



Sustainable supplier evaluation in compressor manufacturing supply chain: An integrated QFD, Fuzzy Delphi, TOPSIS and BWM framework

Keyvan Farshid^a, Soroush Avakh Darestani^{b,*} 

^a Department of Industrial Engineering, Faculty of Industrial and Mechanical Engineering, Islamic Azad University, Qazvin Branch, Qazvin, Iran

^b Guildhall School of Business and Law, London Metropolitan University, London, United Kingdom

ARTICLE INFO

Keywords:

Supply chain
Sustainability
Multi-criteria decision making
TOPSIS
QFD
BWM

ABSTRACT

Sustainable supplier selection has attracted much attention recently, mainly due to the increased awareness of environmental concerns and social responsibility in this field. Supply chain management in the manufacturing industry has always been an important and sensitive issue, with many challenges facing this industry in various aspects, especially in procurement. Meanwhile, the process of sustainable supplier selection is among the most vital activities in creating a sustainable supply chain, considering the quality and the right price of the product and providing the buyer's needs at the right time and volume. Hence, companies require suppliers with the ability to provide proper services to the manufacturers, which highlights the need to evaluate and ensure the suppliers' capabilities. On the other hand, the traditional methods used so far to select suppliers are not compatible with sustainability considerations. Thus, the present research sought to provide a sustainable supplier selection, evaluate the suppliers' performance sustainability, and identify the factors affecting the compressor manufacturing industry's supply chain. For this purpose, the hybrid method of TOPSIS was implemented in the fuzzy environment, and the combination of BWM and QFD methods was used to weigh the criteria. According to the results, flexibility in responding to customer demand, environmental management certificates, and reputation and supplier brand won the first to third ranks among the supplier requirements, respectively. Based on the evaluation results, suppliers No. 4, No. 6, and No. 5 won the first to third ranks, respectively.

1. Introduction

Fundamental changes in the laws governing production and market took place following the emergence and rapid growth of economic enterprises and companies in the second half of the 20th century. Consequently, the managers of the companies felt the necessity of paying special attention to other areas, such as the purchase of raw materials and customer-related issues, in addition to those associated with the product and production, leading to the supply chain management formation. The right supplier selection with the greatest ability to meet the company's needs and standards is one of the most critical and strategic issues in supply chain management [1]. In the meantime, one of the most essential activities to create a sustainable supply chain is the process of selecting a sustainable supplier capable of meeting the buyer's needs in terms of quality products at the right price, time, and volume [2].

Sustainable Supply Chain (SSC) refers to the network of suppliers, manufacturers, and distributors that operate under sustainability

principles, focusing on products, processes, and flows that minimize environmental and social impacts while Sustainable Supply Chain Management (SSCM) focuses on the strategic planning, coordination, and control of a sustainable supply chain, integrating economic, environmental, and social considerations into decision-making and operations.

Decision on supplier selection plays an undeniable role in the production and logistics management of companies, and many experienced companies believe that selecting the right supplier makes a significant difference in the future of an organization in terms of reduced operating costs and improved quality of final products [3]. On the other hand, incorrect supplier selection decisions would result in negative consequences and heavy losses for the company. Companies must select suppliers with the best coordination and establish long-term and profitable relationships with them to achieve growth and progress in today's competitive global market [4]. Since supplier selection and decision-making is basically a multi-criteria problem [5], it is of strategic importance for most organizations. The nature of such decisions is

* Corresponding author.

E-mail addresses: k1farshid@gmail.com (K. Farshid), s.avakhdarestani@londonmet.ac.uk (S.A. Darestani).

Table 1
Recent sustainable supplier evaluation and selection contributions.

Outcomes and contributions	Purpose	Year	Author
FAHP is mainly used in manufacturing, industry, and government sectors; Asia, where FAHP is mostly applied in the subject areas of selection and assessment, is at the forefront of this issue; a significant number of research papers combine FAHP with other tools, especially TOPSIS, QFD, and ANP (type of AHP); Chang's analysis method, used to derive the weights of FPCMs in FAHP, is still the most popular.	Literature review of 190 applied research published between 2004 and 2016 and classifying them by region	2016	Kubler et al [8]
Decision Making Unit 5 (DMU-05) is the best supplier for the oil and gas industry in this research. The research contributes to proposing a new hybrid MCDM model for supplier selection in oil and gas industry.	Proposing an MCDM model through a combination of supply chain operations reference criteria (SCOR metrics), Analytical Hierarchy Process (AHP) model, and Technique for Order Preference by Similarity to Goal Solution (TOPSIS)	2018	Wang et al [6]
The decision units DMU01, DMU04, and DMU10 are the best suppliers. A multi-criteria decision-making model is presented for supplier evaluation and selection in oil production projects, and useful guidelines are provided for supplier selection processes in other industries.	Proposing the MCDM model, including Supply Chain Operations Reference Model (SCOR), Analytical Hierarchy Process (AHP), and Data Envelopment Analysis (DEA), to evaluate and select the optimal supplier in the oil industry	2020	Wang et al [9]
Mandatory government pressure is not enough for the real development of sustainable social practices in organizations if organizations themselves do not show initiative. Policymakers should be aware that coercive pressure alone does not lead to continuous improvement of social sustainability performance.	Specific gaps in the literature investigating supplier selection through a theoretical lens, based on contextual factors, institutional pressures, and industry characteristics	2020	Rentizelas et al [10]
Photovoltaic solar energy is the most optimal green energy source with the highest rating value, and annual production is the most prioritized criterion.	Selecting optimal green energy sources for sustainable planning from a set of given options	2020	Bhowmik et al [11]
Fuzzy TOPSIS is a versatile and suitable method for supplier selection problems, with low computational complexity and better user experience. This	Applying the fuzzy TOPSIS method in evaluating three suppliers according to four HSE criteria	2021	Haddad et al [12]

Table 1 (continued)

Outcomes and contributions	Purpose	Year	Author
method contributes to greater effectiveness and agility in supplier selection processes regarding HSE management.			
Quality indicators of materials purchased from suppliers and commitment to contracts are ranked first and second among all criteria.	Providing a comprehensive framework for ranking and selecting sustainable suppliers in the oil and gas industry	2021	Jermstittipersert et al [13]
An integrated multi-criteria decision-making (MCDM) method was proposed to analyze the interrelationships between response strategies to the COVID-19 pandemic and triple criteria (TBL) for SSS.	Presenting pandemic response strategies as an important aspect of the impact of the COVID-19 pandemic and examining the relative importance of such strategies in the implementation of SSS.	2021	Orji and Ojadi [14]
Management implications for effective resource allocation, as well as policy recommendations for broader operations and supply chain systems, are presented.	How different dimensions of a supplier's sustainability affect managers' evaluation and the supplier selection	2021	Zhan et al [15]
The results of the three-dimensional evaluation were integrated using the Decision Making Trial and Evaluation Laboratory method (DEMATEL), and an illustrative application of the proposed framework and model was carried out in one of the largest Chinese petrochemical companies to verify its feasibility and reliability.	Proposing a multi-method and multi-criteria hybrid decision-making framework for SSS in chemical industry	2021	Wu et al [16]
Supplier sustainability has an important impact on the sustainable development of the project. In addition, the supplier's sustainable financial capabilities and technology solutions are key factors to consider when selecting a sustainable supplier.	Introducing the Shapley value method to modify the index weights determined by the Analytical Hierarchy Process (AHP) in order to overcome differences in expert knowledge	2021	Li et al [17]
Considering the robustness of the ranking method, the multiplicative Multi-objective Optimization by Ratio Analysis (MULTIMOORA) is enhanced by developing a new aggregated model and the improved Borda rule, which can consider both the subordinate utility values and ranks.	Development of a new SSS method considering robustness and correlation between experts	2021	Liu [18]
Although different fuzzy environments or decision-making methods in supplier selection cause slight differences in criterion weights, they do not lead	Developing a strategy for the supplier selection process by examining the effects of different fuzzy environments and decision-making	2022	Demiralay and Paksoy [19]

(continued on next page)

Table 1 (continued)

Outcomes and contributions	Purpose	Year	Author
to any differences in supplier evaluation.	methods on the selection of an intelligent and sustainable supplier.		
Cost, credit, and corporate volatility are three important aspects for SMEs to evaluate supplier performance.	Development of a supplier selection evaluation framework for SMEs and a developed PROMETHEE II methodology to achieve a sustainable supplier selection process	2022	Tong et al [20]
A new feedback mechanism is developed by considering benefit or cost criteria to obtain the individual consensus evaluation matrix. The Shapley value based on the fuzzy measure is also used to determine the weight of experts to reflect their global relationship.	Proposing a trapezoidal fuzzy multi-attribute group decision-making (GDM) approach for sustainable supplier selection (SSS).	2022	Xing et al [21]
An improved fuzzy MULTIMOORA method for ranking alternative suppliers is introduced, which considers both the minimum distance from the positive ideal point and the maximum distance from the negative ideal point.	Proposing a new method based on Fuzzy MULTIMOORA for SSS	2022	Shang et al [22]
Economic factors still dominate during sustainable supplier selection. In selecting a sustainable supplier, prominence is given to human rights, safety systems and occupational health, pollution control and resource reduction and consumption, code of conduct, and transparency in suppliers' business and accounting criteria, which covers the other dimensions of sustainability.	Proposing a combined AHP-TOPSIS multi-criteria decision-making approach considering the existing uncertainty and quantitative and qualitative data evaluation	2022	Menon and Ravi [23]
The new fuzzy MCDM approach can provide a new concept for decision-makers with different risk preferences to select the most sustainable supplier in an uncertain environment.	Proposing a new fuzzy MCDM approach based on the combination of intuitionistic fuzzy sets, interval-valued fuzzy sets, and cumulative prospect theory to select the most sustainable supplier	2023	Chai et al [24]

Table 1 (continued)

Outcomes and contributions	Purpose	Year	Author
A new method has been introduced a sustainable supplier selection, which improves both the quality and the speed of the operation.	Proposing QFD-TOPSIS multi-criteria decision-making approach in fuzzy environment	2023	Current research

usually complex and unstructured, necessitating the use of management science techniques to solve problems in this regard. According to managers, traditional methods (based on the proposed price) are not suitable for the supplier selection because many factors such as warranty, fulfillment of obligations, including the time and place of orders, discounts on the quality of the cooperation period, etc., in addition to price are involved in the quality and quantity of production and even sales [6]. Thus, managers require new techniques to analyze these numerous and different criteria, which sometimes are not of the same type, and the complex issues of selection and design. One of these techniques is the use of multi-criteria decision-making models that can solve many problems in selecting the best decision. Multi-criteria decision-making methods (MCDM) can be divided into two categories of multi-objective decision-making (MODM) and multi-criteria decision-making (MADM). The purpose of decision-making is to select the best option or to give weight to decision-making factors. Each decision-making method has a specific task; one is to weigh the criteria, one is to rank the options, and the other is to evaluate the criteria [7]. The potential supplier's selection and evaluation include a group of multi-criteria decision-making problems that require evaluating the degree of data uncertainty, the number of decision-makers, and the nature of the criteria. Supplier and contractor performance assessment in the supply chain is a process to measure, analyze, and manage their performance to reduce costs and risks while continuously improving value creation and operations. In general, recognizing and evaluating the existing performance of the organization will clarify the development and improvement stages.

