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A Novel Interval Value Extension of Picture Fuzzy Sets Into Group Decision Making: An Approach to Support Supply Chain Sustainability in Catastrophic Disruptions

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ABSTRACT In critical times when disasters and unpredicted events collapse human judgments, formation and structure of social infrastructure gets to be rather important. Acute risk of catastrophic events such as a rare disaster, a coronavirus pandemic, trigger a global scale setback which has a substantial impact on people's lives and livelihoods. Catastrophic events halt economic landscape, collapse commodity prices, and silence production engines which interact in complex ways. During this phase of volatility and opacity, roles of sustainable supply chain, productions and circular economy get more important than ever. Such disruptions are therefore to be addressed by identifying sustainable supply chain strategies. This paper intends to establish underlying patterns of disruptive factors in the supply chain to evaluate strategies in formation and structuring of sustainable supply chain by applying it to real world example in Turkish Kitchen Equipment Manufacturer (KEM). Selection of sustainable supply chain strategy is a complex Multi-Criteria Decision-Making (MCDM) issue involving various parameters that may be contradictory at the same time. Analytical-Hierarchy-Process (AHP) and VlseKriterijumska-Optimizacija-I-Kompromisno-Resenje (VIKOR) methods can be used to solve such problems. In order to strengthen these methods in terms of their lacking capability of coping with uncertainty and incomplete information, they are extended with Interval-Valued Picture-Fuzzy Set (IVPFS) to better simulate human judgment. MCDM processes can be enhanced with Group-Decision-Making (GDM) to combine individual Decision Makers' (DMs) opinions into group judgments. Found outcome reveal that supply chains to respond catastrophic disruptions, businesses should primarily diversify supply chain from a geographic perspective, and should diversify disruptive forces in motion from a physical perspective. Originality of article is based on integrated AHP and VIKOR approaches in IVPFS based GDM algorithm as a first in the literature and presentation of its application for supply chain sustainability in catastrophic disruptions as a decision support tool.

INDEX TERMS Sustainability assessment, supply chain disruption, multi-criteria decision-making (MCDM), interval-valued picture-fuzzy set (IVPFS), analytic hierarchy process (AHP), VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR).

I. INTRODUCTION

The latest deepened crisis of coronavirus in the world has revealed the darkness in non-dynamism supply chains. Countries have begun to shut their borders, institute movement controls and enforce restrictions of varying degrees known as stay-at-home orders, shutdowns, and lockdowns. This creates a cascading collapse of logistics systems, financial affairs, and entire production process due to a systemic and vicious combination of supply and demand shocks [1]. Especially the countries mostly rely on entertainment, tourism, and logistics for their economic growth have been experiencing large disruptions. The action of governments to prevent the spread of coronavirus, let ordinary people to stock up on consumer staples by purchasing months' worth of goods in a single day. Even the perfectly forecastable products would not be able to respond to massive spike in demands [2].

When a catastrophic event happens in a global scale, massive disruptions in supply, demand, and production is created. Supply chain undergoes something utterly different due to

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occurring outbreak such as a rare disaster, a coronavirus pandemic [3]. This pandemic clearly has demonstrated that countless businesses have not yet entirely aware and could not be able to educate their Decision Makers (DMs) about the possible considerable risks of Covid19 like disruptions on large scale relationships of their supply chain. However, supply chain experts should find it a second nature to reconsider global chain and supply dependencies.

This study aims to address the advantages and consequences of a sustainable and dynamic supply chain system along with its connected elements. It endeavors to establish an analytical and intelligent framework for the issues and problems, as consequences by the coronavirus pandemic. The research in this paper would also help academics and practitioners to find solutions on how to manage their supply chain risks, how to improve global chains in recovering from catastrophic disruptions of future, and how to improve supply chain sustainability by the digital enablers of Industry 4.0. In particular, with coronavirus pandemic affecting supply chains today, this study can guide managers and practitioners for an effective sustainable supply chain design process.

Decision-making is the daily life activity based on identification and selection of alternatives by the expectations and preferences of the DMs [4]. A decision-making process has several steps to be followed [5]: defining the problem, determining the requirements, establishing the goal, identifying the candidates, defining the criteria, selecting the solution methodology, evaluating the alternatives with respect to criteria, and finally the validating the found solutions. In real-life situations, these steps are mostly automated and too complex. Thus, the real decision-making challenges are not typically evaluated by traditional decision-making practices. The traditional procedures characterize the DMs' opinions in crisp sets. Yet, for the majority of the regular cases, the data is ill structured and vague, or the DMs have no capability to assign crisp values to their opinions due to subjectivity and qualitative nature of judgment criteria. Since it may be very difficult for DMs to give their judgments using crisp preferences, DMs usually prefer expressing their preferences in linguistic evaluations [6]. Furthermore, the traditional techniques tend to have little effect while dealing with vague and imprecise nature of the linguistic valuations. The decision-making in the real-life situations is usually very intricate and entail imprecision and fuzziness and the accurate representation of DMs' verbal assessment is a central theme in the Multi-Criteria Decision Making (MCDM) literature. That is why, Zadeh represent the data rather fuzzy, but not precise and developed fuzzy set theory [7], in which assessments are collected in the form of verbal variables rather than crisp values. This theory delivers a scientific validation to apprehend the vagueness connected to human cognitive. Bellman and Zadeh has introduced the fuzzy decision-making term as indicating the means in which the goals or the constraints are fuzzy in nature but not necessarily the system [8]. Also, conferred that the information can be inadequate, resulting in an incomplete and inexact data at hand. Based on this, Zadeh introduced an operation theory to compute by verbal variables. Fuzzy set theory is able to provide a comprehensive solution to the uncertainty created by humans' subjective evaluation. Fuzzy set theory is essentially a generalization of crisp set theory that does not contain sharp boundaries of classes. The integration of MCDM methods with fuzzy logic is frequently used because it allows more precise decision-making in uncertain situations and judgments. Several types of extensions have been developed to tackle the weaknesses of crisp and the conventional fuzzy sets [7], such as Type 2, Neutrosophic, Hesitant, Intuitionistic, Pythagorean, Orthopair, and very recently Picture Fuzzy Sets [9]–[11]. The Picture Fuzzy Set (PFS) is the extension of the Intuitionistic Fuzzy Set, which is primarily designed to address uncertainty [9], [11]. Uncertainty (vagueness) means a lack of certainty or sharp separation. Partial membership of set elements is allowed in fuzzy sets. It has been observed that one of the significant concepts of hesitancy degree is lacking in Intuitionistic Fuzzy Set. Hesitancy degree can be observed during circumstances in cases if human judgments involve more answers of such yes, no, abstain, and refusal [12]. It is clear that the PFSs provide a more comprehensive assessment of the degree of positive membership, degree of negative membership, degree of neutral, and degree of refusal, so it is more beneficial than conventional fuzzy sets in the environment of uncertainty [13]. In real-life applications, the sum of the degrees of positive membership, negative membership, and neutral membership to problems where people's thoughts are essential can be less than 1 and degree of refusal membership is the complementary value to 1 [14]. Therefore, to meet this need, fuzzy set theory is generalized, and the PFS theory is obtained. Interval-Valued Picture-Fuzzy Set (IVPFS) is the new extension of PFS [10]. IVPFS sets are very effective concept to deal with vagueness by taking the degree of positive membership, negative membership, neutral, and refusal functions in an interval and so more capable of solving and modelling complex problems [15], [16].

MCDM have been evolving to assist decision-making since the development of modern MCDM theory in the early sixties to accommodate a variety of different applications [17]. Its role in various application areas has expanded substantially, particularly as novel techniques are introduced, and as previous techniques are enhanced. MCDM techniques can deliver robust tools in allocation of resources within challenging activities, in complex exercises in terms of selecting alternatives, weighting criteria, and structuring priorities. MCDM techniques consist of approaches and methods that try to reach the best possible/appropriate solution where there is more than one conflicting criterion. MCDM methods use complex weight information to solve complex problems with conflicting qualities. First, alternatives and qualifications are defined. Then, the evaluation of each alternative is obtained according to each criterion. Later, the weights are assigned according to each criterion. The fused criterion weights and the individual criterion assessment values are aggregated to compute the total values of the alternatives. Finally, sensitivity analyses are performed, and result suggestions and evaluations are presented. MCDM methods are built on the selection of the most satisfying objectives/aims of the DM from a large number of potential options, taking into account many concrete or abstract qualities or factors [18]. Methods such as SWARA (Step-wise Weight Assessment Ratio Analysis) [19], COPRAS (COmplex PRoportional ASSessment) [20], MULTIMOORA (Multi-Objective Optimization by Ratio Analysis plus the Full Multiplicative Form) [21], TODIM (Portuguese acronym for Interative Multi-criteria Decision Making) [22], TOPSIS (Technique for Order Preference by Similarity to Ideal Solutions) [23], and VIKOR (Vlse Kriterijumska Optimizacija I Kompromisno Resenje) [24], etc., are some examples of MCDM methods. Lots of dissimilar techniques have been created, with even minor modifications to existing techniques prompting the formation of brand-new branches of research. This study employs a combination of two different types of common MCDM techniques, utilizes the aggregated advantages of the performed techniques to discard the individual disadvantages of them, and rationalizes how their common applications relate to their relative weaknesses and strengths. The application of given MCDM techniques presented in this study delivers a clear guide for how MCDM techniques should be used for the supply chain sustainability in catastrophic disruptions as a decision support tool.

AHP is one of the most frequently used MCDM method that was first developed by T. Saaty in the 1970s and used in various settings in decision-making processes [25], [26]. The strengths of the AHP technique are its suitability for Group-Decision-Making (GDM), its hierarchical decision-making process, and its ability to measure the consistency of assessments given by DMs. VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje), proposed by [24], is also one of the most frequently used MCDM techniques [27]. The methodology provides maximum group utility and minimum individual regret for the majority and the opponent, respectively. It also presents the MCDM ranking index based on the particular measure of closeness to the ideal solution [24], [28].

However, both techniques have a common disadvantage that cannot cope with the uncertainty problem. In this article, AHP and VIKOR methods are extended with IVPFS sets to cope with uncertainties. IVPFS sets provide a useful tool that help solve complex decision-making problems thanks to their membership and non-membership functionality. Combination of AHP and VIKOR methods with IVPFS sets will provide easier, more logical and more effective solutions. So far, IVPFS-AHP and IVPFS-VIKOR techniques have not used at all, let alone them to be applied together in the field of supply chain sustainability strategy selection. This study will also contribute to this gap in the literature.

Most MCDM techniques are applied under GDM setting due to the requirement of more than one DM's participation in decision-making process. Several types of GDM approaches are deployed for MCDM methods in the literature [4], [29], [30]. This study contributes to the literature by offering the following novelties: first, its presentation of an assessment framework for supply chains to adapt their structures into catastrophic disruptions and thus gain the value from achieving a truly supply chain sustainability. Added contribution is the presentation of integrated IVPFS-AHP (IVPFS Set based AHP) method. The AHP is built on IVPFS environment so that assessments under IVPFS values can be used in the evaluation of criteria weights. The next state-of-art contribution is the use of and IVPFS-VIKOR (IVPFS Set based VIKOR) in a GDM setting as a unique ranking method for the first time. IVPFS Sets can model and solve complex problems more adequately. The last but not the least substantial contribution of the study is the structuring of disruption factors by the given feedback from real industrial experts and evaluation of sustainability strategies under catastrophic disruptions.

