	PFAHP and PFTOPSIS	A case study consisting of hospitals in Turkey
[52]	Proposal of new generalized distance measure and weighted generalized distance measures	PFAHP, PFTOPSIS Pythagorean fuzzy entropy	An international company
[53]	Evolution of a novel SCOR 4.0 model	BWM and PFAHP	The oil supply chain
[54]	Investigation of the critical risk factors for hazardous material transportation operations	PFAHP	A public company in Istanbul
[55]	Prioritization risks in self-driving vehicles	PFAHP and PFVIKOR	Application with experts

Moreover, the criteria system is suitable for general supplier selection for industries including the automotive industries, and we have mainly utilized the case of the Turkish automotive industry as a suitable scenario presentation. There are several reasons why the automotive industry was specifically chosen. First, just as it plays a major role in the Turkish's economy, it also plays significant roles in several other economies across the globe. In the case study country, for instance, the leading three largest industries are all in the automotive sector, which saw significant sales disruptions in 2020. The capability of crucial suppliers, including those of steel, glass, plastic, and advanced electrical systems, is essential to the success of car manufacturing companies. Second, most car items are put together from several sub-components. Finding and selecting the right supplier in the automotive industry is like picking a book out of a mountain of books. The selection of a company will be based on a wide range of variables, including the reliability and quality of the service provided, followed by the cost. Thirdly, the COVID-19 epidemic has caused shortages that have affected every vehicle manufacturer in the world, resulting in production halts and backlogs. The automotive industry, semiconductor manufacturers, and governments have concentrated on mitigation strategies to ensure sourcing and capacity expansion. To minimize business uncertainty and maintain themselves in an environment of international competitiveness, manufacturers should prioritize the integration of resilience viewpoint with supplier selection.

3. Materials and Methods

The proposed hybrid approach for RSS is presented in Figure 1, and the details of the methods used are given as follows. The hierarchical criterion structure is created in this study to specify the standards for selecting suppliers who will provide service during the pandemic. Three steps of analysis constitute the current study. A literature review was conducted in the first step, during which research gaps were found. The Pythagorean Fuzzy-based Analytic Hierarchy Process (PF-AHP) calculates the weights of each main and sub-criteria in the second stage, and the Pythagorean Fuzzy-based VlseKriterijumska Optimizacija I Kompromisno Resenje (PF-*VIKOR*) approach was then used to rank the suppliers in the third stage once appropriate suppliers have been assessed. AHP and *VIKOR* methods are widely popular MCDM techniques that provide more reliable solutions, especially when integrated. AHP assesses the problem as it is presented at various levels of hierarchy and uses pairwise comparisons of criteria to specify the importance level of criteria [56]. *VIKOR* presents compromising solutions based on the proximity to the ideal solution [57]. Since the preferences of decision-makers are unable to accurately capture exact numbers, fuzzy numbers can be utilized to handle imprecise information in the judgments of decision-makers [55]. Therefore, AHP and *VIKOR* methods are integrated under the Pythagorean fuzzy environment.

3.1. The PFAHP

The steps of PFAHP are presented as follows.

Step 1: The pairwise comparison matrix $A = (a_{ik})_{m \times m}$ is constructed based on the linguistic evaluation of experts. The linguistic terms that are given [37] are presented in Table 3.

Step 2: The difference matrices $D = (d_{ik})_{m \times m}$ between the lower and upper values of the membership and nonmembership functions are calculated using Equations (1) and (2):

$$d_{ik_L} = \mu_{ik_L}^2 - \nu_{ik_U}^2, \quad (1)$$

$$d_{ik_U} = \mu_{ik_U}^2 - \nu_{ik_L}^2 \quad (2)$$

Step 3: Interval multiplicative matrix $S = (s_{ik})_{m \times m}$ is computed using Equations (3) and (4):

$$s_{ik_L} = \sqrt{1000^{d_L}}, \quad (3)$$

$$s_{ik_U} = \sqrt{1000^{d_U}} \tag{4}$$

Step 4: The determinacy value $\tau = (\tau_{ik})_{m \times m}$ is calculated using Equation (5):

$$\tau_{ik} = 1 - \left(\mu_{ik_U}^2 - \mu_{ik_L}^2 \right) - \left(v_{ik_U}^2 - v_{ik_L}^2 \right) \tag{5}$$

Step 5: The determinacy degrees are multiplied with $S = (s_{ik})_{m \times m}$ matrix for obtaining the matrix of weights, $T = (t_{ik})_{m \times m}$ before normalization using Equation (6).

$$t_{ik} = \left(\frac{s_{ik_L} + s_{ik_U}}{2} \right) \tau_{ik} \tag{6}$$

Step 6: The priority weights w_i of criteria are normalized by using Equation (7):

$$w_i = \frac{\sum_{k=1}^m t_{ik}}{\sum_{i=1}^m \sum_{k=1}^m t_{ik}} \tag{7}$$

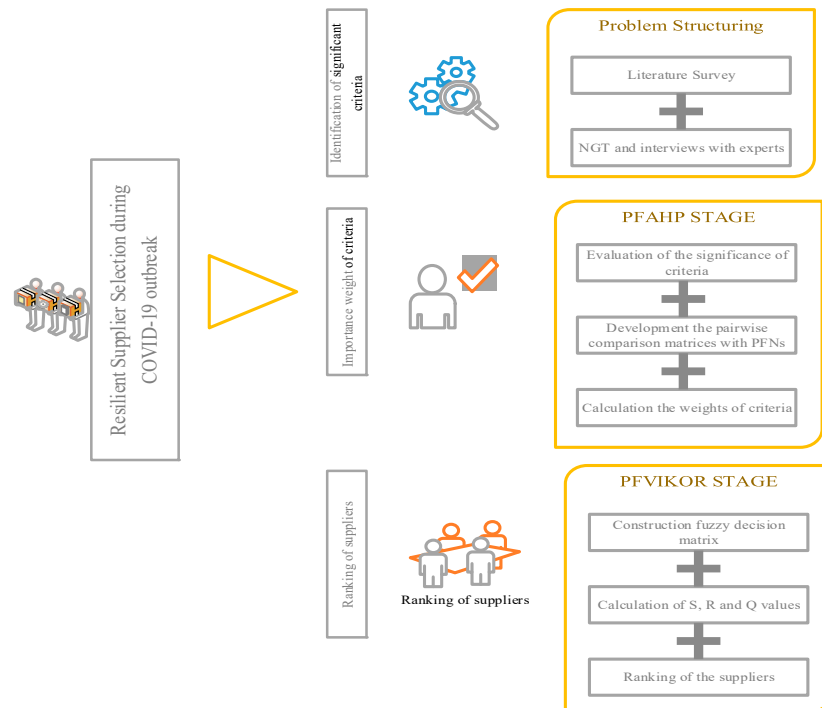


Figure 1. The framework of the proposed hybrid approach.

