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Research Article

Ethical Dimensions in Supplier Selection Sustainability: Introducing the Modified MARCOS Method via Fuzzy-Rough Set with the LMAW Approach

Adis Puška[1*], Darko Božanić[2], Anđelka Štilić[3], Dragan Pamučar[4], Miroslav Nedeljković[5], Dragan Marinković[6,7]

[1] Department of Public Security, Government of Brčko District of Bosnia and Herzegovina, Brčko, 76100, Bosnia and Herzegovina
[2] Military Academy, University of Defence in Belgrade, Veljka Lukica Kurjaka 33, Belgrade, 11000, Serbia
[3] The College of Tourism, Academy of Applied Studies Belgrade, Belgrade, 11070, Serbia
[4] Sustainability Competence Centre, Széchenyi István University, Győr, 9026, Hungary
[5] Institute of Agricultural Economics, Belgrade, 11060, Serbia
[6] Department of Structural Analysis, Technical University of Berlin, Berlin, 10623, Germany
[7] Korea University, 145 Anam-ro, Seoul, Korea
E-mail: adispuska@yahoo.com

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Abstract: This research presents a novel approach to supplier selection by integrating economic, environmental, and ethical criteria. The case study of Company 3B, a food production company, illustrates this process. Expert decision-making, using a fuzzy-rough approach, is supported by the fuzzy-rough Logarithm Methodology of Additive Weights (LMAW) and the fuzzy-rough modified Measurement Alternatives and Ranking according to Compromise Solution (MARCOS) methods. The fuzzy-rough LMAW method helps determine the importance of criteria, revealing that experts consider the economic criterion the most significant. The Modified MARCOS (M-MARCOS), a simplified version of the MARCOS method, is used to rank suppliers. Results show that Supplier S3 performs the best. These findings are validated through comparisons with other fuzzy-rough methods and a sensitivity analysis. With the MARCOS method comparisons confirming a consistent ranking order, this paper advances supplier selection methodology by introducing a novel approach and improving the usability of the MARCOS method through modifications.

***Keywords*:** supplier selection, ethical criteria, fuzzy-rough approach, modified Measurement Alternatives and Ranking according to Compromise Solution (MARCOS) method

MSC: 90B50, 03E72, 68T37

1. Introduction

In today's dynamic and interconnected business environment, a company's sustainability and resilience heavily rely on the supplier selection process [1]. It is crucial to have prompt access to raw materials, equipment, and all other necessary resources for smooth operations. Additionally, with the increasing number of suppliers in the market [2], companies have

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a wide range of options to choose from. Therefore, the first step for any company is to select a supplier who can serve as a dependable partner.

Over time, the criteria for choosing suppliers have changed. In the mid-20th century, the main goal was to obtain materials and raw goods at the lowest cost, quickly and of the highest quality. Economic criteria, essential for supplier selection, were the priority during this period [3]. By the end of the 20th century, new approaches had emerged that incorporated environmental and social criteria into the supplier selection process. These models focus on economic efficiency, environmental impact, and social responsibility—the key aspects of sustainability [4].

In modern business, companies are increasingly aware of the risks associated with unethical corporate actions. Numerous examples exist of companies collapsing due to unethical conduct [5]. Therefore, when selecting a supplier, it is important to consider ethical criteria. However, the development of ethical considerations [6] has led to a fundamental change in the evaluation process, requiring a more detailed approach to supplier assessment.

To build trust in forming business partnerships, companies first examine how a potential supplier interacts with its employees and interest groups. Additionally, the supplier's relationship with the local community is highly important [7]. Ethical business practices reflect a supplier's behavior and values. It makes sense that if a company follows well-established ethical standards, positive relationships will extend to its partners. Therefore, it is essential to incorporate ethical criteria into the supplier selection process. These ethical criteria, which are closely linked to social criteria, focus on employees and interest groups. When considering ethical criteria, the scope broadens to include the local community, and adherence to ethical standards governs the company's overall conduct. It is essential to evaluate how the supplier implements these ethical principles in their business [8]. Following these principles naturally leads to stronger relationships, especially with both customers and suppliers.

This paper posits that ethical criteria are broader and more reliable than social criteria. If a supplier invests significant efforts in applying ethical practices, it logically follows that they will treat their employees well. Therefore, ethical criteria inherently encompass social criteria. This paper presents an enhanced approach to supplier selection, with a specific focus on incorporating an ethical criterion into the sustainability framework. Going beyond traditional social criteria, the methodology presented in this paper incorporates ethical considerations, acknowledging their crucial role in maintaining the future viability and integrity of business relationships [9].

In this way, applying ethical criteria is crucial for selecting suppliers, as ethics form the foundation of a company's responsibility. Implementing ethical codes in business means that the company respects the law, upholds human rights, and promotes fair practices, thereby protecting its reputation. By applying ethical codes, companies set clear boundaries that they will not cross, ensuring sound business practices within these organizations. Therefore, using ethical criteria in supplier selection helps the 3E company avoid issues when working with suppliers. Unlike social criteria, which focus on the company's external contributions through social responsibility toward society and employees, ethics and related criteria are closely tied to trust, reputation, and security. Sometimes, even if a company scores well on social indicators, it does not guarantee that it applies ethical principles in its business practices. Thus, it is more important for a company to evaluate ethical criteria than social ones, because when a company follows a code of ethics, it also upholds it in mutual business transactions.

This paper introduces the use of ethical criteria instead of social criteria as an innovation. Additionally, it offers a modification of the Measurement Alternatives and Ranking according to Compromise Solution (MARCOS) method to establish a supplier ranking. The reason for changing the existing MARCOS method is its complexity, specifically the number of steps involved. By simplifying this method, the number of steps is reduced, making it more practical to use. The decision maker no longer needs to calculate the utility degree, which simplifies the determination of the final value using the Modified MARCOS (M-MARCOS) method. Practical applications demonstrate that the MARCOS method is reliable for ranking alternatives, as it remains consistent even when the number of alternatives decreases and the ranking order remains the same. However, the current version has more steps than similar methods. Therefore, it was necessary to simplify this method to help decision makers more easily employ the MARCOS method through its modification.

This research aims to provide companies with additional assurance when selecting suppliers by incorporating ethical criteria into their sustainable supplier selection process. Therefore, alongside economic and ecological criteria, ethical considerations are also key in the supplier selection. This approach does not significantly change the overall sustainability strategy; rather, it enhances it. It is easier to see a company's contribution to the local community through its social responsibility efforts than to assess internal activities, such as employee training. External activities related to the local community are more noticeable to potential partners than internal procedures such as training programs.

Furthermore, this paper aims to introduce a novel application of the M-MARCOS method, a modified version of the MARCOS method. The goal of this application is to support the practical development of Multi-Criteria Decision-Making (MCDM). The M-MARCOS method simplifies its practical use by requiring fewer calculations. While maintaining the core steps of the MARCOS method, it makes it easier to obtain a rank interval.

Another motivation for this research is to streamline the application of MCDM and the final decision-making process. This will be achieved by integrating two methods: the Logarithm Methodology of Additive Weights (LMAW) for determining the importance of criteria and the M-MARCOS method for ranking suppliers. The LMAW method enables a straightforward evaluation of the importance of criteria without requiring direct comparisons, thereby eliminating the need to rank criteria by importance. The MARCOS method, introduced in 2020, is a newer MCDM approach widely used in practice. Simplifying calculations and steps will improve the practical application of this method. Additionally, the research is motivated by the opportunity to incorporate imprecise data into decision-making through the fuzzy approach and to introduce uncertainty reduction and reduced subjectivity using the rough approach. The fuzzy-rough approach is adopted, uniting these two methodologies.

This research aims to improve the security and reliability of companies through a refined sustainable supplier selection process. The comprehensive evaluation framework combines economic, ecological, and ethical criteria (3E criteria). This combination helps create a safer business environment, building trust in suppliers. By including ethical criteria and using advanced fuzzy-rough methodologies, this paper seeks to offer companies a strong supplier selection framework, focusing on specific research goals:

• Criterion redefinition: Replacing the social criterion with an ethical one to strengthen security and reduce risk.

• Comprehensive framework: Developing a robust evaluation model integrating sustainability criteria with an ethical lens.

• Advanced methodologies: Applying fuzzy-rough methodologies like Fuzzy-Rough LMAW and Fuzzy Rough M-MARCOS for precise supplier assessments.

This framework not only recognizes the importance of traditional sustainability criteria but also emphasizes the crucial role of ethical considerations in enhancing the security and reliability of supplier networks within a complex and interconnected global business environment. It contextualizes the integration of ethical criteria in supplier selection by reviewing theories and methodologies related to supplier selection, sustainability, and ethics. Methodologically, it explains the use of Fuzzy-Rough LMAW and the M-MARCOS method in assessing suppliers. The results underline the effectiveness of ethical criteria. The discussion examines the implications, limitations, and future research directions, while the conclusion summarizes the main findings and highlights the importance of ethics in supplier selection.

2. Literature review

The landscape of supplier selection has long centered on traditional aspects, such as economic efficiency, environmental impact, and social responsibility [10–13]. However, changing global commerce and ethical concerns have led to a fundamental reexamination of these ideas [14–18]. This literature review aims to examine both the historical roots and recent advances in supplier selection frameworks, with a focus on the shift toward incorporating ethical criteria for a more comprehensive evaluation process.