The course of this paper flows as follows: Section 2 delivers a brief overview of extant literature on the subject. Section 3 follows by presenting the detailed description of the proposed methodology to support supply chain sustainability in catastrophic disruptions. Section 4 addresses the case background, disruption factors, and sustainability strategies, as well as the application of integrated technique involving a real case study in Turkey. In Section 5, the results are discussed, and managerial implications are presented. Finally, Section 6 concludes the study and offers future research directions.

II. LITERATURE REVIEW

In this section, indexed studies are investigated by searching the databases of Web of Science, Scopus, and Google Scholar to look for IVPFS literature and sustainable supply chain studies integrated with MCDM techniques in order to observe and discuss the availability of proposed approach and mentioned topics in the existing literature. The concise meta-analysis on sustainable supply chain management for the years between 2004 and 2019 is given by the study of Khan *et al.* [31]. For the years between 2004 and 2018, another analysis on sustainability-related supplier risk management has also been made by [32], [33]. Apart from these analyses, our review succinctly focuses on recent studies in the context of sustainable supply chain studies with MCDM applications. From the analysis of extant literature, 7 different studies are systematically reviewed and their details regarding our analysis are presented in Table 1.

In this article, AHP and VIKOR methods are extended with IVPFS sets to cope with uncertainties. However, both techniques have a common disadvantage that cannot cope with the uncertainty problem. IVPFS sets provide a useful tool that help solve complex decision-making problems thanks to their membership and non-membership functionality. Combination of AHP and VIKOR methods with IVPFS sets will provide easier, logical, and more effective solutions. When we examined the studies using IVPFS-AHP and IVPFS-VIKOR techniques alone or together, we came across to no study.

So far, IVPFS-AHP and IVPFS-VIKOR techniques are not used together in the field of sustainable supply chain strategy selection. This study will contribute to this gap in the literature. Table 2 reviews the extant literature on IVPFS.

TABLE 1. Sustainable supply chain studies with MCDM techniques.

References	Setting	Environment	Methodology	Subject	Application area	Type
[39]	Crisp	Individual Evaluation	TODIM-TOPSIS-BWM	Sustainable Supply Chain finance	Gas Industry	Case Study
[40]	Type I Fuzzy	Individual Evaluation	AHP	Sustainable Third-party Logistics	Dairy Industry	Case Study
[41]	Type I Fuzzy	Individual Evaluation	Delphi-Dematel	Sustainable Supply Chain Practices	Iron and Steel Development	Illustrative Study
[42]	Type I Fuzzy	Individual Evaluation	TOPSIS	Sustainable Supply Chain Indicators	Automotive Industry	Case Study
[43]	Type I Fuzzy	Individual Evaluation	AHP-TOPSIS	Sustainable Supplier Selection	Textile Manufacturing	Case Study
[44]	Type II Fuzzy	GDM Evaluation	Dematel-QFD	Sustainable Supply Chain Drivers	Agricultural Production Systems	Case Study
[45]	Type I Fuzzy	Individual Evaluation	AHP-TOPSIS	Social Sustainability	Automotive Industry	Case Study

As far as Author aware, Table 2 verifies that there is no study of VIKOR and AHP under IVPFS setting and Table 1 illustrates, sustainable supply chain applications are applied in many different subjects (finance, supplier selection, logistics, practices, indicators, etc.) with several different MCDM techniques (AHP, TOPSIS, Dematel, Delphi, etc.) but mainly under type I fuzzy settings with individual evaluations for case study applications. This review reveals that the IVPFS-AHP and IVPFS-VIKOR methods are not combined so far for determining and evaluating disruptive factors and sustainable supply chain strategies. To close this gap, this study presents a new approach to select sustainable supply chain strategies.

The preliminaries for the proposed methodology will be given in the next section.

III. METHODOLOGY

A. PRELIMINARIES: INTERVAL-VALUED PICTURE FUZZY SETS (IVPFSs)

The PFSs, initially proposed by Cuong, establish a distinctive theory to deal with information vagueness by considering the positive, negative, and neutral membership degrees as well as involving refusal membership degree as fourth parameter [9]–[11].

TABLE 2. IVPFS literature.

References	Setting	Environment	Methodology	Subject	Application area	Type
[15]	IVPF Soft Set	Individual Evaluation	New Operations of IVPFS	Decision-Making Algorithm	Numerical Analysis	Illustrative Study
[16]	IVPFS	GDM Evaluation	Uncertain Linguistic Aggregation	Supplier Selection Decision-Making	Logistics Service Value Concretion	Illustrative Study
[34]	Generalized IVPFS Interval	GDM Evaluation	Linguistic Induced Hybrid Operator	TOPSIS MCDM	investment strategy	Illustrative Study
[35]	Valued Rung Picture Fuzzy Interval	Individual Evaluation	Heronian Mean Operators	Decision-Making Algorithm	Partner Selection	Illustrative Study
[36]	Valued Picture Hesitant Fuzzy	Individual Evaluation	Aggregation Operators	Multi-Period Decision Making	Impact of Coronavirus Disease	Illustrative Study
[37]	IVPF Soft Set	Individual Evaluation	Euclidean distance	Decision-Making Algorithm	Pattern Recognition	Illustrative Study
[38]	IVPFS	Individual Evaluation	Similarity Measures	Decision-Making	Mineral Field Recognition	Illustrative Study

X is a fixed non-empty universe; A PFS $\tilde{A}$ on the universe of discourse X is an object given by;

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x), \eta_{\tilde{A}}(x), v_{\tilde{A}}(x))|x \in X\} \tag{1}$$

where $\mu_{\tilde{A}}(x) \in [0, 1]$, $\eta_{\tilde{A}}(x) \in [0, 1]$, $v_{\tilde{A}}(x) \in [0, 1]$, and

$$\mu_{\tilde{A}}(x) + \eta_{\tilde{A}}(x) + v_{\tilde{A}}(x) \leq 1 \, for \quad \forall x \in X,$$

$\mu_{\tilde{A}}(x)$ denotes the positive membership degree, $v_{\tilde{A}}(x)$ denotes the negative membership degree, and $\eta_{\tilde{A}}(x)$ denotes the neutral membership degree. Thus,

$$1 - (\mu_{\tilde{A}}(x) + \eta_{\tilde{A}}(x) + v_{\tilde{A}}(x)) \tag{2}$$

could be denoted as refusal membership degree.

Cuong [10] extended PFS into IVPFS. Here, $D \subseteq [0, 1]$ is the set of all closed subintervals of the interval and X be a universe of discourse. An IVPFS' basic elements are the ordered pair, where it is an object having the form of:

$$\tilde{A} = \left\{x, \mu_{\tilde{A}}(x), \eta_{\tilde{A}}(x), v_{\tilde{A}}(x) \, |x \epsilon X\right\} \tag{3}$$

$\mu_{\tilde{A}} \to D \subseteq [0,1]$, $\eta_{\tilde{A}}(x) \to D \subseteq [0,1]$, and $\nu_{\tilde{A}} \to D \subseteq [0,1]$,

$$0 \leq sup\ \mu_{\tilde{A}}(x) + sup\ \eta_{\tilde{A}}(x) + sup\ \nu_{\tilde{A}}(x) \leq 1, \quad \forall x \epsilon X.$$

The intervals $\mu_{\tilde{A}}(x)$, $\nu_{\tilde{A}}(x)$, and $\eta_{\tilde{A}}(x)$ denotes the positive membership, the negative membership, and the neutral membership grades of the elements $x \epsilon X$, respectively. Thus, the starting and ending points of positive membership is denoted by $\mu_{\tilde{A}}(x) = \left[\mu_{\tilde{A}}^L, \mu_{\tilde{A}}^U\right] \subseteq [0,1]$, the starting and ending points of negative membership is denoted by $\nu_{\tilde{A}}(x) = \left[\nu_{\tilde{A}}^L, \nu_{\tilde{A}}^U\right] \subseteq [0,1]$, and the starting and ending points of neutral membership is denoted by $\eta_{\tilde{A}}(x) = \left[\eta_{\tilde{A}}^L, \eta_{\tilde{A}}^U\right] \subseteq [0,1]$,

Then, IVPFS $\tilde{A}$ is denoted by the Equation (4).

$$\tilde{A} = \left\{x, \left[\mu_{\tilde{A}}^L, \mu_{\tilde{A}}^U\right], \left[\eta_{\tilde{A}}^L, \eta_{\tilde{A}}^U\right], \left[\nu_{\tilde{A}}^L, \nu_{\tilde{A}}^U\right] | x \epsilon X\right\} \quad (4)$$

$$\left\{\begin{matrix} 0 \leq \mu_{\tilde{A}}^U + \eta_{\tilde{A}}^U + \nu_{\tilde{A}}^U \leq 1, \\ \mu_{\tilde{A}}^L \geq 0, \eta_{\tilde{A}}^L \geq 0, \ and\ \nu_{\tilde{A}}^L \geq 0 \end{matrix}\right\} \quad (5)$$

Refusal degree denoted by $\pi_{\tilde{A}}$ can be computed by the Equation (6).

$$\pi_{\tilde{A}} = \left[\pi_{\tilde{A}}^L, \pi_{\tilde{A}}^U\right] = \left\{\begin{bmatrix} 1 - \mu_{\tilde{A}}^U - \eta_{\tilde{A}}^U - \nu_{\tilde{A}}^U, \\ 1 - \mu_{\tilde{A}}^L - \eta_{\tilde{A}}^L - \nu_{\tilde{A}}^L \end{bmatrix}\right\} \quad (6)$$

The arithmetic operations using the values of the IVPFS set [16] are presented as follows:

Let $\tilde{A} = \left(\mu_{\tilde{A}}(x), \eta_{\tilde{A}}(x), \nu_{\tilde{A}}(x)\right)$ and $\tilde{B} = (\mu_{\tilde{B}}(x), \eta_{\tilde{B}}(x), \nu_{\tilde{B}}(x))$ be two IVPFS value and λ as a scalar value $\lambda > 0$. Some of the basic IVPFS operators [16] are defined as follows:

$$\tilde{A} \oplus \tilde{B} = \begin{pmatrix} \begin{bmatrix} 1 - \left(1 - \mu_{\tilde{A}}^L\right) * \left(1 - \mu_{\tilde{B}}^L\right), \\ 1 - \left(1 - \mu_{\tilde{A}}^U\right) * (1 - \mu_{\tilde{B}}^U) \end{bmatrix}, \\ \left[\eta_{\tilde{A}}^L * \eta_{\tilde{B}}^L, \eta_{\tilde{A}}^U * \eta_{\tilde{B}}^U\right], \\ \left[\nu_{\tilde{A}}^L * \nu_{\tilde{B}}^L, \nu_{\tilde{A}}^U * \nu_{\tilde{B}}^U\right] \end{pmatrix} \quad (7)$$

$$\tilde{A} \oplus \tilde{B} = \begin{pmatrix} \left[\mu_{\tilde{A}}^L * \mu_{\tilde{B}}^L, \mu_{\tilde{A}}^U * \mu_{\tilde{B}}^U\right], \\ \begin{bmatrix} 1 - \left(1 - \eta_{\tilde{A}}^L\right) * \left(1 - \eta_{\tilde{B}}^L\right), \\ 1 - \left(1 - \eta_{\tilde{A}}^U\right) * \left(1 - \eta_{\tilde{B}}^U\right) \end{bmatrix}, \\ \begin{bmatrix} 1 - \left(1 - \nu_{\tilde{A}}^L\right) * \left(1 - \nu_{\tilde{B}}^L\right), \\ 1 - \left(1 - \nu_{\tilde{A}}^U\right) * (1 - \nu_{\tilde{B}}^U) \end{bmatrix} \end{pmatrix} \quad (8)$$

$$\lambda\tilde{A} = \begin{pmatrix} \begin{bmatrix} 1 - \left(1 - \mu_{\tilde{A}}^L\right)^{\lambda}, \\ 1 - \left(1 - \mu_{\tilde{A}}^U\right)^{\lambda} \end{bmatrix}, \\ \left[(\eta_{\tilde{A}}^L)^{\lambda}, (\eta_{\tilde{A}}^U)^{\lambda}\right], \\ \left[(\nu_{\tilde{A}}^L)^{\lambda}, (\nu_{\tilde{A}}^U)^{\lambda}\right] \end{pmatrix} \quad (9)$$

$$\tilde{A}^{\lambda} = \begin{pmatrix} \left[(\mu_{\tilde{A}}^L)^{\lambda}, (\mu_{\tilde{A}}^U)^{\lambda}\right], \\ \begin{bmatrix} 1 - \left(1 - \eta_{\tilde{A}}^L\right)^{\lambda}, \\ 1 - \left(1 - \eta_{\tilde{A}}^U\right)^{\lambda} \end{bmatrix}, \\ \begin{bmatrix} 1 - \left(1 - \nu_{\tilde{A}}^L\right)^{\lambda}, \\ 1 - \left(1 - \nu_{\tilde{A}}^U\right)^{\lambda} \end{bmatrix} \end{pmatrix} \quad (10)$$

