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Integrated Fuzzy SiWeC-CORASO Framework for Sustainable Supplier Selection in the Construction Industry

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ABSTRACT

The construction industry is confronted with the challenge of greenhouse gas emissions. Additionally, this industry is responsible for CO2 emissions through its supply chain operations and the production of construction materials. To address this issue, this research investigates the role of suppliers in the decarbonisation process. Selecting a supplier is a strategic choice for every organization. The goal of this research is to evaluate suppliers of modular materials for the purpose of reducing CO2 emissions in the construction industry. In this research, four generic suppliers were analysed based on 11 criteria. The evaluation of these suppliers was conducted using seven companies involved in the construction of modular homes. A fuzzy approach was employed to assess the significance of these criteria and to evaluate the degree to which suppliers fulfill these established objectives. By utilizing the fuzzy SiWeC (Simple Weight Calculation) technique, the significance of the criteria was analyzed, revealing that the foremost criterion in the selection of suppliers is waste management and recycling. Suppliers were ranked through the fuzzy CORASO (Compromise Ranking from Alternative Solutions) method, demonstrating that a large international supplier best meets the established goals. The research conducted indicated that with the appropriate selection of suppliers, it is feasible to impact the reduction of carbon dioxide emissions within the construction industry.

1. Introduction

The global tendency towards decarbonization is influenced by the international regulatory frameworks established by the European Green Deal and the Carbon Border Adjustment Mechanism (CBAM). Additionally, the increasing expectations of investors and consumers have placed emissions within supply chains at the forefront of sustainability discussions [1, 2]. It is particularly crucial to emphasize indirect emissions, referred to as Scope 3 emissions, which

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predominantly occur in supply chains and constitute the largest portion of the carbon footprint [3]. Tackling these emissions necessitates not only technological advancements but also strategic choices in the selection of suppliers.

Consequently, the selection of suppliers emerges as a crucial strategic decision that affects both economic and environmental efficiency [4]. Traditional methods, which were mainly focused on the lowest price, are no longer viable in a context where supply chains are required to be not only efficient [5, 6] but also in accordance with environmental, social, and corporate responsibility (ESG) standards [7]. The challenge resides in the systematic assessment and balancing of various, often contradictory criteria – including cost, quality, carbon footprint, energy efficiency, and social responsibility – during the supplier selection process [8, 9].

The objective of this research is to create and implement a comprehensive framework for multi-criteria decision-making (MCDM), which integrates the fuzzy SiWeC (SImple WEight Calculation) and CORASO (COMpromise Ranking from Alternative SOlutions) methods. This framework aims to facilitate the sustainable selection of suppliers within the construction industry, thereby contributing to a reduction in CO_2 emissions produced by this industry. According to the Global Alliance for Buildings and Construction [10], this industry represents a considerable portion of global CO_2 emissions, making it imperative to decrease these emissions. In addition, suppliers are key factors in any supply chain, because materials and raw materials are procured from them. If these raw materials and materials are of high quality, the final product will be of high quality. To achieve this objective, the research will address the following research questions:

i. What are the key criteria that should be considered when evaluating suppliers in the construction industry?
ii. Which suppliers should be chosen for the procurement of materials and raw materials to minimize CO_2 emissions?
iii. What actions should construction companies implement to lower CO_2 emissions?

This paper makes significant contributions to the existing literature on multiple fronts. Firstly, it broadens the set of criteria typically employed in supplier selection by incorporating environmental, economic, and socio-operational dimensions into a more comprehensive ESG framework. While prior research has predominantly concentrated on economic factors, and more recently on environmental considerations, socio-operational criteria such as working conditions, ethics, transparency, and reputation have been insufficiently explored [11]. Secondly, within the construction industry, only one study has been published thus far, conducted by Tushar et al. [12] which addressed supplier selection based on circular economy principles. The authors utilized the construction industry of Bangladesh, a developing nation, as a case study. Their findings indicated that suppliers of recycled materials with enhanced logistics and reduced waste content received better rankings compared to those who competed exclusively on price.

In contrast to the aforementioned research, this paper centers on the construction industry in Croatia, a member of the European Union (EU), where regulatory pressures, investor expectations, and market standards are considerably elevated. Furthermore, it offers deeper insights into the variations in the supplier selection process concerning the institutional and regulatory framework. By developing a conceptual model for supplier selection, construction companies are equipped with a structured tool for making procurement decisions, which are in line with the objectives of minimizing Scope 3 emissions and conforming to European sustainability policies.