Historically, supplier selection models primarily focused on economic efficiency, aiming to cut costs and improve operations [19–21]. While this approach effectively reduces expenses, it often overlooks broader sustainability criteria. Later, environmental considerations were added, acknowledging the ecological impact of supplier decisions [22–25]. These early steps toward sustainability marked a significant shift in how suppliers are evaluated.

Table 1. Overview of previous studies

Author(s)	Subject	Method	Variables	Advantages	Disadvantages
Govindan et al. [26]	Integration of Corporate Social Responsibility (CSR) into supplier selection	Hybrid multi-criteria model with 3 phases: expert analysis, dependencies, selection	CSR practices, interdependencies	Structured CSR model	Specific context
Cole and Aitken [27]	Study of supplier selection for socially sustainable supply chains	Qualitative analysis of changes in practices	Previous sustainability criteria in selection	Practical paradigm shift	No quantitative data
Kraft et al. [28]	Investigation of CSR incentives for suppliers with limited visibility	Theoretical model with investments and information disclosure	Company roles, information disclosure	Flexible approach	Unrealistic assumptions
Thomas et al. [29]	Study of the role of social sustainability in supplier selection	Experiments in the transport context	Employee well-being, philanthropy, and pricing	Clear customer preferences	Industry limitation
Shidpour et al. [30]	Integration of CSR into SSOAP in developing countries	Fuzzy multi-criteria methodology	Traditional criteria and CSR, uncertainties	Solves economic-social dilemmas	Complex model
Waheed and Zhang [31]	Examination of the impact of CSR on the sustainable competitiveness of SMEs	Quantitative analysis with surveys in China and Pakistan	CSR practices, Ethical Cultural practice (ECL)	Connects CSR and performance	Regional limitations
Kim and Chae [32]	Analysis of the economic effects of ethical sourcing	Shareholder reaction analysis (159 companies)	Ethical Initiatives (ESIs), shareholder value	Proven financial benefits	Data bias
Wang and Feng [33]	Study of the impact of ethical leadership in the chain on green integration	Surveys (317 Chinese firms)	Ethical leadership, green image, integration	Strong link between ethics and sustainability	Single country

Based on this literature review (Table 1), it is clear that there are gaps in previous research, which this paper aims to fill. This study aims to establish ethical criteria for supplier selection to enhance the efficiency of the supply chain process. Since supplier selection is the first step in every supply chain, this is crucial. Moreover, this paper proposes a simplification of the MARCOS method, which has seen significant practical use; this change is expected to lead to even greater adoption of this method. Additionally, the study will explore the long-term dynamics of selecting ethical criteria in supplier selection.

On a methodological note, theoretical frameworks in supplier selection have traditionally focused on optimizing decision-making criteria [34–39]. However, the inclusion of ethical dimensions adds complexities that require a reevaluation of these frameworks. Incorporating ethics involves more than superficial inclusion; it requires a comprehensive restructuring of evaluation methodologies, emphasizing the importance of supplier practices that align with ethical principles. Recent advancements in methodologies [40–44] have opened new ways for incorporating ethical criteria into supplier evaluation, offering a more detailed and precise assessment that considers the complexities of ethical considerations within supplier selection frameworks.

3. Methodology

In this research, the LMAW method and the M-MARCOS method will be used to evaluate suppliers and select the one with the best indicators. The reason these two methods are used in supplier selection can be attributed to their characteristics. First, the LMAW method does not require decision-makers to compare or rank criteria when determining the weights of the criteria. Decision-makers for this method only need to assess the importance of each criterion based on their own opinion. Then, based on these assessments, the weights of the criteria are formed. The LMAW method is connected to the M-MARCOS method by keeping the obtained weights of the criteria in a fuzzy-rough form and using them as such for weighting. In this way, these two methods will be combined through a hybrid approach to determine which supplier has the best indicators for company 3B. On this basis, the LMAW method was chosen due to its simplicity in guiding the decision-maker. The application of the fuzzy-rough approach will support this methodology, as shown in Figure 1.

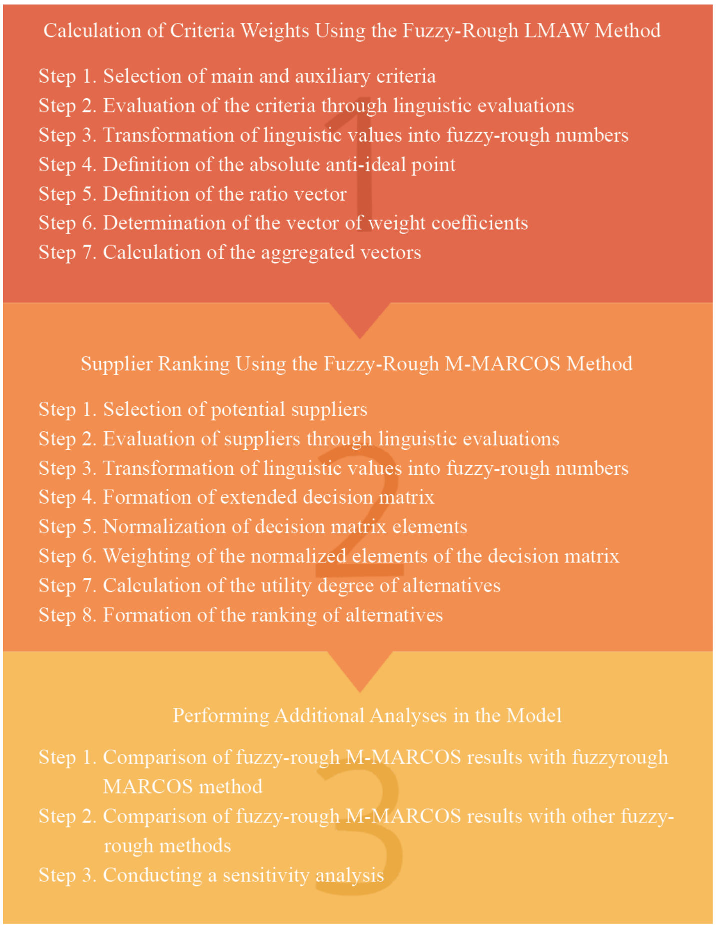

Figure 1. Hybrid fuzzy-rough model for supplier selection using 3E criteria

Given the application of the fuzzy-rough approach, we will first introduce this methodology and explain the methods used. The fuzzy-rough approach combines two techniques: the fuzzy approach, which allows for the inclusion of unclear, incomplete, and imprecise information in decision-making [45], and the rough approach, which helps manage uncertainties and reduces subjectivity in decision-making. This research uses imprecise information in the form of linguistic values. To use these values, it is necessary to convert them into fuzzy numbers using the membership function [46]. For easier decision-making, the same linguistic value will be applied with seven degrees of affiliation, ranging from very bad to very good (Table 2).

Table 2. Linguistic values with fuzzy number membership function [47]

Linguistic values	Fuzzy numbers
Very Bad (VB)	(0, 0, 1)
Bad (B)	(0, 1, 3)
Medium Bad (MB)	(1, 3, 5)
Medium (M)	(3, 5, 7)
Medium Good (MG)	(5, 7, 9)
Good (G)	(7, 9, 10)
Very Good (VG)	(9, 10, 10)

Once the fuzzy numbers are determined, a rough set is used to determine the lower and upper limits of each fuzzy number. The selected methods' steps are then executed. To perform the steps of the LMAW and M-MARCOS methods, it is imperative to define the basic operations for fuzzy-rough numbers. If there are two fuzzy-rough numbers, denoted as $FR(\overline{\alpha})$ and $FR(\overline{\beta})$ the basic operations with fuzzy-rough numbers are as follows:

Addition:

$$\begin{aligned} FR(\overline{\alpha})+FR(\overline{\beta}) &= \left(\left[\alpha^{lL},\, \alpha^{lU}\right],\, \left[\alpha^{mL},\, \alpha^{mU}\right],\, \left[\alpha^{uL},\, \alpha^{uU}\right]\right)+\left(\left[\beta^{lL},\, \beta^{lU}\right],\, \left[\beta^{mL},\, \beta^{mU}\right],\, \left[\beta^{uL},\, \beta^{uU}\right]\right) \\ &= \left[\alpha^{lL}+\beta^{lL},\, \alpha^{lU}+\beta^{lU}\right],\, \left[\alpha^{mL}+\beta^{mL},\, \alpha^{mU}+\beta^{mU}\right],\, \left[\alpha^{uL}+\beta^{uL},\, \alpha^{uU}+\beta^{uU}\right] \end{aligned} \tag{1}$$

Subtraction:

$$\begin{aligned} FR(\overline{\alpha})-FR(\overline{\beta}) &= \left(\left[\alpha^{lL},\, \alpha^{lU}\right],\, \left[\alpha^{mL},\, \alpha^{mU}\right],\, \left[\alpha^{uL},\, \alpha^{uU}\right]\right)+\left(\left[\beta^{lL},\, \beta^{lU}\right],\, \left[\beta^{mL},\, \beta^{mU}\right],\, \left[\beta^{uL},\, \beta^{uU}\right]\right) \\ &= \left[\alpha^{lL}-\beta^{uU},\, \alpha^{lU}-\beta^{uL}\right],\, \left[\alpha^{mL}-\beta^{mU},\, \alpha^{mU}-\beta^{mL}\right],\, \left[\alpha^{uL}-\beta^{lU},\, \alpha^{uU}-\ \beta^{lL}\right] \end{aligned} \tag{2}$$