Table 3. Linguistic terms for importance weights of criteria [37].

Linguistic Variables	Pythagorean Fuzzy Numbers			
	μ_L	μ_U	v_L	v_U
Certainly Low Importance—CLI	0.00	0.00	0.90	1.00
Very Low Importance—VLI	0.10	0.20	0.80	0.90
Low Importance—LI	0.20	0.35	0.65	0.80
Below Average Importance—BAI	0.35	0.45	0.55	0.65
Average Importance—AI	0.45	0.55	0.45	0.55
Above Average Importance—AAI	0.55	0.65	0.35	0.45
High Importance—HI	0.65	0.80	0.20	0.35
Very High Importance—VHI	0.80	0.90	0.10	0.20
Certainly High Importance—CHI	0.90	1.00	0.00	0.00
Exactly Equal—EE	0.1965	0.1965	0.1965	0.1965

3.2. The PFVIKOR

The Vlse Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method is an effective tool to reach compromise solutions. In this study, the VIKOR method under Pythagorean fuzzy environment namely (PFVIKOR) was employed and briefly reviewed as follows:

Step 1: The Pythagorean fuzzy decision matrix is constructed by aggregation of decision-makers' judgments. Let $\tilde{P}_i = P(\mu_i, v_i), i = 1, 2, \dots, n$ be a collection of PFNs. The following Pythagorean fuzzy weighted averaging (PFWA) operator is utilized to aggregate different opinions [40]:

$$PFWA(\tilde{P}_1, \tilde{P}_2, \dots, \tilde{P}_n) = (\sqrt{1 - \prod_{i=1}^n (1 - (\mu_i)^2)^{w_i}}, \prod_{i=1}^n [v_i]^{w_i}) \tag{8}$$

where $w_i = (w_1, w_2, \dots, w_n)$ is the weight vector of \tilde{P}_i with $w_i \in [0, 1]$ and $\sum_{i=1}^n w_i = 1$.

Step 2: Pythagorean fuzzy positive ideal solution (PFPIIS) $f_j^* = (\mu_j^*, v_j^*), j = 1, 2, \dots, m$ and Pythagorean fuzzy negative ideal solution (PFNIS) $f_j^- = (\mu_j^-, v_j^-), j = 1, 2, \dots, m$ of alternatives ($i = 1, 2, \dots, n$) are computed using Equations (18) and (19):

$$f_j^* = \begin{cases} \binom{max}{i} f_{ij} & \text{for benefit criteria} \\ \binom{min}{i} f_{ij} & \text{for cost criteria} \end{cases} \tag{9}$$

$$f_j^- = \begin{cases} \binom{min}{i} f_{ij} & \text{for benefit criteria} \\ \binom{max}{i} f_{ij} & \text{for cost criteria} \end{cases} \tag{10}$$

Step 3: S_i and R_i values are computed through generalized Pythagorean fuzzy ordered weighted standardized distance operator (GPFOWSD) in the following [40]:

$$S_i = GPFOWSD(\langle f_1^*, f_1^-, f_{i1} \rangle, \dots, \langle f_j^*, f_j^-, f_{im} \rangle) = (\sum_{k=1}^n w_k \bar{d}_k^\lambda)^{1/\lambda} \tag{11}$$

$$R_i = (\max_k w_k \bar{d}_k^\lambda)^{1/\lambda} \tag{12}$$

where \bar{d}_k^λ represents the k th largest of the standardized Pythagorean fuzzy distance, w_k is the weights of criteria, and λ is the operator in GPFOWSD.

Step 4: Q_i values are computed using Equation (12):

$$Q_i = q \frac{(S_i - S^*)}{S^- - S^*} + (1 - q) \frac{(R_i - R^*)}{R^- - R^*} (i = 1, 2, \dots, n) \tag{13}$$

where $S^* = \binom{min}{i} S_i; S^- = \binom{max}{i} S_i; R^* = \binom{min}{i} R_i; R^- = \binom{max}{i} R_i$ and q is a weight for the strategy of the maximum group utility, whereas $(1 - q)$ is the weight of the individual regret.

Step 5: Rank the alternatives according to the values $S, R,$ and Q in ascending order.

Step 6: Propose, as a compromise solution, the alternative ($A^{(1)}$), which is the best ranked by the measure Q_i and was proposed if the conditions in [55] were satisfied.

4. A Case Study

To evaluate the performance of the proposed hybrid decision-making approach, a real case study was conducted for a company from the automotive industry in Turkey. The company manufactures basic transfer systems such as vacuum lines, air suspension lines, ventilation lines, and fuel lines. The company meets the production needs of many automobile manufacturers with more than 400 employees and a production facility of 10 thousand square meters. The company, which creates plans within the framework of

resilience, harmony, and cooperation with its suppliers, seeks a methodology that will enable them to understand the principles of RSS process and to minimize disruptions in the supply chain. Company executives support nine suppliers to improve their production and operation activities to supply materials, even in the case of disruption. Five experts from the case study company were invited to the data collection process. The first specialist is the company’s 15-year-experienced logistics manager who is responsible for supply chain operations. The second expert is the purchasing manager with 10 years of experience. Third is the production manager with 25 years of experience. Finally, an industrial engineer who is responsible for the distribution business with 10 years of experience also took part in the research. Decision-makers were assigned the following weights, based on years of experience in the company: 0.12, 0.16, 0.16, 0.12, 0.08, 0.12, 0.12, 0.06, and 0.06.

