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Research Article

Supplier Selection Utilizing AHP and TOPSIS in a Fuzzy Environment Based on KPIs

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Abstract: In today's competitive and rapidly changing business landscape, organizations face significant challenges such as resource limitations, fluctuating demand, and evolving customer needs. Addressing these challenges requires effective strategies, with supplier selection playing a vital role in building resilient and efficient supply chains. This study introduces an innovative framework for supplier evaluation and selection, integrating the analytic hierarchy process (AHP) and the technique for order preference by similarity to the ideal solution (TOPSIS) within a fuzzy environment. The AHP method was employed to systematically identify and prioritize key performance indicators (KPIs) critical for evaluating suppliers. Criteria such as transportation cost, flexibility in meeting product requirements, defect reduction, and effective communication and responsiveness were identified as the most significant factors. These priorities formed the foundation for applying the fuzzy TOPSIS method, which facilitated the ranking of suppliers under conditions of uncertainty. The analysis revealed Sepidar Darb, Aram Plastic Sabalan, Sanaye Plastic Markaz, and Amin Avar Plastic as the top-performing suppliers, followed by Pegah Zanjan Company. The relevance of this research is heightened by the impact of the COVID-19 pandemic, which has disrupted global supply chains and fundamentally altered supplier selection criteria. While pre-pandemic evaluations predominantly focused on cost efficiency and product quality, the pandemic has underscored the importance of additional criteria such as supplier agility, risk management capabilities, geographical proximity, and digital integration. These emerging priorities highlight the necessity of rethinking traditional approaches to supplier selection and adapting to the evolving demands of global supply chains. By incorporating these updated criteria into the AHP-TOPSIS framework, this study offers a robust and practical tool for supplier evaluation in uncertain and dynamic environments. The proposed framework not only improves upon traditional methods but also provides valuable insights for organizations striving to create resilient and adaptable supply chains capable of withstanding future disruptions.

***Keywords*:** supplier selection, KPIs, AHP, TOPSIS, fuzzy environment, fuzzy multi-criteria decision making, supply chain, post-COVID-19

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1. Introduction

The competitive environment in today's time is such that competitors are trying in all ways to get access to the relevant markets. Further, the organizations try to achieve excellence and growth by offering their improved quality goods and services at a low cost to the customers in minimal time and their efficiency level within the supply chain also provides them with a competitive edge over others [1].

It is befitting to mention here that the increasing competitive pressure during the 1990s compelled organizations to work on attaining efficiency in almost all the different aspects of the business. Hence, the industry managers realized that the mere production of a quality product was of no avail alone; rather, they needed to focus on supplying products considering customer preferences with regard to where, when, and how, as well as their quality and cost considerations.

Under these conditions, organizations understood the need to manage the units that provide inputs to the organization and the centers involved with delivery and after-sales services to customers. With this methodology, the theory of supply chain management emerged. In today's highly competitive global markets, with the emergence of short product life cycles and increasing customer expectations, businesses are being forced to invest in supply chain management.

Moreover, from the perspective of customer satisfaction and competitiveness, the effective supply chain means one preponderance flow of material, goods, and information across various functional areas internally and among partners. Now, to perform this task, the supply chain suppliers have to be evaluated [2].

The supplier selection problem refers to the process whereby, considering a number of qualitative and quantitative criteria, a set of the best and most effective suppliers is chosen with the aim of enhancing the general efficiency in the supply chain and leading to an improved competitive standing within the network. During the last years, there has been an increasing focus on the importance of assessing and selecting suppliers [3]. In this regard, based on a profound literature review regarding the selection of suppliers, it is possible to understand that supplier selection represents a very important and core issue for industrial organizations. Business units should adopt a supplier selection system in order to be competitive in the market, increase profitability, and maintain an advantage against rivals [4].

Supplier selection is related to two kinds of processes. Sometimes, one capable supplier can meet all the needs of the producer, and the management needs to make a decision to select the best and most effective supplier who holds the highest score. But sometimes, even one supplier cannot meet all the demands of the producer. Hence, more than one supplier must be chosen. That is why these kinds of problems need to plan an order allocation to suppliers [5].

At this point, based on these, the selection of suppliers has been generally said to be a fundamental and important issue that organizations have to decide on so as to maintain their strategic competitive position because this selection has a direct effect on profitability and cash flow. It has been considered the process of evaluation and selection of suppliers for a number of reasons that best encompass the influencing factors on a composite variable of qualitative and quantitative selection criteria, breadth, comprehensiveness, and diversity of suppliers throughout the supply chain [6]. Assessment and selection of suppliers under the multi-criteria decision-making framework involve several alternatives that are to be evaluated against a predefined set of criteria. The selection of appropriate suppliers is actually a strategic decision in supply chain management, and having an influence on the price and quality of the company's final product [7]. Choosing a reliable and suitable group of suppliers is crucial to a company's success [8].

Not long ago, with the development and diffusion of supply chain management, most managers, researchers, scholars, and scientists came to the view that selecting and managing suitable suppliers was one of the tools that could be used in furthering competitiveness within the supply chain [9]. Thus, the selection of suppliers is one of the basic, fundamental, and strategic decisions in the supply chain [10]. In this regard, the appropriate method shall be used for the evaluation and selection of suppliers. In the present study, with respect to the importance of the issue, the evaluation and selection of a supplier for the Pegah Zanjan Company, based on key performance indicators by using the AHP and TOPSIS techniques in a fuzzy environment, have been addressed. The innovation in Pegah Zanjan Company could be influenced by the following:

1. Identifying and monitoring the key performance indicators, followed by the selection of suppliers.
2. Applying the Analytic Hierarchy Process method while prioritizing the key performance indicators.
3. The use of the TOPSIS method in selecting the best decision-making option.

4. Bringing a new combined approach for evaluating and selecting suppliers in one step.

1.1 *Evolution of supplier selection criteria in the post-COVID-19 era*

The COVID-19 pandemic has drastically changed the landscape of supplier selection and underlined deficiencies in an exclusive concentration on traditional metrics of cost and quality. Whereas, in times prior to the pandemic, these factors were considered paramount and organizations sought to find suppliers who could provide the right balance between these two: affordable or excellent products. The pandemic highlighted the fragilities intrinsic to this narrow approach and the resultant importance of having a more multi-faceted evaluation framework with regard to assessing resilience and adaptability, among comprehensive risk management perspectives. The unprecedented disruptions from COVID-19 underlined how important it was to assess the capabilities of suppliers in ensuring continuity of operations when unexpected challenges arise. Now, organizations are incorporating new criteria into their processes for evaluating suppliers: the ability of a supplier to respond to changes in demand rapidly; the ability of a supplier to effectively manage supply chain risks; and flexibility in operations. This represents a larger trend of recognizing that the resilience of suppliers is at least as important as cost and quality, and traditional metrics need a revisit to better reflect the realities facing companies in the post-pandemic supply chain environment [11].