Multiplication:

$$\begin{aligned} FR(\overline{\alpha})\times FR(\overline{\beta}) &= \left(\left[\alpha^{lL},\, \alpha^{lU}\right],\, \left[\alpha^{mL},\, \alpha^{mU}\right],\, \left[\alpha^{uL},\, \alpha^{uU}\right]\right)+\left(\left[\beta^{lL},\, \beta^{lU}\right],\, \left[\beta^{mL},\, \beta^{mU}\right],\, \left[\beta^{uL},\, \beta^{uU}\right]\right) \\ &= \left[\alpha^{lL}\times\beta^{lL},\, \alpha^{lU}\times\beta^{lU}\right],\, \left[\alpha^{mL}\times\beta^{mL},\, \alpha^{mU}\times\beta^{mU}\right],\, \left[\alpha^{uL}\times\beta^{uL},\, \alpha^{uU}\times\beta^{uU}\right] \end{aligned} \tag{3}$$

Division:

$$FR(\overline{\alpha}) \div FR(\overline{\beta}) = \left(\left[\alpha^{lL}, \alpha^{lU}\right], \left[\alpha^{mL}, \alpha^{mU}\right], \left[\alpha^{uL}, \alpha^{uU}\right]\right) + \left(\left[\beta^{lL}, \beta^{lU}\right], \left[\beta^{mL}, \beta^{mU}\right], \left[\beta^{uL}, \beta^{uU}\right]\right)$$
$$= \left[\alpha^{lL} \div \beta^{uU}, \alpha^{lU} \div \beta^{uL}\right], \left[\alpha^{mL} \div \beta^{mU}, \alpha^{mU} \div \beta^{mL}\right], \left[\alpha^{uL} \div \beta^{lU}, \alpha^{uU} \div \beta^{lL}\right] \tag{4}$$

Scalar multiplication:

$$\lambda \times FR(\overline{\alpha}) = \lambda \times \left(\left[\alpha^{lL}, \alpha^{lU}\right], \left[\alpha^{mL}, \alpha^{mU}\right], \left[\alpha^{uL}, \alpha^{uU}\right]\right)$$
$$= \left(\left[\lambda \times \alpha^{lL}, \lambda \times \alpha^{lU}\right], \left[\lambda \times \alpha^{mL}, \lambda \times \alpha^{mU}\right], \left[\lambda \times \alpha^{uL}, \lambda \times \alpha^{uU}\right]\right) \tag{5}$$

Applying these operations, the MCDM methods are adapted for the fuzzy-rough approach.

3.1 *Fuzzy-rough LMAW method*

When making multi-criteria decisions, determining the importance of criteria is crucial for considering alternatives. This involves assigning weights to criteria to represent their significance. In this research, the fuzzy-rough LMAW method, previously applied in practice [47], is used. The steps of this method are outlined as follows:

Step 1. Evaluation of criteria by experts using linguistic evaluations.

Step 2. Transformation of linguistic values into fuzzy-rough numbers.

$$\widetilde{\gamma}^{e}_{Cn} = \left(\left[\alpha^{lL}, \alpha^{lU}\right], \left[\alpha^{mL}, \alpha^{mU}\right], \left[\alpha^{uL}, \alpha^{uU}\right]\right) \tag{6}$$

Step 3. Defining the absolute anti-ideal point ($\widetilde{\gamma}_{AIP}$)

Step 4. Definition of the ratio vector

$$\widetilde{\mu}^{e}_{Cn} = \left(\frac{\widetilde{\gamma}^{e}_{Cn}}{\widetilde{\gamma}_{AIP}}\right) = \left(\left[\frac{\alpha^{lL}}{\widetilde{\gamma}_{AIP}} \cdot \frac{\alpha^{lU}}{\widetilde{\gamma}_{AIP}}\right] \cdot \left[\frac{\alpha^{mL}}{\widetilde{\gamma}_{AIP}} \cdot \frac{\alpha^{mU}}{\widetilde{\gamma}_{AIP}}\right] \cdot \left[\frac{\alpha^{uL}}{\widetilde{\gamma}_{AIP}} \cdot \frac{\alpha^{uU}}{\widetilde{\gamma}_{AIP}}\right]\right) \tag{7}$$

Step 5. Determination of the vector of weight coefficients for individual expert values.

$$\widetilde{\omega}^{e}_{j} = \left(\frac{ln(\widetilde{\mu}^{LU}_{Cn})}{ln(\prod_{j=1}^{n} \widetilde{\mu}^{LU}_{Cn})}\right)$$
$$= \left(\left[\frac{ln(\widetilde{\mu}^{lL}_{Cn})}{ln(\prod_{j=1}^{n} \widetilde{\mu}^{uU}_{Cn})}, \frac{ln(\widetilde{\mu}^{lU}_{Cn})}{ln(\prod_{j=1}^{n} \widetilde{\mu}^{uL}_{Cn})}\right] \cdot \left[\frac{ln(\widetilde{\mu}^{mL}_{Cn})}{ln(\prod_{j=1}^{n} \widetilde{\mu}^{mU}_{Cn})}, \frac{ln(\widetilde{\mu}^{mU}_{Cn})}{ln(\prod_{j=1}^{n} \widetilde{\mu}^{mL}_{Cn})}\right] \cdot \left[\frac{ln(\widetilde{\mu}^{uL}_{Cn})}{ln(\prod_{j=1}^{n} \widetilde{\mu}^{lU}_{Cn})}, \frac{ln(\widetilde{\mu}^{uU}_{Cn})}{ln(\prod_{j=1}^{n} \widetilde{\mu}^{lL}_{Cn})}\right]\right) \tag{8}$$

Step 6. Calculation of the aggregated vectors of weight coefficients using the Bonferroni aggregator.

$$\widetilde{\omega}_j = \left(\frac{1}{k(k-1)} \sum_{\substack{i.j=1 \\ i \neq j}}^{k} \widetilde{\omega}_i^{(UL)p} \widetilde{\omega}_i^{(UL)q} \right)^{\frac{1}{p+q}} \tag{9}$$

The obtained weight values in fuzzy-rough form will be used in the ranking of alternatives without conversion into crisp values.

3.2 *Fuzzy-rough M-MARCOS method*

The MARCOS method was originally used for sustainable supplier selection [48]. In this study, the method is simplified, where the ranking of alternatives is done immediately after calculating the utility degree, and the utility function values are omitted. The steps of this method are as follows:

Step 1. Formation of the linguistic decision matrix.

Step 2. Transformation of linguistic values into fuzzy-rough values.

Step 3. Expansion of the initial decision matrix with ideal and anti-ideal solutions.

$$AAI = \min_i FR_i\left(\overline{X_i}\right) \text{ for benefit criteria and } AAI = \max_i FR_i\left(\overline{X_i}\right) \text{ for cost criteria} \tag{10}$$

$$AI = \max_i FR_i\left(\overline{X_i}\right) \text{ for benefit criteria and } AI = \min_i FR_i\left(\overline{X_i}\right) \text{ for cost criteria} \tag{11}$$

Step 4. Normalization of the expanded decision matrix.

For benefit criteria

$$\overline{\overline{n}}_{ij} = \left(\left[\frac{x_{ij}^{lL}}{\max x_j^{uU}}, \frac{x_{ij}^{lU}}{\max x_j^{uL}} \right], \left[\frac{x_{ij}^{mL}}{\max x_j^{mU}}, \frac{x_{ij}^{mU}}{\max x_j^{mL}} \right], \left[\frac{x_{ij}^{uL}}{\max x_j^{lU}}, \frac{x_{ij}^{uU}}{\max x_j^{lL}} \right] \right) \tag{12}$$

for cost criteria

$$\overline{\overline{n}}_{ij} = \left(\left[\frac{\min x_j^{lL}}{x_{ij}^{uU}}, \frac{\min x_j^{lU}}{x_{ij}^{uL}} \right], \left[\frac{\min x_j^{mL}}{x_{ij}^{mU}}, \frac{\min x_j^{mU}}{x_{ij}^{mL}} \right], \left[\frac{\min x_{ij}^{uL}}{x_{ij}^{lU}}, \frac{\min x_j^{uU}}{x_{ij}^{lL}} \right] \right) \tag{13}$$

Step 5. Weighting the normalized fuzzy-rough decision matrix

$$\overline{\overline{v}}_{ij} = \overline{\overline{w}}_j \cdot \overline{\overline{n}}_{ij} \tag{14}$$

Step 6. Calculating the utility degree of alternatives.

$$\overline{\overline{K}}_i^- = \frac{\overline{\overline{S}}_i}{\overline{\overline{S}}_{aai}} \tag{15}$$

$$\overline{\overline{K}}_i^+ = \frac{\overline{\overline{S}}_i}{\overline{\overline{S}}_{ai}} \tag{16}$$

Where:

$$\overline{\overline{S}}_i = \sum_{i=1}^{m} \overline{\overline{v}}_{ij} \tag{17}$$

Step 7. Calculation of the value of the M-MARCOS method.

$$f\left(\overline{\overline{K}}_i\right) = \frac{\overline{\overline{K}}_i^+ + \overline{\overline{K}}_i^-}{2} \tag{18}$$

Since the value of the M-MARCOS method is in the form of a fuzzy-rough number, transforming this value into a crisp value is necessary to obtain the final value of this method. This is achieved by applying the following expression:

$$f(K_i) = \frac{f\left(\overline{\overline{K}}_{i1}^L\right) + f\left(\overline{\overline{K}}_{i1}^U\right) + f\left(\overline{\overline{K}}_{i2}^L\right) + f\left(\overline{\overline{K}}_{i2}^U\right) + f\left(\overline{\overline{K}}_{i3}^L\right) + f\left(\overline{\overline{K}}_{i3}^U\right)}{6} \tag{19}$$

Based on the above steps of the M-MARCOS method, it can be seen that its steps differ from the MARCOS method after calculating the utility degree of alternatives. In the MARCOS method, the utility degree is then calculated based on the utility degrees of the alternatives. This makes the calculation of the MARCOS method even more complicated. A further difference is in the calculation of the final MARCOS value, which is much more complex than in the M-MARCOS method.