The strategic level is one of the critical steps to consider sustainability criteria and achieve a SSC. This research has employed an integrated approach of FTOPSIS, QFD, and BWM to evaluate and select suppliers. Besides, a Delphi method has been used for sustainable evaluation criteria.

The rest of this work is structured as follows. The literature review is provided in Section 2. Section 3 describes the research method, and the data analysis and results are presented in Section 4. Finally, the conclusion and implications of the study are presented in Section 5.

2. Literature review

This section presents a comprehensive review of the literature on sustainable supplier selection and evaluation. First, recent studies in this field are examined to provide an overview of current developments. Following this, two comparative literature review tables are presented: the first highlights the contributions of recent work in sustainable supplier evaluation and selection, while the second provides a detailed analysis of sustainability-related and traditional criteria used in supplier selection (Tables 1 and 2). At the end of each table, this study is benchmarked against the reviewed literature to highlight its contribution and positioning within the field.

According to many experts, competition in today's fast-changing world has moved from the level of companies to the competition between their supply chains, making efficient design and exploitation of these complex logistics systems an essential part of planning the activities of manufacturing companies. Thus, an efficient and agile supply chain is a very important and determining advantage in competition. Recently, supply chain management and the process of supplier selection have attracted the attention of many researchers and experts, who

Table 2
Reviewed literature.

Authors	Year	Method	Industry	Country	Flexible responding	After-sale service	Technology	Reputation	Environmental	Price	On-time delivery	Risk	Quality
Liu et al. [25]	2014	ITL-TOPSIS	robotic	China	✓				✓	✓	✓	✓	✓
Lima [3]	2014	FUZZY-TOPSIS, AHP-TOPSIS	automotive	China	✓			✓		✓	✓		✓
Abdollahi et al [4]	2015	MCDM, ANP, DEMTEL, DEA	Production	Iran	✓		✓	✓		✓	✓		✓
Memon et al. [1]	2015	A hybrid of gray system theory and uncertainty theory	Various industries	South Korea	✓	✓		✓		✓	✓		✓
Orji and Ojadi [14]	2021	MCDM and TBL	Production	Nigeria	✓		✓		✓				✓
Zhan et al [15]	2021	Evaluation and comparison	Different industries	China				✓		✓			✓
Wu et al [16]	2021	FGRA and FMEA and EWM and DEMATEL	chemical industry	China				✓		✓			✓
Li et al [17]	2021	AHP and TOPSIS and IVIFS	public-private partnership projects	China			✓	✓		✓			✓
Yazdani et al [26]	2021	IVFN and CRITIC and CoCoSo under IVFN environment	dairy	Iran		✓	✓	✓		✓		✓	✓
Tong et al. [20]	2022	PROMETHEE II	small and medium	China	✓	✓						✓	✓
Demiralay and Paksoy [27]	2022	Different fuzzy environments and different decision making methods	Auto Parts	Türkiye		✓				✓		✓	✓
Xing et al [21]	2022	IT2TrFS	automobile manufacturing	China	✓			✓		✓		✓	✓
Shang et al [22]	2022	A new method based on fuzzy MULTIMOORA	Forklift	China		✓	✓	✓		✓			✓

have sought to examine supplier evaluation and selection [28].

In this regard, Kubler et al. [8] carried out a literature review of 190 applied research, published between 2004 and 2016, classifying them by region and summarizing them in different tabular formats and diagrams. Unlike previous reviews, the results and findings are available through an online (and free) test platform, which can serve as an accessible reference for those who wish to apply, modify, or extend the Fuzzy Analytic Hierarchy Process for various application areas. This online test platform also makes available one or more Fuzzy Pairwise Comparison Matrixes (FPCM) from all reviewed articles (255 matrices in total). According to this review, (i) FAHP is mainly used in manufacturing, industry, and government sectors, (ii) Asia, where FAHP is mostly applied in the subject areas of selection and assessment, is at the forefront of this issue, (iii) a significant number of research papers (43% of the reviewed literature) combine FAHP with other tools, especially with TOPSIS, QFD, and ANP (type of AHP), and (iv) despite criticisms in recent years, Chang's analysis method, used to derive the weights of FPCMs in FAHP, is still the most popular [8].

An MCDM model was developed by Wang et al. [6] using a combination of reference criteria for supply chain operations evaluation and supplier selection in the oil and gas industry (SCOR metrics), the Analytic Hierarchy Process (AHP) model, and a priority ordering technique based on a similarity to the goal solution (TOPSIS) approach proposed in [6]. In the first step, all the criteria affecting supplier selection were defined using the literature review of SCOR criteria. The AHP model was applied to determine the weight of each factor in the second stage. The optimal supplier was determined in the final stage using the TOPSIS model. Decision Making Unit 5 (DMU-05) was shown to be the best supplier for the oil and gas industry in this research. This research contributes to proposing a new hybrid MCDM model for supplier selection in the oil and gas industry.

Wang et al. [9] proposed an MCDM model, including Supply Chain Operations Reference Model (SCOR), Analytical Hierarchy Process (AHP), and Data Envelopment Analysis (DEA), a method to evaluate and select the optimal supplier in the oil industry. Here, the criteria used to evaluate potential suppliers were determined through the SCOR model, the weight of all criteria was defined by the AHP model through expert opinion, and DEA was used to rank the suppliers in the final stage. After the model implementation, the decision units DMU 01, DMU 04, and DMU 10 were shown as the best suppliers. This research presented a multi-criteria decision-making model for supplier evaluation and selection in oil production projects. It also provides useful guidelines for supplier selection processes in other industries [9].

An research aimed at developing an integrated approach to supplier selection in the oil and gas industry was presented by Kaviani et al. [29], in which a new uncertain decision-making framework was proposed using the gray Delphi approach first to help evaluate and refine it by various existing metrics to obtain the most important and relevant metrics for the oil and gas industry [29]. The theoretical concept of gray systems was adopted to address subjectivity and uncertainty in human judgments. Shannon's gray entropy approach was used to determine the weights of the criteria, and finally, the EDAS gray method (estimation based on the distance from the average solution) was employed to determine the ranking of suppliers. From the literature review, 21 criteria were determined, of which 16 were finally considered using the gray Delphi approach. The top four criteria for supplier evaluation in Iran's oil and gas industry include warranty level and experience time, closeness of relationship, supplier's technical level, and risk, as one of the most critical and influential criteria obtained using Gray Shannon entropy. Supplier rankings are obtained, and the best and worst suppliers are also identified.

Haddad et al. [12] used the Fuzzy TOPSIS method in the evaluation of three suppliers according to four HSE criteria. This method was used in a case study of the oil and gas industry, including the contractor's bidding process. The results showed Fuzzy TOPSIS as a versatile and suitable method for supplier selection problems, with low

computational complexity and better user experience. This method contributes to greater effectiveness and agility in supplier selection processes regarding HSE management. The fuzzy TOPSIS model is suitable for supplier selection problems, allows the weighting of documents according to the importance level of each criterion, and takes into account the complexity, subjectivity, and uncertainty of the decision-making process [12].

Shang et al. [22] proposed a new method based on Multi-Objective Optimization (MULTIMOORA) based on Ratio Analysis plus a full multiplicative fuzzy form for SSS, which first obtained the weights by the best-worst (subjective) and fuzzy Shannon entropy (objective) methods, respectively. Then the two types of weights were sensibly and effectively combined using the deviation maximization method. Finally, this paper introduced an improved fuzzy MULTIMOORA method for ranking alternative suppliers with both minimum distance from the positive ideal point and maximum distance from the negative ideal point. The practicability and effectiveness of the proposed method were confirmed by applying it at L Company, an international forklift manufacturer in China [22].

A supplier selection evaluation framework for SMEs was developed by Tong et al. [20], who proposed a developed method (PROMETHEE II: A Preference Ranking Organization Method) to achieve a sustainable supplier selection process. First, a supplier selection evaluation framework was created from the three dimensions of product and service capability, degree of cooperation, and risk factors. Then, the PROMETHEE II approach was combined with subjective preference parameters and the Probability Language Term Set (PLTS) to obtain an extended PROMETHEE II approach. Finally, the method of this paper was used to implement sustainable supplier selection for a small and medium-sized enterprise (Company M) in China. The practical case and sensitivity analysis confirmed the feasibility and effectiveness of the evaluation framework and method proposed in this paper. Practical case and sensitivity analysis showed that cost, credit, and corporate irregularities are three important aspects for SMEs to evaluate supplier performance.

To scientifically evaluate the SSS, a new SSS method was presented by Liu et al. [30] considering robustness and correlation between experts. First, a new concept of Intuitive Linguistic Approximate Numbers (ILRN) was proposed to accurately express the opinions of expert groups for SSS and consider the interactive relationship between experts [30]. Then, a process was presented to construct ILRN and introduced arithmetic operations, distance measurement, correlation measurement, ranking rules, aggregation operators, and some related features. In addition, a weight determination method was introduced based on the correlation coefficients between traits. To ensure the robustness of the ranking method, multiobjective optimization by ratio analysis (MULTIMOORA) was improved by developing a new aggregated model and Burda's law, taking into account both sub-optimal values and ratings and an intuitive. The linguistic MULTIMOORA method and intuitive linguistic rough MULTIMOORA method are developed, respectively. Finally, a real case of a common SSS power bank was conducted to demonstrate the application of the proposed method and a comparison was made to explain the superiority and feasibility of the proposed method.

Simić et al. [31] studied fifty years of fuzzy set theory and model for supplier evaluation and selection based on a literature review. As one of the important components of supply chain management, supplier evaluation is usually a multi-criteria decision-making problem. Decision-making is the thought process of selecting a rational choice from available options. Fuzzy decision-making uses sets whose boundaries are not clearly defined. This article sought to show the application of fuzzy set theory, fuzzy decision-making, and fuzzy-based hybrid solutions in different models for supplier evaluation and selection in a 50-year period [31]. Wan et al. [32] investigated supplier selection using ANP and ELECTRE in the binary interval language environment, examining a type of multi-criteria decision-making problem with binary criteria, which is a cumulative method. A new combination of TL-ANP

binary linguistic analytic network processes and IT-ELECTRE II is interval binomial elimination and selection transition reality. Considering the interaction between the criteria, a TL-ANP approach is proposed, in which the comparison matrices are compatible pairwise linguistic preference relations, to determine the weights of the criteria and sub-criteria. An IT-ELECTRE I approach is proposed to deal with the case where criteria do not compensate each other. In this regard, the scores of the choices about the sub-criterion are represented as interval binary linguistic variables. A degree of possibility and a probability-based priority is defined for the matching, non-matching, and indifference sets. Then, the indicators of conformity and non-conformity are identified and used to form indices of pure conformity and pure non-conformity. In the following, the comprehensive dominance values of the choices are obtained to rank the choices, and as a result, a new hybrid method is obtained for multi-criteria decision-making with double-level criteria in the double-interval language environment. At the end, the choice between two real suppliers is discussed and comparative analyses are put on the agenda to show the application and superiority of the proposed method. The triple decision-making method based on fuzzy sets has been used to evaluate and select the supplier in this method.