The IVPFS linguistic entropy [34] operator is defined as:

$$e_i = \left\{\begin{matrix} 1 - \frac{1}{3} * \left(1 - \frac{\left|\mu_{\tilde{A}}^L - \eta_{\tilde{A}}^L - \nu_{\tilde{A}}^L\right| * \left|\mu_{\tilde{A}}^U - \eta_{\tilde{A}}^U - \nu_{\tilde{A}}^U\right|}{3}\right) \\ * \left(1 + \frac{\pi_{\tilde{A}}^L + \pi_{\tilde{A}}^U}{3}\right) \end{matrix}\right\}, \quad (11)$$

where, $i = 1, \ldots, m$

B. PROPOSED IVPFS-AHP AND IVPFS-VIKOR METHOD

In this article, an MCDM approach is introduced under IVPFS environment by integrating AHP and VIKOR techniques. The developed method consists of two periods, criteria weight determination phase and alternative ranking phases based on weighted criteria from the first stage. Its steps are presented next.

Step 1: Gather the judgments on each factor.

Evaluations of DMs for the given criteria and alternatives are gathered.

Let K be the number of DMs evaluating m alternatives with respect to n criteria.

Step 2: Determine the priorities of DMs.

The linguistic scale in Table 3 is applied to calculate the weights of each DMs. The Equation (12) is applied for the calculation of the priorities of DMs (λ_k) by the utilization of the IVPFS linguistic entropy [34] operator.

$$\lambda_k = \frac{e_{\lambda_k}}{\sum_{k=1}^{K} e_{\lambda_k}} \quad (12)$$

Step 3: Construct pairwise comparison matrix.

Linguistic evaluations of DMs are converted to IVPFS set values with the help of Table 4 to construct the IVPFS pairwise comparison matrix.

Step 4: Aggregate pairwise comparison matrix.

Individual evaluations of criteria values in the form of IVPFS set values are fused into GDM matrix of criteria. The Equation (13) is used for aggregation.

$$\left\{\begin{matrix} \left[1 - \prod_{j=1}^{n}\left(1 - \mu_{\tilde{A}}^L\right)^{w_j}, 1 - \prod_{j=1}^{n}\left(1 - \mu_{\tilde{A}}^U\right)^{w_j}\right], \\ \left[\prod_{j=1}^{n}\left(\eta_{\tilde{A}}^L\right)^{w_j}, \prod_{j=1}^{n}\left(\eta_{\tilde{A}}^U\right)^{w_j}\right], \\ \left[\prod_{j=1}^{n}\left(\nu_{\tilde{A}}^L\right)^{w_j}, \prod_{j=1}^{n}\left(\nu_{\tilde{A}}^U\right)^{w_j}\right] \end{matrix}\right\}, \quad (13)$$

where, $w = (w_1, w_1, \ldots, w_n)$; $w_j \in [0,1]$; $\sum_{j=1}^{n} w_j$,

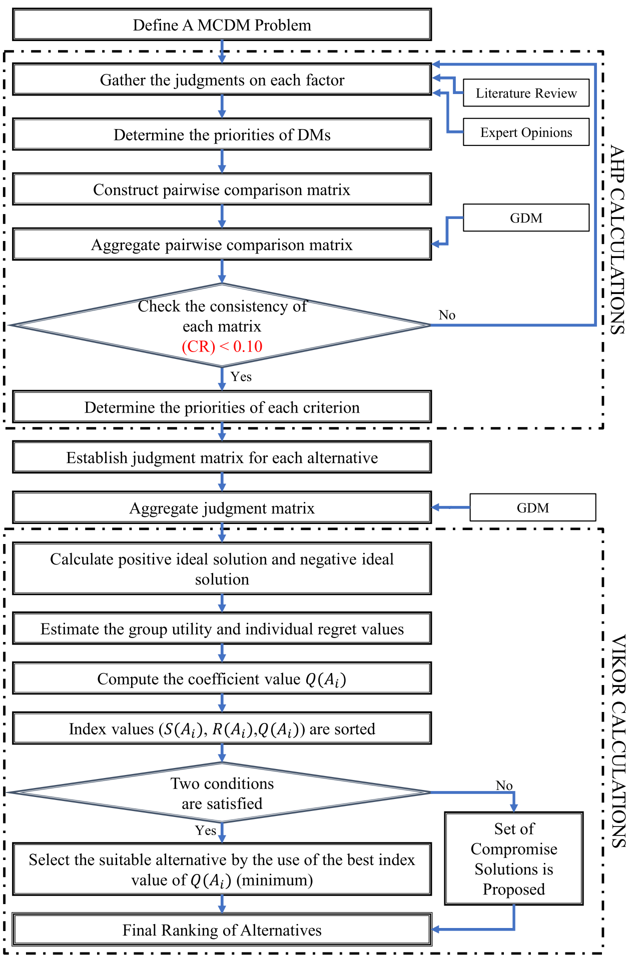

FIGURE 1. General structure of the sustainable supply chain strategy evaluation framework.

TABLE 3. Linguistic scale for the calculation of DMs' priorities.

Linguistic Term		IVPFS Values					
		$\mu_{\tilde{A}}^{L}$	$\mu_{\tilde{A}}^{U}$	$\eta_{\tilde{A}}^{L}$	$\eta_{\tilde{A}}^{U}$	$v_{\tilde{A}}^{L}$	$v_{\tilde{A}}^{U}$
Absolutely High	(AH)	0.650	0.700	0.050	0.100	0.150	0.200
Very High	(VH)	0.550	0.600	0.100	0.150	0.200	0.250
High	(H)	0.450	0.500	0.150	0.200	0.250	0.300
Medium High	(MH)	0.350	0.400	0.200	0.250	0.300	0.350
Exactly Equal	(EE)	0.250	0.300	0.250	0.300	0.350	0.400
Approximately Equal	(AE)	0.150	0.200	0.300	0.350	0.400	0.450

Step 5: Check the consistency of each matrix.

Using the Random Index (RI) values [25] and Consistency Ratio (CR) Equation, CR values are checked. If the calculated CR value is less than or equal to 0.10, it is deemed acceptable. Otherwise, judgments are collected once more.

Step 6: Determine the priorities of each criterion.

Let $w = (w_1, w_2, \ldots, w_n)$ be a weight vector of criteria and $w_j > 0$, $\sum_{j=1}^{n} w_j = 1$. Equation (11) is applied to find the entropy weights of criteria, and Equation (14) is used to find the priority weights of each criterion.

$$w_j = \frac{e_{w_j}}{\sum_{J=1}^{n} e_{w_j}} \tag{14}$$

Step 7: Establish judgment matrix for each alternative.

Linguistic evaluations of DMs are converted to IVPFS set values with the help of Table 5 to construct the IVPFS judgment matrix.

Step 8: Aggregate judgment matrix.

Individual evaluations of each alternative in the form of IVPFS set values are fused into a GDM matrix of alternative. Equation (13) is used for aggregation.

Step 9: Calculate positive ideal solution and negative ideal solution.

Equation (15) is applied to calculate the positive ideal solution ($\tilde{f}_j^{+}$) and Equation (16) is used to find the negative ideal solution ($\tilde{f}_j^{-}$).

$$\tilde{f}_j^{+} = \langle[[\mu_{\tilde{A}}{}^{L^+}, \mu_{\tilde{A}}{}^{U^+}][\eta_{\tilde{A}}{}^{L^+}, \eta_{\tilde{A}}{}^{U^+}][v_{\tilde{A}}{}^{L^+}, v_{\tilde{A}}{}^{U^+}]]\rangle$$
$$= \langle\begin{bmatrix} \left[\mu_{\tilde{A}}{}^{L^+} = max_i \mu_{\tilde{A}}{}^{L}, \mu_{\tilde{A}}{}^{U^+} = min_i \mu_{\tilde{A}}{}^{U}\right] \\ \left[\eta_{\tilde{A}}{}^{L^+} = min_i \eta_{\tilde{A}}{}^{L}, \eta_{\tilde{A}}{}^{U^+} = max_i \eta_{\tilde{A}}{}^{U}\right] \\ \left[v_{\tilde{A}}{}^{L^+} = min_i v_{\tilde{A}}{}^{L}, v_{\tilde{A}}{}^{U^+} = max_i v_{\tilde{A}}{}^{U}\right] \end{bmatrix}\rangle \tag{15}$$

TABLE 4. Linguistic scale for IVPFS AHP and its corresponding values.

Linguistic Term		IVPFS Values					
		$\mu_{\tilde{A}}^{L}$	$\mu_{\tilde{A}}^{U}$	$\eta_{\tilde{A}}^{L}$	$\eta_{\tilde{A}}^{U}$	$v_{\tilde{A}}^{L}$	$v_{\tilde{A}}^{U}$
Quite Strong Priority	(QSP)	0.900	0.950	0.010	0.020	0.020	0.030
Intermediate Value IV	(IVIV)	0.720	0.850	0.030	0.050	0.050	0.100
High Priority	(HP)	0.520	0.720	0.050	0.070	0.080	0.210
Intermediate Value III	(IVIII)	0.320	0.620	0.070	0.080	0.080	0.300
Strong Preference	(SP)	0.130	0.530	0.090	0.110	0.070	0.360
Intermediate Value II	(IVII)	0.030	0.470	0.110	0.130	0.030	0.400
Rather Preferred	(RP)	0.100	0.430	0.130	0.150	0.030	0.420
Intermediate Value I	(IVI)	0.290	0.410	0.150	0.160	0.120	0.430
Equal Priority	(EP)	0.380	0.420	0.160	0.180	0.220	0.400

TABLE 5. Linguistic scale for IVPFS VIKOR and its corresponding values.