4.1. Identifying Criteria and Obtaining the Weights of the Criteria

After the goal was determined, the criteria and sub-criteria to be used to evaluate the performance and ranking of the suppliers were subsequently determined. A nominal group technique was composed and implemented through face-to-face interviews with decision-makers. Following the literature review and interviews with decision-makers, the hierarchical structure that is presented in Figure 2 of the two main criteria, eight sub-criteria, and 28 criteria RSS problems were created. Definitions of the assessment criteria are explained in Table 4.

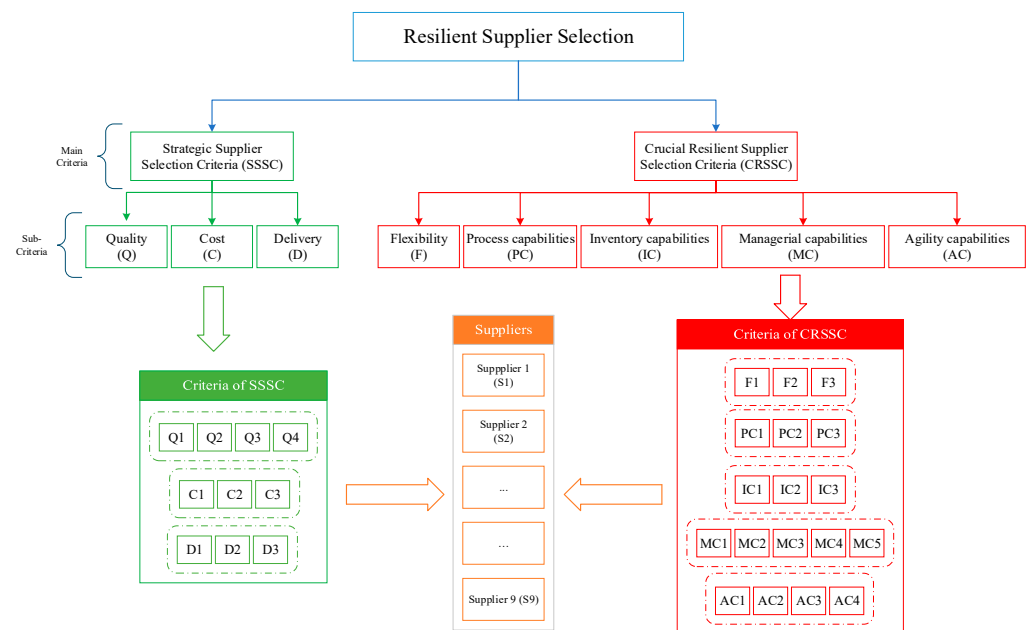


Figure 2. The hierarchical structure of the RSS problem.

Table 4. Identified criteria of RSS assessment.

Main Criteria	Criteria	Sub-Criteria	Definition	Reference
Crucial Resilient Supplier Selection Criteria (CRRSC)	Flexibility (F)	Flexibility in delivery time (F1)	The ability to respond to variations in the customer demand	[58–61]
		Flexibility in ordering (F2)	The ability to accommodate the competitive market environment	[62]
		Customization (F3)	The ability to customize the product mix as requested by the buyer.	[3,30]

Table 4. Cont.

Main Criteria	Criteria	Sub-Criteria	Definition	Reference
	Process capabilities (PC)	Facility fortification (PC1)	The ability to alleviate risks through proactive capability	[63–65]
		Restorative capacity (PC2)	The ability to repair or restore damaged facilities	[25,28]
		Investment in capacity buffers (PC3)	The ability to reduce risks with level of safety stock	[23,29]
	Inventory capabilities (IC)	Capacity for holding strategic inventory stocks for crises (IC1)	The capacity for holding a large stock of parts and goods	[23,29,33,35]
		Surplus inventory (IC2)	The supplementary inventory for crises	[20,28]
		Adaptive capability (IC3)	The ability to merge new knowledge and intelligence	[10,26]
	Managerial capabilities (MC)	Reputation (MC1)	The perceptual image of suppliers	[10,31,66]
		Level of collaboration (MC2)	The ability of two or more companies to work together	[30,67]
		Financial strength (MC3)	The ability to absorb fluctuations in cash flow	[68,69]
		Management skills and compatibility (MC4)	The skills of managers in risky and unexpected events	[70]
Responsiveness (MC5)		The reaction speed of suppliers to market demand	[27,33,34]	
Agility capabilities (AC)	Digitalization of supply chain(s) (AC1)	The ability to adopt innovative and disruptive technologies	[71,72]	
	Process integration (AC2)	The ability to establish partnership linked into a network	[73–75]	
	Delivery speed (AC3)	The ability to meet the delivery target	[76,77]	
	Information integration (AC4)	The ability of sharing information by supply chain partners	[75,78]	
Strategic Supplier Selection Criteria (SSSC)	Quality (Q)	Rejection rate of the product (Q1)	This criterion shows the rejected parts by the buyers	[20]
		After-sale services (Q2)	The ability to provide necessary supports and guaranty/warranty services	[79–81]
		Quality certificates (Q3)	The ability of suppliers complying with standards	[82,83]
		Capability of Handling Abnormal Quality (Q4)	The ability of supplier handling abnormal quality problem	[3,20]
	Cost (C)	Purchasing cost (C1)	The price of goods and materials of suppliers	[15,84]
		Transportation cost (C2)	The unit transportation cost of suppliers	[85,86]
		Order cost (C3)	The order cost of suppliers	[87,88]
	Delivery (D)	On-time delivery (D1)	The ability to measure delivery in time	[30]
		Order lead time (D2)	The ability of time that it takes to fulfill customer orders	[32,68]
		Distribution network quality (D3)	The service ability of suppliers in delivering products	[3,68,81]

In the first step towards determining the criterion weights, each of the decision-makers created the pairwise comparison matrices using the linguistic scale presented in Table 3. Following that, the consistency of the pairwise comparison matrices of each decision-maker was checked, and it was found that the consistency rates were below 0.10. Table 5 shows the interval-valued PFSs with corresponding linguistic variables for the main criteria. Other pairwise comparison matrices were performed (results are not provided here because of space constraints). Following that, the aggregated pairwise comparison matrix, which is indicated in Table 6 of the main criteria, was carried out using the interval-valued Pythagorean fuzzy weighted geometric operator given in [89]. All these procedures are

also applied to the sub-criteria and criteria, and the final priority weights for all criteria are given in Table 7.