An analytical framework for SSCM is presented in the research conducted by Dubey et al. [33], who focused on the effectiveness of the supply chain (costs, risks, transaction costs, and stakeholder issues) and provide a guide for managers who may struggle with such concerns. This work proposed three factors (costs, benefits, and risks), including the nature of the target and one of the parameters related to the inherent nature of sustainable contracts. The paper presented a representative data collection framework (target) from suppliers, the integration of behavioral (mental) elements, and the use of constrained optimization techniques to compare five interaction supplier contract policies [33]. Then, this cost-based solution is modified to achieve a more specific contract policy to develop three business formulations with welfare cost and risk and demonstrate them using simulated data. This framework is based on network-based supplier and network effects, supplier and network effectiveness, and transaction costs, and consequently, a mechanism for creating a sustainable supply network with a coordinator. The purpose of this research is to evaluate and select a sustainable supplier in the supply chain of the compressor manufacturing industry.

To ensure relevance and difficulty, the sustainability-oriented criteria were extracted from the literature and subsequently validated and refined through consultation with experts in the compressor manufacturing industry using the Fuzzy Delphi method. This process guarantees that sustainability is embedded at the core of the framework, rather than treated as a minor addition, while maintaining practicality for real-world implementation. Table 1 shows a summary of the relevant research background:

- Evaluation and selection of a sustainable supplier

As a popular core issue in many business areas, such as manufacturing, health, services, energy and agriculture, etc, and also due to climate change, resource dependence, and transaction cost issues, the concept of sustainability has become an influential research topic. Meanwhile, today's companies are forced to pay attention to green and sustainability issues in supply chain management (SCM) operations due to the increasing trend of globalization, public awareness, and pressures from governments and stakeholders. Sustainable supply chain management (SSCM), along with traditional SCM dimensions, considers three aspects of sustainable development, i.e., economic, environmental, and social dimensions. SSCM arises from increasing customer needs, government regulations, and environmental laws [34]. The concept of SSCM is one of the results of these topics, leading to more efficiency in SCMs by implementing the three dimensions of sustainability. Environmental, social, and economic characteristics of suppliers are essential considerations in sustainable supplier evaluation and selection [35].

Companies should extend sustainability initiatives to other members

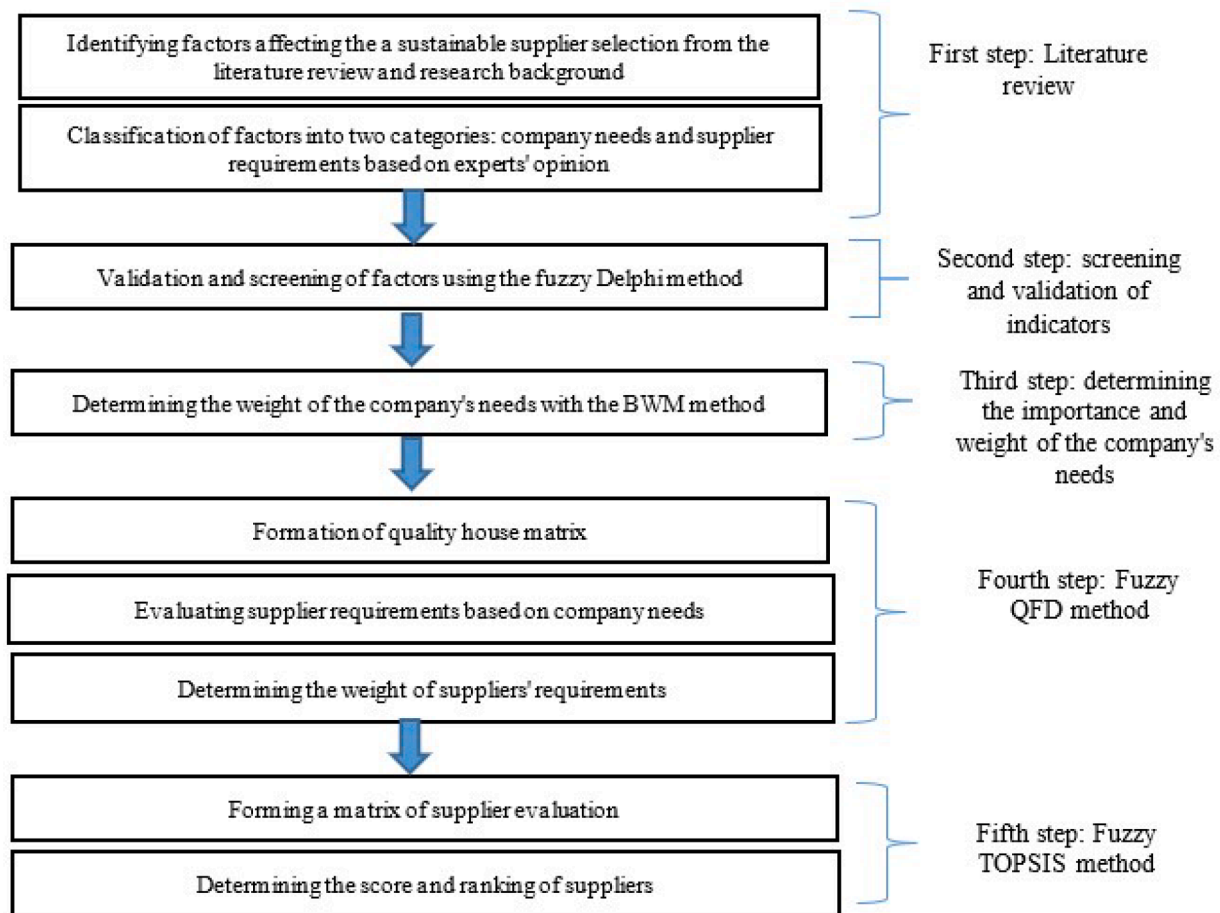


Fig. 1. Research framewzork.

of their SC, especially to suppliers, in order to maintain supply chain (SC) sustainability and build successful business alliances. Suppliers contribute significantly to creating a SSC. SSCs are supply chains that manage the economic, social, and environmental impacts of their network to protect long-term profitability and value and ensure the survival of companies.

Table 2 presents some recent research in the scope of sustainable supplier evaluation compared against evaluation criteria, method, and industry.

2.1. Research gap and contribution of work

The literature review shows that there are a few studies in the area of sustainable supplier selection and evaluation using Delphi, QFD, and FBWM. Therefore, the current research tries to solve the supply chain problems of the compressor manufacturing industry by providing a comprehensive sustainable supplier evaluation framework.

Despite the growing importance of sustainable supplier selection, few studies have integrated Delphi, QFD, and fuzzy decision-making methods in a comprehensive framework, specially for industry-specific applications such as the compressor manufacturing sector. To address this gap, the present study formulates the following research questions:

Research Question 1 (RQ1): How can a hybrid fuzzy multi-criteria decision-making framework integrating BWM, QFD, and TOPSIS be designed to effectively support sustainable supplier selection in the compressor manufacturing industry?

Research Question 2 (RQ2): Which sustainability-oriented criteria are most critical, and how can suppliers in the compressor manufacturing industry be evaluated and ranked based on these criteria

to enhance sustainable supply chain performance?

For this purpose, a sustainable supplier evaluation model has been proposed in a compressor manufacturing supply chain framework using integrated QFD, fuzzy Delphi, TOPSIS, and BWM. According to Table 1, scant research has incorporated QFD and Delphi in SSC problems using hybrid decision-making methods. Therefore, the novelty of this work is to develop an integrated hybrid Delphi, QFD, and decision-making framework involving uncertainty. Also, the experts and data gathered from the compressor manufacturing industry contribute significantly to the research novelty.

Research objectives:

Given the limited number of studies that integrate Delphi, QFD, and fuzzy best-worst methods within sustainable supplier selection, particularly under uncertainty, a clear research gap is identified in the existing literature. Moreover, prior research has paid little attention to industry-specific applications, such as the compressor manufacturing sector. To address this gap, the present study aims to develop a comprehensive and integrated fuzzy decision-making framework by combining fuzzy Delphi, QFD, BWM, and TOPSIS. Accordingly, the research objectives focus on identifying and weighting sustainability-oriented supplier evaluation criteria and on evaluating and ranking suppliers to support sustainable decision-making in the compressor manufacturing supply chain.

- To develop a hybrid fuzzy multi-criteria decision-making framework integrating BWM, QFD, and TOPSIS for sustainable supplier selection in the compressor manufacturing industry.
- To evaluate and rank suppliers based on sustainability-oriented criteria and identify the most influential factors affecting

Table 3
Verbal expressions and corresponding fuzzy numbers by Guo and Zhao [37].

verbal expressions	fuzzy number
Equally important	(1,1,1)
slightly important	(0.67,1,1.5)
Relatively important	(1.5,2,2.5)
Very important	(2.5,3,3.5)
absolutely important	(3.5,4,4.5)

sustainable supply chain performance in the compressor manufacturing industry.

3. Research method

The current study is applied research in terms of the purpose because it deals with finding the context to solve a problem in the real world. It is also a survey research in terms of data collection. The statistical population of this research includes all real or hypothetical members to whom the findings of this research can be generalized. For this purpose, a Compressor Company was selected, and the convenience sampling method was used to select the research sample, including experts. Accordingly, supply chain specialists and experts in the Compressor Company, who had more than ten years of work experience in the commercial and purchasing department and complete familiarity with suppliers, were selected ($n = 12$). Fig. 1 shows the research framework.

The research data were collected using a review of the literature. First, similar studies conducted in this field were reviewed, and then the decision problem model was extracted through interviews with the Compressor Company experts. Due to the dispersion of the obtained data and the different importance of each component, the opinions of the relevant experts were extracted in the form of a questionnaire, and the consensus of their opinions was used to evaluate the important components. In fact, the criteria and sub-criteria are determined as the result of studies and the opinions of relevant industry experts. Finally, in the second step, the identified components (criteria) and sub-criteria have been weighted by the BWM method. In the third step, the weighted components obtained from the BWM method were used as the input of the house of quality in the fuzzy QFD approach, and after the final review and formation of the house of quality matrices, the final weight was obtained and used for the final ranking by the fuzzy TOPSIS method.

Justification for the integrated framework: While the framework may appear complex, each component addresses a specific needs: BWM ensures efficient and consistent weighting, QFD links criteria to supplier attributes, Fuzzy Delphi captures expert consensus under uncertainty, and TOPSIS provides a robust ranking mechanism. Make all of them together, they generate a comprehensive, transparent, and practically implementable method that improves on simpler alternatives which may overlook uncertainty, expert consensus, or operational translation of criteria.

This integrated approach not only enhances methodological difficulty but also ensures that the framework is directly relevant and actionable for practitioners specially in the compressor manufacturing industry.