1.2 *Agility and flexibility: their role in supplier selection*

Agility and flexibility are now the number one characteristics of importance in supplier selection since the beginning of the pandemic. COVID-19 disruptions within supply chains worldwide have made suppliers that can adapt quickly to fluctuating market conditions, unexpected demand shifts, and disrupted operations key. Traditional metrics on suppliers centered around cost-efficiency are already insufficient in a world where the ability to answer change rapidly and flexibly has become paramount. Nowadays, every organization is searching for a supplier that can demonstrate a high level of operational agility, such as a capacity to adapt lead times, scale up or down in production, and shift the production lines as per the changing requirements of the customers. Actually, this provides the base for supply chain continuity, thereby enabling companies to capitalize on emerging market opportunities. Additionally, agile supplier management has come to include the integration of digital tools that allow for rapid information sharing and decision-making in real-time. This move toward agility and flexibility reflects a larger shift in supply chain strategy away from static, efficiency-focused models and toward dynamic, resilience-oriented frameworks [12].

1.3 *Geographical proximity and digital integration are emerging criteria*

The COVID-19 pandemic has indeed brought a sea-change in two significant ways to supply chain strategy: nearshoring and the adoption of digital technologies have gained as key parameters while choosing suppliers. This is because over-reliance on faraway suppliers is found to be quite vulnerable on three counts-one, the rising transport cost; two, delays; and three, inability to respond quickly in case of sudden disruption. Because of such risks, companies are increasingly using geographically closer suppliers in what has come to be called nearshoring. The result of this type of strategy is not only shorter lead times and reduced transportation-related vulnerabilities but also an ability to respond more agilely to market fluctuations.

Meanwhile, the pandemic accelerated the implementation of digital technologies like IoT, AI, and blockchain in supply chain management. This will further enhance real-time data exchange, visibility, and coordination between businesses and their suppliers. Digital integration enables businesses not only to monitor and predict the performance of their supply chains but also promptly respond to changes in them and make rational data-driven decisions. Companies draw up a priority list of suppliers, considering their advantages in geography and the ability to strengthen the supply chain connections and its resilience with the use of digital technologies. This dual focus on geographic proximity and digital integration underlines a paradigm shift in the process of supplier selection in the post-pandemic scenario, wherein a greater necessity is felt toward a more responsive and technologically fit supply chain framework [13].

1.4 *Traditional supplier metrics critically need reevaluation in light of new challenges*

The COVID-19 pandemic has led to a reconsideration of traditional criteria for the selection of suppliers, widening the scope to include environmental sustainability and ethical behavior. This crisis has heightened awareness about corporate responsibility and underlined the need for more transparency and ethics in supply chain operations. More often than not, organizations nowadays consider sustainability parameters while evaluating suppliers, reflecting a broader commitment towards environmental care and social responsibility. This now involves how the suppliers work toward reducing carbon emissions, managing their wastes, and ensuring that the labor practices are not unfair. By integrating these dimensions into their assessment tools, companies are bringing their supplier selection processes in line with today's standards of corporate responsibility and sustainability and thus ensuring supply chains that are resilient and responsible.

In this context, the integrated AHP-TOPSIS methods provide a step-by-step method for evaluating and ranking suppliers against an exhaustive set of criteria, which incorporates both pre- and post-pandemic considerations. This research aims at enhancing the process of supplier selection by embedding such advanced techniques to better meet the dynamic needs of the supply chain in response to the COVID-19 pandemic [14].

In recent years, supplier selection has become increasingly crucial for organizations seeking to optimize their supply chains, especially with the rise of complex global markets and the effects of external disruptions such as the COVID-19 pandemic. While there is a wealth of literature on supplier selection techniques, several limitations persist in current methodologies. Traditional models often rely on static criteria or simplistic approaches that fail to account for the dynamic and uncertain nature of the supply chain environment. For example, many existing methods do not sufficiently incorporate the fuzziness inherent in human judgment and the variability of market conditions. Furthermore, the application of Multi-Criteria Decision-Making (MCDM) techniques like AHP and TOPSIS in supplier selection, while effective in some contexts, often overlook the importance of integrating fuzzy logic to better handle uncertainty and imprecision in the decision-making process.

Moreover, few studies have explored how the COVID-19 pandemic has altered the criteria for selecting suppliers. The pandemic has underscored the need for more resilient and adaptable supplier selection strategies, emphasizing factors such as risk management, flexibility, and supplier reliability, which were not prioritized in pre-pandemic models.

This research aims to address these gaps by applying fuzzy AHP and TOPSIS methods in a more comprehensive framework that includes a dynamic evaluation of supplier performance under uncertain and changing conditions. By focusing on the integration of fuzzy logic and considering the impact of recent global disruptions, this study offers a more robust and adaptable approach to supplier selection.

2. Literature review

Supplier selection has been a critical area of research, particularly with the increasing complexity of global supply chains. Traditional supplier selection methods have often relied on straightforward decision-making models, but in recent years, the application of fuzzy multi-criteria decision-making (MCDM) methods, such as Fuzzy Analytic Hierarchy Process (FAHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), have gained significant attention. These methods offer advantages in handling uncertainty and subjective judgment, which are often inherent in supplier selection processes.

In recent years, significant advancements have been made in supplier selection methodologies that incorporate uncertainty and risk factors. Traditional methods such as the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) has been enhanced to better handle the complex, uncertain, and dynamic nature of modern supply chains.

A key advancement in this area is the integration of fuzzy logic and uncertainty modeling to address the inherent vagueness in human judgments and the variability of supply chain performance. Studies have applied fuzzy AHP and fuzzy TOPSIS to supplier selection, where fuzzy triangular numbers are used to capture uncertainty in decision-making. These methods are capable of representing linguistic expressions such as "more important" or "less important", offering more flexibility than crisp numerical values.