Table 5. Pairwise comparison matrix for main criteria.

	SSSC	CRSSC
SSSC	EE, EE, EE, EE, EE, EE	HI, VLI, AAI, CLI, VHI, LI
CRSSC	LI, VHI, BAI, CHI, VLI, HI	EE, EE, EE, EE, EE, EE

Table 6. Aggregated pairwise comparison matrix for the main criteria.

	C1	C2
C1	([0.197, 0.197], [0.197, 0.197])	([0.000, 0.000], [0.662, 1000])
C2	([0.399, 0.547], [0.523, 0.649])	([0.197, 0.197], [0.197, 0.197])

Table 7. The weights of the criteria.

Main Criteria	Weights	Criteria	Weights	Sub-Criteria	Weights	Global Weights						
SSSC	0.4077	Q	0.3729	Q1	0.5224	0.0794						
				Q2	0.1086	0.0165						
				Q3	0.2926	0.0445						
				Q4	0.0765	0.0116						
		C	0.3295	D	0.2975	C1	0.4459	0.0599				
						C2	0.2578	0.0346				
						C3	0.2962	0.0398				
						D1	0.2705	0.0328				
		D	0.2975	D	0.2975	D2	0.4663	0.0566				
						D3	0.2631	0.0319				
						CRSSC	0.5923	F	0.4175	F1	0.2478	0.0613
										F2	0.1960	0.0485
F3	0.5562	0.1376										
PC	0.3007	IC	0.1406	PC1	0.3600			0.0641				
				PC2	0.4423			0.0788				
				PC3	0.1977			0.0352				
MC	0.0434	AC	0.0977	IC1	0.3100			0.0258				
				IC2	0.3482			0.0290				
				IC3	0.3419			0.0285				
AC	0.0977	AC	0.0977	MC1	0.2616			0.0067				
				MC2	0.3440			0.0088				
				MC3	0.2062			0.0053				
				MC4	0.1468	0.0038						
AC	0.0977	AC	0.0977	MC5	0.0414	0.0011						
				AC1	0.5971	0.0346						
				AC2	0.1396	0.0081						
				AC3	0.1474	0.0085						
AC	0.0977	AC	0.0977	AC4	0.1159	0.0067						
				AC4	0.1159	0.0067						

4.2. Ranking of Suppliers

In the second stage, the applicable suppliers were ranked by applying the PFVIKOR method with the weights obtained in the previous stage. The decision-makers evaluated nine suppliers using the linguistic variables presented in Table 8 and the corresponding PFNs. The linguistic evaluations of decision-makers for nine suppliers were performed (results are not provided here because of space constraints). Decision-makers' evaluations were aggregated using the previous equation. The aggregated Pythagorean fuzzy decision matrix is given in Table 9. Applying the steps given in Section 3.2, the ranking of the suppliers was obtained as shown in Table 10.

Table 8. Linguistic scale for rating of suppliers.

Linguistic Term	Corresponding Pythagorean Fuzzy Number (u, v)
Very Poor (VP)	(0.15, 0.85)
Poor (P)	(0.25, 0.75)
Medium Poor (MP)	(0.35, 0.65)
Medium (M)	(0.50, 0.45)
Medium Good (MG)	(0.65, 0.35)
Good (G)	(0.75, 0.25)
Very Good (VG)	(0.85, 0.15)

Table 9. Aggregated fuzzy decision matrix of suppliers.