The paper presents multiple scientific contributions, both methodological and practical, aimed at addressing the case study, specifically: 1) a set of criteria for selecting suppliers in the construction industry is established, taking into account economic, ecological, social-operational, and ethical factors, as well as transportation and supplier reputation; 2) low carbon optimization was implemented in the supply chain, focusing on supplier selection within the construction industry; 3) a case study involving generic suppliers in Zadar County, Republic of Croatia was conducted; 4) a fuzzy MCDM model was created and qualitatively validated.

The paper is composed of six chapters in total. The second chapter focuses on the literature review, underscoring the significance of evaluating supplier selection within the construction industry. Additionally, it emphasizes the necessity of incorporating comprehensive ESG criteria in the supplier selection process. The third chapter outlines the research methodology, while the fourth chapter showcases the findings from the empirical research. The fifth chapter offers a discussion and implications, and the sixth chapter concludes with findings, contributions, and suggestions for future research.

2. Literature review

Initial supplier selection models predominantly emphasized economic factors such as price, quality, and delivery reliability, whereas environmental and social considerations were largely overlooked [13]. Nevertheless, due to the increasing focus on sustainable development and the influence of regulatory frameworks, particularly within the European Union and global efforts to mitigate greenhouse gas emissions, research in the area of "green supplier selection" has broadened the criteria to encompass ecological factors [3]. In this regard, there is a growing trend to incorporate criteria such as CO_2 emissions, utilization of renewable energy sources, waste recycling, and eco-friendly packaging into the supplier selection process.

Althaqafi et al. [8] specifically highlight the significance of incorporating environmental and economic criteria, illustrated through the automobile industry. Their research demonstrates that the inclusion of social and environmental factors can notably alter the supplier rankings when compared to conventional models that focus solely on price and quality. In a similar vein, Abuzaid et al. [9] apply multi-criteria methods such as AHP and TOPSIS, using the electronics industry as a case study, to reconcile price, quality, and delivery with sustainability criteria. The findings indicate that the transparency and reputation of suppliers are becoming increasingly vital. The research findings indicate that the transparency and reputation of suppliers are becoming increasingly more significant.

In the chemical industry, advanced models have been created that connect economic, environmental, and social criteria. For instance, the application of fuzzy AHP and the CoCoSo methods has enabled the ranking of suppliers according to the Triple Bottom Line, demonstrating that factors such as employee safety and social responsibility can hold equal significance to price [11]. In the food and packaging industry, the emphasis is frequently placed on green materials, recyclability, and food safety, while also ensuring competitive pricing and reliable delivery, which further underscores the necessity of incorporating environmental and social factors [3].

While an integrated methodology that merges economic, environmental, and socio-operational criteria is becoming more prevalent across various industries, such research is still infrequent within the construction industry. A notable exception is the research conducted by Tushar et al. [12], which investigates supplier selection in Bangladesh's construction industry, a developing nation, utilizing the FAHP and PROMETHEE II methods. The findings indicate that suppliers providing recycled materials, along with more efficient logistics and reduced waste levels, attain superior rankings compared to those that focus exclusively on price. Nevertheless, despite addressing environmental and operational factors, this study falls short by not incorporating the comprehensive ESG framework, particularly social criteria such as working conditions, ethics, and transparency of reporting.

This is exactly where the research gap exists, which this paper aims to address. In contrast to earlier studies, this paper combines economic, environmental, and socio-operational criteria within the framework of the construction industry, using the Republic of Croatia as a case study. This sector is experiencing rapid growth and constitutes a substantial portion of the Croatian economy, while simultaneously facing rising demands for sustainability and emission reduction. Labor and construction expenses are the primary challenges confronting this industry [14].

The construction industry ranks as one of the most significant contributors to global greenhouse gas emissions. As reported by the Global Alliance for Buildings and Construction [10], it accounts for roughly 39% of worldwide CO_2 emissions, including 11% attributed to what is termed "embodied carbon," which refers to emissions that are integrated into building materials and their supply chains. This underscores the vital importance of suppliers in the comprehensive decarbonization efforts within the construction industry.

With the implementation of the Corporate Sustainability Reporting Directive (CSRD) and the EU taxonomy for sustainable activities, construction companies in Croatia and other member states are required to provide transparent reports on sustainability, which encompasses emissions associated with suppliers [1]. This establishes ESG criteria in procurement as a means of adhering to regulations and mitigating regulatory risk [15].