4. Real case demonstration

In selecting a supplier based on the 3E criteria, company 3B, which specializes in food production in Bosnia and Herzegovina, was used. For the company to operate successfully, it must meet the standards set by customers and the market. Increased consumer awareness and health concerns [49] highlight the importance of reducing environmental impact. The packaging must follow ecological principles and comply with established standards. Additionally, devotion to the strict criteria of the European Union, where the company plans to market its products, is essential. The packaging also needs to be attractive and innovative to satisfy customer preferences. This complexity makes the decision-making process more challenging when determining the most suitable supplier for company 3B. Therefore, it was decided to use three main criteria: economic, ecological, and ethical, each divided into six additional criteria (Table 3). The selected criteria enable company 3B to choose a supplier that supports its business security.

Table 3. Research criteria

Main criteria	Auxiliary criteria	Description	References
C1 economic criteria	C11 Cost/Price	Ensuring competitive prices for the invested money	[48, 50–52]
	C12 quality	Evaluating the degree of customer satisfaction	[48, 50–53]
	C13 delivery	Assessing the ability to deliver products on time and in required quantities	[50, 52, 54, 55]
	C14 technical capacities	Examining the level of technical capacities	[50, 54, 56]
	C15 reliability	Gauging the company's reliability in past operations	[48, 51, 56]
	C16 flexibility	Evaluating the ability to adapt to customer and market demands	[50, 51, 56, 57]
C2 ecological criteria	C21 pollution control	Implementing measures and standards to reduce environmental impact	[48, 51–53, 55, 58]
	C22 environmental management system	Applying ISO 14001 standards	[48, 51–53, 57, 58]
	C23 green products	Introducing environmentally friendly products	[48, 52, 57, 58]
	C24 resource consumption	Reducing the use of resources without compromising product quality	[50, 58, 59]
	C25 green packing	Designing packaging under environmental standards	[57–59]
	C26 green image	Demonstrating commitment through sustainable practices and environmental protection	[51, 57, 59]
C3 ethical criteria	C31 ethical standards	Upholding moral values and integrity in business	[56, 57, 60]
	C32 social responsibility	Contributing to a positive social impact through sustainable practices and community support	[57, 61, 62]
	C33 business transparency	Building trust through open communication	[57, 60, 63]
	C34 code of conduct	Upholding standards of behavior that the company should follow	[53, 55, 57, 61]
	C35 reputation	Creating a positive opinion about the company through past operations	[48, 50, 56, 62]
	C36 data sharing and security	Handling and sharing information responsibly, as well as protecting sensitive data	[51, 53, 56]

During the supplier selection process, a list of five experts from various departments of company 3B, including logistics, marketing, production, procurement, and finance, was initially compiled. All selected experts have over 10 years of experience within the company, establishing them as seasoned professionals in their respective fields. Additionally, the company had multiple potential suppliers, but a shortlist of six suppliers was created. These suppliers underwent evaluation based on the 3E criteria.

4.1 *Application of fuzzy-rough LMAW and modified fuzzy-rough M-MARCOS methodology*

In this research, a hybrid fuzzy-rough LMAW and M-MARCOS method is employed. The determination of criterion importance begins with the main criteria and then extends to auxiliary criteria. Criteria and alternative importance ratings are aligned (Table 1). To elucidate the transformation of linguistic values into fuzzy-rough numbers and the later manipulation of these numbers, we will illustrate the process using the fuzzy-rough LMAW method and the main criteria.

The initial criteria weight determination involved expert evaluation (Table 4), followed by data processing and weight acquisition. Linguistic values were transformed into fuzzy numbers using a defined membership function (Table 1). For example, the value "very good" was transformed into the fuzzy number (9, 10, 10), and "good" transformed into (7, 9, 10). Lower and upper limits for the rough numbers were then established for each fuzzy triangular number.

Table 4. Linguistic values of the main criteria and ratings expressed through fuzzy numbers

	Linguistic value			Fuzzy number		
	C1	C2	C3	C1	C2	C3
Expert 1	VG	G	G	(9, 10, 10)	(7, 9, 10)	(7, 9, 10)
Expert 2	G	G	G	(7, 9, 10)	(7, 9, 10)	(7, 9, 10)
Expert 3	VG	G	VG	(9, 10, 10)	(7, 9, 10)	(9, 10, 10)
Expert 4	VG	G	G	(9, 10, 10)	(7, 9, 10)	(7, 9, 10)
Expert 5	G	G	G	(7, 9, 10)	(7, 9, 10)	(7, 9, 10)

For criterion C1 and Expert 1, the lower and upper limits are as follows:

$$C_1^{lL} = \frac{9+7+9+9+7}{5} = 8.20, \quad C_1^{lU} = \frac{9+9+9}{3} = 9.00,$$

$$C_1^{mL} = \frac{10+9+10+10+9}{5} = 9.60, \quad C_1^{mU} = \frac{10+10+10}{3} = 10.00,$$

$$C_1^{uL} = \frac{10+10+10+10+10}{5} = 10.00, \quad C_1^{uU} = \frac{10+10+10+10+10}{5} = 10.00.$$

When establishing the lower limits, the process involves examining each expert's fuzzy number values and selecting all identical or lower values from the other experts. On the other hand, for determining the upper limits, the process involves examining the same values and those provided by experts. This approach ensures the comprehensive determination of lower and upper limits across all experts, forming a fuzzy-rough decision matrix to which the steps of the fuzzy-rough LMAW method are later applied.

The first step is determining the absolute anti-ideal point ($\widetilde{\gamma}_{AIP}$), a value smaller than any in the decision matrix. Next, the values of the fuzzy-rough decision matrix are divided by this value to form a ratio vector. The vector of weight coefficients is determined by calculating the natural logarithm of the ratio vector value, dividing it by the natural logarithm of the product of corresponding fuzzy-rough numbers, and applying the Bonferroni aggregator. This process produces the final weight value for the main criteria (Table 5), with detailed calculations shown in Puška et al. [47].

The weights for auxiliary criteria are calculated similarly. Experts evaluate these criteria using linguistic values (Table 6), and the fuzzy-rough LMAW method steps are executed. Multiplying the weights of the main and auxiliary criteria produces final weights for ranking selected suppliers. Results indicate that the auxiliary criterion C22—Environmental

Management System carries the highest weight, followed by criteria C21—Pollution Control and C26—Green Image. Notably, the differences between these criteria are subtle, suggesting that their collective influence on the final ranking of observed suppliers is significant.

Table 5. Determination of the vector of weight coefficients and the weights of the main criteria

	C1						C2						C3					
	l	*u*	*l*	*u*	*l*	*u*	*l*	*u*	*l*	*u*	*l*	*u*	*l*	*u*	*l*	*u*	*l*	*u*
Expert 1	0.27	0.30	0.34	0.36	0.44	0.47	0.22	0.22	0.32	0.33	0.44	0.47	0.22	0.24	0.32	0.33	0.44	0.47
Expert 2	0.22	0.27	0.32	0.36	0.46	0.50	0.22	0.22	0.32	0.33	0.46	0.50	0.22	0.24	0.32	0.34	0.46	0.50
Expert 3	0.27	0.30	0.33	0.36	0.41	0.46	0.22	0.22	0.31	0.32	0.41	0.46	0.24	0.30	0.32	0.36	0.41	0.46
Expert 4	0.27	0.30	0.34	0.36	0.44	0.47	0.22	0.22	0.32	0.33	0.44	0.47	0.22	0.24	0.32	0.33	0.44	0.47
Expert 5	0.22	0.27	0.32	0.36	0.46	0.50	0.22	0.22	0.32	0.33	0.46	0.50	0.22	0.24	0.32	0.34	0.46	0.50
W	0.25	0.29	0.33	0.36	0.44	0.48	0.22	0.22	0.32	0.33	0.44	0.48	0.22	0.25	0.32	0.34	0.44	0.48

Table 6. Linguistic evaluations of auxiliary criteria by experts and final weights of auxiliary criteria