	S1		S2		S3		S4		S5		S6		S7		S8		S9	
	u	v	u	v	u	v	u	v	u	v	u	v	u	v	u	v	u	v
Q1	0.508	0.549	0.470	0.535	0.561	0.422	0.726	0.275	0.529	0.532	0.546	0.478	0.540	0.489	0.661	0.368	0.581	0.445
Q2	0.362	0.651	0.707	0.317	0.637	0.350	0.754	0.267	0.331	0.695	0.494	0.520	0.596	0.438	0.768	0.243	0.536	0.496
Q3	0.609	0.402	0.633	0.411	0.749	0.252	0.792	0.208	0.740	0.260	0.555	0.432	0.713	0.301	0.689	0.331	0.527	0.516
Q4	0.554	0.496	0.644	0.400	0.542	0.480	0.745	0.269	0.368	0.654	0.482	0.507	0.375	0.659	0.643	0.374	0.591	0.447
C1	0.344	0.660	0.688	0.312	0.462	0.554	0.765	0.237	0.349	0.656	0.638	0.370	0.741	0.261	0.691	0.315	0.382	0.629
C2	0.616	0.434	0.573	0.470	0.739	0.271	0.700	0.301	0.581	0.440	0.468	0.574	0.470	0.570	0.673	0.351	0.331	0.697
C3	0.241	0.770	0.562	0.439	0.625	0.371	0.684	0.326	0.259	0.748	0.675	0.347	0.575	0.451	0.650	0.367	0.579	0.413
D1	0.376	0.621	0.751	0.260	0.539	0.462	0.675	0.319	0.591	0.424	0.402	0.605	0.419	0.561	0.498	0.553	0.756	0.245
D2	0.198	0.807	0.701	0.295	0.593	0.414	0.745	0.256	0.438	0.624	0.398	0.604	0.526	0.476	0.702	0.313	0.533	0.492
D3	0.634	0.371	0.727	0.272	0.626	0.394	0.784	0.217	0.484	0.521	0.730	0.283	0.691	0.318	0.598	0.395	0.479	0.520
F1	0.601	0.400	0.761	0.266	0.701	0.314	0.800	0.202	0.642	0.363	0.675	0.334	0.558	0.463	0.785	0.218	0.567	0.456
F2	0.459	0.594	0.493	0.527	0.679	0.365	0.645	0.402	0.389	0.669	0.630	0.414	0.777	0.223	0.705	0.327	0.624	0.388
F3	0.460	0.592	0.725	0.282	0.483	0.493	0.632	0.381	0.819	0.182	0.593	0.403	0.428	0.610	0.772	0.246	0.723	0.301
PC1	0.497	0.556	0.582	0.448	0.635	0.394	0.655	0.376	0.543	0.483	0.596	0.423	0.449	0.572	0.754	0.257	0.389	0.602
PC2	0.709	0.322	0.587	0.444	0.664	0.341	0.528	0.518	0.792	0.211	0.616	0.388	0.575	0.473	0.736	0.284	0.672	0.363
PC3	0.512	0.541	0.741	0.267	0.685	0.317	0.742	0.272	0.558	0.450	0.570	0.419	0.587	0.420	0.797	0.211	0.611	0.407
IC1	0.407	0.642	0.705	0.318	0.753	0.249	0.778	0.223	0.694	0.350	0.503	0.536	0.676	0.341	0.750	0.252	0.684	0.345
IC2	0.384	0.667	0.564	0.472	0.624	0.387	0.775	0.226	0.570	0.477	0.723	0.275	0.743	0.262	0.600	0.396	0.591	0.450
IC3	0.553	0.480	0.789	0.225	0.637	0.369	0.699	0.296	0.672	0.350	0.630	0.382	0.782	0.232	0.769	0.238	0.642	0.387
MC1	0.553	0.506	0.577	0.480	0.554	0.486	0.612	0.432	0.635	0.398	0.581	0.428	0.739	0.270	0.728	0.279	0.608	0.435
MC2	0.443	0.549	0.632	0.372	0.687	0.332	0.682	0.333	0.503	0.476	0.427	0.570	0.700	0.324	0.533	0.454	0.235	0.773
MC3	0.727	0.281	0.617	0.415	0.608	0.434	0.629	0.396	0.584	0.433	0.612	0.392	0.611	0.428	0.740	0.275	0.517	0.524
MC4	0.456	0.595	0.563	0.438	0.640	0.358	0.715	0.299	0.457	0.589	0.545	0.498	0.743	0.257	0.552	0.450	0.590	0.404
MC5	0.523	0.470	0.767	0.241	0.575	0.408	0.535	0.437	0.454	0.553	0.519	0.529	0.658	0.346	0.661	0.369	0.775	0.242
AC1	0.573	0.476	0.676	0.334	0.403	0.638	0.607	0.430	0.447	0.588	0.466	0.582	0.577	0.450	0.713	0.284	0.459	0.584
AC2	0.593	0.448	0.707	0.298	0.569	0.437	0.801	0.200	0.596	0.453	0.435	0.588	0.712	0.287	0.716	0.293	0.502	0.537
AC3	0.555	0.466	0.828	0.173	0.665	0.354	0.660	0.366	0.631	0.403	0.598	0.395	0.411	0.624	0.606	0.422	0.422	0.601
AC4	0.496	0.523	0.742	0.256	0.597	0.405	0.701	0.299	0.434	0.581	0.321	0.687	0.551	0.493	0.677	0.341	0.581	0.427

Table 10. S, R, and Q values and ranking orders for suppliers.

	Si	Ranking	Ri	Ranking	Qi	Ranking
S1	0.621	9	0.085	6	0.967	9
S2	0.437	4	0.083	5	0.343	4
S3	0.430	3	0.051	2	0.450	7
S4	0.426	2	0.111	9	0.204	2
S5	0.483	5	0.079	4	0.372	5
S6	0.538	7	0.065	3	0.412	6
S7	0.531	6	0.094	7	0.871	8
S8	0.363	1	0.047	1	0.000	1
S9	0.540	8	0.098	8	0.253	3

5. Sensitivity Analysis and Validation of the Results

The robustness of the obtained results was investigated in three subsections. In the first part, 50 different scenario analyses were carried out by changing the weight of the most important criterion. In the second part, the dependence of the obtained results on the change of the q parameter is analyzed. In the third part, a comparison of ranking results with different MCDM methods is explained.

5.1. Variation of Criteria Weights

In this section, the performance of the proposed approach was evaluated according to the weights of the most important criterion. In this study, certainty-based reusable sample selection and correction (CRSSC) criterion was determined as the most important criterion, with a weight of 0.5923. In the first scenario analysis, the value of the CRSSC criterion was reduced by 2%, and the values of the remaining criteria were adjusted proportionally according to the recommendations of [90,91]. The change of the values of the weight coefficients CRSSC and SSSC in the interval $CRSSC \in [0.2157, 0.5805]$ and $SSSC \in [0.4195, 0.7843]$ was simulated through 50 scenarios. The vectors of CRSSC criterion coefficients are depicted in Figure 3. After creating 50 coefficient vectors, the effects of these values on alternative rankings were analyzed. The change of alternatives according to the Q values is shown in Figure 4.