The financial aspect further highlights the significance of this subject. Investors and financial institutions are progressively requiring ESG indicators as a prerequisite for funding substantial infrastructure initiatives. Companies that exhibit proficiency in managing their supply chains sustainably enjoy improved access to capital and more advantageous financing conditions [2].

The social dimension is equally significant. The construction industry frequently encounters criticism regarding emissions, resource depletion, and the working conditions present at construction sites. Collaborating with suppliers that possess certifications like ISO 14001, FSC, EPD, or SA8000 can enhance reputation and mitigate the risk of adverse publicity [3].

Ultimately, operational resilience and innovation are essential in a globally unstable environment. Suppliers that adopt ESG criteria tend to invest more frequently in innovative materials and processes, including eco-concrete, recycled steel, or CLT (cross-laminated timber), which enhances the resilience of supply chains and lowers costs over the long term [16-18].

The aforementioned points indicate that selecting suppliers in the construction industry from an ESG perspective is not merely a matter of sustainability; it is also a strategic necessity. This selection process has a simultaneous impact on the reduction of Scope 3 emissions, adherence to European regulations, access to financing, corporate reputation, and the resilience of the supply chain. It is crucial to examine the current practices within the construction industry to establish guidelines and recommendations for the future based on the existing circumstances. This approach not only aids in environmental preservation and alignment with European Union policies but also enhances awareness regarding the significance of sustainability and promotes more responsible and sustainable competitive practices within the sector. Involving industry experts guarantees the relevance of the research findings, while employing the SiWeC and CORASO methodologies facilitates a thorough evaluation of suppliers that aligns with ESG objectives.

3. Methodology and research methods

This research sought to investigate the impact of supplier selection on CO_2 emissions within the construction industry. Accordingly, this research is structured to assess generic suppliers. A total of four suppliers were chosen for evaluation in these surveys, specifically:

- The local supplier of construction materials (SUP1) is situated close to the construction site, which is marked by short transportation routes. The benefits of this supplier are evident in reduced costs and lower CO_2 emissions during transport, as well as quicker delivery times. The drawback of this supplier is evident in its restricted innovation and partial sustainability in its business operations.
- The national producer of construction materials (SUP2) is situated within the country, albeit outside the region, and is characterized by medium-distance transportation. The benefits of this supplier are evident in consistent availability and a broader selection of materials. The drawback of this supplier is reflected in increased costs and extended transport routes.
- The local provider of recycled construction materials (SUP3) is situated within the same city or region, characterized by notably short transportation routes. This supplier's advantage is evident in the utilization of recycled building materials, which leads to decreased emissions in logistics and supports the advancement of the circular economy. The drawback of this supplier is reflected in inconsistent material quality, and the quantities available are frequently restricted.
- A large international supplier possessing certificates (SUP4) is situated in various countries, whether within the EU or globally, and has specific extended transport routes. The benefits of this supplier are evident in the presence of multiple certifications (ISO, EPD, FSC), as well as in their high reliability and stability of deliveries. The drawback of this supplier includes increased CO_2 emissions resulting from transportation and a more intricate supply chain.

To assess these four suppliers, it was essential to first identify who would conduct the evaluation. This research involved selecting construction companies situated in Zadar County that specialize in the construction of modular houses. The unique characteristic of these houses is that they are composed of modules that can be combined, providing a versatile product in the form of a residential dwelling. Modular houses are prefabricated structures made up of multiple modules. They are manufactured in a factory, subsequently transported to the site, and assembled into a complete unit. These modules can be arranged either horizontally or vertically, leading to various square footage and room configurations. In contrast to traditional buildings, these houses can be expanded, reconfigured, or even relocated to a different site. They are well-regarded due to their ability to provide a rapid solution to the housing dilemma for purchasers, and their pricing is significantly more advantageous compared to traditional homes. In Zadar County, these houses are manufactured by a limited number of companies; therefore, seven companies were chosen as respondents for this research. Their task is to assess these suppliers based on the 11 selected criteria (Table 1). These criteria are distinctive as they encompass ecological, economic, and social factors in the supplier selection process. They embody traditional sustainability standards, with this research particularly emphasizing ecological criteria and CO_2 emissions from the suppliers.