3.1. Fuzzy delphi method (FDM)

Fuzzy logic is useful for solving problems that have ambiguity and uncertainty. First proposed by Zadeh [36], the Fuzzy theory aims to reconcile the uncertainty of human understanding of the model. The fuzzy Delphi technique is a survey method based on experts' opinions and has three main features, including anonymous response, repetition and controlled feedback, and statistical group response. This technique is a systematic way to collect and coordinate the informed judgments of a group of experts about a particular question or issue. It is a suitable

tool to deal with ambiguity and uncertainty in the decision-making process.

The Delphi method is recognized as a valuable group technique to help reach a consensus of a panel of experts through interactive surveys. FDM incorporates the fuzzy set theory to deal with the uncertainty in the application of the traditional Delphi method [20].

Therefore, this research has used the fuzzy Delphi method to verify and screen the identified indicators. After identifying the criteria, a decision-making group consisting of experts related to the research topic was formed and questionnaires were sent to them to determine the relevance of the identified indicators to the main topic of the research. The screening was subsequently performed using the linguistic variables.

Verification and screening of indicators are performed by comparing the acquired value of each indicator with the threshold value of \tilde{S} This research considers the value of 0.5 as the threshold value. For this purpose, the triangular fuzzy values of experts' opinions should be primarily calculated, followed by estimating then their fuzzy average to calculate the average of n respondents' opinions. The fuzzy number τ is calculated for each of the indicators using the following relations [37].

$$\tilde{\tau}_{ij} = (a_{ij}, b_{ij}, c_{ij}), \quad i = 1, 2, \dots, n \quad j = 1, 2, \dots, m \tag{1}$$

$$a_j = \sum \frac{a_{ij}}{n} \tag{2}$$

$$b_j = \sum \frac{b_{ij}}{n} \tag{3}$$

$$c_j = \sum \frac{c_{ij}}{n} \tag{4}$$

In the above relationships, the index i refers to the expert, and the index j refers to the decision-making index. Also, the fuzzy Delphi value of the average fuzzy number is obtained from the following relationship [37]

$$Crisp = \frac{a + b + c}{3} \tag{5}$$

3.2. The best-worst method

Several options are evaluated in multi-criteria decision-making methods, based on some indicators to select the best option. According to the best-worst method introduced by Rezaei [7], the best and worst indicators are determined by the decision-maker, and a pairwise comparison is made between each of these two (best and worst) and other indicators [7].

Choice of BWM over AHP: The Best-Worst Method (BWM) was chosen instead of the more common AHP because of its higher consistency and efficiency in pairwise comparisons. Unlike AHP, which requires a large number of comparisons ($n(n - 1)/2$ for n criteria), BWM significantly decreases the number of comparisons while maintaining reliable and robust weighting results. For this work, this is particularly advantageous when involving experts in the compressor manufacturing industry, where expert time and cognitive effort are limited.

3.3. The fuzzy best-worst method

Developed by Guo and Zhao [37], this algorithm is similar to the crisp best-worst method, and the use of fuzzy numbers causes more accuracy and better results in calculations due to the verbal ambiguity of the respondents. The steps of this method are as follows:

Suppose there are n criteria; the pairwise comparisons of these n criteria are compared through the verbal terms in Table 3; that is, the respondents' linguistic expressions are converted into corresponding fuzzy numbers.

The first step is to create a criteria decision system in which the

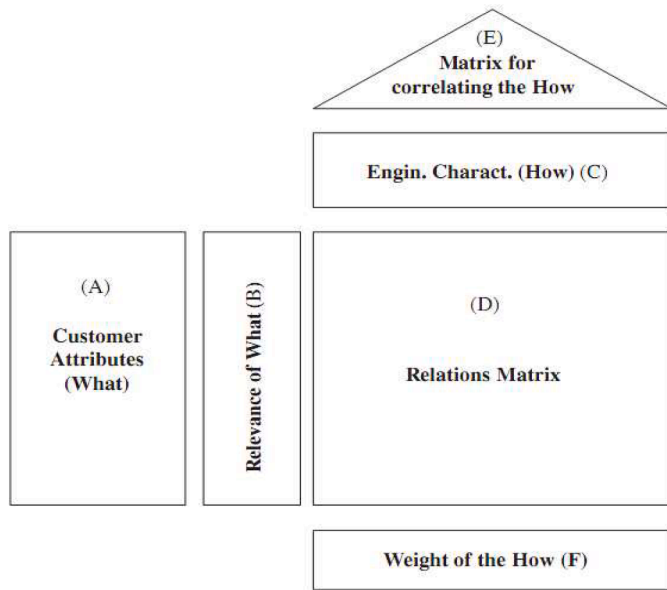


Fig. 2. House of quality (HOQ).

Table 4
Linguistic expressions and corresponding fuzzy numbers for the relationship between WHATs and HOWs [39].

Fuzzy equivalent of priorities	The extent of the connection	No.		
upper limit (u)	Medium limit (m)	Lower limit (L)		
2	1	0	very low	1
4	3	2	Low	2
6	5	4	medium	3
8	7	6	Much	4
10	9	8	very much	5

research criteria, including n evaluation criteria, should be extracted to make a comparison. The second step is to determine the best (most important) and the worst (least important) criteria. Here, the experts' opinions, group meetings, or methods such as Delphi can be used. The best criterion is denoted by C_B , and the worst criterion by C_W . After the pairwise comparison of the best criterion with other criteria and the pairwise comparison of other criteria with the worst criterion, the optimal weight of the criteria is obtained. The last step is to determine the incompatibility rate based on the following relationship:

The inconsistency rate is in the range [0 1], and the closer it is to zero, the more consistent and stable the comparisons are, while the closer it is to one, the less consistent and stable the comparisons are.

The compatibility index can be calculated through the following relationship.

$$\xi^2 - (1 + 2u_{BW})\xi + (u_{BW}^2 - u_{BW}) = 0 \tag{6}$$

3.4. House of quality matrix

Different tools and methods are used to achieve quality goals and what are called QFD goals. The main tool for implementing QFD is the House of Quality. The house of quality is a matrix in which the relationship between Whats and Hows is specified. In fact, QFD is an advanced quality tool with the aim of increasing market share through customer satisfaction [38]. The house of quality receives the client's needs as input, translates them into design specifications, and presents them as output as shown in Fig. 2.

Role of QFD (House of Quality): QFD works as an intermediary step

to systematically translate the weighted criteria into actionable supplier requirements. The HOQ system provides a structured link between criteria and practical supplier attributes, ensuring that the subsequent ranking reflects the real operational priorities of the manufacturing industry. This step adds transparency and traceability between what is important (criteria weights) and how suppliers are assessed on concrete measures.

The implementation of this matrix in the fuzzy environment gives more accuracy in the results due to the elimination of uncertainties. The steps of the fuzzy QFD method are given below:

- Determining WHATs and their weight (regions A & B)

In this section, WHATs are extracted based on previous studies and the experts' opinions. In this research, WHATs are the company's needs in relation to contractors.

- Determining the HOWs and their weight (regions C & F)

In this section, based on HOW to do WHATs, HOWs are extracted as the ones that solve the issues related to WHATs. In this research, the HOWs are actually the contractors' criteria.

- Determining the correlation between HOWs (region E)

In this section, the correlation between HOWs is presented by positive or negative correlation.

- Determining the relationships between WHATs and HOWs (region D)

In this section, the relationship between WHATs and HOWs is determined based on the spectrum of Table 4.

When the opinions of several experts are used to determine the relationships between WHATs and HOWs, the arithmetic mean method based on Eq. (12) is used for integration.

$$Score = \{S_{ij}, i = 1, 2, \dots, k; j = 1, 2, \dots, m\} \tag{7}$$

$$S_{ij} = \frac{1}{n} \otimes (S_{ij1} \oplus S_{ij2} \oplus S_{ij3} \oplus \dots \oplus S_{ijn})$$

In the above relationship, k, m, and n are the number of WHATs, the number of HOWs, and the number of experts, respectively.

- Determining the fuzzy weight of HOWs

In this step, the fuzzy weight of HOWs is calculated using Eq. (13).

$$Weight = \{W_j, j = 1, 2, \dots, m\} \tag{8}$$

$$W_j = \frac{1}{K} \otimes (S_{j1} \otimes w_1) \otimes \dots \otimes (S_{jk} \otimes w_k)$$

- Determining the non-fuzzy weight of HOWs

In this section, we convert the fuzzy weight to non-fuzzy using the following relationship.

$$W_j^{non-fuzzy} = \frac{W_{ja} + W_{jb} + W_{jc}}{3} \tag{9}$$

3.5. The fuzzy topsis method

After determining the weight of the sub-criteria, the options should be prioritized. This process, presented by Huang and Yun in 1981 using the fuzzy TOPSIS technique, is as follows.

The use of TOPSIS for final ranking: TOPSIS was chosen as the

Table 5
Linguistic expressions and corresponding fuzzy numbers to rank options (Patil and Kant [41]).

Fuzzy equivalent of priorities	Priorities	No.		
upper limit (u)	Medium limit (m)	Lower limit (L)		
3	1	1	Very weak	1
5	3	1	weak	2
7	5	3	medium	3
9	7	5	Good	4
11	9	7	very good	5

final ranking method because it identifies alternatives that are closest to the ideal solution and farthest from the negative-ideal solution. In the context of sustainable supplier selection, where trade-offs exist between multiple criteria, also TOPSIS provides an intuitive and interpretable ranking that balances all criteria simultaneously. Its ability to handle fuzzy data in combination with the other methods makes it suitable for capturing uncertainty in expert judgments.

First step: creating a decision matrix of opinions

Suppose the decision matrix of experts' opinions is as follows:

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \tilde{x}_{mn} \end{bmatrix} \quad i = 1, 2, \dots, m; j = 1, 2, \dots, n \quad (10)$$

Each column represents a measure, and each row represents an option. X_{ij} represents the quantity of the i th option in the j -th sub-criterion. Also, the sub-criteria may be negative or positive depending on the impact on the options.

This research has used verbal expressions and fuzzy numbers in Table 5 to evaluate options for each criterion.

Second step: normalizing the decision matrix

At this stage, the fuzzy decision matrix of people's opinions should be converted into a fuzzy non-scale matrix (\tilde{R}). To obtain the \tilde{R} matrix, it is enough to use the following relationship if the components are positive.

$$\tilde{R} = [\tilde{r}_{ij}]_{m \times n}$$

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*} \right) \text{ and } c_j^* = \max_i c_{ij} \quad (11)$$

If it is negative, the following relationship must be used:

Table 6
Results of expert opinions.

Level of influence	Criteria	Dimension				
Very low	low	medium	High	Very high		
0	1	4	5	2	Company requirements	
0	0	1	5	6		
1	1	5	2	3		
1	1	5	2	3		
0	4	4	3	1		
0	0	4	6	2		
0	1	4	4	3		
0	0	5	5	2		
0	1	4	3	4		
0	0	0	5	7		
0	0	2	7	3	Supplier requirement	
0	1	5	3	3		
0	0	5	5	2		
0	1	6	3	2		
0	2	4	6	0		
0	1	5	3	3		
0	0	5	7	0		
1	0	8	3	0		

Table 7
Fuzzy Delphi results.