Moreover, recent research has extended traditional models by incorporating risk analysis and multi-objective optimization techniques. The application of fuzzy stochastic programming in supplier selection has become particularly prominent, as it integrates both uncertainty and risk factors, such as price volatility, supply chain disruptions, and delivery failures. This combination of fuzzy sets and stochastic models has been proven effective in creating more resilient and reliable supplier selection frameworks that account for potential risks.

For example, Kao et al. [15] proposed a fuzzy multi-criteria decision-making (MCDM) model for supplier selection that integrates both supplier performance data and risk factors. The authors combined fuzzy AHP with a risk assessment approach, enabling a more comprehensive evaluation of suppliers, particularly under uncertain conditions.

In addition, the increasing focus on sustainability and environmental risks has led to the development of green supplier selection models. These models use fuzzy logic to assess environmental performance and integrate risk factors related to sustainability into the supplier evaluation process. For instance, Zhu et al. [16] extended the fuzzy AHP model to incorporate environmental and social risks, reflecting the growing importance of sustainability in supplier selection decisions.

These advancements demonstrate the evolving nature of supplier selection methodologies, as decision-makers are now better equipped to evaluate suppliers amidst uncertainty and complex risk factors.

3. Background about the selection of an optimal supplier

Optimal supplier selection is a formal process in which an organization identifies and evaluates a number of suppliers before establishing a suitable contractual agreement. Among the major objectives of such a process is to minimize perceived purchasing risks while maximizing perceived value. The development in steps would eventually lead to the evolution of a sustainable buyer-supplier relationship. In value chain and supply chain management, the basis of selection among the available suppliers is considered of paramount importance. This subject has gained significant interest among academics as well as industrialists. This matter is of considerable relevance, especially within the domains of industrial marketing and inter-organizational interactions. Entities endeavor to enhance their management of supplier relationships by recognizing and choosing leading suppliers.

This issue closely resembles the challenge of identifying the most suitable contractor. A range of factors and indicators inform the selection process, and there are many methods for ranking and identifying appropriate suppliers. It goes without saying that the application of proper scientific methodologies can help frame and enhance the efforts of an organization in this area. In the past few years, a variety of approaches have been introduced for assessing and determining the most suitable supplier [17]. This includes studies that have explored the supplier selection issue and appraised suppliers through multi-criteria decision-making techniques.

In another study, Hajiaghaei et al. [18] addressed the problem of supplier selection and used the multi-criteria decision-making approach of TOPSIS for analysis. This study concluded that the method was useful and able to find out the best choice. It was observed from the results that the approach presented identified the best choice. The paper [19] also presented supplier selection issues utilizing TOPSIS methods of decision-making. The paper proposes an optimization approach using a classic TOPSIS algorithm for the determination of the best alternative by calculating the minimum distance from the Positive Linguistic Probabilistic Ideal Solution and the maximum distance to the Negative Linguistic Probabilistic Ideal Solution.

In other words, to illustrate the value of the proposed approach in a supplier selection context, a case study was conducted.

The results showed that the methodology is straightforward, easy to compute, and effective without using unnecessary complications. The study by Chen et al. [6], suggested an intelligent supply chain framework using Decision-Making Trial and Evaluation Laboratory (DEMATEL) and TOPSIS techniques. Proposed the application of DEMATEL methodology to compute criteria weights and then apply the TOPSIS technique for the ranking of suppliers. Rough Set theory and Fuzzy logic have been integrated into two major established methodologies that reduce ambiguities in supplier selection. Moreover, researchers compared single and combined methods; it was found that the studies that used combined methods of supplier evaluation in different organizations produced better results. This was investigated and verified by Karakoç [20], who determined that integrated methodologies may possibly result in the solution to practical problems. Table 1 summarizes state-of-the-art studies on supplier selection, which have been carried out using hybrid methodologies.

Another research study [21], has enhanced the TOPSIS approach and combined it with the Best-Worst Method in a fuzzy setting for selecting green suppliers. This research shows the fact that using Best-Worst Method (BWM) for determining criterion weights, along with enhanced TOPSIS for ranking suppliers, might bring more accuracy and efficiency to the process of selection. These techniques have been used by [22] for supplier selection in the Indian automotive industry. These findings from this research therefore indicate that these methods could be used to improve the process of supplier selection and reduce associated risks. This has been applied to the construction industry in the selection and evaluation of suppliers using both AHP and fuzzy TOPSIS approaches [23].

This research illustrates that the application of these techniques can assist in identifying the most suitable suppliers and mitigating project risks. Several studies have focused on integrated models for supplier selection. For instance, Islam and Arakawa [24] proposed a hybrid framework that combines Intuitionistic Fuzzy Set (IFS), Fuzzy Analytic Hierarchy Process (AHP), and Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) in order to enhance the process of supplier selection. The results of this study show that the suggested model improves precision in assessing the suppliers and leads to better decision-making. Another work has been proposed by Thanh [25] in which the combined model using Fuzzy AHP and Fuzzy TOPSIS was used for supplier selection in the plastic sector. This model is useful in choosing sustainable suppliers and decreasing environmental impacts, as the present research has shown.

Also, in the review of combined methods for supplier selection, the performance of a combined approach using AHP and TOPSIS has recorded good results with higher accuracy and process efficiency in some research. Indeed, this problem has been proved by numerous studies in recent years. For instance, Chung et al. [26] explored selection problems of green suppliers in a fuzzy information context and further proposed an integrated approach based on Fuzzy AHP and Fuzzy TOPSIS. The results of this study confirm that, by this approach, data provided by experts can be rated in a more objective way. Steps in conducting research.

From analyzing several studies done on the evaluation and selection of suppliers, it has been concluded that many different single and combined methods have been developed for the purpose. Among these methods, the combined AHP-TOPSIS approach has been widely applied in the last decades due to its distinct advantages over using either of these methods separately. These advantages include:

1. Pairwise comparison reduction: the AHP technique states that as the number of criteria increases, the amount of pairwise comparisons grows exponentially. This makes calculations complicated and lessens the disposition of experts to answer the questionnaire. Therefore, combined AHP-TOPSIS can reduce the amount of pairwise comparisons and make the calculation more straightforward.

2. The integration of the strengths of both approaches: The AHP technique effectively assigns weights to the criteria, whereas the TOPSIS method excels at ranking the alternatives. Employing the integrated approach allows for the benefits of both techniques to be leveraged effectively.

3. Better results: Despite the individual capabilities of each method, experience has shown that the combination of AHP and TOPSIS and their simultaneous use yield better results.