	C11	C12	C13	C14	C15	C16	C21	C22	C23	C24	C21	C26	C31	C32	C33	C34	C35	C36
Expert 1	G	VG	VG	MG	MG	M	VG	VG	G	MG	G	VG	VG	G	MG	G	VG	MG
Expert 2	G	G	G	MG	G	MG	G	VG	G	MG	MG	G	VG	G	G	VG	VG	G
Expert 3	G	VG	G	G	G	M	VG	G	MG	G	G	VG	VG	G	MG	VG	G	G
Expert 4	MG	G	G	MG	MG	M	G	VG	G	MG	G	VG	G	VG	MG	G	VG	MG
Expert 5	G	G	G	MG	G	MG	VG	VG	MG	MG	MG	G	VG	G	MG	G	VG	G
	C11						C12						C13					
W	0.03	0.04	0.05	0.07	0.11	0.15	0.03	0.04	0.06	0.07	0.11	0.15	0.03	0.04	0.06	0.07	0.11	0.15
	C14						C15						C16					
W	0.02	0.03	0.05	0.06	0.11	0.14	0.02	0.03	0.05	0.07	0.11	0.15	0.01	0.02	0.03	0.05	0.09	0.13
	C21						C22						C23					
W	0.02	0.03	0.06	0.07	0.13	0.20	0.03	0.03	0.06	0.07	0.13	0.20	0.01	0.02	0.04	0.06	0.11	0.19
	C24						C25						C26					
W	0.00	0.01	0.03	0.05	0.11	0.18	0.01	0.02	0.04	0.06	0.11	0.19	0.02	0.03	0.06	0.07	0.13	0.20
	C31						C32						C33					
W	0.03	0.04	0.06	0.07	0.12	0.17	0.02	0.03	0.05	0.07	0.12	0.17	0.00	0.01	0.03	0.05	0.10	0.16
	C34						C35						C36					
W	0.02	0.03	0.05	0.07	0.12	0.17	0.03	0.04	0.06	0.07	0.12	0.17	0.01	0.02	0.04	0.06	0.11	0.17

Table 7. Initial linguistic decision matrix

Expert 1	C11	C12	C13	C14	C15	C16	C21	C22	C23	C24	C21	C26	C31	C32	C33	C34	C35	C36
Supplier 1	M	MG	M	G	MG	M	M	M	MG	M	M	MG	MG	MG	G	MG	MG	M
Supplier 2	M	M	M	G	M	M	M	MG	M	MB	M	MG	M	MG	MB	M	MG	G
Supplier 3	G	G	MG	VG	G	VG	MG	G	G	MG	G	G	G	G	VG	VG	G	VG
Supplier 4	M	MG	M	MB	M	M	M	M	M	M	MG	M	MG	MG	M	MG	MG	M
Supplier 5	MB	M	MG	M	M	M	MB	MG	MG	MG	MG	MG	MG	M	M	MB	MG	MB
Supplier 6	G	MG	G	MG	G	MG	G	MG	MG	G	G	G	MG	MG	VG	MG	MG	G
Expert 2	C11	C12	C13	C14	C15	C16	C21	C22	C23	C24	C25	C26	C31	C32	C33	C34	C35	C36
Supplier 1	M	M	MG	MG	MG	G	MG	MG	MG	M	MG	MG	M	M	MG	M	MG	MG
Supplier 2	M	MG	M	MG	M	M	M	M	M	M	MG	M	MG	M	MB	MG	G	MG
Supplier 3	G	G	G	VG	VG	G	MG	MG	MG	G	MG	VG	G	G	G	G	G	G
Supplier 4	MB	M	MG	MB	M	MB	MG	M	MG	M	MG	MB	M	M	MG	M	M	M
Supplier 5	M	MB	M	M	MG	MG	M	G	G	G	MG	M	MG	M	MG	M	MG	M
Supplier 6	MG	G	MG	MG	G	MG	MG	G	G	G	MG	MG	G	MG	G	MG	G	MG
Expert 3	C11	C12	C13	C14	C15	C16	C21	C22	C23	C24	C25	C26	C31	C32	C33	C34	C35	C36
Supplier 1	MG	M	M	MG	MG	MG	MG	M	M	MG	M	G	MG	MG	MG	MG	M	M
Supplier 2	M	M	MB	G	MB	MG	MG	MG	MG	MB	MG	MG	M	MG	M	MG	G	MG
Supplier 3	VG	VG	G	G	G	G	MG	MG	G	G	MG	VG	VG	G	G	G	VG	VG
Supplier 4	MB	M	M	M	MB	MB	MG	M	MG	MG	M	MB	M	M	MG	M	M	MG
Supplier 5	MB	M	M	M	MG	M	M	MG	MG	MG	G	M	M	MG	M	M	G	M
Supplier 6	G	G	G	G	MG	G	G	MG	G	MG	G	MG	G	MG	G	G	G	G
Expert 4	C11	C12	C13	C14	C15	C16	C21	C22	C23	C24	C25	C26	C31	C32	C33	C34	C35	C36
Supplier 1	M	MG	MG	G	M	MG	M	M	MG	M	MG	G	M	M	G	M	MG	MG
Supplier 2	MB	MG	MB	MG	M	MG	M	MG	M	M	MG	MG	M	M	M	MG	MG	MG
Supplier 3	G	G	G	G	G	G	G	G	G	G	G	VG	VG	G	VG	VG	G	VG
Supplier 4	M	MG	M	MB	MB	MB	MG	MG	M	M	M	M	MG	M	MG	M	M	M
Supplier 5	MB	M	MG	MB	M	M	MB	G	MG	G	G	MG	M	M	MG	MB	MG	MB
Supplier 6	MG	G	G	MG	G	MG	G	MG	MG	G	G	G	G	G	G	MG	G	G
Expert 5	C11	C12	C13	C14	C15	C16	C21	C22	C23	C24	C25	C26	C31	C32	C33	C34	C35	C36
Supplier 1	MG	MG	MG	MG	MG	MG	M	MG	M	MG	MG	MG	MG	M	MG	MG	M	M
Supplier 2	M	M	M	MG	MB	M	M	M	M	MB	M	M	MG	M	MB	M	G	G
Supplier 3	VG	G	MG	VG	VG	VG	MG	G	G	G	G	G	VG	VG	G	G	G	VG
Supplier 4	MB	MG	MG	MB	MB	M	M	MG	M	M	MG	M	M	MG	M	MG	MG	MG
Supplier 5	MB	MB	MG	M	M	MG	M	G	G	MG	MG	M	MG	M	M	MB	MG	MB
Supplier 6	G	MG	G	G	MG	MG	G	G	G	G	MG	MG	MG	MG	VG	G	MG	G

After determining the importance values of auxiliary criteria using the fuzzy-rough LMAW method, the fuzzy-rough M-MARCOS method is applied to rank the selected suppliers. The initial decision matrix is constructed, with experts evaluating suppliers based on auxiliary criteria using linguistic values (Table 7). The following steps, similar to those in the fuzzy-rough LMAW decision matrix, lead to the development of an overall initial fuzzy-rough decision matrix. This includes converting to fuzzy numbers, establishing lower and upper limits for rough numbers, and creating the summary decision matrix using the geometric mean.

After the formation of the collective initial fuzzy-rough decision-making matrix, the matrix is expanded, and ideal and anti-ideal solutions are introduced. Then, the expanded decision-making matrix undergoes normalization. As the initial evaluations were in the form of linguistic values ranging from very bad to very good, all criteria are treated as benefit criteria (Expression 12). The following steps involve multiplying the normalized decision-making matrix values by the corresponding weighting coefficients. Since these are standard procedures in MCDM methods, they will not be explained here. The process continues with the summation of the weighted values for an individual supplier, resulting in the value $\overline{\overline{S}}_i$. Degrees of utility are then calculated concerning both the ideal solution $\overline{\overline{K}}_i^+$ and the anti-ideal solution $\overline{\overline{K}}_i^-$. In the utility degree concerning the ideal solution, the value for suppliers is divided by the ideal value. At the same time, in the utility degree concerning the anti-ideal solution, division is performed with the anti-ideal solution (Table 8).

Table 8. Calculation of the utility degree

	$\overline{\overline{S}}_i$						$\overline{\overline{K}}_i^+$						$\overline{\overline{K}}_i^-$					
IA	0.24	0.42	0.80	1.25	2.45	4.41												
S1	0.17	0.30	0.61	0.95	1.95	3.49	0.04	0.12	0.49	1.19	4.69	14.68	0.06	0.18	0.76	1.86	8.01	25.09
S2	0.16	0.28	0.58	0.90	1.86	3.33	0.04	0.12	0.46	1.13	4.47	13.98	0.05	0.17	0.72	1.76	7.64	23.89
S3	0.24	0.41	0.79	1.25	2.44	4.39	0.05	0.17	0.63	1.56	5.84	18.43	0.08	0.24	0.98	2.42	9.98	31.50
S4	0.15	0.27	0.56	0.87	1.81	3.25	0.03	0.11	0.45	1.09	4.35	13.66	0.05	0.16	0.69	1.70	7.43	23.34
S5	0.16	0.28	0.58	0.91	1.89	3.38	0.04	0.11	0.46	1.13	4.53	14.21	0.05	0.16	0.72	1.76	7.75	24.28
S6	0.21	0.36	0.72	1.10	2.25	3.96	0.05	0.14	0.57	1.38	5.39	16.66	0.07	0.21	0.89	2.14	9.21	28.48
AIA	0.14	0.24	0.51	0.81	1.69	3.04												

The final value according to the fuzzy-rough M-MARCOS method is obtained by averaging the utility degrees. Unlike the MARCOS method, there is no need to calculate the utility function or use a formula for the final value, which includes both the utility degree and the utility function [64]. This makes the application of the MARCOS method easier. The rankings from the M-MARCOS method show supplier 3 at the top, followed by supplier 6, while supplier 4 is ranked the lowest (Table 9).