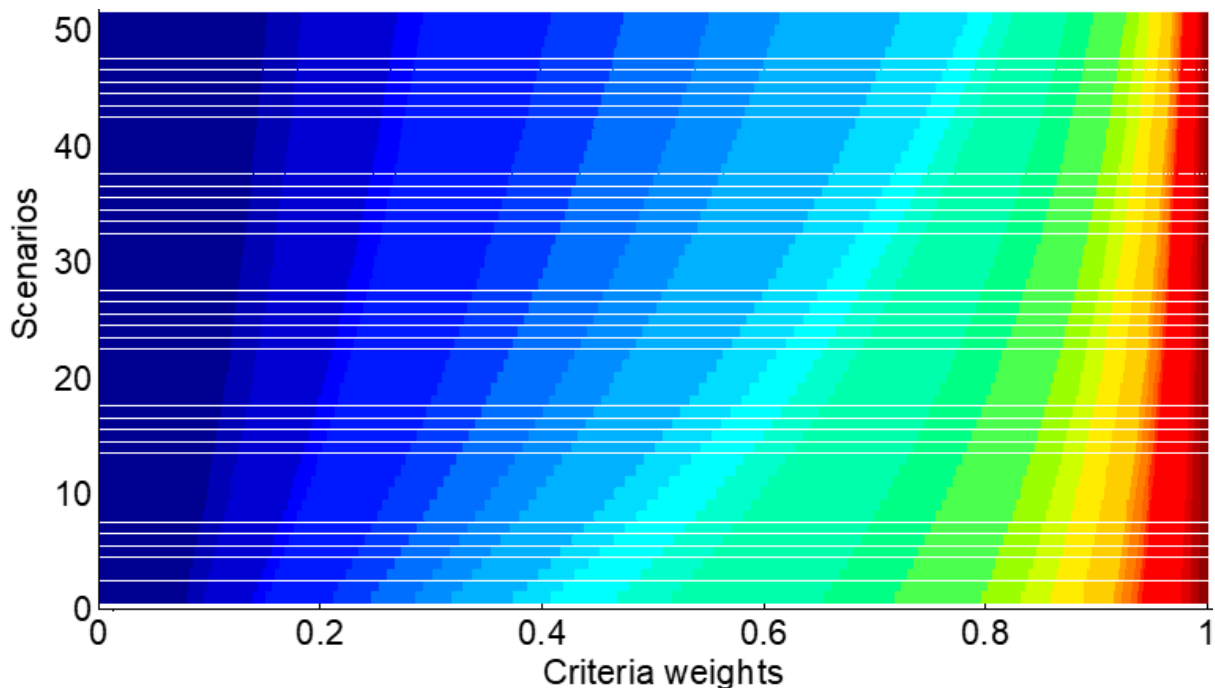


Figure 3. The change of CRSSC criterion weights in 50 scenarios.

According to the scenario analysis results, it was concluded that the first supplier (S8) keeps its order in 38 out of 50 scenarios. For interval $CRSSC \in [0.2157, 0.2749]$, the best supplier (S8) is losing its place and S3 took the first rank. After this interval, S8 and S3 exchanged their places. One of the main reasons for these changes is that the weight of the SSSC criterion is noticeably increased and the CRSSC criterion becomes dominant at about 28% of the weight. The S1 supplier ranks last in all 50 scenarios.

In the second 50 scenarios, the different weights for the most important sub-criterion in CRSSC are analyzed. The weight of flexibility that is the highest influence in CRSSC criterion was decreased by 2% as seen in Figure 5, and a new set of weight coefficients was generated from the interval $F \in [0.152, 0.409]$. From the results given in Figure 6, it is concluded that the best supplier in the current result (S8) is the dominant one that captures first place in all rankings.

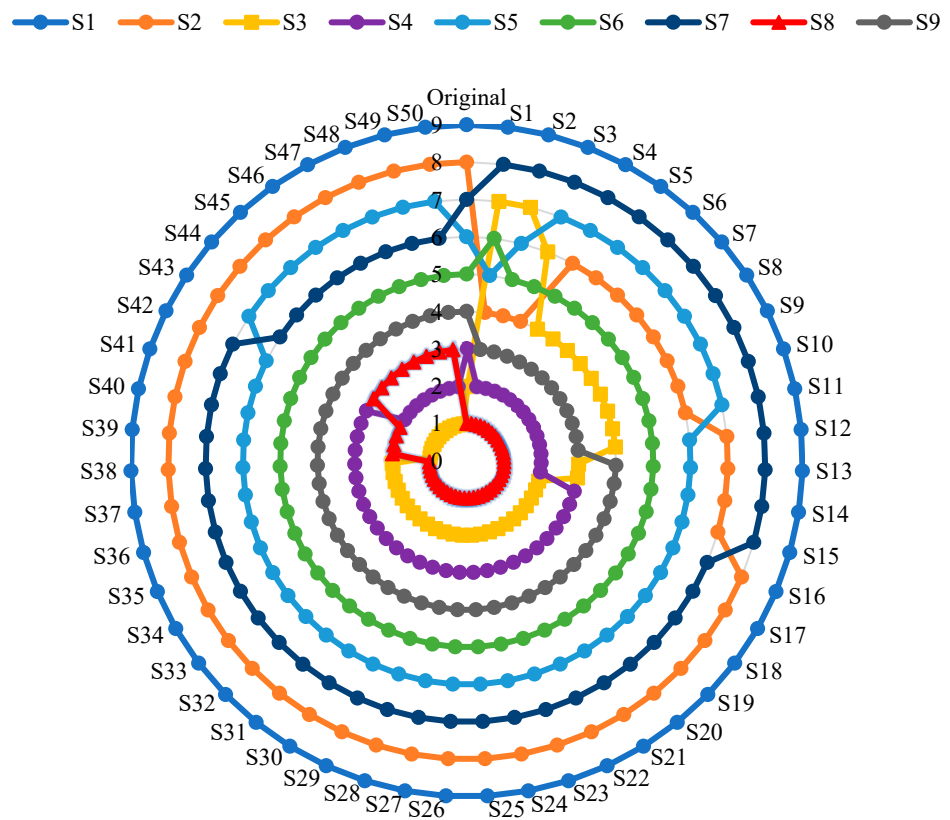


Figure 4. Ranking results of the first scenario analysis.