4. Overall, the combined AHP-TOPSIS method, with its reduction in calculations and combination of the advantages of both methods, provides more accurate results, distinguishing it from other methods.

Table 1. A review of recent studies on supplier selection

Case study	Analysis methods	Subject of study	Year of publication	Author/authors
-	VPI and AHP framework	Evaluation of suppliers based on the vendor performance index (VPI) and the analytic hierarchy process (AHP) method	2024	Mukti et al.
Public universities in Kenya	Statistical methods	The connection between choosing suppliers and the efficiency of the procurement department. in public universities in Kenya	2024	Musyoka et al.
Furniture industry	ENTROPY, Fuzzy ARAS and Fuzzy TOPSIS methods	The integration of sustainable and efficient supplier selection within the furniture industry	2023	Ince et al.
Renewable energy	DT2R2ML algorithm	Selection of renewable energy supplier using DT2R2ML	2023	Fazlollahtabar
Automotive Electronics Industry	Principal component analysis (PCA)	An analysis of performance metrics for managing supplier quality within the automotive electronics sector	2023	Petkova et al.
Food company	TOPSIS method	Selecting sustainable suppliers through neutrosophic methods for multi-criteria decision-making	2023	Mohamed et al.
-	Data envelopment analysis (DEA) method	Evaluating the performance of green supplier selection using data envelopment analysis (DEA)	2022	Yan et al.
Oil and Gas industry	Hierarchical fuzzy inference system (HFIS)	A hierarchical fuzzy inference approach for selecting suppliers and enhancing performance in the oil and gas sector	2022	Sarfaraz et al.
E-commerce companies	Data envelopment analysis (DEA) is a performance measurement technique	Choosing and assessing suppliers in E-commerce businesses.	2021	Pratap et al.
-	Two-dimensional fuzzy model	Supplier selection using a two-dimensional fuzzy test based on high confidence intervals	2021	Chen and Yu
India's cement industry	Step-wise weight assessment ratio analysis (SWARA) and weighted aggregated sum product assessment (WASPAS) methods	Supplier selection using SWARA and WASPAS	2020	Singh and Modgil

4. Research methodology

This research is classified as applied research within the categorization of scientific research. In this research, various library resources, including books and articles, are utilized, along with a blend of decision-making techniques designed for data analysis in uncertain conditions. The AHP and TOPSIS methods are employed within a fuzzy framework because of the hierarchical characteristics of the research factors. The study's statistical population includes 10 specialists from

Pegah Zanjan Company, all of whom possess at least a decade of experience in the commercial and procurement sectors. Figure 1 below presents the steps of conducting the research in order.

To further validate the effectiveness of the proposed methodology, it is essential to compare its performance with other widely adopted methods in the field. This comparison highlights the advantages and limitations of the proposed approach, showcasing its superiority in specific contexts.

In the context of supplier selection, for example, several traditional methods, such as the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), have been widely used. However, these methods often suffer from limitations, including susceptibility to decision-maker biases and the inability to handle uncertainty effectively. In contrast, our fuzzy-based AHP and TOPSIS integration not only addresses the inherent uncertainty in decision-making through fuzzy triangular numbers but also enhances the robustness of the final decision by providing a more comprehensive and accurate evaluation of alternatives.

To further strengthen our argument, we compare the results of our proposed methodology with those obtained through standard AHP and TOPSIS methods. We present the performance metrics for each approach across different criteria, showing that the fuzzy-enhanced methodology consistently outperforms the traditional methods in terms of decision accuracy, computational efficiency, and flexibility in handling ambiguous data. For instance, the fuzzy AHP-TOPSIS approach shows a higher consistency ratio in pairwise comparisons, indicating more reliable results. Additionally, the fuzzy methodology demonstrates better adaptability in real-world supplier selection scenarios, where uncertainty and imprecision are prevalent.

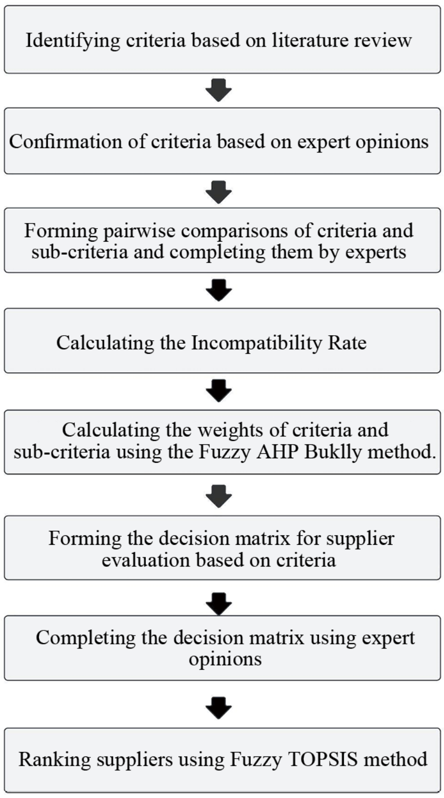

Figure 1. Research process

4.1 *Fuzzy theory*

Judgments of individuals regarding preferences are often vague when it comes to estimating precise numerical values. Additionally, fuzzy logic is useful for addressing issues involving ambiguity and uncertainty. The theory of fuzzy logic was first introduced by Zadeh [27] to handle the uncertainty in human perception of models.

Fuzzy triangular numbers are denoted as (l, m, u), with the parameters l, m, and u indicating the minimum anticipated value, the most likely anticipated value, and the maximum feasible expected value, respectively.

4.2 *Fuzzy analytic hierarchy process (FAHP) technique*

Consider $\widetilde{P}_{ij}$ as a collection of preferences from decision-makers concerning one specific indicator in relation to other indicators. The matrix for pairwise comparisons is constructed as follows:

$$\widetilde{A} = \begin{bmatrix} 1 & \widetilde{P}_{12} & \widetilde{P}_{1n} \\ \widetilde{P}_{21} & 1 & \widetilde{P}_{2n} \\ \widetilde{P}_{n1} & \widetilde{P}_{n2} & 1 \end{bmatrix} \tag{1}$$

The geometric mean of the fuzzy comparison values for index i in relation to each index can be derived using the Equation 2. [28]. The triangular fuzzy number derived from equation 3 represents the fuzzy weight of the i-th index. Following the computation of the fuzzy weight factors, they undergo defuzzification and normalization as outlined in Formula 4. To achieve normalization, each non-fuzzy weight must be divided by the total of all non-fuzzy weights.

$$\tilde{r}_i = \left(\prod_{j=1}^{n} \tilde{P}_{ij} \right)^{1/n} \qquad i = 1, 2, 3, \ldots, n \tag{2}$$

$$w_i = r_i \otimes (r_1 \oplus r_2 \oplus \ldots \oplus r_m)^{-1} \tag{3}$$

$$w_{\text{crisp}} = \frac{l + 2m + u}{4} \tag{4}$$

In this research, pairwise weights are computed using linguistic expressions and triangular fuzzy numbers as presented in Table 2.