Linguistic Term		IVPFS Values					
		$\mu_{\tilde{A}}^{L}$	$\mu_{\tilde{A}}^{U}$	$\eta_{\tilde{A}}^{L}$	$\eta_{\tilde{A}}^{U}$	$v_{\tilde{A}}^{L}$	$v_{\tilde{A}}^{U}$
Absolutely High	(AH)	0.75	0.80	0.01	0.05	0.10	0.15
Very High	(VH)	0.65	0.70	0.05	0.10	0.15	0.20
High	(H)	0.55	0.60	0.10	0.15	0.20	0.25
Medium High	(MH)	0.45	0.50	0.15	0.20	0.25	0.30
Approximately Equal	(AE)	0.35	0.40	0.20	0.25	0.30	0.35
Medium Low	(ML)	0.25	0.30	0.25	0.30	0.35	0.40
Low	(L)	0.15	0.20	0.30	0.35	0.40	0.45
Very Low	(VL)	0.05	0.10	0.35	0.40	0.45	0.50
Absolutely Low	(AL)	0.01	0.01	0.40	0.44	0.50	0.55

$$\tilde{f}_j^{+} = \langle[[\mu_{\tilde{A}}{}^{L^-}, \mu_{\tilde{A}}{}^{U^-}][\eta_{\tilde{A}}{}^{L^+}, \eta_{\tilde{A}}{}^{U^+}][v_{\tilde{A}}{}^{L^-}, v_{\tilde{A}}{}^{U^-}]]\rangle = \langle\begin{bmatrix}\left[\mu_{\tilde{A}}{}^{L^-} = max_i\mu_{\tilde{A}}{}^{L}, \mu_{\tilde{A}}{}^{U^-} = min_i\mu_{\tilde{A}}{}^{U}\right] \\ \left[\eta_{\tilde{A}}{}^{L^-} = min_i\eta_{\tilde{A}}{}^{L}, \eta_{\tilde{A}}{}^{U^-} = max_i\eta_{\tilde{A}}{}^{U}\right] \\ \left[v_{\tilde{A}}{}^{L^-} = min_i v_{\tilde{A}}{}^{L}, v_{\tilde{A}}{}^{U^-} = max_i v_{\tilde{A}}{}^{U}\right]\end{bmatrix}\rangle \quad (16)$$

Step 10: Estimate the group utility and individual regret values

The IVPFS normalized Euclidean distance operator is utilized for calculating the separations. Equation (19) is applied to calculate the group utility value and Equation (20) is applied to calculate the individual regret value.

$$Ed_j\left(\tilde{f}_j^{+}, \tilde{x}_{ij}\right) = \left\{\frac{1}{6}\begin{bmatrix}\left|\mu_{\tilde{A}}^{L}(\tilde{x}_j^{+}) - \mu_{\tilde{B}}^{L}(\tilde{x}_{ij})\right| + \left|\mu_{\tilde{A}}^{U}(\tilde{x}_j^{+}) - \mu_{\tilde{B}}^{U}(\tilde{x}_{ij})\right| \\ + \left|\eta_{\tilde{A}}^{L}(\tilde{x}_j^{+}) - \eta_{\tilde{B}}^{L}(\tilde{x}_{ij})\right| + \left|\eta_{\tilde{A}}^{U}(\tilde{x}_j^{+}) - \eta_{\tilde{B}}^{U}(\tilde{x}_{ij})\right| \\ + \left|v_{\tilde{A}}^{L}(\tilde{x}_j^{+}) - v_{\tilde{B}}^{L}(\tilde{x}_{ij})\right| + \left|v_{\tilde{A}}^{U}(\tilde{x}_j^{+}) - v_{\tilde{B}}^{U}(\tilde{x}_{ij})\right| \\ + \left|\pi_{\tilde{A}}^{L}(\tilde{x}_j^{+}) - \pi_{\tilde{B}}^{L}(\tilde{x}_{ij})\right| + \left|\pi_{\tilde{A}}^{U}(\tilde{x}_j^{+}) - \pi_{\tilde{B}}^{U}(\tilde{x}_{ij})\right|\end{bmatrix}\right\} \quad (17)$$

$$Ed_j\left(\tilde{f}_j^{+}, \tilde{f}_j^{-}\right) = \left\{\frac{1}{6}\begin{bmatrix}\left|\mu_{\tilde{A}}^{L}(\tilde{x}_j^{+}) - \mu_{\tilde{B}}^{L}(\tilde{x}_j^{-})\right| + \left|\mu_{\tilde{A}}^{U}(\tilde{x}_j^{+}) - \mu_{\tilde{B}}^{U}(\tilde{x}_j^{-})\right| \\ + \left|\eta_{\tilde{A}}^{L}(\tilde{x}_j^{+}) - \eta_{\tilde{B}}^{L}(\tilde{x}_j^{-})\right| + \left|\eta_{\tilde{A}}^{U}(\tilde{x}_j^{+}) - \eta_{\tilde{B}}^{U}(\tilde{x}_j^{-})\right| \\ + \left|v_{\tilde{A}}^{L}(\tilde{x}_j^{+} - v_{\tilde{B}}^{L}(\tilde{x}_j^{-})\right| + \left|v_{\tilde{A}}^{U}(\tilde{x}_j^{+} - v_{\tilde{B}}^{U}(\tilde{x}_j^{-})\right| \\ + \left|\pi_{\tilde{A}}^{L}(\tilde{x}_j^{+} - \pi_{\tilde{B}}^{L}(\tilde{x}_j^{-})\right| + \left|\pi_{\tilde{A}}^{U}(\tilde{x}_j^{+} - \pi_{\tilde{B}}^{U}(\tilde{x}_j^{-})\right|\end{bmatrix}\right\} \quad (18)$$

$$S(A_i) = \sum\nolimits_{j=1}^{n}\left[w_j\frac{d\left(\tilde{f}_j^{+}, \tilde{x}_{ij}\right)}{d\left(\tilde{f}_j^{+}, \tilde{f}_j^{-}\right)}\right] \quad (19)$$

$$R(A_i) = \max_j\left[w_j\frac{d\left(\tilde{f}_j^{+}, \tilde{x}_{ij}\right)}{d\left(\tilde{f}_j^{+}, \tilde{f}_j^{-}\right)}\right] \quad (20)$$

Step 11: Compute the coefficient value $Q(A_i)$.

By using Equation (21), the coefficient value $Q(A_i)$ is calculated by the use of τ parameter to define a weight for the majority of criteria. τ parameter is usually accepted as 0.5.

$$Q(A_i) = \tau\left(\frac{S(A_i - S_i^{+}}{S_i^{-} - S_i^{+}}\right) + (1-\tau)\left(\frac{R(A_i - R_i^{+}}{R_i^{-} - R_i^{+}}\right) \quad (21)$$

where $S_i^{+} = \min_i S(A_i)$, $S_i^{-} = \max_i S(A_i)$, $R_i^{+} = \min_i R(A_i)$, $R_i^{-} = \max_j R(A_i)$

Step 12: Index values ($S(A_i)$, $R(A_i)$, $Q(A_i)$) are ordered increasingly, as instructed originally [24]. As a result, 3 separate ranking lists are obtained as a result denoted by $S[i]$, $R[i]$ *and* $Q[i]$.

The alternative i having the first position in the $Q[i]$ list, that means the smallest $Q(A_i)$ value, is then identified as a compromise solution under the following conditions.

A_i has an acceptable advantage, where $Q[2] - Q[1] \geq DQ$, *and* $DQ = 1/(z-1)$ and z is total number for the alternatives.

A_i is constant, that is, A_i is also the best ranking alternative in $S[i]$ *and* $R[i]$ lists.

In case none of these states are satisfied, a compromise solution list is proposed by following procedures.

A_i having the first position in the $Q[i]$ list and A_{i+2} having the second position in the $Q[i]$ list is proposed as compromise solutions when the 2. condition is only the one not satisfied,

$A_1, A_2, \ldots, A_z$ is proposed as compromise solutions when 1. condition is not satisfied. A_z is estimated by using the relation of $Q[z] - Q[1] < DQ$.

IV. CASE STUDY

To validate the applicability of the proposed method, it is used on a case study to analyze the factors causing disruptions in supply chains and develop sustainable supply chain strategies. IVPFS-AHP is applied first to determine the importance weights of disruptive factors. Second, alternative sustainable supply chain strategies are developed to help to deal with disruptions and ranked by using IVPFS-VIKOR methodology.

A. CASE BACKGROUND

This research is motivated by a real-world issue faced by a leading international Kitchen Equipment Manufacturer (KEM) brand in Turkey. In the 1980s, starting with export-based growth strategy, Turkish firms quickly adapted to the new "export-oriented" economic policies. As an extension of small handicrafts such as coppersmith and aluminum making, the metal kitchenware sector has also taken its share from the same industrialization trend. Approximately 50% of the raw materials to be used in the production of kitchenware, i.e., steel pot, teapot, and sheet pan, etc., entering Turkey has continued to be processed in the city where the case study company is located. The annual production volume of Case company has reached the level of approximately 3 million cookware with the presentations made to domestic and international markets with stainless steel pots and pans, teapots, pressure cookers, coffee pots and non-stick coated aluminum cooking utensils with a capacity to sell advanced and high quality products in 85 countries worldwide. Although some production is made to order, most of the products are sold from stock. In this way, stocked production costs remain with the manufacturer. The global position and integration of new technologies also make this KEM brand more vulnerable to potential risks and threats. Thus, the proposed sustainable supply chain strategy evaluation methodology is tested in Turkish KEM (company name is not disclosed due to privacy concerns), which intents first to validate the sustainable supply chain strategy evaluation criteria, and then to test the usability of the proposed approach in GDM setting. Deciding with "consensus" in a group is one of the most effective methods of decision-making. Unfortunately, this is a very time-consuming technique. It is also important to know that consensus is not the same as a solid unanimous vote. The GDM process in the proposed method acts as collecting individual judgments of distinctive experts and form a consensus. The evaluations are done using a focus group consisting of 3 DMs with different background and experience. The first DM is a supply chain expert, who completed his undergraduate or graduate education in industrial engineering departments of universities, knowledgeable about SAP Material Management and Production Planning Modules, has a good command of several languages spoken in the world, and creates plans and strategies by providing cooperation and coordination with logistics departments to follow sales and production realizations instantly and to update them periodically according to necessity. The second DM is an academic, who has many articles, papers, and book chapters in the fields of industrial engineering, logistics, supply chain and digitalization, provides industrial consultancy services on various topics, especially strategic management, logistics and supply chain, and delivers strategic consultancy services focused on establishing innovative systems, system improvement and digitalization, and implements various industrial projects. The third DM is an engineer, who is a postgraduate of Industrial Engineering having advanced knowledge of several computer programs in analysis of data in the supply chain management process, to make efficiency analysis of operational processes and to suggest recommendations for improvement.

B. DISRUPTIVE FACTORS IN SUSTAINABLE SUPPLY CHAIN MANAGEMENT

Reaction speed and correction level of disruptions in sustainable supply chain management, no matter the impact or size of the disruption, depends largely on apprehending the types of arising disruptions and understanding how vulnerable supply chains are to be subjected to each kind. Knowing the interrelated global nature of nowadays' supply chain and spread-out network of transportation hubs, warehouses, and, production facilities, gets clear that there is more opportunity than ever before for supply chain managers to encounter breakdowns or disruptions at more touch points across their supply system [46].