Table 9. Result of the application of the M-MARCOS method

	$f\left(\overline{\overline{K}}_i\right)$						$f(K_i)$	Rank
S1	0.05	0.15	0.62	1.52	6.35	19.89	4.76	3
S2	0.05	0.14	0.59	1.44	6.05	18.94	4.54	5
S3	0.07	0.21	0.81	1.99	7.91	24.97	5.99	1
S4	0.04	0.13	0.57	1.39	5.89	18.50	4.42	6
S5	0.04	0.14	0.59	1.45	6.14	19.24	4.60	4
S6	0.06	0.18	0.73	1.76	7.30	22.57	5.43	2

To validate these results, a comparison with other MCDM methods will be conducted. Additionally, the role of criteria in supplier ranking will be explored through a sensitivity analysis.

4.2 *Comparative method and sensitivity analysis*

Comparative analysis is a common practice used to validate and ensure the reliability of results obtained [65, 66]. Its main goal is to confirm the quality of results [67, 68] and show that improvements or modifications produce better or similar outcomes compared to earlier versions of the method [69]. In this study, a comparative analysis will first compare the results of the M-MARCOS method with the MARCOS method, and then with other MCDM methods.

The comparison of results between the fuzzy-rough M-MARCOS and fuzzy-rough MARCOS methods reveals a consistent ranking order. A detailed analysis, including correlation analysis, reveals a perfect correlation (r = 1.00), indicating a consistent ranking. The main difference is in the numerical values; the fuzzy-rough MARCOS method produces smaller values compared to the M-MARCOS method. This difference comes from the decision to limit the MARCOS method results to the interval between zero and one. In contrast, the M-MARCOS method allows values greater than one because of its utility function and specific formula for deriving the final value [48]. As a result, the intervals between individual alternatives vary depending on the application of these different methods.

Once the ranking consistency between the M-MARCOS and MARCOS methods is confirmed, a wider comparison is made with other fuzzy-rough techniques, including fuzzy-rough Compromise Ranking of Alternatives from Distance to the Ideal Solution (CRADIS), fuzzy-rough Simple Additive Weighting (SAW), fuzzy-rough Additive Ratio Assessment (ARAS), fuzzy-rough Combined Compromise Solution (CoCoSo), fuzzy-rough Multi-Attributive Border Approximation area Comparison (MABAC), fuzzy-rough Weighted Product Method (WPM), and fuzzy-rough Weighted Aggregated Sum Product Assessment (WASPAS). To ensure fairness, all methods use the same fuzzy-rough decision matrix and identical weights. This consistency allows for a thorough comparison, considering aspects such as (1) different normalization techniques in MABAC, ARAS, and CoCoSo, (2) simplicity in SAW and WPM methods, and (3) the unique steps each method follows in obtaining results. The analysis aims to assess the impact of these different steps on the overall ranking results.

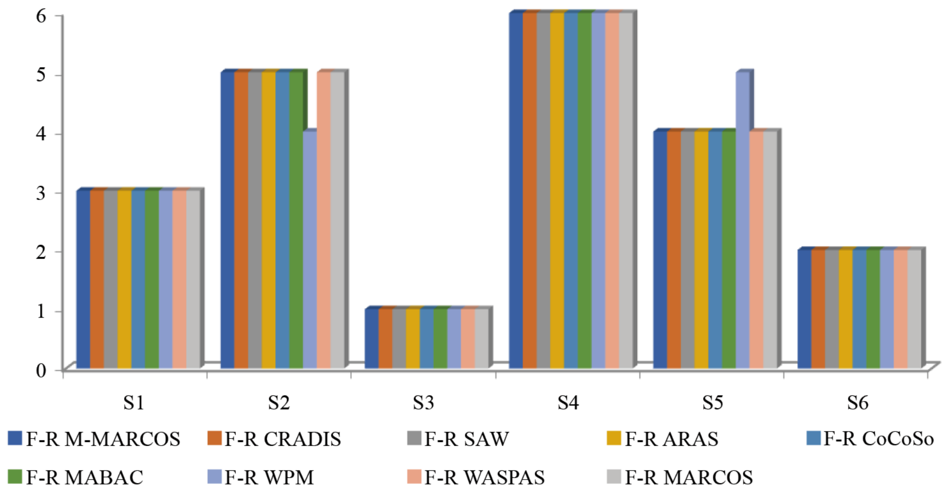

Figure 2. Results of comparative analysis

The application of various methods (Figure 2) generated consistent ranking orders across most methodologies, except for the fuzzy-rough WPM, where the ranking difference occurs between suppliers S2 and S5. In this method, S2 is ranked higher than S5 because of the unique nature of the normalized decision-making matrix. Unlike other methods, fuzzy-rough WPM scales the normalized decision matrix with appropriate weights without multiplying. Despite this difference, supplier S3 is the top performer across nine different methods.

After completing the comparison with other MCDM methods, the focus shifts to understanding how specific main and auxiliary criteria influence the ranking of alternatives. Sensitivity analysis can be performed in different ways, such as changing parameters inherent to the method [70, 71]. The most common approach involves adjusting the weight coefficients of criteria [72, 73]. Following the methodology used by Ahmadi et al. [74], a sensitivity analysis is conducted by increasing individual criterion weights by 2 or 3 times, while proportionally decreasing the weights of the other criteria. Two sensitivity analyses are performed based on the main and auxiliary criteria.

In the first sensitivity analysis, all auxiliary criteria within a main criterion are gradually increased by 2, 3, 4, ... up to 9 times, while auxiliary criteria within other main criteria are simultaneously decreased by the same amount. This process examines how suppliers behave when focusing solely on the auxiliary criteria of one main criterion while adjusting the values of auxiliary criteria for other main criteria. With eight cycles of increase and decrease across three main criteria, a total of 24 scenarios were evaluated. The weight calculation process for these scenarios was conducted as follows: all the weights of the auxiliary criteria within a specific main criterion were increased by a certain level. In contrast, the weights for the auxiliary criteria in the other two main criteria were proportionally decreased as the primary weights were increased. For example, if the weights of criteria from C11 to C16 increase by 3 times, then the weights of criteria from C21 to C36 decrease by 3 times. The increase and decrease are performed from 2 to 9 times.

Results from this analysis show that suppliers S3 and S6 consistently kept their ranking order across all scenarios, while other suppliers experienced changes (Figure 3). Supplier S1 showed stability in its ranking when the main economic and ethical criteria were increased, outperforming S2, S4, and S5. However, when the value of auxiliary criteria within the ecological criterion increased, supplier S5 improved its results, reflecting better evaluations in ecological criteria compared to S1. On the other hand, S5 ranked the lowest when the weight of ethical criteria was increased. Similar patterns appeared for S4 with increased economic criteria and for S2 when all ecological criteria were elevated. Overall, supplier S3 consistently achieved the top results across scenarios, followed by supplier S6, making them the preferred choices for establishing partner relationships.

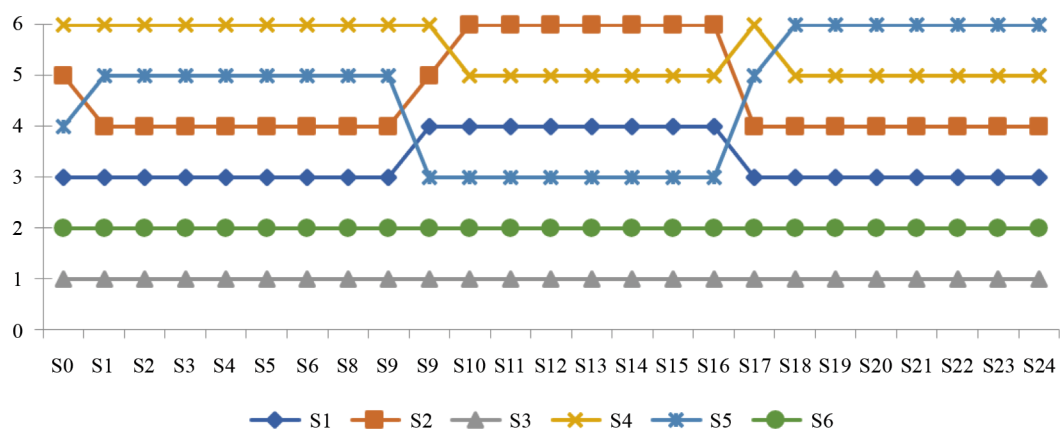

Figure 3. Sensitivity analysis using the main criteria

Statistically, these results indicate that the rankings of suppliers S3 and S6 remain unchanged, with a standard deviation (*SD* = 0.0000) between them, suggesting consistent rankings. The data also reveal that supplier S5 has the highest deviation (*SD* = 1.2247), experiencing the most fluctuations in its position. Regarding average rankings, the best results were achieved by supplier S3 (mean = 1.000), while the poorest average ranking was for supplier S4 (mean = 5.440). In addition to supplier S4, suppliers S2 and S5 also ranked poorly in several scenarios (Table 10).