Table 2. Linguistic phrases and fuzzy numbers for pairwise comparisons [29]

Crisp number	Linguistic	Scale of fuzzy number
9	Perfect	(8, 9, 10)
8	Absolute	(7, 8, 9)
7	Very good	(6, 7, 8)
6	Fairly good	(5, 6, 7)
5	Good	(4, 5, 6)
4	Preferable	(3, 4, 5)
3	Not bad	(2, 3, 4)
2	Weak advantage	(1, 2, 3)
1	Equal	(1, 1, 1)

4.3 *Consistency index (CI) and consistency ratio (CR)*

In AHP and FAHP, ensuring the consistency of the judgments made by decision-makers is crucial to obtaining reliable results. Inconsistent pairwise comparisons can distort the final decision. To measure this, we use the **Consistency Index (*CI*)** and **Consistency Ratio (*CR*)**.

• **Consistency Index (*CI*):** The **Consistency Index** quantifies the degree of inconsistency in the pairwise comparison matrix. It is defined as:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

where $\lambda_{\max}$ is the maximum eigenvalue of the comparison matrix, and n is the number of criteria or alternatives being compared. A CI value close to 0 indicates that the matrix is nearly consistent, while a larger CI suggests a higher level of inconsistency in the judgments.

• **Consistency Ratio (*CR*):** The **Consistency Ratio** normalizes the CI value by dividing it by the Random Consistency Index (RI), which depends on the number of criteria being compared. The formula for CR is:

$$CR = \frac{CI}{RI}$$

where RI is a predefined value that depends on n, the number of criteria. The CR is used to assess whether the pairwise comparisons are consistent enough to be trusted for further analysis. Typically, a CR value of less than 0.1 is considered acceptable, indicating that the judgments are reasonably consistent.

These two indices (CI and CR) help ensure that the judgments made during the pairwise comparison process do not undermine the validity of the results. A high CI or CR may require revising the comparisons to improve consistency.

4.4 *Explanation of fuzzy scales*

The choice of fuzzy scales in this study was based on their widespread use and reliability in multi-criteria decision-making (MCDM) problems, as demonstrated in prior research. These scales allow for the incorporation of linguistic terms, which effectively capture the subjective judgments of decision-makers. The triangular fuzzy numbers (TFNs) were selected for their simplicity, computational efficiency, and ability to model uncertainty in human preferences. Additionally, the scales provide consistency across pairwise comparisons and evaluations, ensuring robust results [30].

4.5 *Fuzzy TOPSIS technique*

4.5.1 *Creating a decision matrix*

Consider the decision matrix reflecting the perspectives of individuals as follows:

$$\widetilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \quad i = 1,\ 2,\ \ldots,\ m;\, j = 1,\ 2,\ \ldots,\ n \tag{5}$$

Each column represents a metric of measurement, whereas each row indicates a particular option. X_{ij} represents the quantity of option i related to sub-criterion j. Additionally, the sub-criteria may affect the options in either a favorable or unfavorable manner. This research employs linguistic terms and fuzzy numbers in the evaluation Table 3 to assess the options concerning each criterion.

Table 3. Linguistic terms and associated fuzzy values for assessing alternatives [31]

Crisp number	Linguistic	Scale of fuzzy number
1	Equally important/preferred	(1, 1, 3)
3	Weakly important/ preferred	(1, 3, 5)
5	Strongly more important/ preferred	(3, 5, 7)
7	Very strongly important/ preferred	(5, 7, 9)
9	Extremely more important/ preferred	(7, 9, 11)

4.5.2 *Normalization process for the decision matrix*

At this point, it is necessary to convert the fuzzy decision matrix reflecting individual opinions into a non-fuzzy scaled matrix ($\widetilde{R}$). To acquire matrix $\widetilde{R}$, it is adequate to standardize the decision matrix in accordance with Equations 7 and 8.

$$\widetilde{R} = [\widetilde{r}_{ij}]_{m\times n} \tag{6}$$

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \text{ and } c_j^* = \max_i c_{ij} \tag{7}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right) \text{ and } a_j^- = \min_i a_{ij} \tag{8}$$

4.5.3 *Creating a weighted normal matrix*

In this section, based on Relation 9, the weighted fuzzy matrix $\widetilde{R}$ is formed assuming the vector $\widetilde{w}_{ij}$, (***criteriaweights***).

$$\begin{aligned} &i = 1,\ 2,\ \ldots,\ mj = 1,\ 2,\ \ldots,\ n \quad \tilde{V} = [\tilde{v}_{ij}]_{m\times n} \\ &\tilde{v}_{ij} = \tilde{r}_{ij}\cdot \widetilde{w}_j \end{aligned} \tag{9}$$

4.5.4 *Identifying the values of positive ideal and negative ideal*

In this stage, the positive and negative ideals are established according to equations 10 and 11.

$$A^{+} = \left(\tilde{v}_1^*,\ \tilde{v}_2^*,\ \ldots,\ \tilde{v}_n^*\right) \text{ where } \tilde{v}_j^* = \left(\tilde{c}_j^*,\ \tilde{c}_j^*,\ \tilde{c}_j^*\right) \text{ and } \tilde{c}_j^* = \max_i \left\{\tilde{c}_{ij}\right\} \tag{10}$$

$$A^{-} = \left(\tilde{v}_1^-,\ \tilde{v}_2^-,\ \ldots,\ \tilde{v}_n^-\right) \text{where } \tilde{v}_j^- = \left(\tilde{a}_j^-,\ \tilde{a}_j^-,\ \tilde{a}_j^-\right) \text{and } \tilde{a}_j^- = \min_i \left\{\tilde{a}_{ij}\right\} \tag{11}$$

$$\forall i = 1,\ 2,\ \ldots,\ m; \quad j = 1,\ 2,\ \ldots,\ n$$

4.5.5 *Pairwise distance between options and ideals*

The total distances from each component to both the positive fuzzy ideal and the negative fuzzy ideal can be determined using Equation 12, where A and B represent two fuzzy numbers. The measurement of the distance between the two fuzzy numbers is calculated using Equation 13.