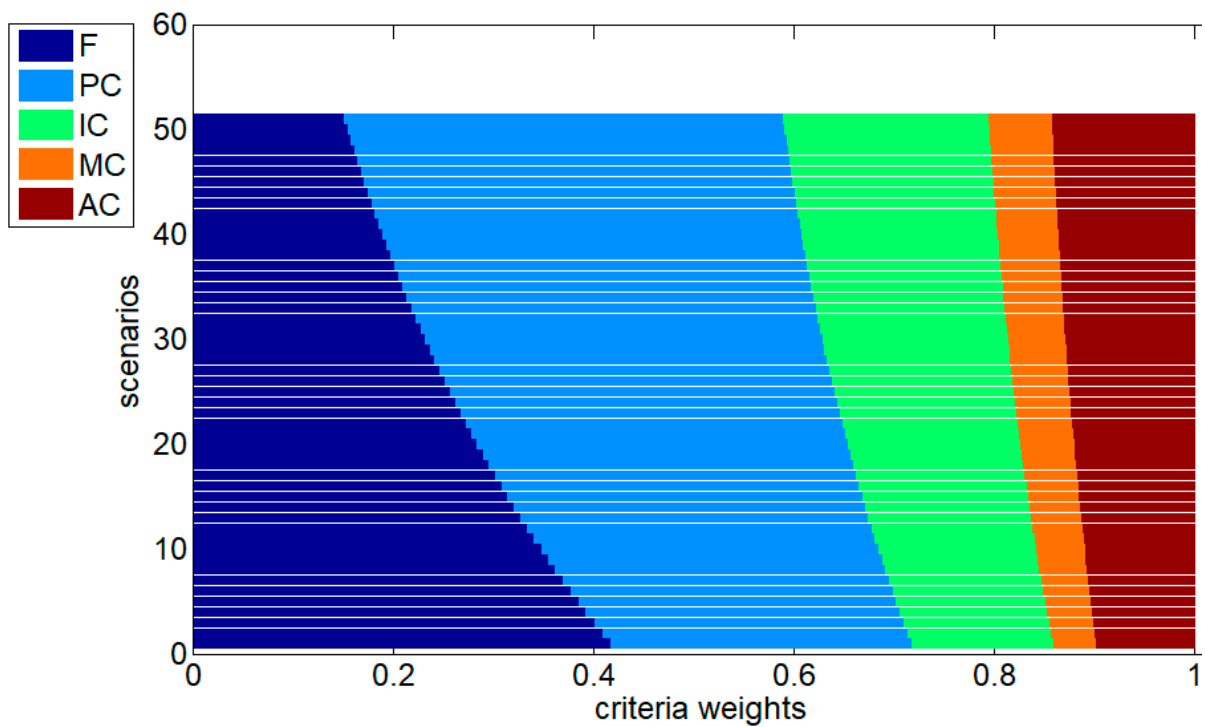


Figure 5. The change of flexibility criterion weights in 50 scenarios.

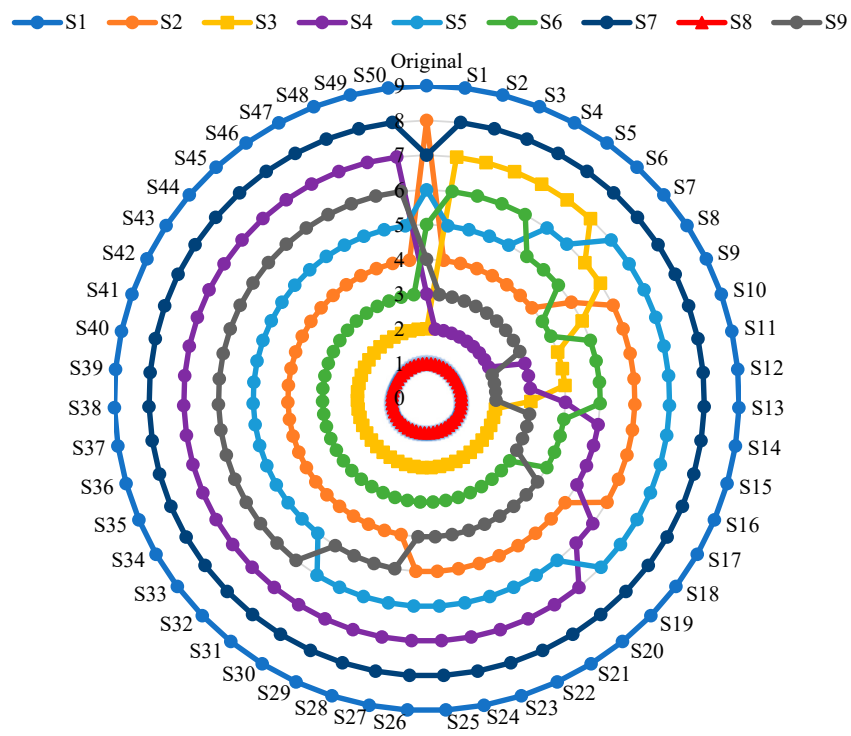


Figure 6. Ranking results of second scenario analysis.

5.2. Influence of Parameter q on the Ranking Results

In the VIKOR method, the value of q is generally accepted as 0.5. However, q can take any value in the interval 0–1. To prove the validity and robustness of the obtained sequences, sensitivity analysis was performed for the q parameter. Based on various q values from 0 to 1, Q_i values were calculated. Figure 7 shows the ranking order results. As can be seen in Figure 7, the ranking of the best supplier is not affected at all by the q value. However, when q takes values from 0 to 0.3, supplier S4 leaves its second rank to S9. Supplier S9, which was the third supplier, is not affected by q at values larger than 0.4. This result indicates that the evaluation results obtained from the proposed PFVIKOR model are robust and reliable.

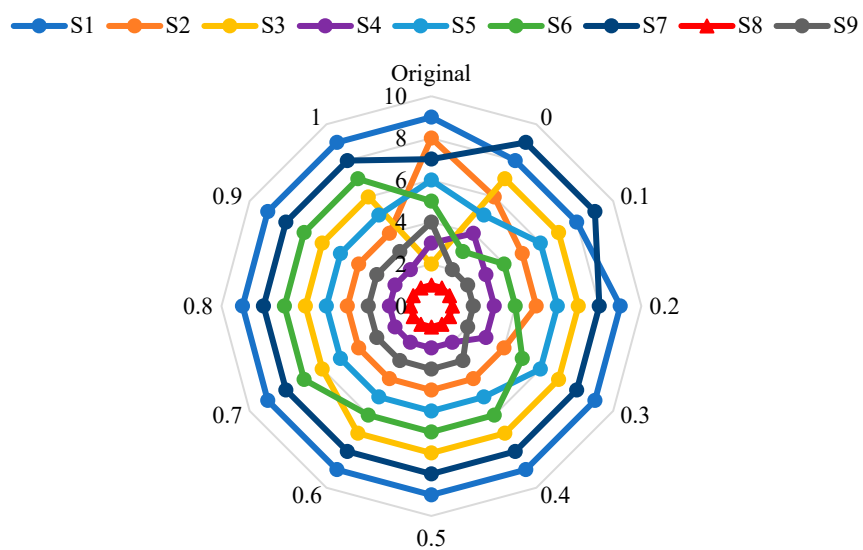


Figure 7. The effect of changing the parameter q in ranking results.