Validation status	Crisp weight	Fuzzy weight	Code	Criteria	Dimension	
Approved	0.653	(0.417,0.667,0.875)	W1	Product variety	Company requirements	
Approved	0.813	(0.604,0.854,0.979)	W2	Product quality		
Approved	0.590	(0.375,0.604,0.792)	W3	updated technology		
Approved	0.590	(0.375,0.604,0.792)	W4	Low cost		
Approved	0.514	(0.271,0.521,0.75)	W5	Easy to order		
Approved	0.694	(0.458,0.708,0.917)	W6	Delivery reliability		
Approved	0.667	(0.438,0.688,0.875)	W7	After-sales service and problem solving		
Approved	0.674	(0.438,0.688,0.896)	W8	Environmentally friendly		
Approved	0.681	(0.458,0.708,0.875)	H1	Supplier production capacity		Supplier requirement
Approved	0.847	(0.646,0.896,1)	H2	Supplier work experience		
Approved	0.750	(0.521,0.771,0.958)	H3	Product and production innovation		
Approved	0.646	(0.417,0.667,0.854)	H4	Supplier's financial position		
Approved	0.674	(0.438,0.688,0.896)	H5	technological skills		
Approved	0.611	(0.375,0.625,0.833)	H6	Latest machines		
Approved	0.583	(0.333,0.583,0.833)	H7	Reputation and brand of the supplier		
Approved	0.646	(0.417,0.667,0.854)	H8	Flexibility in meeting customer demand		
Approved	0.646	(0.396,0.646,0.896)	H9	Environmental management certifications		
Approved	0.528	(0.292,0.521,0.771)	H10	Online and accessible ordering system		

Table 8
Pairwise comparison of company needs.

	W1	W2	W3	W4	W5	W6	W7	W8	
Best Criteria	W2	(1.416,1.88,2.426)	-	(2.109,2.621,3.129)	(1.07,1.498,2.021)	(3.042,3.548,4.053)	(1.258,1.565,1.903)	(1.12,1.55,2.092)	(1.643,2.14,2.678)
Worst criteria	W5	(1.038,1.335,1.688)	-	(1.165,1.348,1.536)	(1.4,1.861,2.424)	-	(1.871,2.378,2.952)	(1.165,1.603,2.137)	(1.29,1.642,2.066)

Table 9
Final weight and ranking of the main criteria.

Rank	Crisp weight	Fuzzy weight	Criterion	Code
6	0.102	(0.083,0.105,0.111)	Variety of products	W1
1	0.213	(0.185,0.219,0.219)	Product quality	W2
7	0.089	(0.065,0.092,0.099)	updated technology	W3
3	0.134	(0.098,0.14,0.145)	Low cost	W4
8	0.065	(0.058,0.066,0.066)	Ease to order	W5
2	0.163	(0.132,0.166,0.183)	Delivery reliability	W6
4	0.121	(0.094,0.123,0.137)	After-sale service and problem solving	W7
5	0.112	(0.075,0.116,0.133)	Environmentally friendly	W8

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}^-}, \frac{a_j^-}{b_{ij}^-}, \frac{a_j^-}{a_{ij}^-} \right) \text{ and } a_j^- = \min_i a_{ij} \tag{12}$$

Third step: creating the weighted normal matrix

Creating the scale-free fuzzy weight matrix \tilde{V} assuming the vector \tilde{W}_{ij} based on the equation:

$$i = 1, 2, \dots, m \quad j = 1, 2, \dots, n \quad \tilde{V} = [\tilde{v}_{ij}]_{m \times n} \tag{13}$$

$$\tilde{v}_{ij} = \tilde{r}_{ij} \cdot \tilde{w}_j$$

Fourth step: specifying positive and negative ideal values

$$A^+ = (\tilde{v}_1^*, \tilde{v}_2^*, \dots, \tilde{v}_n^*) \text{ where } \tilde{v}_j^* = (\tilde{c}_j^-, \tilde{c}_j^+, \tilde{c}_j^+) \text{ and } \tilde{c}_j^+ = \max_i \{\tilde{c}_{ij}^+\} \tag{12a}$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_n^-) \text{ where } \tilde{v}_j^- = (\tilde{a}_j^-, \tilde{a}_j^-, \tilde{a}_j^-) \text{ and } \tilde{a}_j^- = \min_i \{\tilde{a}_{ij}^-\} \tag{13a}$$

Fifth step: calculating the distance of the options from the ideals

Calculating the total distances of each component from the fuzzy positive ideal and the fuzzy negative ideal: the distance between these two fuzzy numbers is obtained by the following relationship if A and B are two fuzzy numbers as follows:

$$\tilde{A} = (a_1, b_1, c_1) \quad \tilde{B} = (a_2, b_2, c_2)$$

$$D(A, B) = \sqrt{\frac{1}{3} [(a_2 - a_1)^2 + (b_2 - b_1)^2 + (c_2 - c_1)^2]} \tag{14}$$

According to the above explanations about how to calculate the distance between two fuzzy numbers, we calculate the distance of each component from ideal and anti-ideal.

$$d_i^+ = \sum_{j=1}^n d(\tilde{v}_{ij} - \tilde{v}_j^+) \quad i = 1, 2, \dots, m \tag{15}$$

$$d_i^- = \sum_{j=1}^n d(\tilde{v}_{ij} - \tilde{v}_j^-) \quad i = 1, 2, \dots, m \tag{16}$$

Sixth step: calculating the similarity index to the ideal option (CL)

This similarity is calculated through the following relationship:

$$Cl = \frac{d_i^-}{d_i^+ + d_i^-} \quad i = 1, 2, \dots, m \tag{17}$$

Seventh step: ranking the options

The available options of the assumed problem can be ranked based on the descending order of CL.

- Implementation and practicality

Although the proposed framework integrates multiple fuzzy-based methods (Fuzzy Delphi, Fuzzy BWM, Fuzzy QFD, and Fuzzy TOPSIS), it is also practical for real-world application specially in manufacturing

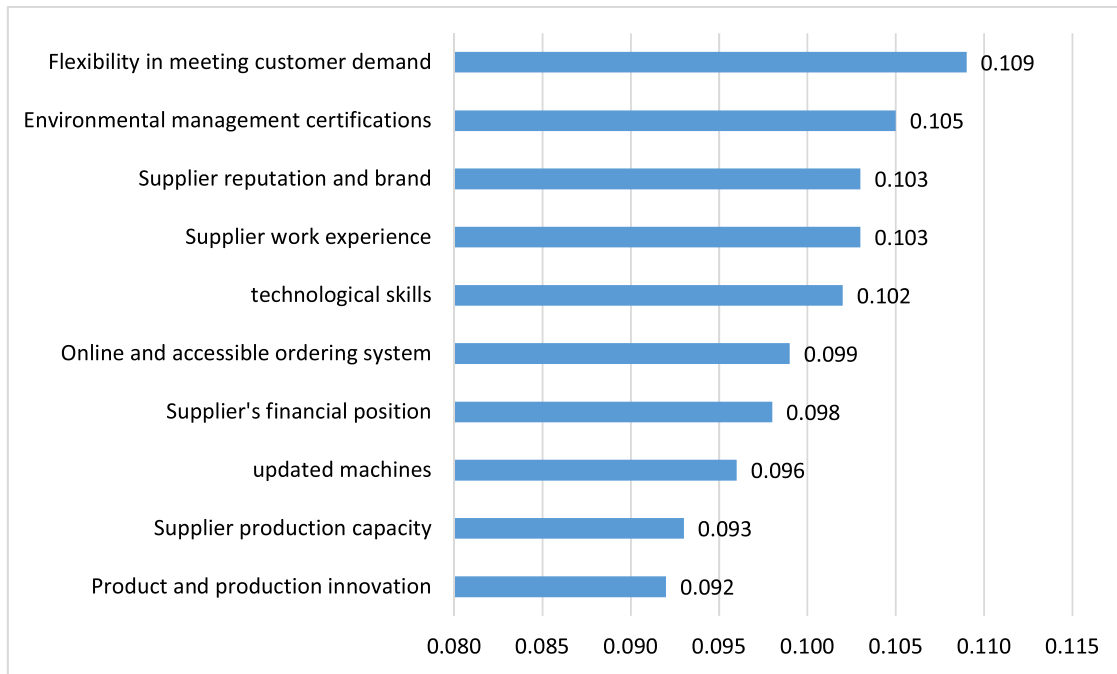


Fig. 3. final weight and priority of supplier requirements.

industries. Each method works a distinct role in the decision-making process, and the research framework is structured to guide experts step by step, reducing thinking responsibility. Calculations can be performed using standard software tools such as Excel or MATLAB, making implementation available without requiring specialized programming skills from procurement or purchasing department staff. The framework also gives opportunity to decision-makers to focus on critical stages without being overwhelmed by all steps simultaneously. Moreover, to maximize effectiveness, the framework can be integrated with company sourcing and purchasing procedures, facilitating collaboration with quality, financial, and production departments. Therefore, despite its multi-stage design, the framework is both implementable and actionable for sustainable supplier selection in the manufacturing sector.

4. Data analysis

For the current research, which is to select a sustainable supplier in the supply chain of the compressor manufacturing industry, the influential factors were initially extracted in the form of the company's needs and the suppliers' requirements, followed by confirming and screening these factors by the fuzzy Delphi method. In the second step, the company's needs were weighted by the fuzzy BWM method, and then the importance of the supplier's requirements was determined by the fuzzy QFD method. Finally, the suppliers of the Compressor Company were ranked by the fuzzy TOPSIS method.

In this research, first, the designed questionnaire was given to 12 experts. Respondents aged 30 to 40 years, from bachelor's degree to doctorate with ten to twenty years of work experience. The importance of the following criteria extracted through a questionnaire was evaluated by experts in this field. Sub-criteria with more frequency and greater relevance to the subject under study were extracted to check the importance by the experts in this field, and sub-criteria with <50% importance were removed from the reviews. Then, the criteria influencing the selection of a sustainable supplier in the compressor manufacturing industry were identified and screened using the fuzzy Delphi method. Hence, a questionnaire, including 8 requirements of the Compressor Company and 10 suppliers' requirements, was initially given to the members of the expert group, who were asked to express

their opinions about each criterion in the form of linguistic variables included in the questionnaire. The preliminary results of expert opinions are presented in Table 6.

In this research, the value of 0.5 was chosen as the threshold value. Based on the minimum threshold value, the results of the fuzzy Delphi computations confirmed all criteria as shown in Table 7.