In this sub-section, main catastrophes and sub-disruptions regarding sustainable supply chain management are identified. Given what has been said, 4 main catastrophes and 24 sub-disruptions are revealed with an extensive literature review and attentive experts' opinions. The detailed description and definition of these 4 disruption factors are presented as follows:

Natural and Human-made disasters ($\boldsymbol{D_1}$): Disasters are defined as the results of natural calamities or man-made crises that exceed human capabilities in terms of preventing the moment of their occurrence, spreading over widespread regions, causing damages, causing humanitarian crises in the regions where they occur. Natural disasters, on the other hand, are deadly natural events such as earthquakes, floods, deadly epidemics, hurricanes and tsunamis that occur due to ground-based or climatic changes. In addition to natural disasters that occur partially or completely beyond human control and cause substantial loss of property and life, man-made disasters in contrast are the result of situations arising from human behavior. These behaviors include war, negligence, cyberattacks, inertia, or serious errors, and are often fires, road / rail / air accidents, etc. Each disaster creates postponed or paused deliveries, security problems, livelihood difficulties, closed ports, canceled cargo flights, unbalanced supply and demand, and inevitably disrupt local and global supply chains [47].

Social Strife ($\boldsymbol{D_2}$): Social strife refers to a disastrous situation in which the concerned parties feels their political, economic, and cultural interests are diverging. The social catastrophes do not entail armed conflicts or civil wars, but it does refer to political instability, financial crisis, labor unrest and strikes, food shortage, energy scarcity, and regulatory changes. Social strife, especially in nowadays, is happening around the world and effecting supply chains by instituting social distancing, quarantine, curfews, massive restriction of movement of goods and people, etc. These series of drastic measures, which had to be taken before even the nature of the corona virus (Covid19) was fully understood, has almost brought the global economy to a halt, which has already been interrupted by trade wars and still has to deal with the specter of the 2008-2009 crisis. All sectors of the economic spectrum, from transportation to industry, from energy to tourism, from agriculture to banking services, have been affected by this voluntary and massive supply and demand shock, which is unprecedented in history [48].

Operational Contingencies ($\boldsymbol{D_3}$): In such circumstances of operational contingencies, some sectors can experience a negative demand shock, while some other sectors may also experience positive demand shocks. The sudden and unprecedented change in demand and supply poses significant supply chain and logistic challenges from sustainability perspective. Demand and supply shocks causes many companies to question their current supply chain management strategies regarding supplier problems, equipment malfunctions and systemic failures, software failures, poor-quality products and services, unskilled employees and lack of their training. After the first wave of arising operational contingencies is over, a dynamic management is important to ensure the balancing of supply chain processes [47], [48].

Strategic Causes ($\boldsymbol{D_4}$): Sustainable supply chain management from the viewpoint of strategic causes of calamities is focused on developing effective, efficient, and viable strategies in the areas of transportation failures and delays, falling behind the technology trends, lagging behind in competition, unpredictable and fluctuating demand, making them applied in daily routine and providing the most effective sustainable strategy. Therefore, evaluation of strategic causes and developing sustainable strategies in this direction is a significant factor and can be characterized as catastrophes from inadequate and unsuccessful implementation of supply chain sustainability strategies [47], [48].

Table 6 present the disruptive factors in supply chain sustainability under each main catastrophe by defining their description with references.

C. SUPPLY CHAIN SUSTAINABILITY STRATEGIES

There are many reasons why businesses should start their sustainable supply chain journey. The main reasons are to ensure compliance with laws and regulations, to adhere to and support international standards established for sustainable business ethics and codes of conduct. Furthermore, businesses are increasingly turning to actions that create better environmental, economic, and social impacts, because there is such expectation in society and there are commercial advantages to taking action. By managing and trying to enhance environmental, economic, and social performance throughout their supply chain, businesses act both in their own interests and in the interests of their participants and the whole society. In this section, after identifying the supply chain disruptive factors in the previous section, the supply chain sustainability strategies are determined. Strategies are ranked by using IVPFS-VIKOR methodology and the best strategy is selected. Sustainable supply chain strategies are given in the following.

Establish a well-designed supply and demand system (S_1): Maintaining the costs low while keeping the customers satisfied requires companies to perform supply and demand management proactively using the latest techniques. Also, with a better balance of supply and demand in supply chains; uncertainties, product prices, lead times, and shortages will decrease and companies' high service levels will increase [53]. Therefore, companies will be able to get higher profit rates and customers will receive better service.

Adapt and use digital technologies (S_2): Adapting and using digital technologies is critical for the companies to continue their success. The most important component of business success is to rapidly adopt emerging technologies and use them to in an effective way [1], [56], [57]. The critical goal of this process is to transform to digitalization era in time.

Build buyer supplier collaboration and partnerships (S_3): Buyer supplier collaboration and partnerships is a process that defines how the companies will develop relationships with its suppliers. As the name suggests, this process is a reflection of customer relationship management. Companies need to improve their relations with their suppliers as well as improve their relations with their customers.

Set well-defined administrative & environmental policies and regulations (S_4): Another factor affecting the way products are purchased and distributed is the legal and environmental regulations set by governments. Issues such as recycling, ecology and waste minimization affect supply chain management. Whether trade barriers will increase in the future is an important issue. As the Internet becomes able to connect to all world markets, firms' supply chain managers believe in the importance of governments removing barriers to restricting free trade. With the emergence of trade wars and Covid19, etc., it is not yet known how this issue will develop in the future.

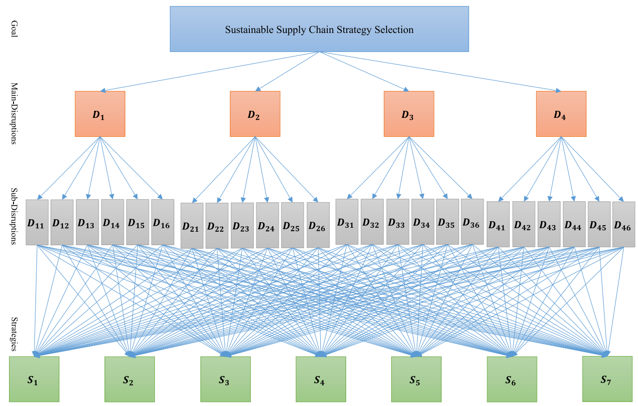

FIGURE 2. Hierarchical structure of the proposed framework.

Employees training and education to increase sustainable supply proficiency (S_5): This study puts the focus that the appropriate rules to be followed for all employees in the supply chain should be established and an infrastructure should be created to guide, raise awareness, and ensure, if possible, digital traceability of products.

Establish the financial resources, capabilities, and contingency plans (S_6): The study emphasizes that companies with particularly complex supply chains should be vital to establish financial resources, capabilities, and contingency plans to ensure business continuity at the same time as current business challenges.

Diversify supply chain from a geographic perspective (S_7): Diversifying supply chains from a geographic perspective to provide sustainability and mitigate risk from a single region reduces dependency on a specific supplier or a certain country and thus enable gain access to crucial goods despite unprecedented events, such as embargos, wars, or disease outbreaks, etc.

The hierarchical structure of the proposed framework is presented in Figure 2. This framework includes prioritizing the implementation steps and strategies that companies can take to ensure supply chain sustainability. The strategies proposed and summarized in this paper are based on principles that provide a flexible framework for continuous improvement. In the supply chain, which consists of a series of intertwined and independent steps from the first to the last step, it is necessary to reveal the synergy arising from the interaction of the parts with each other and to understand the role of each part in the supply chain. It is difficult to find a management area such as supply chain where the total benefit created by the parts interacting with each other is greater than the benefit they create if they work independently. The strategies outlined and described throughout this study will be prioritized in the next section. These strategies that companies can implement in order to create more sustainable supply chains are in fact complementary actions. In addition, it will be revealed as a result of this study which of these strategies should be considered more at every step for a successful

TABLE 6. Disruptive factors in supply chain sustainability.

Main catastrophes and sub-disruptions	Description	References
D_1: Natural and Human-made disasters		
D_{11}: Armed conflicts	Communal violence, revolts and terrorism like disasters imperil the health of hundreds of millions of people and substantially causes supply chain disruptions in all levels.	[46], [47], [49], [50]
D_{12}: Cyberattacks and data breaches	The activities of advanced persistent threat groups, data breaches, and ransomware events cause significant damages to supply chains.	[3], [46], [47], [50]
D_{13}: Extreme weather conditions	Snow, flooding, storm, tornado, and wildfire like disasters effect supply chain and cause supply chain disruptions.	[49], [50]
D_{14}: Infectious disease outbreak	Biological terrorism, infectious disease outbreaks, and pandemics like disasters reveal vulnerabilities of supply chains and cause major disruptions.	[2], [47], [50]–[52]
D_{15}: Plate tectonics activities	Volcanoes, Earthquakes and Tsunamis like disasters can trigger huge disruptions in supply chains.	[47], [50]
D_{16}: Occupational accidents	Industrial accidents, fire, arson, and nuclear meltdown and disasters jeopardize ecological life and substantially cause supply chain disruptions.	[46], [47], [50]
D_2: Social Strife		
D_{21}: Political instability	The political upheaval, propensity for regime or government change, or instability and uncertainty in government policy is an enormous threat to supply chains and cause a major turmoil.	[49], [50], [52]
D_{22}: Financial Crisis	Recessions, banking panic, increase in bank interest, foreign exchange rates and currency fluctuations, etc. have a degrading impact on the sustainability, viability, and performance of the supply chain.	[46], [47], [50]
D_{23}: Labor Unrest and Strikes	Worker protests or strikes have the potential to hinder a company's production, making it impossible to sustain its delivery, thus causing stock outages, lost sales, and have the potential to disrupt supply chains.	[49], [50]
D_{24}: Food Shortage	The availability of food on the shelves, increased food prices have a triggering effect on people and causes a disruption in the supply chain	[50], [53]
D_{25}: Energy Scarcity	Climb in raw material and gasoline prices, petrol embargoes, security breach on energy services and power disruptions cause significant damages to supply chains.	[3], [50]
D_{26}: Regulatory Changes	Human rights law, property rights, tax, export/import policies, industry rules or other regulatory changes can cause a major disruption in supply chains.	[3], [50], [51], [54]
D_3: Operational Contingencies		
D_{31}: Supplier Problems	The main objectives of working with suppliers are to create a shared mentality regarding sustainability issues, to ensure that the sustainability vision, strategy, and practices are owned by the suppliers, and to work more closely with suppliers within the framework of shared priorities.	[50], [51], [55]
D_{32}: Equipment malfunctions and systematic failures	This can be defined as malfunctions that tend to occur occasionally and suddenly but easily noticeable, such as dysfunction of an equipment in the supply chain, and systematic failures that result from a performance decrease and noninterfering with the operation of the supply chain, but cause performance efficiency and can be discovered only with careful observations.	[3], [46], [50]
D_{33}: Software failures	Software contributing to supply chain optimization includes forecasting, customer interaction, advanced planning, distribution management, production planning, storage, transportation planning and chain-wide optimization. This software help managers find opportunities that even the most experienced cannot foresee with their hunches. And failure in one of these areas can devastatingly affect the sustainability of the supply chain process.	[3], [50]
D_{34}: Poor-quality products and services	Problems with the services and products quality would have a negative effect on consumers and might cause a company to lose its clients faster than they can gain new ones.	[46], [50]
D_{35}: Unskilled employees	Due to the inefficient use of existing resources or insufficient resources causes an increase in the educated unemployed and a decrease in the marginal return of education. In order to train qualified workforce, it is necessary to establish a functional relationship between economic investments and the education system.	[3], [46], [50]
D_{36}: Lack of training	Failure of education system to create skilled workforce due to the inefficient use of existing resources or insufficient resources causes an increase in the educated unemployed and a decrease in the marginal return of education. In order to train qualified workforce, it is necessary to establish a functional relationship between economic investments and the education system.	[50]–[52]
D_4: Strategic Causes		
D_{41}: Transportation failures and delays	Renewed production and information technologies have increased competition and consumer expectations, this has led to variable and unpredictable markets with shortened product life cycles. In addition, natural disasters, accidents, and supply disruptions have increased risk in today's global supply chains.	[46], [50], [54]
D_{42}: Falling behind the technology trends	Advances in technology, increasing globalization, shorter product lifetimes, faster access to information and increased joint investments are forcing supply chain management that aims to offer higher value products to their customers. Thanks to the use of advanced technology, it is possible to reduce costs by making resource use efficient.	[3], [50]
D_{43}: Lagging behind in competition	Nowadays, the supply networks of companies are getting more and more complex. In addition, the globalization of the business world, the increasing variety of products, and the gradual decrease in product life cycles, especially the more effective use of Internet technology in supply chain approaches, has increased competition.	[3], [50], [52]
D_{44}: Demurrage and detention	Delays due to incorrect documentation, late receipt of documents, loss of documents customs clearance or cargo inspection, release of cargo at destination, or receiver being unreachable should be taken into account.	[46], [50], [54]
D_{45}: Price fluctuations	The purchasing function, which aims to provide inputs such as raw materials required for the creation of the product or service offered by the company, constitutes one of the first areas directly linked to success in supply chains. Price fluctuations have a negative effect on suppliers and might cause a company to lose its dealers faster than they can gain new ones.	[46], [50]
D_{46}: Unpredictable and fluctuating demand	The demand management process tries to balance the needs of the customers with the supply possibilities of the company. Unpredictable and fluctuating demand have a negative effect on suppliers and might cause a company to lose its dealers faster than they can gain new ones.	[50], [51], [55]