5.3. Comparative Analysis Based on Different MCDM Methods

A comparative analysis was carried out by the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Combinative distance-based assessment (CODAS) methods under Pythagorean fuzzy environment. The reasons for selecting these methods for comparison are first to integrate with PFAHP method, and secondly, to allocate PFNs for evaluation of suppliers. A Kendall's tau-b correlation was conducted to specify the relationship between obtained ranking results amongst methods. There was a strong, positive correlation between the rankings, which was statistically significant ($\tau = 0.833$, $p = 0.002$) for the result of TOPSIS and ($\tau = 0.722$, $p = 0.007$) for the result of CODAS. According to the obtained results, the S8 and S4 suppliers were the best alternatives in both methods. However, the rank of the third alternative is changed. The S1 alternative is the worst alternative of all three methods, as it is ranked last. S8 is the best supplier for all employed fuzzy methods when the ranking results derived from the Pythagorean fuzzy approaches were evaluated. Additionally, the ranking performance of S4 has not changed, although it has been noted that the ranking performances of the other alternatives have slightly changed. The superiority of alternative S4 was verified through the use of all multi-criteria methods. Given that there is a very high similarity coefficient between the ranking results of the proposed approach and those of the established MCDM frameworks, the obtained findings demonstrate that the suggested model is stable and consistent at a satisfactory level.

6. Conclusions, Policy, and Limitations of the Study

With the transition to the new normal, the disruptions are expected to improve, but the impact of COVID-19 on the economy and businesses will continue. Although there is no proven method or tool for addressing supply chain disruptions during the COVID-19 crisis, this study proposed a new approach to RSS.

The main contributions of this study to RSS are thus included: creating a detailed and comprehensive set of resilience criteria sub-criteria, choosing the most suitable supplier using the PFAHP-PFVIKOR hybrid method, and proposing detailed theoretical and managerial inferences. With the COVID-19 period, the literature was comprehensively analyzed in order to address the need for durability emphasized in supply chain management in the selection of suppliers, and applicable durability criteria was determined in line with expert opinions. Subsequently, a new hybrid MCDM approach was proposed with the aim of ensuring robustness in supplier selection problems. In the present study, the PFAHP-PFVIKOR hybrid method was employed to cope with uncertainty in the decision-making process.

In many studies strategic criteria such as quality, cost, and delivery are found to be the most important criteria in supplier selection, however, the COVID-19 outbreak process has changed the opinion of decision-makers, and the most important criterion in the present study was found to be CRSSC. Therefore, this study revealed that flexibility is the most important criterion to improve the operations of the supply chain for RSS. Next to flexibility is process capabilities, while quality (Q) and cost (C) are found as the first and second in the category of influential criteria for strategic supplier selection criteria, respectively. To verify the robustness of the results from the study, two different sensitivity analyses and comparative analyses were performed, and the obtained results were confirmed to be robust.

6.1. Policy Implications

The proposed PFAHP-PFVIKOR approach enables decision-makers to better reflect the subjectivity and uncertainty that exists in the evaluation process, as it includes PFNs in the decision-making process. PFNs give decision-makers more flexibility in expressing uncertain, imprecise, and inconsistent information. From this point of view, in order to increase the flexibility of decision-makers in the evaluation process, AHP and VIKOR methods have been integrated under PFSs.

The established list of RSS can help decision-makers by acting as a checklist in unexpected situations such as the COVID-19 outbreak. This study provides new contributions to the existing knowledge by taking into account the RSS criteria (two main criteria namely traditional and critical) and determining the list of corresponding criteria and sub-criteria through a nominal group technique. This study revealed that flexibility is the most important criterion to improve the operations of the supply chain for RSS. Supply chain networks can be strengthened with not only flexibility but also with other resilience capabilities. For example, facility fortification, safety stock, and direct-to-store deliveries can be used to reduce the impact of disruptions. Facility fortification can lower the total cost of operation and also meet more demand in the post-disruption phase. Additionally, inventory sharing can provide flexibility in dealing with disruptions [63]. According to KPMG global automotive executive survey (2020), international cooperation is needed on issues such as controlling global demand decline and managing digital demand. For instance, Procter & Gamble (P&G), the global consumer goods giant, used digital tools to reposition their inventory, thereby avoiding disruptions and financial losses in Hurricane Irma in 2017.

In the context of RSS, the study highlights flexibility as the most crucial factor for enhancing supply chain operations. Hiring suppliers should be prioritized based on a supplier's capacity for quick adaptation and response to changing conditions. This can include flexible supply schedules, flexible production processes, and quick reactions. Decision-makers should concentrate on increasing various resilience characteristics inside their supply chain networks, in addition to flexibility. Facility fortification can lessen the effects of disruptions and enhance overall operating effectiveness. Holding excess inventory on hand can serve as a cushion during disruptions. Direct-to-store deliveries can also be used to get around clogged distribution routes and keep the flow of merchandise constant.

Lastly, digital tools should be used by companies to enhance supply chain management and reduce disruptions. In addition, fostering international cooperation is also essential for controlling the reduction in global demand and addressing issues with digital demand. While focusing on resilience capabilities, decision-makers should also assess the total cost of operation. Overall, the results highlight how flexibility and the use of digital technologies are important to enhancing supply chain resilience. Organizations may improve their supply chains and better manage unforeseen interruptions by putting these management and policy implications into practice, which will ultimately enhance their operational performance and customer satisfaction.

6.2. Limitations of the Study

Although this study proposed a novel MCDM methodology, it still has some limitations in the following aspects.

The data collection: The experts expressed their judgments on criteria and alternatives in different periods because of the various restrictions and initial confusion during the COVID-19 outbreak process. Thus, the interview with experts took a much longer time than in normal circumstances.

The current study is limited to a company in the automotive industry solely. Therefore, similarities and differences in the results can be examined and compared by analyzing different companies, although the approach can also be applied in various industries such as chemistry, machinery, and electronics.

The determined criteria and sub-criteria were narrowed according to the experts' judgments. Therefore, they may be company-specific in nature, and other resilient criteria have not been specified.

Lastly, supplier evaluations and rankings have been handled by various MCDM methods within a Pythagorean environment.

Therefore, for future studies, different extensions of fuzzy sets such as interval type-2, spherical, hesitant, and picture sets can be considered to deal with the specificity in the decision-making process. In addition, future studies can also be expanded by considering various evaluation criteria and sub-criteria. Moreover, methods such as DEMATEL,

MACBETH, and ANP may also be useful in analyzing the relationships between criteria under different fuzzy sets. Overall, the proposed model in this study may be useful in other real-world applications.

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