4.1. Results of the best-worst fuzzy method

In this section, the fuzzy best-worst method is used to weigh the 8 needs of the company. In the first step of the best-worst method, the most (best) and least (worst) important criteria among the 8 needs of the company should be determined using the average experts' opinions in the fuzzy Delphi method, with product quality criteria (W2) as the most important and easy ordering (W5) the least important criteria. Then, pairwise comparisons of the best criteria compared to other criteria (BO) and other criteria compared to the worst criteria (OW) are performed. In this research, pairwise comparisons were initially formed and given to 12 experts to determine the degree of preference in pairwise comparisons based on the spectrum of the 5-point fuzzy table. Table 8 shows the post-response pairwise comparisons merged with the geometric mean method.

Then, the linear model of the fuzzy BWM method was formed and solved by Lingo 17 software. The weights of the criteria were subsequently obtained, which are presented in Table 9.

The fuzzy weight is obtained directly from solving the model in Lingo software, which is presented in Table 8, and then these fuzzy weights are converted into definite weights by the relation $R(\tilde{a}_i) = \frac{l_i + 4m_i + u_i}{6}$. For instance, the fuzzy weight of the product diversity criterion is (0.083, 0.105, 0.111), and its crisp weight is $\frac{0.083 + 4 \times 0.105 + 0.111}{6} = 0.102$. Based on this, the product quality, the delivery reliability, and low cost won the first to third with the weights of 0.213, 0.163, and 0.134, respectively. To calculate the inconsistency rate, a quadratic equation is primarily solved for the pairwise comparison table, and the Eq. (5) $\xi^2 - (1 + 2u_{BW})\xi + (u_{BW}^2 - u_{BW}) = 0$ is used to calculate the unknown value ξ , which is the compatibility index equal to 8.081. The optimal value of the objective function (ξ^{**}) calculated by Lingo is 0.247. The

Table 10
Fuzzy TOPSIS decision matrix.

	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
S1	(4.333,6.333,8.333)	(3.4,5.6,5)	(4,6,8)	(3.5,5,7)	(2.167,3.333,5.333)	(3.833,5.167,7.167)	(4.5,6.67,7.667)	(3.4,8.333,6.833)	(2.5,3.833,5.833)	(4.5,6.167,8.167)
S2	(3.333,5.333,7.333)	(2.833,4.833,6.833)	(2.5,4.5,6.5)	(3.5,7)	(3.833,5.833,7.833)	(3.5,7)	(3.333,5.333,7.333)	(3,5,7)	(3.5,5,7.5)	(3.333,5.333,7.333)
S3	(4.167,5.667,7.667)	(2.833,4.167,6.167)	(2.5,3.833,5.833)	(2.667,4.333,6.333)	(3.333,4.833,6.833)	(3.833,5.5,7.5)	(3.4,5.6,5)	(3.5,5,7.167)	(3.333,5.167,7.167)	(3.167,4.667,6.667)
S4	(5,7,9)	(5,7,9)	(5.167,7.167,9.167)	(5.167,7.167,9.167)	(4.333,6.333,8.333)	(5,7,9)	(5.333,7.333,9.333)	(4.667,6.667,8.667)	(5.333,7.333,9.333)	(5.333,7.333,9.333)
S5	(4.333,5.833,7.833)	(3.4,1.67,6.167)	(4.667,6.5,8.5)	(3.167,4.833,6.833)	(3.833,5.333,7.333)	(2.5,4.333,6.333)	(4.167,5.833,7.833)	(3.667,5.167,7.167)	(3.167,4.833,6.833)	(2.833,4.667,6.667)
S6	(4.333,6.167,8.167)	(3.5,5.167,7.167)	(4.5,6.67,7.667)	(3.833,5.5,7.5)	(4.5,8.333,7.833)	(3.4,6.67,6.667)	(4.333,5.833,7.833)	(4.167,6,8)	(3.4,6.67,6.667)	(3.167,4.833,6.833)
S7	(2.667,4.167,6.167)	(3.167,5,7)	(3.333,5,7)	(3.667,5.5,7.5)	(2.667,4.167,6.167)	(3.167,4.5,6.5)	(3.4,6.67,6.667)	(3,4,5,6,5)	(2.833,4.167,6.167)	(4.5,5,7.5)

Table 11
Fuzzy TOPSIS normal matrix.

	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
S1	(0.481,0.704,0.926)	(0.333,0.5,0.722)	(0.436,0.655,0.873)	(0.382,0.545,0.764)	(0.26,0.4,0.64)	(0.426,0.574,0.796)	(0.429,0.607,0.821)	(0.346,0.558,0.788)	(0.268,0.411,0.625)	(0.482,0.661,0.875)
S2	(0.37,0.593,0.815)	(0.315,0.537,0.759)	(0.273,0.491,0.709)	(0.327,0.545,0.764)	(0.46,0.7,0.94)	(0.333,0.556,0.778)	(0.357,0.571,0.786)	(0.346,0.577,0.808)	(0.375,0.589,0.804)	(0.357,0.571,0.786)
S3	(0.463,0.63,0.852)	(0.315,0.463,0.685)	(0.273,0.418,0.636)	(0.291,0.473,0.691)	(0.4,0.58,0.82)	(0.426,0.611,0.833)	(0.321,0.482,0.696)	(0.404,0.596,0.827)	(0.357,0.554,0.768)	(0.339,0.5,0.714)
S4	(0.556,0.778,1)	(0.556,0.778,1)	(0.564,0.782,1)	(0.564,0.782,1)	(0.52,0.76,1)	(0.556,0.778,1)	(0.571,0.786,1)	(0.538,0.769,1)	(0.571,0.786,1)	(0.571,0.786,1)
S5	(0.481,0.648,0.87)	(0.333,0.463,0.685)	(0.509,0.709,0.927)	(0.345,0.527,0.745)	(0.46,0.64,0.88)	(0.278,0.481,0.704)	(0.446,0.625,0.839)	(0.423,0.596,0.827)	(0.339,0.518,0.732)	(0.304,0.5,0.714)
S6	(0.481,0.685,0.907)	(0.389,0.574,0.796)	(0.436,0.618,0.836)	(0.418,0.6,0.818)	(0.48,0.7,0.94)	(0.333,0.519,0.741)	(0.464,0.625,0.839)	(0.481,0.692,0.923)	(0.321,0.5,0.714)	(0.339,0.518,0.732)
S7	(0.296,0.463,0.685)	(0.352,0.556,0.778)	(0.364,0.545,0.764)	(0.4,0.6,0.818)	(0.32,0.5,0.74)	(0.352,0.5,0.722)	(0.321,0.5,0.714)	(0.346,0.519,0.75)	(0.304,0.446,0.661)	(0.429,0.589,0.804)

Table 12
Fuzzy TOPSIS weighted matrix.

	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
S1	(0.015,0.022,0.028)	(0.005,0.007,0.01)	(0.011,0.017,0.022)	(0.01,0.014,0.02)	(0.001,0.002,0.003)	(0.007,0.009,0.013)	(0.003,0.005,0.006)	(0.02,0.033,0.046)	(0.01,0.015,0.023)	(0.011,0.014,0.019)
S2	(0.011,0.018,0.025)	(0.005,0.008,0.011)	(0.007,0.013,0.018)	(0.009,0.014,0.02)	(0.002,0.004,0.005)	(0.005,0.009,0.013)	(0.003,0.004,0.006)	(0.02,0.034,0.048)	(0.014,0.021,0.029)	(0.008,0.013,0.017)
S3	(0.014,0.019,0.026)	(0.005,0.007,0.01)	(0.007,0.011,0.016)	(0.008,0.012,0.018)	(0.002,0.003,0.004)	(0.007,0.01,0.014)	(0.002,0.004,0.005)	(0.024,0.035,0.049)	(0.013,0.02,0.028)	(0.007,0.011,0.016)
S4	(0.017,0.024,0.031)	(0.008,0.011,0.014)	(0.014,0.02,0.026)	(0.015,0.02,0.026)	(0.003,0.004,0.005)	(0.009,0.013,0.016)	(0.004,0.006,0.008)	(0.032,0.045,0.059)	(0.021,0.028,0.036)	(0.013,0.017,0.022)
S5	(0.015,0.02,0.027)	(0.005,0.007,0.01)	(0.013,0.018,0.024)	(0.009,0.014,0.02)	(0.002,0.003,0.005)	(0.005,0.008,0.011)	(0.003,0.005,0.006)	(0.025,0.035,0.049)	(0.012,0.019,0.027)	(0.007,0.011,0.016)
S6	(0.015,0.021,0.028)	(0.006,0.008,0.011)	(0.011,0.016,0.021)	(0.011,0.016,0.021)	(0.003,0.004,0.005)	(0.005,0.008,0.012)	(0.003,0.005,0.006)	(0.028,0.041,0.054)	(0.012,0.018,0.026)	(0.007,0.011,0.016)
S7	(0.009,0.014,0.021)	(0.005,0.008,0.011)	(0.009,0.014,0.019)	(0.01,0.016,0.021)	(0.002,0.003,0.004)	(0.006,0.008,0.012)	(0.002,0.004,0.005)	(0.02,0.031,0.044)	(0.011,0.016,0.024)	(0.009,0.013,0.018)

Table 13
Ideals of fuzzy TOPSIS.

	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
A+	(0.031,0.031,0.031)	(0.014,0.014,0.014)	(0.026,0.026,0.026)	(0.026,0.026,0.026)	(0.005,0.005,0.005)	(0.016,0.016,0.016)	(0.008,0.008,0.008)	(0.059,0.059,0.059)	(0.036,0.036,0.036)	(0.022,0.022,0.022)
A-	(0.009,0.009,0.009)	(0.005,0.005,0.005)	(0.007,0.007,0.007)	(0.008,0.008,0.008)	(0.001,0.001,0.001)	(0.005,0.005,0.005)	(0.002,0.002,0.002)	(0.02,0.02,0.02)	(0.01,0.01,0.01)	(0.007,0.007,0.007)

Table 14
Final ranking of options.

Rank	Final score	Distance to the negative ideal	Distance to the positive ideal	Code	Name of the supplier
4	0.419	0.079	0.110	S1	Supplier 1
5	0.406	0.078	0.114	S2	Supplier 2
6	0.392	0.074	0.115	S3	Supplier 3
1	0.641	0.124	0.069	S4	Supplier 4
3	0.427	0.080	0.108	S5	Supplier 5
2	0.462	0.087	0.102	S6	Supplier 6
7	0.367	0.069	0.119	S7	Supplier 7

consistency rate is also $\frac{\tilde{c}_{ij}}{c_{ij}}$, which is 0.031 in this research, indicating an acceptable rate.

4.2. Fuzzy QFD results

In fuzzy QFD, the goal is to calculate the weight of suppliers' requirements, so the weight column of the company's requirements is the same weight that was calculated in the previous stage of the fuzzy BWM method (Table 8). According to the first matrix of the house of quality, the final weight of the supplier's requirements is obtained, which is also given in Fig. 3. Accordingly, flexibility in responding to customer demand has been ranked first with a weight of 0.109. The environmental management certificate with a weight of 0.105 won the second place, and the supplier's reputation and brand won the third place with a weight of 0.103.