Table 10. Descriptive statistical analysis of the first sensitivity analysis

Supplier	Min	Max	Mean	Standard deviation
S1	3	4	3.320	0.476
S2	4	6	4.640	0.907
S3	1	1	1.000	0.000
S4	5	6	5.440	0.507
S5	3	6	4.600	1.225
S6	2	2	2.000	0.000

Further analysis of the sensitivity analysis results will be performed using the Spearman correlation coefficient. This coefficient is appropriate for comparing the rank order of variables. Since the sensitivity analysis examines how changes in the criteria weights influence the rank order, it will be observed how the impact of these changes relates to the initial rank order, referred to as the zero (0) scenario. These rank orders were obtained using the fuzzy-rough M-MARCOS method, and the weights were determined with the fuzzy-rough LMAW method. Because some values are the same across certain scenarios, they will be presented together. The results (Table 11) show that the greatest deviation from the initial scenario occurs in scenarios S18-S24 ($r = 0.829$), where the weights of the ethical criteria were adjusted. In these scenarios, the rank order was altered for three suppliers, whereas in other scenarios, it was changed for only two suppliers. There is a significant statistical correlation between the rankings for all scenarios ($p < 0.05$). Based on this, it can be said that these rankings of different scenarios are related.

Table 11. Results of Spearman correlation coefficients for the first sensitivity analysis

	S1-S9	S10-S16	S17	S18-S24
S0	0.943	0.886	0.943	0.829
Sig.	0.005	0.019	0.005	0.042

The second sensitivity analysis involves increasing a single auxiliary criterion by 3, 6, and 9 times while simultaneously decreasing all other auxiliary criteria by the same amount. This method emphasizes the importance of a single auxiliary criterion over others and aims to examine how individual criteria affect supplier rankings. With 18 auxiliary criteria, each multiplied by 3, a total of 54 scenarios are analyzed. Unlike the previous sensitivity analysis, which examined a group of auxiliary criteria within a specific main criterion, this analysis focuses on each criterion individually. As a result, that single criterion receives priority over others by 3, 6, and 9 times. The calculation process remains the same as in the previous analysis: only individual auxiliary criteria are increased, while the remaining criteria are proportionally decreased to maintain balance. The results from this analysis (Figure 4) show variations in the rankings of all suppliers.

Starting with supplier S3, which emerged as the top choice in 52 scenarios and second in 2, a notable shift occurred when the auxiliary criterion C21—Pollution control was increased, where supplier S6 received higher evaluations from experts. Similarly, supplier S6 ranked third in one scenario, specifically in 24 scenarios where the value of auxiliary criterion C22—Environmental Management System increased ninefold, with supplier S5 securing second place. Following these two suppliers, the consistently third-ranked supplier was S1, which never fell to last place in any scenario. However, when two auxiliary criteria were changed, it dropped to fifth place. These criteria are C22—Environmental Management System and C35—Reputation. The remaining three suppliers at the bottom showed fluctuations based on the modified auxiliary criterion. In most scenarios, supplier S4 consistently presented the least favorable results. These outcomes provide actionable insights for the suppliers, guiding efforts to improve indicators and foster partnerships with more companies. It is important to note that while these rankings suggest some suppliers may be viewed as less favorable based on specific criteria, individual companies might prioritize different criteria, which can lead to varied outcomes when choosing a supplier.

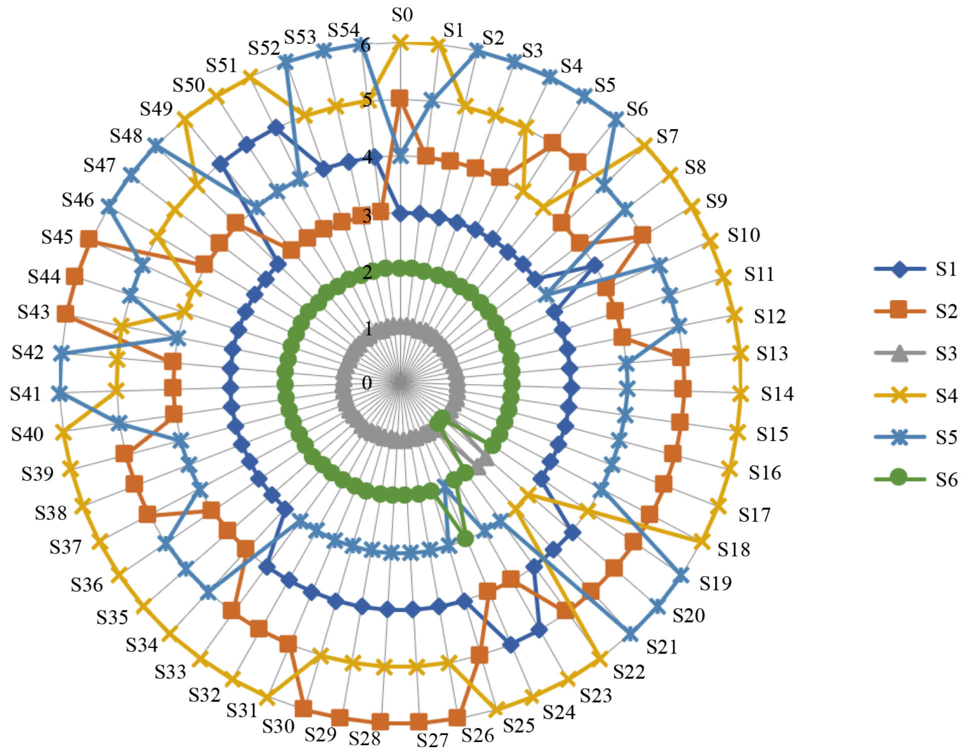

Figure 4. Sensitivity analysis using auxiliary criteria

The descriptive statistical analysis of the second sensitivity analysis reveals that there were changes in the ranking of all suppliers, resulting in a standard deviation value for each. The smallest deviation in the ranking is for supplier S23 (*SD* = 0.189), while the largest is for supplier S5 (*SD* = 1.183). Regarding the average ranking value, the lowest is for supplier S3 (mean = 1.036), and the highest is for supplier S4 (mean = 5.400). This indicates that supplier S3 was ranked first most often, while supplier S4 was ranked worst most frequently. Additionally, suppliers S2 and S5 were ranked worst in some scenarios, and supplier S6 was ranked best in two scenarios (Table 12).

Table 12. Results of Spearman correlation coefficients for the first sensitivity analysis

Supplier	Min	Max	Mean	Standard deviation
S1	3	5	3.423	0.663
S2	3	6	4.564	0.877
S3	1	2	1.036	0.189
S4	3	6	5.400	0.807
S5	2	6	4.546	1.183
S6	1	3	1.981	0.235

The application of Spearman correlation coefficients in the second sensitivity analysis was more complex to carry out and present, as each criterion was adjusted three times, resulting in a total of 54 scenarios (Table 13). During this analysis, it was evident that several scenarios produced the same ranking as the initial scenario. Specifically, these were scenarios S13-S18 and S37-S39. This indicates that changing the importance of criteria C5, C6, and C13 does not affect the ranking of the alternatives. Conversely, the largest shift in ranking occurred when the weight of criterion C7 was increased by 6 or 9 times ($r = 0.543$). This scenario has the highest significance, which shows that the rankings of scenario 7 and scenario 0 are not statistically significant at all. With this adjustment, only one supplier maintained the same position in the ranking, while the positions of the other suppliers changed. In addition, there is no statistical significance in other scenarios as the significance value is greater than 0.05 ($p > 0.05$).

Table 13. Results of Spearman correlation coefficients for the second sensitivity analysis

	S1	S2-S4	S5-S6	S7-S12	S13-S18	S19	S20-S21	S22	S23	S24
S0	0.943	0.829	0.771	0.943	1.000	0.771	0.543	0.943	0.829	0.714
Sig.	0.005	0.042	0.072	0.005	0.000	0.072	0.266	0.005	0.042	0.111
	S25	S26-S30	S31-S36	S37-S39	S40	S41-S42	S43	S44-S48	S49-S51	S52-S54
S0	0.943	0.886	0.943	1.000	0.943	0.829	0.943	0.829	0.771	0.714
Sig.	0.005	0.019	0.005	0.000	0.005	0.042	0.005	0.042	0.072	0.111

5. Discussion

The role of a supplier is crucial in any company's operations, particularly in global markets [75]. Choosing the right supplier is crucial for smooth business operations. However, a supplier must demonstrate competitiveness in the market to be considered for selection [76]. In this context, competitiveness is achieved by aligning with the goals set by customers and the broader market [77]. In addition to competitiveness, many aspects influence the supplier selection process. This research examines multiple criteria, including economic, ecological, and ethical criteria. The study by Menon and Ravi [57] highlighted these three criteria along with the social criterion. However, the social criterion is excluded here because it is assumed that ethical regulations within a company extend not only to employees but also to customers. This assumes that a company following ethical rules would prioritize customer well-being, thereby strengthening overall supply chain security. The criteria chosen provide a comprehensive framework for selecting suppliers.