supply chain sustainability management. Numerical results for weighting factors and strategies are described in the next section.

D. THE APPLICATION OF THE PROPOSED METHOD TO SUPPLY CHAIN SUSTAINABILITY STRATEGIES

In the proposed method, the VIKOR method is used to reflect multiple criteria inherited in the selection problem to the solution, and the AHP method is used to determine the criterion weights. An interval-valued evaluation model is established during these MCDM evaluation. Owing to the benefits created by IVPFS environment, problem-specific constraints have been added to the solution. Supply chain sustainability strategies alternatives are prioritized as a result of the application of proposed approach. It is seen that the established integration is effective in solving MCDM problems under constraints. The solutions steps are presented as follows:

Step 1: Evaluations are accomplished by using a focus group consisting of three DMs with different background and experience. These evaluations for the 4 main criteria and 24 sub-criteria are gathered from three DMs in a linguistic form. The judgments on 7 alternatives are also collected from three DMs in a linguistic form. Table 7 presents the linguistic terms of the given judgments on main criteria for each DM. Due to space limits, only the main criteria evaluations are displayed here. Table 8 presents the linguistic terms of the alternative evaluations regarding the first criterion for three DMs.

Step 2: By the use of linguistic scale given in Table 3, the weights of each DMs are calculated with Equation (12). Table 9 presents the priority weights of each DM.

TABLE 7. Linguistic evaluations of pairwise comparison matrix for main criteria.

DM_1	c_1	c_2	c_3	c_4
c_1	EP	1/RP	IVI	SP
c_2	RP	EP	IVI	QSP
c_3	1/IVI	1/IVI	EP	HP
c_4	1/SP	1/QSP	1/HP	EP
DM_2	c_1	c_2	c_3	c_4
c_1	EP	RP	1/RP	IVI
c_2	1/RP	EP	1/IVI	IVIV
c_3	RP	IVI	EP	1/RP
c_4	1/IVI	1/IVIV	RP	EP
DM_3	c_1	c_2	c_3	c_4
c_1	EP	IVI	1/HP	1/SP
c_2	1/IVI	EP	RP	QSP
c_3	HP	1/RP	EP	IVIV
c_4	SP	1/QSP	1/IVIV	EP

TABLE 8. Linguistic evaluations of preference matrix for each alternative with regard to the first criterion.

c_1	DM_1	DM_2	DM_3
A_1	H	H	H
A_2	VL	L	L
A_3	AE	L	VL
A_4	ML	L	L
A_5	AE	AE	L
A_6	VL	VL	AL
A_7	MH	AE	ML

TABLE 9. Priority weights of each DM.

DM	Linguistic Judgments	$\mu_{\tilde{A}}^L$	$\mu_{\tilde{A}}^U$	$\eta_{\tilde{A}}^L$	$\eta_{\tilde{A}}^U$	$\nu_{\tilde{A}}^L$	$\nu_{\tilde{A}}^U$	e_{λ_k}	λ_k
1	AH	0.65	0.70	0.05	0.10	0.15	0.20	0.67	0.339
2	H	0.45	0.50	0.15	0.20	0.25	0.30	0.65	0.329
3	VH	0.55	0.60	0.10	0.15	0.20	0.25	0.65	0.332

TABLE 10. The pairwise comparison matrix of main criteria for the first DM.

	c_1						c_2					
	$\mu_{\tilde{A}}^L$	$\mu_{\tilde{A}}^U$	$\eta_{\tilde{A}}^L$	$\eta_{\tilde{A}}^U$	$\nu_{\tilde{A}}^L$	$\nu_{\tilde{A}}^U$	$\mu_{\tilde{A}}^L$	$\mu_{\tilde{A}}^U$	$\eta_{\tilde{A}}^L$	$\eta_{\tilde{A}}^U$	$\nu_{\tilde{A}}^L$	$\nu_{\tilde{A}}^U$
c_1	0.40	0.45	0.05	0.10	0.40	0.45	0.40	0.45	0.30	0.35	0.10	0.20
c_2	0.10	0.20	0.30	0.35	0.40	0.45	0.40	0.45	0.05	0.10	0.40	0.45
c_3	0.45	0.50	0.35	0.40	0.05	0.10	0.45	0.50	0.35	0.40	0.05	0.10
c_4	0.30	0.35	0.20	0.25	0.30	0.40	0.05	0.07	0.02	0.03	0.80	0.90
	c_3						c_4					
	$\mu_{\tilde{A}}^L$	$\mu_{\tilde{A}}^U$	$\eta_{\tilde{A}}^L$	$\eta_{\tilde{A}}^U$	$\nu_{\tilde{A}}^L$	$\nu_{\tilde{A}}^U$	$\mu_{\tilde{A}}^L$	$\mu_{\tilde{A}}^U$	$\eta_{\tilde{A}}^L$	$\eta_{\tilde{A}}^U$	$\nu_{\tilde{A}}^L$	$\nu_{\tilde{A}}^U$
c_1	0.05	0.10	0.35	0.40	0.45	0.50	0.30	0.40	0.20	0.25	0.30	0.35
c_2	0.05	0.10	0.35	0.40	0.45	0.50	0.80	0.90	0.02	0.03	0.05	0.07
c_3	0.40	0.45	0.05	0.10	0.40	0.45	0.60	0.70	0.05	0.10	0.15	0.20
c_4	0.15	0.20	0.05	0.10	0.60	0.70	0.40	0.45	0.05	0.10	0.40	0.45

TABLE 11. Aggregated pair-wise comparison matrix of main criteria.

		c_1				
	$\mu_{\tilde{A}}^L$	$\mu_{\tilde{A}}^U$	$\eta_{\tilde{A}}^L$	$\eta_{\tilde{A}}^U$	$\nu_{\tilde{A}}^L$	$\nu_{\tilde{A}}^U$
c_1	0.265	0.324	0.160	0.225	0.322	0.406
c_2	0.483	0.584	0.105	0.149	0.161	0.222
c_3	0.440	0.517	0.122	0.183	0.171	0.245
c_4	0.248	0.303	0.068	0.106	0.410	0.495

Step 3: Linguistic assessments are transformed into IVPFS set values with Table 4. The constructed IVPFS sets pairwise comparison matrix of main criteria for the first DM is presented in Table 10 as an example.

Step 4: Individual IVPFS set values are fused into GDM matrix for the main criteria using the Equation (13). The aggregated matrix is shown in Table 11.

Step 5: CR values are checked, and all CR values are less than or equal to 0.10. Thus, each pair wise comparison matrix is considered as acceptable.

Step 6: Equation (11) is applied to find the entropy weights of criteria and Equation (14) is used to compute the priority weights of each criterion. Table 12 presents the final weights of each criterion.

Step 7: Values are converted into IVPFS set values with Table 5, as displayed in Table 13. Due to space limits, the preference matrix of each alternative is presented only for the first criterion here.

Step 8: The individual IVPFS set values of alternatives regarding the first criterion are fused into GDM matrix by the use of Equation (13). The computed outcome is presented in Table 14.

Step 9: Equations (15) and (16) are used to calculate the positive ideal solution ($\tilde{f}_j^+$) and negative ideal solution ($\tilde{f}_j^-$). The outcome is listed in Table 15.

Step 10: Using Equations (17) and (18), the separations are calculated. Equation (19) is applied to calculate the group utility value and Equation (20) is applied to calculate the

TABLE 12. Priority weights of each criterion.

Disruptive factors	Main Criteria Weights	Sub-factors	Sub-Criteria Weights	Overall Weights	Rank
c_1	0.252	c_{11}	0.174	0.0437	4
		c_{12}	0.165	0.0415	11
		c_{13}	0.159	0.0400	23
		c_{14}	0.179	0.0451	1
		c_{15}	0.161	0.0404	19
		c_{16}	0.163	0.0411	12
c_2	0.251	c_{21}	0.177	0.0444	2
		c_{22}	0.174	0.0437	5
		c_{23}	0.165	0.0415	10
		c_{24}	0.162	0.0406	16
		c_{25}	0.160	0.0402	21
		c_{26}	0.162	0.0406	17
c_3	0.248	c_{31}	0.164	0.0406	15
		c_{32}	0.168	0.0418	8
		c_{33}	0.163	0.0404	20
		c_{34}	0.165	0.0410	14
		c_{35}	0.163	0.0405	18
		c_{36}	0.177	0.0439	3
c_4	0.249	c_{41}	0.160	0.0398	24
		c_{42}	0.173	0.0430	6
		c_{43}	0.165	0.0410	13
		c_{44}	0.161	0.0402	22
		c_{45}	0.168	0.0418	9
		c_{46}	0.173	0.0430	7

TABLE 13. Individual IVPFS set values of each alternative with respect to the first criterion.

c_{11}		A_1	A_2	A_3	A_4	A_5	A_6	A_7
	$\mu_{\tilde{A}}^{L}$	0.55	0.05	0.35	0.25	0.35	0.05	0.45
	$\mu_{\tilde{A}}^{U}$	0.60	0.10	0.40	0.30	0.40	0.10	0.50
	$\eta_{\tilde{A}}^{L}$	0.10	0.35	0.20	0.25	0.20	0.35	0.15
	$\eta_{\tilde{A}}^{U}$	0.15	0.40	0.25	0.30	0.25	0.40	0.20
DM_1	$\nu_{\tilde{A}}^{L}$	0.20	0.45	0.30	0.35	0.30	0.45	0.25
	$\nu_{\tilde{A}}^{U}$	0.25	0.50	0.35	0.40	0.35	0.50	0.30
	$\mu_{\tilde{A}}^{L}$	0.55	0.15	0.15	0.15	0.35	0.05	0.35
DM_2	$\mu_{\tilde{A}}^{U}$	0.60	0.20	0.20	0.20	0.40	0.10	0.40
	$\eta_{\tilde{A}}^{L}$	0.10	0.30	0.30	0.30	0.20	0.35	0.20
	$\eta_{\tilde{A}}^{U}$	0.15	0.35	0.35	0.35	0.25	0.40	0.25
	$\nu_{\tilde{A}}^{L}$	0.20	0.40	0.40	0.40	0.30	0.45	0.30
	$\nu_{\tilde{A}}^{U}$	0.25	0.45	0.45	0.45	0.35	0.50	0.35
	$\mu_{\tilde{A}}^{L}$	0.55	0.15	0.05	0.15	0.15	0.01	0.25
DM_3	$\mu_{\tilde{A}}^{U}$	0.60	0.20	0.10	0.20	0.20	0.01	0.30
	$\eta_{\tilde{A}}^{L}$	0.10	0.30	0.35	0.30	0.30	0.40	0.25
	$\eta_{\tilde{A}}^{U}$	0.15	0.35	0.40	0.35	0.35	0.44	0.30
	$\nu_{\tilde{A}}^{L}$	0.20	0.40	0.45	0.40	0.40	0.50	0.35
	$\nu_{\tilde{A}}^{U}$	0.25	0.45	0.50	0.45	0.45	0.55	0.40

TABLE 14. Aggregated GDM matrix of alternatives with respect to first criterion.