As shown in Fig. 3, the higher weight of flexibility reflects the critical importance of meeting dynamic customer needs in the compressor manufacturing industry, which remains a key operational priority. At the same time, the strong ranking of environmental management certification demonstrates that sustainability considerations are also a major factor in supplier evaluation in this respect. Similarly, supplier reputation and brand also contribute to both operational reliability and long-term partnership stability. Overall, these results highlight that supplier selection in practice involves a balanced consideration between traditional operational requirements and sustainability factors, confirming both immediate performance and long-term responsible sourcing.

4.3. Fuzzy topsis method

The opinion decision matrix is formed in this step. The decision matrix of the fuzzy TOPSIS method consists of criteria (10 supplier requirements) and research options (7 suppliers). The decision matrix of

Table 10 is calculated using relations 9 and 10. The normalized decision matrix is given in Table 11. Table 12 shows the Fuzzy TOPSIS weighted matrix. Then, using relations 12 and 13, the positive (A+) and negative (A-) goals are calculated. Table 13 shows the positive ideal, which means the largest number of the third item of the criteria column, and the negative ideal, which means the smallest number in the first item of the criteria column in the weighted matrix.

4.4. Calculating the distance of the options from the positive and negative ideal

In this step, the distance of the options from the positive ideal (d+) and the negative ideal (d-) is calculated through relations 3-17 and 3-18 (second and third columns of Table 13). For instance, the first option (S1) calculations are as follows.

$$d_{s1}^+ = \sqrt{\frac{1}{3}[(0.015 - 0.031)^2 + (0.022 - 0.031)^2 + (0.028 - 0.031)^2]} + \sqrt{\frac{1}{3}[(0.005 - 0.014)^2 + (0.007 - 0.014)^2 + (0.01 - 0.014)^2]} + \dots + \sqrt{\frac{1}{3}[(0.011 - 0.022)^2 + (0.014 - 0.022)^2 + (0.019 - 0.022)^2]} = 0.11$$

$$d_{s1}^- = \sqrt{\frac{1}{3}[(0.015 - 0.009)^2 + (0.022 - 0.009)^2 + (0.028 - 0.009)^2]} + \sqrt{\frac{1}{3}[(0.005 - 0.005)^2 + (0.007 - 0.005)^2 + (0.01 - 0.005)^2]} + \dots + \sqrt{\frac{1}{3}[(0.011 - 0.007)^2 + (0.014 - 0.007)^2 + (0.019 - 0.007)^2]} = 0.079$$

4.5. Calculating similarity index (CCI) and ranking options

We calculate the similarity index of each option based on equation 22 and rank the options (third column of Table 14). For instance, the similarity index for the first option (S1) is calculated as follows.

$$Cl_{s1} = \frac{d_i^-}{d_i^+ + d_i^-} = \frac{0.079}{0.079 + 0.11} = 0.419$$

Fig. 4 represents the final score and priority of suppliers.

As can be seen in Table 14, suppliers 4, 6, and 5 have won the first to third ranks, respectively.

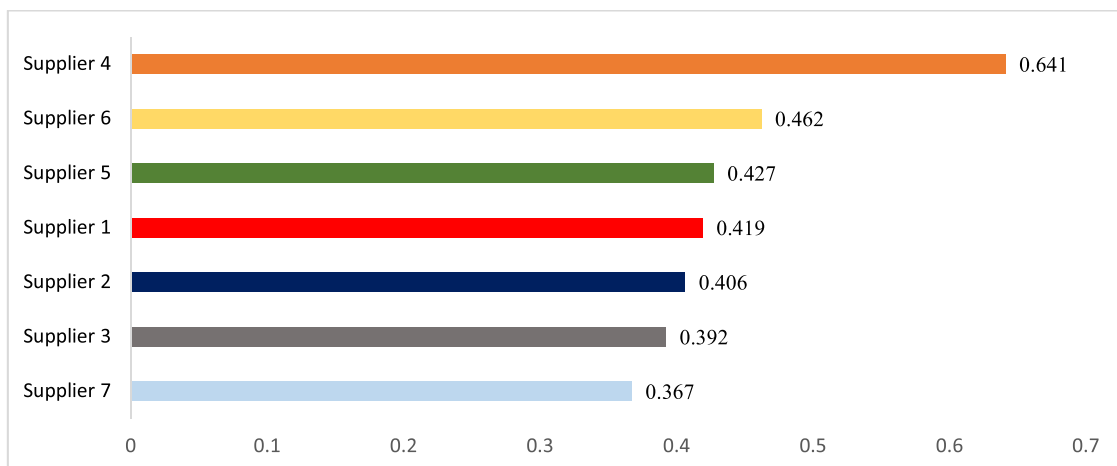


Fig. 4. The final score and priority of suppliers.

Table 15
Weight changes in different sensitivity analysis scenarios.

	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
S1	(0.1,0.1,0.1)	(0.1,0.1,0.1)	(0.1,0.1,0.1)	(0.1,0.1,0.1)	(0.1,0.1,0.1)	(0.1,0.1,0.1)	(0.1,0.1,0.1)	(0.1,0.1,0.1)	(0.1,0.1,0.1)	(0.1,0.1,0.1)
S2	(0.014,0.014,0.014)	(0.031,0.031,0.031)	(0.026,0.026,0.026)	(0.026,0.026,0.026)	(0.005,0.005,0.005)	(0.016,0.016,0.016)	(0.008,0.008,0.008)	(0.059,0.059,0.059)	(0.036,0.036,0.036)	(0.022,0.022,0.022)
S3	(0.026,0.026,0.026)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.026,0.026,0.026)	(0.005,0.005,0.005)	(0.016,0.016,0.016)	(0.008,0.008,0.008)	(0.059,0.059,0.059)	(0.036,0.036,0.036)	(0.022,0.022,0.022)
S4	(0.026,0.026,0.026)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.005,0.005,0.005)	(0.016,0.016,0.016)	(0.008,0.008,0.008)	(0.059,0.059,0.059)	(0.036,0.036,0.036)	(0.022,0.022,0.022)
S5	(0.005,0.005,0.005)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.016,0.016,0.016)	(0.008,0.008,0.008)	(0.059,0.059,0.059)	(0.036,0.036,0.036)	(0.022,0.022,0.022)
S6	(0.016,0.016,0.016)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.059,0.059,0.059)	(0.036,0.036,0.036)	(0.022,0.022,0.022)
S7	(0.008,0.008,0.008)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.016,0.016,0.016)	(0.031,0.031,0.031)	(0.059,0.059,0.059)	(0.036,0.036,0.036)	(0.022,0.022,0.022)
S8	(0.059,0.059,0.059)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.016,0.016,0.016)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.036,0.036,0.036)	(0.022,0.022,0.022)
S9	(0.036,0.036,0.036)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.016,0.016,0.016)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.022,0.022,0.022)
S10	(0.022,0.022,0.022)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.016,0.016,0.016)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)	(0.031,0.031,0.031)

4.6. Sensitivity analysis

One of the reliable methods to determine the model efficiency and sensitivity is the sensitivity analysis of each model in specific conditions and comparing it with other conditions.

This section uses the TOPSIS fuzzy method for sensitivity analysis to validate the results, considering 10 scenarios (S) in sensitivity analysis according to Table 15. In scenario 1, the weight of all criteria is considered equal, and in the following scenarios, the weight of the H1 option has changed with others. The results presented in Fig. 5 shows the stability of the fuzzy TOPSIS results.

5. Conclusion and implications

Based on what companies have learned at this time, supplier selection is one of the most critical activities of an organization. As a result, wrong decisions in the selection of suppliers will have many negative consequences for companies. In supply chain management, selecting the right supplier is a challenging issue because it requires criteria or characteristics that are complex and ambiguous in nature.

According to the research results, flexibility in responding to customer demand has the first rank among supplier requirements. Evaluating and selecting effective suppliers, as one of the important issues in supply chain management, creates a competitive advantage and improves the organization's performance. Thus, companies and production and service centers need flexibility in the supply of their products and services, and decisions related to purchase and supplier evaluation and selection have become more important due to the increasing importance of purchasing tasks in organizations. Also, the continuous change of customers' demands requires more flexible strategies in the supply chain and supplier selection and evaluation. Environmental management certificates have won the second rank of supplier requirements for supplier selection. Failure to observe the scientific rules in the extraction and monitoring of these resources can lead to the pollution of the soil, water, and air environment, exposing the environment and the living organisms to huge irreparable challenges. Some harmful effects such as air pollution, respiratory problems, destruction and contamination of the environment, etc., are an undeniable problem in some areas, especially oil-rich and gas-rich regions. It seems that the institutionalization of environmental culture is one of the best solutions to overcome these problems. Investing in education and awareness is very important. As the third level of supplier requirements, the supplier's reputation and strong brand can create value for both the customer and the organization. On the one hand, brands are a brief and useful tool for simplifying the process of selecting and purchasing a product or service for the customer, leading to the simplification and acceleration of the data and information processing and creating value for customers. The results of data analysis show that suppliers 4, 6, and 5 have won the first to third ranks, respectively.

Supplier evaluation and selection, according to Yazdani et al. [40] is a significant strategic decision to reduce operation costs and improve organizational competitiveness to develop business opportunities. Also, with increasing concerns related to environmental preservation and sustainable development, paying more attention to environmental requirements, evaluating potential suppliers, and helping green factors in the selection process become more important day by day [40].

It is suggested that compressor manufacturing industry managers address holding courses to increase the employees' level of awareness about the benefits of the right supplier selection. It is suggested that environmental managers inform customers and companies about the consequences of environmental destruction in the relevant cases. It is also essential to take extensive cultural and propaganda measures to introduce the importance of environmental preservation and social health while prioritizing environmental management certificates in sustainable supplier selection in the supply chain of the manufacturing industry. Future research can be conducted on the use of other multi-

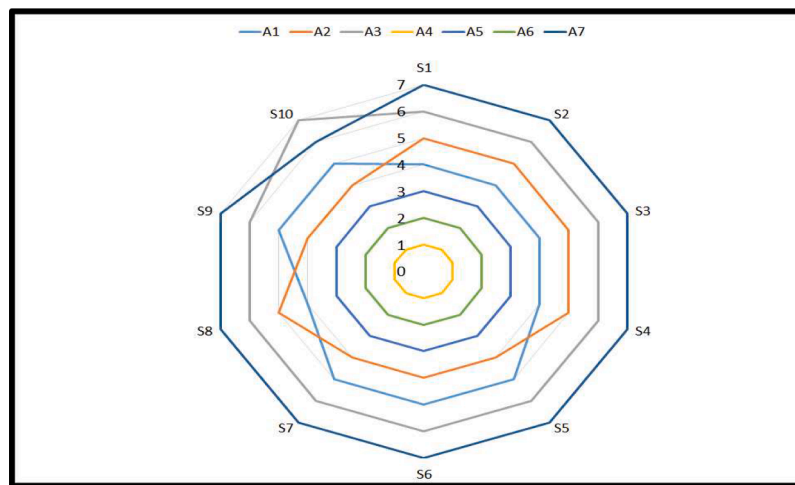


Fig. 5. Sensitivity analysis results.

criteria decision-making methods rather than the TOPSIS that was used in the present study, such as the network analysis process (ANP) for weighting the criteria. Moreover, it is recommended that this model be applied and tested in other industries, with the results serving as a benchmark for comparison.