To apply these criteria in supplier selection, MCDM methods are used in the decision-making process. These methods are especially helpful when evaluating multiple alternatives against various criteria. This research relies on expert decision-making based on linguistic evaluations. Company 3B involved five experts from different departments, ensuring comprehensive coverage of all business segments. The collaborative evaluation of six selected suppliers by these experts improves the coherence and consistency of their responses. When translating linguistic values into practical use, a fuzzy set is used, with a membership function that converts linguistic values into fuzzy numbers. Consistency in the linguistic scale for criteria and suppliers, along with the same membership function, enables easier decision-making. Incorporating a rough approach alongside the fuzzy method addresses uncertainty and reduces subjectivity in the decision process, strengthening the supplier selection mechanisms. This approach demonstrates a commitment to using thorough and objective criteria for supplier evaluation within the global business environment.

To implement the fuzzy-rough approach, two methods were selected: the fuzzy-rough LMAW for determining criteria weights and the fuzzy-rough M-MARCOS method for ranking the selected suppliers based on those criteria. The LMAW method was selected due to its ability to evaluate criteria independently, thereby eliminating the need for inter-criteria ranking or comparison. Decision-making was simplified as experts assessed the main and auxiliary criteria separately. Results for the main criteria evaluation showed that experts prioritized economic criteria over ethical and ecological considerations. Although there was a slight difference in weights, all criteria influenced the final decision. The auxiliary criteria results highlighted the significance of ecological criteria, which received higher weights than expected, despite their lower priority in the main criteria evaluation.

Following the determination of criteria importance, the M-MARCOS method was used to rank the selected suppliers. This method, a modification of the existing MARCOS method, ignores the calculation of the utility function and forms the ranking order based on the degree of utility [78]. Unlike the MARCOS method, the M-MARCOS method does not involve calculating the utility function, as the utility degree results directly contribute to the ranking. The absence of the utility function allows values to exceed one, a characteristic evident in this research due to the nature of operations within the fuzzy-rough approach.

The outcomes from applying the fuzzy-rough M-MARCOS method, based on expert evaluations, indicate that S3 is the top-ranked supplier, followed by S6. These suppliers demonstrate notable performance differences compared to the other observed suppliers, as indicated by the sensitivity analysis. Conducted in two ways, the sensitivity analysis aimed to understand the impact of both main criteria and individual auxiliary criteria on the final supplier ranking. The first sensitivity analysis involved linearly increasing all auxiliary criteria for one main criterion while simultaneously decreasing the weights of auxiliary criteria for the other two main criteria by the same amount. The second sensitivity analysis focused on increasing an individual auxiliary criterion while linearly decreasing all other auxiliary criteria. The initial sensitivity analysis demonstrated how the main criteria influence the final supplier ranking, highlighting the significant impact of ethical criteria. Specifically, with increased emphasis on ethical criteria, supplier S5 showed the least favorable results, despite being ranked fourth. This confirms that each criterion affects the final decision, emphasizing the importance of carefully selecting preliminary criteria in the supplier selection process. The following analysis explored how individual criteria influence the ranking. Since each criterion impacts the final ranking nearly equally, it is crucial to identify suppliers with weaker performance in specific areas to focus on improvements in future business interactions.

Further comparison of the results of the fuzzy-rough M-MARCOS method showed consistent ranking orders with other fuzzy-rough methods, except for the fuzzy-rough WPM method. The difference in ranking between suppliers S2 and S5 in the WPM method was due to the way normalized data was weighted within the decision matrix. However, the comparison revealed that the fuzzy-rough M-MARCOS method aligns with the ranking order of the MARCOS method. This alignment highlights the potential usefulness of the M-MARCOS method in future research and applications.

5.1 *Research implications*

Throughout this research, several important contributions have been identified. Primarily, the study emphasizes the significance of all criteria affecting supplier evaluation in decision-making processes. As a result, establishing research objectives initially is crucial, followed by choosing criteria that best align with these objectives. The research highlights the use of ethical criteria in supplier selection, showing their role in ranking suppliers and their contribution to improved decision-making confidence. However, the study recommends including additional criteria to make the decision-making process more comprehensive. Applying ethical criteria makes it easier for company managers to conduct business, as they are assured that the supplier will meet the requirements regarding goods and delivery through the application of ethical business practices. In this way, managers do not have to worry about purchasing from suppliers and can focus on solving other business problems within the company.

Another notable contribution of this research is the advancement of practical applications for the fuzzy-rough approach. Combining both fuzzy and rough methods, the study introduces the fuzzy-rough LMAW and fuzzy-rough M-MARCOS methods to simplify their implementation. The LMAW method makes it easier to determine criterion weights by requiring experts only to evaluate individual criteria without needing to rank or compare them. The goal is to understand the importance of each criterion to the expert. When using the M-MARCOS method, efforts are made to improve the usability of the MARCOS method, particularly in calculating the final value, which removes the need for utility function calculations and shortens the process compared to the traditional MARCOS method.

Furthermore, applying the fuzzy-rough approach allows for incorporating imprecise information, which is especially important when dealing with qualitative criteria that need evaluation. Using linguistic values is easier for users when assessing these criteria compared to traditional numerical ratings. This change aligns with human thinking, offering a more intuitive framework. The integration of the rough approach helps reconcile expert assessments by including uncertainty in decision-making and reducing subjectivity in the final evaluation. As a result, the outcomes are more reliable, increasing confidence in making the final decision.

5.2 *Limitations and future directions*

During the research process, some limitations have been identified, highlighting areas for improvement in future studies. Specifically, in the field of MCDM, the choice of methods used in this study may be a limitation. The selection of fuzzy-rough LMWA and fuzzy-rough M-MARCOS aimed to simplify the application of the fuzzy-rough approach and enhance expert decision-making. However, future research should include a wider range of methods to determine if alternative approaches may produce more optimal outcomes. Given that each method has its own set of advantages and disadvantages, this exploration will help develop a more complete understanding of the trade-offs involved in MCDM methods.

Further limitations stem from choosing auxiliary criteria, especially within the ethical criteria domain. Assigning certain auxiliary criteria, like reputation, under the ethical criterion might differ from common practices in other research areas. Future research should focus on creating clear guidelines for assigning auxiliary criteria to specific main criteria, which will improve consistency across studies. Furthermore, efforts should focus on identifying criteria that can meet multiple main criteria, encouraging a more refined decision-making process.

The use of the fuzzy-rough approach is recognized as a potential limitation because of its complexity. Decision-makers need to be familiar with fuzzy and rough set principles to use this method effectively. However, it is important to note that despite its complexity, the fuzzy-rough approach provides additional decision-making security by handling imprecise information and uncertainty. To address this limitation, this research attempted to simplify the approach by employing fuzzy-rough LMAW and M-MARCOS methods. Future studies should continue exploring ways to make the fuzzy-rough approach easier to understand, making it more accessible for decision-makers and encouraging its practical use. In future research, it is necessary to continue using the M-MARCOS method because it gives the same results as the MARCOS method, but it is easier to apply.

Furthermore, future research could investigate the challenges and practical implications of incorporating ethical criteria into supplier selection frameworks. Highlighting specific industries or situations where ethical considerations are especially important would further improve the relevance and usefulness of these frameworks. This could provide valuable insights into how ethical considerations evolve in supplier selection processes.

5.3 *Conclusions*

This research has introduced an innovative decision-making approach for supplier selection, covering economic, ecological, and ethical criteria. Significantly, it advances sustainable supplier selection by including ethical criteria instead of social criteria. This choice is based on the idea that a supplier following ethical standards is likely to apply these practices to all stakeholders, including employees and customers. While social criteria primarily focus on the well-being of a supplier's employees, ethical criteria provide a broader assurance that the supplier will establish stronger partnership relations, as demonstrated in the case of the 3B company.

The choice of the 3B company as the focus of this research was driven by the strict standards it must meet in the constantly changing food production landscape. Expanding into the European Union market requires both the 3B company and its packaging suppliers to comply with food safety and environmental standards. Economic criteria are crucial for helping the 3B company obtain quality products at a competitive price. The supplier selection process was supported by expert evaluations, using the fuzzy-rough approach to create the ranking list.

A hybrid methodology that combines the fuzzy-rough LMAW and M-MARCOS methods was used in this research. The fuzzy-rough LMAW method assigned weights to both the main and auxiliary criteria, while the M-MARCOS method ranked the evaluated suppliers. Among the six selected suppliers, S3 showed the most favorable results, making it the preferred choice for establishing partnerships. These findings were confirmed through comparisons with other fuzzy-rough methods. Additionally, the analysis showed that the results of the M-MARCOS and MARCOS methods were consistent. Notably, the fuzzy-rough WPM method ranked suppliers S2 and S5 differently. Sensitivity analyses highlighted how changes in the weights of main and auxiliary criteria affected supplier rankings. Two separate sensitivity analyses revealed that adjustments in criteria weights had a significant impact on the rankings of four suppliers. Nevertheless, the consistent top performance of S3, closely followed by S6, reinforces their status as the best options for forming partnerships with the 3B company.

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Conflict of interest

The authors declare no competing financial interest.

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