	$\mu_{\tilde{A}}^{L}$	$\mu_{\tilde{A}}^{U}$	$\eta_{\tilde{A}}^{L}$	$\eta_{\tilde{A}}^{U}$	$\nu_{\tilde{A}}^{L}$	$\nu_{\tilde{A}}^{U}$
A_1	0.55	0.60	0.10	0.15	0.20	0.25
A_2	0.12	0.17	0.32	0.37	0.42	0.47
A_3	0.19	0.25	0.28	0.33	0.38	0.43
A_4	0.19	0.24	0.28	0.33	0.38	0.43
A_5	0.29	0.34	0.23	0.28	0.33	0.38
A_6	0.04	0.07	0.37	0.41	0.47	0.52
A_7	0.36	0.41	0.20	0.25	0.30	0.35

individual regret value. Table 16 presents the group utility and individual regret values.

Step 11: Using Equation (21), the coefficient value $Q(A_i)$ is calculated with τ parameter being 0.5. Table 16 presents the index values.

Step 12: Three separate ranking lists are presented in Table 16. The smallest $Q(A_i)$ value is in the alternative A_7; i.e., it has the first position in the $Q[i]$ list. Thus, it is proposed as a compromise solution since A_7 has an acceptable advantage. Furthermore, $0.223 - 0.024 \geq 0.167$ where $DQ = \frac{1}{7-1}$ and A_7 is constant. A_7 is also the best ranking alternative in $R[i]$ list and second ranking in the $S[i]$ list.

TABLE 15. Positive ideal solution ($\tilde{f}_j^+$) and negative ideal solution ($\tilde{f}_j^-$).

	$\tilde{f}_j^+$						$\tilde{f}_j^-$					
	$\mu_{\tilde{A}}^{L}$	$\mu_{\tilde{A}}^{U}$	$\eta_{\tilde{A}}^{L}$	$\eta_{\tilde{A}}^{U}$	$\nu_{\tilde{A}}^{L}$	$\nu_{\tilde{A}}^{U}$	$\mu_{\tilde{A}}^{L}$	$\mu_{\tilde{A}}^{U}$	$\eta_{\tilde{A}}^{L}$	$\eta_{\tilde{A}}^{U}$	$\nu_{\tilde{A}}^{L}$	$\nu_{\tilde{A}}^{U}$
c_{11}	0.55	0.07	0.10	0.41	0.20	0.52	0.04	0.60	0.37	0.15	0.47	0.25
c_{12}	0.58	0.41	0.06	0.25	0.18	0.35	0.36	0.64	0.20	0.12	0.30	0.24
c_{13}	0.59	0.17	0.07	0.37	0.18	0.47	0.12	0.64	0.32	0.13	0.42	0.23
c_{14}	0.62	0.24	0.06	0.33	0.16	0.43	0.19	0.67	0.28	0.11	0.38	0.22
c_{15}	0.59	0.37	0.06	0.25	0.18	0.37	0.32	0.64	0.20	0.13	0.31	0.23
c_{16}	0.60	0.30	0.05	0.30	0.17	0.40	0.25	0.65	0.25	0.11	0.35	0.23
c_{21}	0.65	0.17	0.05	0.36	0.15	0.46	0.12	0.70	0.31	0.10	0.41	0.20
c_{22}	0.59	0.28	0.07	0.31	0.18	0.41	0.23	0.64	0.26	0.13	0.36	0.23
c_{23}	0.59	0.16	0.07	0.37	0.18	0.47	0.14	0.65	0.32	0.13	0.42	0.23
c_{24}	0.59	0.08	0.07	0.41	0.18	0.51	0.06	0.64	0.36	0.13	0.46	0.23
c_{25}	0.65	0.29	0.05	0.30	0.15	0.41	0.24	0.70	0.25	0.10	0.35	0.20
c_{26}	0.60	0.17	0.05	0.36	0.17	0.46	0.12	0.66	0.31	0.11	0.41	0.22
c_{31}	0.59	0.24	0.07	0.33	0.18	0.43	0.19	0.64	0.28	0.13	0.38	0.23
c_{32}	0.50	0.17	0.12	0.36	0.22	0.46	0.12	0.55	0.31	0.17	0.41	0.28
c_{33}	0.59	0.30	0.06	0.30	0.18	0.40	0.25	0.64	0.25	0.12	0.35	0.23
c_{34}	0.65	0.37	0.04	0.27	0.15	0.37	0.32	0.70	0.22	0.10	0.32	0.20
c_{35}	0.64	0.17	0.04	0.36	0.16	0.46	0.12	0.69	0.31	0.10	0.41	0.21
c_{41}	0.70	0.32	0.02	0.29	0.13	0.39	0.27	0.75	0.24	0.07	0.34	0.18
c_{42}	0.64	0.30	0.04	0.30	0.16	0.40	0.25	0.69	0.25	0.10	0.35	0.21
c_{43}	0.59	0.19	0.07	0.35	0.18	0.46	0.15	0.65	0.30	0.13	0.41	0.23
c_{44}	0.50	0.17	0.08	0.36	0.22	0.46	0.12	0.56	0.31	0.16	0.41	0.28
c_{45}	0.65	0.20	0.05	0.35	0.15	0.45	0.15	0.70	0.30	0.10	0.40	0.20

TABLE 16. The index values and the respective ranking.

	A_1	A_2	A_3	A_4	A_5	A_6	A_7
$S(A_i)$	0.0220	0.0229	0.0226	0.0228	0.0224	0.0227	0.0222
Rank	1	7	4	6	3	5	2
$R(A_i)$	0.5019	0.5005	0.5040	0.5030	0.5043	0.5041	0.5000
Rank	3	2	5	4	7	6	1
$Q(A_i)$	0.223	0.558	0.684	0.620	0.641	0.703	0.024
Rank	2	3	6	4	5	7	1

E. COMPARISONS, SENSITIVITY AND SPEARMAN'S RATIO CORRELATION

This study is evaluated under different objective world environments to further illustrate the validity of the developed methodology. Here, the proposed method is compared to Interval-Valued Fuzzy (IVF) VIKOR, Interval-Valued Intuitionistic Fuzzy (IVIF) VIKOR, and Interval-Valued Pythagorean Fuzzy (IVPyF) VIKOR methods. These methods have similar solution algorithms but different objective world environment. Figure 3 presents the ranking order of the analysis. The IVF, IVIF, and IVPyF environments are chosen to make comparisons with the proposed IVPFS environment. As it can be spotted from Figure 3, there are substantial differences between the Fuzzy ranking order and the proposed method. For example, Alternative A_7 has the highest priority among the alternatives for the proposed methodology. However, A_7 ranks fourth place when the IVF environment is applied. This comparative analysis reveals the weaknesses of traditional fuzzy-based evaluations in selecting the best candidate. In contrast, the proposed methodology can cope with the disadvantages associated with the conventional fuzzy environment. The second comparison analysis is carried out between the IVIF environment and the proposed methodology. It can be seen that the variation among rankings is observable. The third comparison is with the IVPyF environment, and the ranking variations seem to diminish. It is consistent with the outcome of the proposed methodology. There are lower or higher variations among all evaluation approaches. However, these methods have a different operational mechanism in the determination of the best candidate. Thus, the proposed IVPFS based VIKOR technique can obtain more rational priority rankings.

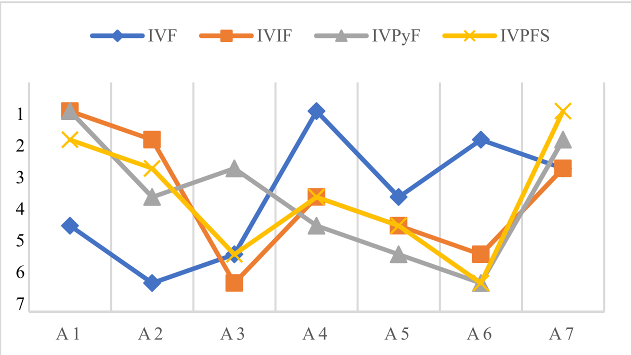

FIGURE 3. The ranking results by using different environments.

Different MCDM methods may result in different but similar results. Here, the proposed method is compared to TOPSIS, COPRAS, and CODAS methods. These methods have different solution algorithms. Therefore, the same input data are utilized in different ways with other methods. For example, CODAS technique makes use of two measures [59], such as Euclidean and Taxicab distances, to select the desired alternative. The higher the value of distance from the negative ideal solution, the more desirable the alternative is. The TOPSIS technique, on the other hand, is based on deviations from the positive and negative ideal solutions [58]. Thus, the various evaluations of distances give different results. Figure 4 presents that there is no significant difference for the best alternative between the proposed method and the other methods used for comparison. The order of other alternatives varies. The observations of DMs on the analysis clearly confirms that the results obtained by the proposed method are plausible.

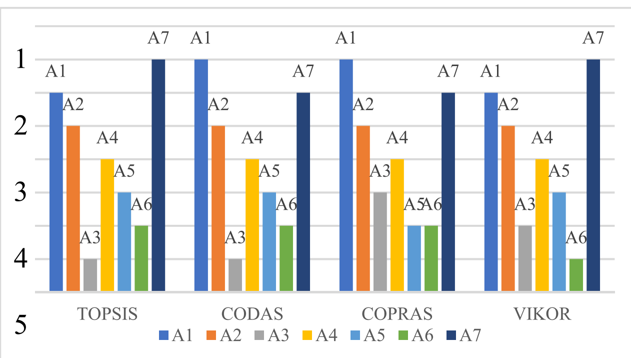

FIGURE 4. Comparison with different MCDM methods.