$$\tilde{A} = (a_1,\ b_1,\ c_1) \quad \tilde{B} = (a_2,\ b_2,\ c_2) \tag{12}$$

$$D(A,\ B) = \sqrt{\frac{1}{3}\left[(a_2 - a_1)^2 + (b_2 - b_1)^2 + (c_2 - c_1)^2\right]} \tag{13}$$

Then, the calculation of the distance for each component from both the ideal and anti-ideal points is performed using Equations 14 and 15.

$$d_i^* = \sum_{j=1}^{n} d\left(\tilde{v}_{ij} - \tilde{v}_j^*\right) \quad i = 1,\ 2,\ \ldots,\ m \tag{14}$$

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

4.5.6 *Final score and ranking the options*

In this section, the final scores of the options are determined based on Equation 16, and the final ranking is conducted accordingly.

$$Cl = \frac{d_i^-}{d_i^* + d_i^-} \quad i = 1,\ 2,\ \ldots,\ m \tag{16}$$

5. Sensitivity analysis

A sensitivity analysis is essential to evaluate the robustness of the supplier ranking under varying conditions. By assessing the impact of changes in the weights of criteria, one can ensure that the decision-making process remains stable even when the input data is subject to uncertainty. The sensitivity of the final rankings can be analyzed by adjusting the weight of each criterion within the fuzzy decision matrix and observing the changes in the final ranking order. This process can reveal how sensitive the model is to variations in the criteria and provide insights into the most influential factors in supplier selection.

The steps involved in performing sensitivity analysis are as follows:

Adjusting Criteria Weights: Recalculate the fuzzy weights and normalized decision matrix by varying the weight of one or more criteria. This can be done by incrementally changing the weight values and observing the shifts in rankings.

Re-ranking Suppliers: After adjusting the weights, the new rankings of suppliers can be derived using the same fuzzy TOPSIS procedure. The impact of these changes on the final rankings can be measured by comparing the results before and after the adjustments.

Impact Assessment: The stability of the final ranking can be assessed by calculating the deviation in rankings after each adjustment. Significant changes in the rankings indicate that the model may be sensitive to particular criteria, which should be carefully considered when making decisions.

This sensitivity analysis provides valuable insights into the reliability and robustness of the decision-making process, allowing decision-makers to understand the extent to which their preferences and weight assignments influence the final supplier rankings [32].

6. Outputs of applying the combined AHP-TOPSIS method

Pegah Company is one of the biggest dairy product manufacturers in Iran and needs suppliers who can supply quality and timely raw materials. Poor supplier selection can lead to issues that include a low quality of the product, an increase in costs, and delays in delivery. This ultimately will affect customer satisfaction and decrease market share. In light of this, Pegah Company needs a system that could approve and select suppliers based on KPIs. They may consider such aspects as quality product, cost of services, and the environmental sustainability of services. But the main problem is how to design and apply an integrated and effective system for appraising and selecting suppliers based on these indicators, so that Pegah Company can choose those suppliers that have the best performance for all of the criteria. The system should be able to evaluate suppliers at intervals and provide them with the necessary feedback for improvements. Figure 1 illustrates in detail a step-by-step application of the integrated approach developed for the Pegah Zanjan Company.

6.1 *Identification and validation of influential criteria*

In the first step, based on a review of the literature and research background, the influential criteria for supplier selection were identified based on key performance indicators. To this end, the literature on supplier evaluation and selection was examined to extract the influential indicators. Then, the experts' final confirmation was obtained through the Fuzzy DELPHI method. Table 3 presents the factors influencing the selection of suppliers for Pegah Zanjan Company.

6.2 *Outputs of prioritizing decision-making criteria using the FAHP method*

In this section, we conducted pairwise comparisons of the primary criteria and sub-criteria, utilizing the research indicators outlined in Table 4, and presented these comparisons to 10 experts in the field. The experts carried out these pairwise comparisons utilizing the fuzzy scale ranging from 1 to 9, as illustrated in Table 2. Subsequently, the geometric mean method was employed to integrate them, resulting in combined pairwise comparisons for the primary criteria, as shown in Table 4.

Table 4. Factors influencing supplier selection

Code	SubCriteria	Criteria
C11	Final cost	Price C1
C12	Continuous communication and responsiveness	
C13	Transportation cost	
C21	Adherence to delivery deadlines	Services C2
C22	Use of advanced technology and equipment	
C23	Continuous communication and responsiveness	
C31	Product quality	Quality C3
C32	Flexibility in producing the required product	
C33	Reduction of defective product production	
C41	Use of recyclable materials	Environmental C4
C42	Environmental certifications	
C43	Waste management	

Table 5. Matrix for pairwise comparisons of the key criteria (inconsistency rate: 0.1)

	C1	C2	C3	C4
C1	(1, 1, 1)	(0.851, 0.992, 1.162)	(0.912, 1.103, 1.274)	(2.107, 2.565, 3.012)
C2	(0.86, 1.008, 1.175)	(1, 1, 1)	(0.584, 0.661, 0.736)	(2.083, 2.922, 3.622)
C3	(0.785, 0.907, 1.096)	(1.358, 1.512, 1.712)	(1, 1, 1)	(2.232, 2.453, 2.653)
C4	(0.332, 0.39, 0.475)	(0.276, 0.342, 0.48)	(0.377, 0.408, 0.448)	(1, 1, 1)

To determine the weights using equations 1 and 2, the initial step involves computing the geometric mean of the fuzzy numbers found in each row of Table 5. Then, each geometric mean is divided by the total of all geometric means to calculate the fuzzy weight. Subsequently, the fuzzy weights are transformed into non-fuzzy weights according to Equation 3. To achieve normalization of each non-fuzzy weight, simply divide the weight by the total of all non-fuzzy weights. The results for the primary criteria are displayed in Table 6.