CRedit authorship contribution statement

Keyvan Farshid: Writing – original draft, Software, Resources, Formal analysis, Data curation, Conceptualization. **Soroush Avakh Darestani:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization.

Declaration of competing interest

I, on behalf of all the authors of our work entitled ‘Sustainable Supplier Evaluation in Compressor Manufacturing Supply Chain: An Integrated QFD, Fuzzy Delphi, TOPSIS and BWM Framework’ has no any financial and personal relationships with other people or organizations that could inappropriately influence (bias) our work. Therefore, there's no financial/personal interest or belief that could affect our objectivity and authors must state explicitly that potential competing interests don't exist, no competing interests exist

Data availability

Data will be made available on request.

References

- [1] M.S. Memon, Y.H. Lee, S.I. Mari, Group multi-criteria supplier selection using combined grey systems theory and uncertainty theory, *Expert. Syst. Appl.* 42 (21) (2015) 7951–7959, <https://doi.org/10.1016/j.eswa.2015.06.018>.
- [2] A. Teymuri, A. Riazifar, *Automatic Identification and Tracking Systems in Supply Chain Management*, Iran University of Science & Technology, Tehran, 2009.
- [3] Jr. F.R. Lima, L. Osiro, L.C.R. Carpinetti, A comparison between fuzzy AHP and fuzzy TOPSIS methods to supplier selection *Appl. Soft. Comput.* 21 (2014) 194–209.
- [4] M. Abdollahi, J. Razmi, M. Arvan, An integrated approach for supplier portfolio selection: lean or agile? *Expert. Syst. Appl.* 42 (1) (2015) 679–690.
- [5] X. Deng, Y. Hu, Y. Deng, S. Mahadevan, Supplier selection using AHP methodology extended by D numbers, *Expert. Syst. Appl.* 41 (1) (2014) 156–167.
- [6] C.N. Wang, Y.F. Huang, I.F. Cheng, V.T. Nguyen, A multi-criteria decision-making (MCDM) approach using hybrid SCOR metrics, AHP, and TOPSIS for supplier evaluation and selection in the gas and oil industry, *Processes* 6 (12) (2018) 252, <https://doi.org/10.3390/pr6120252>.
- [7] J. Rezaei, Best-worst multi-criteria decision-making method, *Omega* (2015), <https://doi.org/10.1016/j.omega.2014.11.009>.
- [8] S. Kubler, J. Robert, W. Derigent, A. Voisin, Y. Le Traon, A state-of-the-art survey and testbed of fuzzy AHP (FAHP) applications, *Expert. Syst. Appl.* 65 (2016) 398–422, <https://doi.org/10.1016/j.eswa.2016.08.064>.
- [9] C.N. Wang, H.T. Tsai, T.P. Ho, V.T. Nguyen, Y.F. Huang, Multi-criteria decision making (MCDM) model for supplier evaluation and selection for oil production projects in Vietnam, *Processes* 8 (2) (2020) 134, <https://doi.org/10.3390/pr8020134>.
- [10] A. Rentizelas, A.B.L. de Sousa Jabbour, A.D. Al Balushi, A. Tuni, Social sustainability in the oil and gas industry, *Ann. Oper. Res.* 290 (1) (2020) 279–300.
- [11] C. Bhowmik, S. Bhowmik, A. Ray, Optimal green energy source selection: an eclectic decision, *Energ. Environ.* 31 (5) (2020) 842–859.
- [12] A.N. Haddad, B.B.F. da Costa, L.S. de Andrade, A. Hammad, C.A.P. Soares, Application of fuzzy-TOPSIS method in supporting supplier selection with focus on HSE criteria: a case study in the oil and gas industry, *Infrastructures* 6 (8) (2021) 105, <https://doi.org/10.3390/infrastructures6070105>.
- [13] K. Jermsittiparsert, M. Zahar, S. Sumarni, O.Y. Voronkova, S.Y. Bakhvalov, R. Z. Akhmadeev, Selection of sustainable suppliers in the oil and gas industry using fuzzy MCDM methods, *Int. J. Ind. Eng. Manag.* 12 (4) (2021) 253.
- [14] I.J. Orji, F. Ojadi, Investigating the COVID-19 pandemic's impact on sustainable supplier selection, *Comput. Ind. Eng.* 160 (2021) 107588.
- [15] Y. Zhan, L. Chung, M.K. Lim, F. Ye, A. Kumar, K.H. Tan, The impact of sustainability on supplier selection, *Int. J. Prod. Econ.* 236 (2021) 108118.
- [16] C. Wu, Y. Lin, D. Barnes, An integrated decision-making approach for sustainable supplier selection in the chemical industry, *Expert. Syst. Appl.* 184 (2021) 115553.
- [17] H. Li, F. Wang, C. Zhang, L. Wang, X. An, G. Dong, Sustainable supplier selection for water environment treatment PPP projects, *J. Clean. Prod.* 324 (2021) 129218.
- [18] P. Liu, The new extension of the MULTIMOORA method for sustainable supplier selection, *Int. J. Sustain. Supplier Sel.* (2021).
- [19] E. Demiralay, T. Paksoy, Strategy development for supplier selection process with smart and sustainable criteria in fuzzy environment, *Clean Logist. Suppl. Chain* 5 (2022) 100076.
- [20] L.Z. Tong, J. Wang, Z. Pu, Sustainable supplier selection for SMEs based on an extended PROMETHEE II approach, *J. Clean. Prod.* 330 (2022) 129830.
- [21] Y. Xing, M. Cao, Y. Liu, M. Zhou, J. Wu, Choquet integral based fuzzy MAGDM for sustainable supplier selection, *Comput. Ind. Eng.* 165 (2022) 107935.
- [22] Z. Shang, X. Yang, D. Barnes, C. Wu, Supplier selection in sustainable supply chains: using the integrated BWM, fuzzy Shannon entropy, and fuzzy MULTIMOORA methods, *Expert. Syst. Appl.* 195 (2022) 116567, <https://doi.org/10.1016/j.eswa.2022.116567>.
- [23] R.R. Menon, V. Ravi, Using AHP-TOPSIS methodologies in sustainable supplier selection, *Clean. Mater.* (2022) 100130.
- [24] N. Chai, W. Zhou, Z. Jiang, Sustainable supplier selection using fuzzy MCDM, *Inf. Sci.* 626 (2023) 710–737.
- [25] H.C. Liu, M.L. Ren, J. Wu, Q.L. Lin, An interval 2-tuple linguistic MCDM method for robot evaluation and selection, *Int. J. Prod. Res.* 52 (10) (2014) 2867–2880, <https://doi.org/10.1080/00207543.2013.854939>.
- [26] M. Yazdani, et al., Interval valued neutrosophic decision-making structure, *Expert. Syst. Appl.* 183 (2021) 115354.
- [27] E. Demiralay, T. Paksoy, Strategy development for supplier selection, *Clean. Logist. Suppl. Chain* 5 (2022) 100076.
- [28] M. Bastani, S. Ketabi, M. Qandehari, Development of an integrated model of product allocation to distributors in the supply chain with the help of data envelopment analysis and goal planning, *J. Oper. Res. Appl.* 11 (1) (2013) 119–131.
- [29] M.A. Kaviani, A.K. Yazdi, L. Ocampo, S. Kusi-Sarpong, An Integrated Grey-Based Multi-Criteria Decision-Making Approach For Supplier Evaluation and Selection in the Oil and Gas Industry, *Kybernetes*, 2019, <https://doi.org/10.1108/K-05-2018-0265>.

- [30] P. Liu, H. Gao, H. Fujita, The new extension of the MULTIMOORA method for sustainable supplier selection with intuitionistic linguistic rough numbers, *Appl. Soft. Comput.* 99 (2021) 106893.
- [31] D. Simić, I. Kovačević, V. Svirčević, S. Simić, 50 years of fuzzy set theory and models for supplier assessment and selection: a literature review, *J. Appl. Log.* 24 (2017) 85–96, <https://doi.org/10.1016/j.jal.2016.11.016>.
- [32] S.-P. Wan, G.-L. Xu, J.-Y. Dong, Supplier selection using ANP and ELECTRE II in interval 2-tuple linguistic environment, *Information Sciences* 385–386 (2017) 19–38, <https://doi.org/10.1016/j.ins.2016.12.032>.
- [33] V.K. Dubey, J.P. Chavas, D. Veeramani, Analytical framework for sustainable supply-chain contract management, *Int. J. Prod. Econ.* 200 (2018) 240–261.
- [34] G. Büyüközkan, G. Çifçi, A novel fuzzy multi-criteria decision framework for sustainable supplier selection with incomplete information, *Computers in Industry* 62 (2) (2011) 164–174, <https://doi.org/10.1016/j.compind.2010.10.009>.
- [35] J. Sarkis, D.G. Dhavale, Supplier selection for sustainable operations, *Int. J. Prod. Econ.* 166 (2015) 177–191.
- [36] L.A. Zadeh, Fuzzy sets, *Inf. Control* 8 (3) (1965) 338–353.
- [37] S. Guo, H. Zhao, Fuzzy best-worst MCDM method, *Knowl. Based. Syst.* 121 (2017) 23–31.
- [38] S. Chen, Y. Zhang, J. Gong, A systematic decision-making approach for quality function deployment based on hesitant fuzzy linguistic term sets, *Appl. Sci.* 13 (24) (2023) 13104, <https://doi.org/10.3390/app132413104>.
- [39] M. Bevilacqua, F.E. Ciarapica, G. Giacchetta, A fuzzy-QFD approach to supplier selection, *J. Purch. Supply Manag.* 12 (1) (2006) 14–27.
- [40] M. Yazdani, P. Chatterjee, E.K. Zavadskas, S. Hashemkhani Zolfani, Integrated QFD–MCDM framework for green supplier selection, *J. Clean. Prod.* 142 (2017) 3728–3740, <https://doi.org/10.1016/j.jclepro.2016.10.095>.
- [41] S.K. Patil, R. Kant, A fuzzy AHP-TOPSIS framework for ranking the solutions of Knowledge Management adoption in Supply Chain to overcome its barriers, *Expert Syst. Appl.* 41 (2) (2014) 679–693, <https://doi.org/10.1016/j.eswa.2013.07.093>.

Keyvan is a master student in industrial engineering from Qazvin Islamic Azad University. His research interests tie in supply chain, sustainability and fuzzy decision making

Dr. Soroush Avakh Darestani is a senior lecturer in business & management at London Metropolitan University. He received his Ph.D. in Industrial and Systems Engineering from University Putra Malaysia (UPM) in 2010. His research interests lie in the areas of sustainable supply chain, lean production, quality management, optimisation. His publications have been appeared in different international journals such as ENERGY, CAIE, ASOC, OPSEARCH, JQME, IJQRM, AJSL, JIPE, MRR, ESPR, JSTPM among others.