By the use of sensitivity analysis, how the changes in criteria weights effect the given decision are investigated. That is, a change in the weights of the 4 main criteria and 24 sub-criteria used in decision-making are investigated to see how it may affect the decision in the strategy evaluation. Thus, a sensitivity analysis is performed depending on the weight of each main criterion indicated by the first four scenarios in the Figure 5. In the sensitivity analysis, each main criterion is examined by changing the priorities of them among the overall weights. In addition, a sensitivity analysis is also carried out according to the highest prioritized sub-criteria indicated by the last three scenarios, which are the most important attributes for the DMs out of 24 sub-criteria. Likewise, in the sensitivity analysis made, each selected sub criterion is examined by changing its priority among the overall weights. Figure 5 presents the outcome of the sensitivity analysis. As can be seen, in the case of C_4 main criterion for the fourth scenario, as in the case study, the ranking of the alternatives is calculated as $A_1 > A_7 > A_2 > \cdots > A_6$, respectively. In the sensitivity analysis carried out for the C_4 main criterion, regardless of what weight it takes between 0 and 1, given decision has a different ranking values for alternatives. For this reason, it can be said that the given decision is dependent of the main criteria weights. To extend the sensitivity analysis made, the decision of the A_7 as the best ranking alternative, given conclusion may change according to the weights of the C_3 and C_4 main criteria and C_{14}, C_{21}, and C_{36} sub-criteria. But in all cases, it can be said that the decision made is not fixed since the mentioned changes not only take place at the extreme points of the criterion weights but also effect the whole ranking.

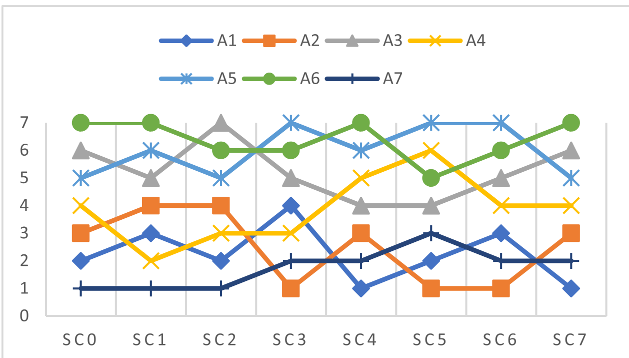

FIGURE 5. Sensitivity analysis.

The review on existing literature revealed that Spearman's correlation coefficient is a quite useful approach to test the relationship of different rankings obtained from various MCDM techniques. Rank correlation has been efficiently used in many existing studies [60]. Its non-parametric properties and abilities on correlation's statistical dependence conveys it as a suitable tool for the presented study. Thus, in the presented research, the ranking relationships of different MCDM techniques and the developed methodology is used to test and verify the given outcome. The coefficient estimated by the Spearman's rank correlation brings out the effect size so that correlation's strength is able to be described verbally by applying the values of statistical significance, such as 0.00–0.19 (Very Weak), 0.20–0.39 (Weak), 0.40–059 (Moderate), 0.60–0.79 (Strong), and 0.80–1.00 (Very Strong). Figure 6 presents the rank correlations of various MCDM techniques under IVPFS set environment. A coefficient value larger than 0.80 implies an extremely high correlation among rankings. This means that the relationship between the compared ranks is statistically significant. As a result, there is an extremely significant correlation among the proposed method and the other three different MCDM comparisons.

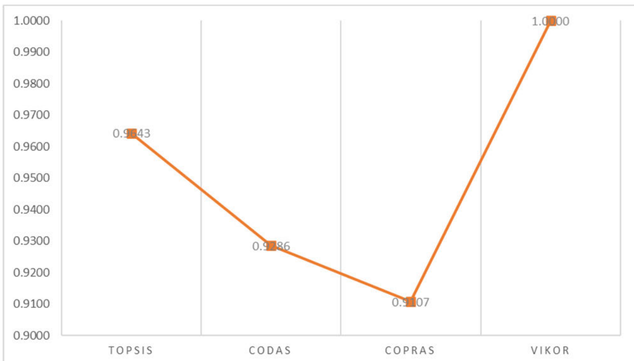

FIGURE 6. **Spearman's rank correlation.**

V. RESULTS AND DISCUSSIONS

Coronavirus pandemic revealed that many businesses had already not fully aware of their vulnerabilities in terms of their supply chain relations in case of global catastrophes. There was a decades-long focus on optimization of supply chains in order to drive-up asset utilization, reduce inventories, and minimize costs. Fortunately, emerging new technologies of digitalization of supply chains dramatically has enhanced the end-to end supply chains visibility and provided necessary tools to support in resisting such disruptions [1], [57]. leveraging the given framework in the presented paper, supply chain sustainability can be devised to anticipate and meet future challenges. Even if catastrophic disruption happens whether it is a ''black swan'' event like supplier bankruptcies, sudden spikes in demands, labor disputes, regulatory changes, act of war or terrorism, trade wars, or Covid19, etc., companies deploying the proposed framework will be prepared to deal with any unpredicted events.

According to the case study results, see Table 12, the key factor among the main catastrophes emerges as the ''Natural and Human-made disasters'' with a priority value of 0.252. Synthesis of evidence from given evaluations, the focus should be prioritized to robust strategies to provide supply chain sustainability by mitigating the effect of disruptions erupted from Natural and Human-made disasters. When the global weights are calculated as overall product of sub-disruptions' and main catastrophes' weights, the highest priority is appeared to be given to Infectious disease outbreak, Political instability, Lack of training. These results have shown that supply chain disruptions directly related to initial Covid19 stay-at-home orders, shutdowns, and lockdowns where largely dependent on the countries imposing restrictions. However, how can we get rid of the losses and get less sensitive to the effect of these disruptions. Thus, the answer to this is to know where to put the focus regarding sustainable supply chain strategies to eliminate the effect of the disruptions. When the Table 16 is thoroughly examined the most important strategies are given as: Diversify supply chain from a geographic perspective, Establish a well-designed supply and demand system, and Adapt and use digital technologies. Prioritized implementation of the concluded strategies by companies will enable organizations to eliminate disruptions and promote sustainability in their supply chains to respond to unexpected events more quickly.

A. MANAGERIAL IMPLICATIONS

The year 2020 will probably be a turning point in history due to the outbreak of Covid19. The coronavirus pandemic caused a seismic shift that put supply chain management in the spotlight worldwide. The pandemic exposed fundamental flaws in the global economy and structural vulnerabilities in supply chains. Companies discovered that agility was crucial to their short-term continuity and even long-term survival. In the coronavirus pandemic, sustainable supply chain becomes urgent in a crisis – and that's exactly where companies find themselves today, which explains the high level of focus on the topic right now. Covid19 has accelerated the need for sustainable supply chain strategy. However, there is concern that this reactive management approach will fade again as soon as the crisis has passed. Therefore, this study provides a useful guide for supply chain mangers to prioritize their strategies in dealing with supply chain sustainability. Companies need to improve their sustainable abilities to ensure that their supply chains flow smoothly to a cascade of sustainable practices. It is clear now that if we do not diversify supply chains from a geographic perspective and line up alternative supply sources in diverse locations to mitigate the risks, any major disruption will put the global supply chains at risk. For example, China has been considered as ''the world's factory'' and many of the global firms had presence in Wuhan, China, a highly industrialized region in the time outbreak instigated, which is hit the hardest by the Covid19. The most important difference of the disruptions caused by the pandemic from the disruptions caused by other crises is that they are large, fast, and disruptive in the direction of supply and demand along all supply chains.

Due to Covid19, most of the employees had to work from home. Now people spend their time working at home and spending time with their families, not just commuting. This change in lifestyle and working style will have permanent effects in terms of demand. Now, while the demand for some products and services has decreased significantly, the demand for some is increasing. Particularly with the coronavirus pandemic, which has genuinely disturbed the supply chains in global scale, how significant the supply chain sustainability is clearly revealed. Companies are not fully aware of the vulnerability of their supply chain. Therefore, the need to transform traditional supply chain models is highlighted in the presented study.

The presented research in this paper enquires the following fundamental questions for a Turkish KEM Company. What factors have the most disruptive effect in Supply Chain Sustainability, which strategies is needed to be implemented to overcome these disruptions and which strategy should be given a priority in creating a sustainable supply chain management? By the use of concluded results of this application, KEM Company will be one step ahead in sustainability concept rather than creating the strategies from a clean slate. Although the method proposed in the study seems complicated, it can be easily implemented with decision support tools. The method's consensus among DMs and providing effective decision support will increase decision quality by reducing the workload of decision-making for managers. Moreover, in this research, DMs have been selected as experts in their field or industry. The criteria and strategies proposed in the study are based on expert opinions as well as the literature review. This contributed to the real-life decision-making process of the study.

VI. CONCLUSION

Today, companies are trying to get prepared for the social, economic, and psychological changes happening radically due to effect of Covid19 and succeed in technology, rational thinking, and taking strategic steps responsibly in order to ensure their supply chains become an element of social welfare and sustainability. These concerns, coupled with the current global crisis, bring with it a demand for a solution that includes not only business, but also politics, ecology, and culture. To address this demand for a solution, sustainable supply chain strategies should be developed and implemented.

MCDM methods is generally used in cases where there are more than one and often contradicting goals and criteria and it is difficult to choose between alternatives. Thus, the findings of the MCDM problems are mostly based on the judgments of DMs. To verify the significance level of the criteria in MCDM problems, thanks to its advantages, such as: getting expert opinions, only comparing two criteria at a time, being straightforward and understandable, etc., an effective integrated approach in the literature, classic pairwise comparison, AHP method and, distance-based ranking, VIKOR method have been proposed. According to the information obtained from the DMs, the criteria weights, the prioritization of disruptive factors, are calculated by utilizing the IVPFS-AHP and the ranking of the best suitable alternative, sustainable supply chain strategies, is made with the IVPFS-VIKOR considering the 7 different candidates with respect to 24 evaluation criteria for a real case study of a Turkish KEM Company. In the proposed model, the importance of DMs is stated in verbal variables and linguistic statements are expressed in IVPFS values. Subsequently, the influences of the criteria and the assessments of the alternatives concerning criteria are presented by the DMs in linguistic variables and linguistic variables are also stated in IVPFS values. The aggregation equation is applied to aggregate these values. There are many applications of AHP and VIKOR methods in different types of fuzzy sets forms. This study utilizes IVPFS sets, which consider the degree of hesitation under an interval and can thus effectively deal with the errors or lack of knowledge of experts when defining the membership function. This is the first attempt in the literature applying IVPFS-AHP and IVPFS-VIKOR approaches in this field.

This study has also some limitations as well as its contributions. Simulation or optimization side in this study is excluded since it is a MCDM motivated research on sustainable supply chain management. An additional restriction is the use of a single case in the research. Although result obtained through this real case study with the judgments of real experts reveals that the proposed framework is reliable and easily applicable, the given outcome may be compared and analyzed by considering the different case studies in the future.

Several possible directions exist for future research to follow-up from the present study. A specific number of disruption factors and sustainable strategy alternatives are evaluated in the given research. For future research, this study may be comprehensively detailed by involving more DMs in the decision process, increasing the number of factors and strategies to be evaluated, and considering the bilateral links, internal/external dependencies between criteria and the strengths of their dependence. In addition, the IVPFS set theory has been applied to a specific GDM problem in this study. Since the proposed method is an effective method to deal with uncertainty caused by human thoughts, it is envisaged to be applied to other selection problems such as technology selection, software selection, production system selection, and investment problems, etc., in the future. Furthermore, the developed method demonstrates how the given methodology is to be applied to real-world decision-making problems so the developed evaluation framework might be able to handle other selection problems and other MCDM problems under different objective world environments such as hesitant fuzzy sets, type-2 fuzzy sets, and other extensions of fuzzy sets or under totally different environments such as simulation or optimization, etc.

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