To ascertain which type of supplier aligns best with the established criteria, an evaluation is conducted utilizing linguistic values. These values are employed due to the specific criteria outlined in this research. Qualitative criteria are applied, which are characterized by the challenge of providing a numerical assessment; however, it is more straightforward to assess them using linguistic values. It is simpler for the decision-maker to determine whether an option is good or bad, somewhat good or somewhat bad, and so forth, rather than to provide an exact numerical evaluation. Consequently, in this research, assessments were articulated in the form of linguistic values with seven levels, ranging from very bad to very good. Nevertheless, to utilize these assessments for evaluating the significance of the criteria as well as the suppliers, a fuzzy approach was adopted. This approach facilitates the application of linguistic values, where the value of the fuzzy number is established through the membership function (Table 2). Fuzzy numbers allow for the representation of a certain linguistic value without assigning an exact figure, instead depicting that value as a triangular fuzzy number. This triangular number comprises a lower value, an upper value, and a middle value (Table 2).

Table 1
Criteria for evaluating module suppliers

Id	Criterion	Description
C1	Product Carbon Footprint	It highlights the significance of the product regarding reduced CO_2 emissions
C2	Energy Management	Utilization of renewable energy sources by suppliers.
C3	Waste Management and Recycling	Utilization of recycled waste and adherence to the principles of a circular economy by suppliers.
C4	Green Packaging	Utilization of recycled and easily recyclable packaging by suppliers.
C5	Product Price	It signifies that the products obtained from the supplier are cost-effective.
C6	Product Quality	It denotes that the product is dependable and free from defects.
C7	Logistics Performance	They assess whether the supplier delivers products accurately and punctually.
C8	Logistics Costs	It implies that transportation costs are minimal and efficient.
C9	Reputation and Certifications	It indicates that the suppliers possess international certifications and a strong reputation.
C10	Technological Capacity	It reflects the supplier's capability to implement innovation and achieve technological advancement.
C11	Labor Conditions and Ethics	Adherence to labor and ethical standards by suppliers.

Table 2
Linguistic value and membership functions

Linguistic values	Id	Fuzzy numbers
Very bad	V-B	(1, 1, 2)
Bad	B-A	(1, 2, 3)
Medium bad	M-B	(2, 3, 4)
Equal	E-Q	(4, 5, 6)
Medium good	M-G	(6, 7, 8)
Good	G-O	(7, 8, 9)
Very good	V-G	(8, 9, 9)

The task of these companies is to evaluate the significance of these criteria for them and to assign a rating represented by linguistic values. Subsequently, they assess suppliers based on these criteria and the corresponding linguistic values. Following this, it is essential to gather and process these values, which is accomplished through MCDM methods. In this research, the fuzzy SiWeC and CORASO methods were selected for use. The choice of these methods was made because these are newer MCDM methods and they need to be promoted in research, and the steps of these methods are simple and enable very fast results.

The fuzzy SiWeC method will be employed to assess the significance of criteria according to company ratings. This approach is categorized under the methods for subjectively evaluating the weight of criteria [19]. The distinctiveness of this method is illustrated in the following:

- Evaluating the importance of criteria is done by assigning linguistic values to individual criteria where criteria do not have to be compared with each other, and it is not necessary to rank these criteria as in other methods [20].
- Data normalization is used, as is done with methods for determining the ranking of alternatives.

- Company ratings are evaluated based on the deviation of these ratings from the central value, and the influence of individual companies in the ranking is determined based on the value of the standard deviation.

Due to the specific characteristics of the fuzzy SiWeC method, it was selected for this research. The implementation steps for this method are as follows:

Step 1. Assessment of criteria by companies. In this step, companies evaluate the significance of each criterion and provide an assessment using linguistic values.

Step 2. Conversion of linguistic values. In this step, linguistic values are converted into corresponding fuzzy numbers through the application of defined membership functions.

Step 3. Normalization of fuzzy numbers. In this step, each fuzzy number is divided by the maximum value of the fuzzy number for specific criteria.

$$\tilde{n}_{ij} = \frac{x_{ij}^{l}}{max\ x_{ij}^{u}}, \frac{x_{ij}^{m}}{max\ x_{ij}^{u}}, \frac{x_{ij}^{u}}{max\ x_{ij}^{u}} \qquad (1)$$

Where $max\ x_{ij}^{u}$ represents the highest value of the fuzzy number.

Step 4. Calculation of standard deviation ($st.dev_j$). In this step, the standard deviation value is utilized to assess the variability of the company's ratings and the extent to which they diverge from the average value. A higher dispersion in the ratings indicates a greater significance of that company in determining the final weight.