Table 6. Fuzzy and crisp weight of the major criteria

Criteria	Geometric mean	Fuzzy weight	Crisp weight	Normal weight
C1	(1.131, 1.295, 1.453)	(0.234, 0.3, 0.381)	0.304	0.299
C2	(1.012, 1.181, 1.33)	(0.209, 0.274, 0.349)	0.276	0.272
C3	(1.242, 1.354, 1.494)	(0.256, 0.314, 0.391)	0.319	0.314
C4	(0.431, 0.483, 0.565)	(0.089, 0.112, 0.148)	0.115	0.114
Total geometric mean	(3.816, 4.313, 4.842)			

Similarly, pairwise comparisons are conducted for the sub-criteria, and their corresponding weights are determined. Finally, The total weights of the sub-criteria are calculated by multiplying each sub-criterion's relative weight with the weight of its corresponding main criterion, as illustrated in Table 7. Based on this, the transportation cost criterion ranks first among all sub-criteria with a weight of 0.1543. Flexibility in producing the required product ranks second with a weight of 0.1306, and reduction of defective product production ranks third with a weight of 0.1084.

Table 7. Local and universal weighting of criteria

Criteria	Weight	SubCriteria	Local weight	Global weight	Global rank
Price (C1)	0.299	Final cost	0.296	0.0886	6
		Continuous communication and responsiveness	0.189	0.0565	10
		Transportation cost	0.515	0.1543	1
Services (C2)	0.272	Adherence to delivery deadlines	0.325	0.0886	5
		Use of advanced technology and equipment	0.299	0.0816	7
		Continuous communication and responsiveness	0.375	0.1022	4
Quality (C3)	0.314	Product quality	0.240	0.0754	8
		Flexibility in producing the required product	0.415	0.1306	2
		Reduction of defective product production	0.345	0.1084	3
Environmental (C4)	0.114	Use of recyclable materials	0.230	0.0261	12
		Environmental certifications	0.529	0.0601	9
		Waste management	0.241	0.0274	11

6.3 *Prioritizing decision options with fuzzy technique for order preference by similarity to ideal solution (FTOPSIS)*

In this part, the fuzzy TOPSIS method is applied to rank four suppliers, which are described as follows:

1. Amin Avar Plastic Company (S1)
2. Aram Plastic Sabalan Company (S2)
3. Sepidar Door Company (S3)
4. Plastic Industries Center Company (S4).

In the initial phase, experts were requested to assess each supplier against the sub-criteria using a fuzzy rating scale ranging from 1 to 5, as illustrated in Table 3. Then, the opinions were aggregated using the fuzzy averaging method and presented in Table 8. The evaluation matrix was normalized and then multiplied by the final obstacle weights, which were determined using the fuzzy AHP method, as illustrated in equation 9, to generate the weighted matrix. Then, The positive and negative ideal solutions were identified by applying equations 10 and 11. Finally, by applying equations 14 and 15, the distances between the alternatives in the weighted matrix and the positive and negative ideal solutions were computed. The final scores for each alternative were then determined through equation 16, with the results displayed in Table 9.

Table 8. Local and universal weighting of criteria

	C11	C12	C13	C21	C22	C23
S1	(2.6, 4.2, 6.2)	(3.8, 5.4, 7.4)	(3.8, 5.4, 7.4)	(2.6, 4, 6)	(3.2, 4.8, 6.8)	(2.8, 4.4, 6.4)
S2	(3.4, 5, 7)	(3.2, 4.8, 6.8)	(2, 3, 5)	(4.4, 6, 8)	(4.2, 6, 8)	(2.6, 4, 6)
S3	(5.6, 7.6, 9.6)	(5.6, 7.6, 9.6)	(4.2, 6.2, 8.2)	(4.8, 6.8, 8.8)	(4.8, 6.8, 8.8)	(4, 5.8, 7.8)
S4	(2.4, 4, 6)	(4.4, 6.4, 8.4)	(3.6, 5.2, 7.2)	(4, 5.6, 7.6)	(2.8, 4.4, 6.4)	(3.4, 5, 7)
	C31	C32	C33	C41	C42	C43
S1	(3.8, 5.8, 7.8)	(2.8, 4.4, 6.4)	(3.4, 5, 7)	(3.4, 4.8, 6.8)	(3.6, 5.2, 7.2)	(2.8, 4, 6)
S2	(4.2, 5.8, 7.8)	(4.6, 6.2, 8.2)	(4.2, 6.2, 8.2)	(3.2, 5.2, 7.2)	(4.2, 6.2, 8.2)	(3.2, 4.4, 6.4)
S3	(3, 4.4, 6.4)	(3.2, 4.6, 6.6)	(2.8, 4.4, 6.4)	(3.6, 5.4, 7.4)	(4.2, 6.2, 8.2)	(4.2, 5.6, 7.6)
S4	(4, 5.8, 7.8)	(4, 6, 8)	(2.6, 3.6, 5.6)	(3.8, 5.2, 7.2)	(4, 6, 8)	(2.8, 4.4, 6.4)

Table 9. Final score of suppliers

	+ D	− D	Ci	Rank
S1	0.446	0.326	0.422	4
S2	0.412	0.361	0.467	2
S3	0.351	0.431	0.552	1
S4	0.417	0.357	0.461	3

6.4 *Graphical representation of supplier rankings*

To visually represent the rankings of the suppliers derived from the fuzzy TOPSIS method, a bar chart is utilized. The graph below shows the relative ranking of each supplier based on their final scores, which integrate both the Fuzzy AHP and Fuzzy TOPSIS evaluation results.

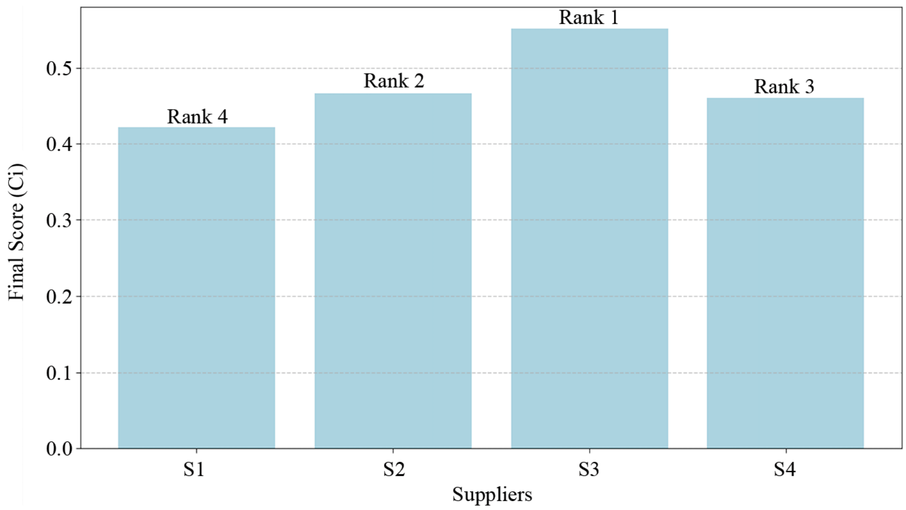

Figure 2. Supplier-rankings

Supplier Rankings Based on Fuzzy AHP and Fuzzy TOPSIS Scores. Figure 2 illustrates the ranking order of suppliers, with the height of each bar representing the supplier's final score. This chart provides a clear comparison and allows decision-makers to easily identify the top-performing suppliers based on the calculated fuzzy criteria.