Step 5. Weighting of normalized values. In this step, the normalized values of the fuzzy numbers are multiplied by the standard deviation values.

$$\tilde{v}_{ij} = \tilde{n}_{ij} \times st.dev_j \qquad (2)$$

Step 6. Calculation of the total weights. In this step, the weighted values for each criterion are summed up.

$$\tilde{s}_j = \sum_{j=1}^{n} \tilde{v}_j \qquad (3)$$

Step 7. Establishment of criteria weights. In this step, the individual values of the collective weights are divided by the overall total of these weights.

$$\tilde{w}_j = \frac{s_j^{l}}{\sum_{j=1}^{n} s_j^{u}}, \frac{s_j^{m}}{\sum_{j=1}^{n} s_j^{m}}, \frac{s_j^{u}}{\sum_{j=1}^{n} s_j^{l}} \qquad (4)$$

Based on these steps, the significance of the criteria is established through the weighting of these criteria.

The fuzzy CORASO method will be employed to identify which suppliers most effectively satisfy the established criteria according to company ratings. The uniqueness of this method lies in its novelty, as it has not yet been widely adopted in practice, thus it is being advocated in this manner. A notable feature of this method is that it produces results that are comparable to those of other MCDM methods. Furthermore, this method demonstrates strong consistency in the ranking of alternatives [21]. For these reasons, this method was selected for use in this research. The steps involved in this method are as follows:

Step 1. Assessment of suppliers through the application of linguistic values. In this step, similar to the criteria, companies assess suppliers using the chosen criteria. They assign scores in the form of linguistic values.

Step 2. Conversion of linguistic values. In this step, the linguistic values are converted into fuzzy numbers according to the established membership function (Table 2). Given that a greater number of companies are involved in this research, it is essential to create a collective decision-making matrix. This matrix is constructed by calculating the average fuzzy numbers for all participating companies. Consequently, each company is afforded equal significance in the supplier ranking process.

Step 3. Normalization of fuzzy numbers. This step is executed in a manner akin to the fuzzy SiWeC method, with the distinction that the single highest value for each criterion is utilized.

$$n_{ij} = \frac{x_{ij}^{l}}{\max x_j^{u}}, \frac{x_{ij}^{m}}{\max x_j^{u}}, \frac{x_{ij}^{n}}{\max x_j^{u}} \quad (5)$$

Where: $x_{j\ max}$ – maximum value of each criterion.

Step 4. Identification of alternative solutions. In this step, alternative solutions are identified. The maximum alternative solution ($max\ AS$) signifies the highest value provided by the supplier for each criterion. The minimum alternative solution ($min\ AS$) indicates the lowest value offered by the supplier for each specific criterion.

Step 5. Assigning weights to normalized data. In this phase, the normalized values are multiplied by the respective weights of the criteria derived from the fuzzy SiWeC method.

$$\tilde{v}_{ij} = \tilde{w}_j \cdot \tilde{n}_{ij} \quad (6)$$

Step 6. Calculation of aggregate values of alternatives. In this step, the total values for all alternatives are computed, meaning that the values of the alternatives across all criteria are summed up.

$$\tilde{S}_j = \sum_{i=1}^{n} \tilde{v}_{ij} \quad (7)$$

Step 7. Calculation of deviations from alternative solutions. In this step, the deviation from both the maximum and minimum alternative solutions is determined.

$$\tilde{R}_j = \frac{\tilde{S}_j}{\tilde{S}_{j\ max\ AS}} \quad (8)$$

$$\widetilde{R'}_j = \frac{\tilde{S}_{j\ min\ AS}}{\tilde{S}_j} \quad (9)$$

Step 8. Defuzzification. This step aims to derive crisp values from fuzzy numbers.

$$R_{j\ def} = \frac{R_i^{l} + 4R_i^{m} + R_i^{u}}{6} \quad (10)$$

$$R'_{j\ def} = \frac{R'^{l}_i + 4R'^{m}_i + R'^{u}_i}{6} \quad (11)$$

Step 9. Calculation of the CORASO method's value.

$$Q_i = \frac{R_j - R'_j}{R_j + R'_j} \quad (12)$$

The best alternative is identified by the highest value according to the CORASO method, and vice versa. Therefore, this method will ascertain which supplier most effectively fulfills the established research criteria.

Following the ranking of suppliers, a sensitivity analysis will be conducted. The aim of this analysis is to assess the extent to which a specific criterion influences the ranking of suppliers. Sensitivity analysis can be executed in various manners [22-23]. In this research, the significance of one criterion will be diminished, while the significance of the other criteria will be proportionately elevated [24]. The individual criteria will be decreased by 30%, specifically at 30%, 60%, and 90%, while the values of the remaining criteria are proportionately increased to ensure that the total of these criteria is roughly equal to three (3). Consequently, each individual criterion will be reduced threefold, and given that there are 11 criteria, a total of 33 scenarios will be executed. Should the ranking order of any supplier decline as a result of this criterion reduction, it indicates that the supplier had a superior value for that criterion compared to the supplier that now holds a better ranking order in relation to it. This observation can also be interpreted in reverse. If a supplier's ranking improves, it necessitates an enhancement in that criterion to achieve a better overall ranking.