7. Recommendations

By analyzing the available routes and transportation modes appropriately, Pegah Zanjan Company can identify and implement the best methods that would serve practical suggestions. This will be achieved by using Transportation Management Systems software and optimization algorithms. Apart from this, long-term contracts with trustworthy transportation companies can result in reduced and more sustainable transportation costs. To this end, for Pegah Zanjan Company to improve the flexibility of production, it is recommended that the company continue close and constant contact with suppliers while applying ERP systems to enhance coordination and planning of production.

Besides, it will be good to arrange contracts that could admit changes in orders when certain conditions occur. Changes may comprise variations in production volume, time of delivery, or specifications of the product. Checking suppliers for the presence of quality management system certification, like ISO 9001, may help enhance their production processes and reduce defects. Moreover, Pegah Zanjan Company can define precise standards for the production and quality control of products for suppliers to ensure that quality is in accordance with those standards.

One of the limitations of this study is the rapid changes in the market and economic environment, which may affect the research results and render them quickly unusable. Additionally, this study pertains specifically to Pegah Zanjan Company in 2024 and cannot be generalized to other dairy companies or other years.

8. Conclusion

A new hybrid approach is proposed for supplier selection and evaluation of the Pegah Zanjan Company in uncertain conditions in this regard. This integrated approach, even in cases of limited input from the decision maker, provides with remarkable validity the latter's effective optimum. AHP was used in the first stage of the process to rank the key criteria of supplier selection based on key performance indicators in Pegah Zanjan Company. The results of this section have shown that transportation cost, flexibility in producing the required product, and reduction of defective products are the most important decision-making criteria. The result from AHP then became an input to the second stage of the integrated technique, namely TOPSIS. In this research, four suppliers were ranked by applying the fuzzy TOPSIS method. According to the obtained results, the first rank belonged to Sepidar Darb Company with the abbreviation S3. The second rank belonged to Aram Plastic Sabalan Company, S2, the third rank by Plastic Industries Markaz Company, S4, while the fourth rank is taken by Amin Avar Plastic Company, S1.

From analyzing several studies done on the evaluation and selection of suppliers, it has been concluded that many different single and combined methods have been developed for the purpose. Among these methods, the combined AHP-TOPSIS approach has been widely applied in the last decades due to its distinct advantages over using either of these methods separately. These advantages include:

1. Pairwise comparison reduction: the AHP technique states that as the number of criteria increases, the amount of pairwise comparisons grows exponentially. This makes calculations complicated and lessens the disposition of experts to answer the questionnaire. Therefore, combined AHP-TOPSIS can reduce the amount of pairwise comparisons and make the calculation more straightforward.

2. The integration of the strengths of both approaches: The AHP technique effectively assigns weights to the criteria, whereas the TOPSIS method excels at ranking the alternatives. Employing the integrated approach allows for the benefits of both techniques to be leveraged effectively.

3. Better results: Despite the individual capabilities of each method, experience has shown that the combination of AHP and TOPSIS and their simultaneous use yield better results.

4. Overall, the combined AHP-TOPSIS method, with its reduction in calculations and combination of the advantages of both methods, provides more accurate results, distinguishing it from other methods.

9. Future research

While the proposed hybrid AHP-TOPSIS approach has demonstrated its effectiveness for supplier selection under uncertain conditions, several areas warrant further investigation to build upon these findings.

9.1 *Impact of emerging technologies on supply chain management*

Suggested Placement: Near the conclusion, after discussing the current limitations of your model and before proposing recommendations for future research.

Emerging technologies, such as blockchain, artificial intelligence (AI), and the Internet of Things (IoT), are increasingly transforming supply chain management. These technologies offer enhanced visibility, real-time tracking, and automated decision-making capabilities that could significantly impact supplier selection processes. For instance, blockchain technology can provide transparent and immutable records of transactions, helping to ensure supplier reliability and reducing fraud. AI-powered tools can facilitate more accurate demand forecasting and risk assessment, while IoT devices allow for the continuous monitoring of supply chain operations, enabling better risk management and more informed decision-making. Future research should explore how these technologies can be integrated into supplier selection models, particularly those using Multi-Criteria Decision Making (MCDM) techniques such as AHP and TOPSIS. Investigating the role of these technologies could lead to more dynamic, responsive, and efficient supplier management systems, ultimately enhancing the resilience and performance of supply chains in the face of unforeseen disruptions.

9.2 *Application of the proposed model in real-world supplier management scenarios*

Suggested Placement: After presenting your proposed model or in the section discussing the practical implications and limitations of your work.

The proposed model for supplier selection, combines the Fuzzy Analytic Hierarchy Process (FAHP) and Fuzzy TOPSIS provides a systematic and effective approach to evaluating and selecting suppliers. However, for real-world application, it is essential to adapt the model to the specific context and needs of each organization. In practice, companies can apply this model by incorporating real-time data, such as market conditions and supplier performance metrics, into the decision-making process. For example, the fuzzy decision matrix can be updated dynamically to reflect changes in supplier performance or external factors such as economic shifts or supply chain disruptions. Additionally, the model can be used to evaluate potential suppliers across various dimensions, such as cost, quality, delivery time, and risk, making it a versatile tool for supply chain managers. By integrating this model with enterprise resource planning (ERP) systems or supplier relationship management (SRM) platforms, organizations can streamline their supplier selection process, ensuring better alignment with strategic goals and improving overall supply chain efficiency. Real-world case studies could be used to validate the model's effectiveness in various industries, demonstrating its applicability and potential for optimizing supplier selection in practice.

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Conflict of interest

The authors declare no competing financial interest.

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