The methodology and research methods' implementation can be illustrated graphically (Figure 1) to enhance the transparency of the methodology.

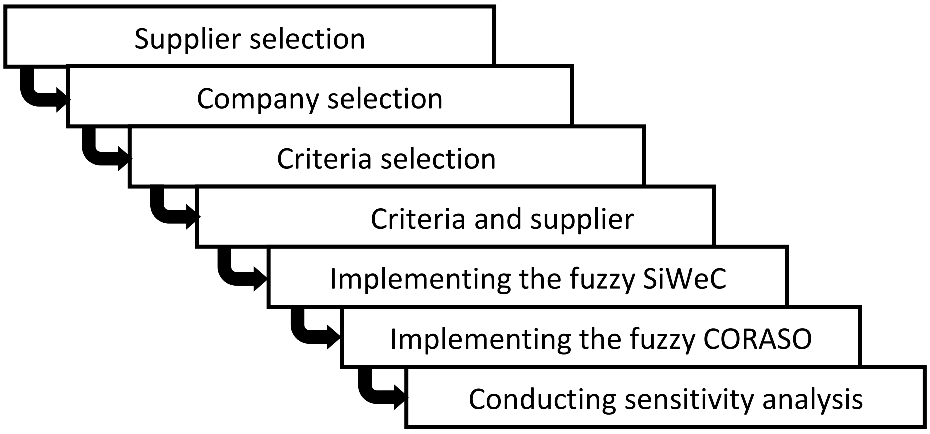

Fig. 1. Research methodology

4. Results

When utilizing the MCDM method, it is essential to first determine the significance of the criteria before ranking the alternatives. Consequently, the fuzzy SiWeC method will be applied first, followed by the steps of the fuzzy CORASO method. The initial step of implementing the fuzzy SiWeC method involves assessing the importance of criteria by companies through linguistic values (Table 3). Subsequently, these values are converted into fuzzy numbers in the second step. This conversion is executed in such a manner that each linguistic value is matched with a corresponding fuzzy number according to the established membership function (Table 2).

Table 3
Evaluation of the importance of criteria

Alt.	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
Company 1	V-G	V-G	V-G	E-Q	V-G	V-G	V-G	V-G	V-G	M-B	M-G
Company 2	B-A	E-Q	M-G	G-O	E-Q	E-Q	E-Q	M-G	E-Q	E-Q	M-G
Company 3	V-G	V-G	M-G	M-G	G-O	V-G	V-G	G-O	G-O	G-O	G-O
Company 4	M-G	M-G	V-G	V-G	M-G	V-G	V-G	M-G	M-G	E-Q	V-G
Company 5	V-G	V-G	V-G	V-G	E-Q	V-G	V-G	M-G	E-Q	E-Q	V-G
Company 6	V-G	V-G	V-G	V-G	E-Q	V-G	V-G	E-Q	V-G	V-G	V-G
Company 7	E-Q	M-G	M-G	M-G	G-O	G-O	G-O	G-O	M-G	M-G	M-G

After the conversion to fuzzy numbers is completed, the subsequent step involves normalizing these numbers. Given that the maximum value of a fuzzy number is nine (9), all values are divided by this figure. For instance, in the case of the linguistic value 'very good', its corresponding fuzzy number (8, 9, 9) is divided by nine. The calculation is performed as follows:

$\tilde{n}_{11} = \frac{8}{9} = 0.89, \frac{9}{9} = 1.00, \frac{9}{9} = 1.00.$

Subsequently, the standard deviation values are computed in the following step. This value serves to assess the ratings provided by companies. The aim of this step is to either diminish or amplify the significance of individual companies' ratings in relation to the deviation of these ratings from the average value. Following this, the weighting is performed in such a manner that the normalized values of the fuzzy numbers are multiplied by the standard deviation values (equation (2)). Next, the collective weights are determined (equation (3)), and ultimately, the weight of the criteria is calculated (equation (4)). The findings from this methodology indicate that the most critical criterion for companies is C3 - Waste management and recycling, succeeded by criteria C6 - Product quality and C7 - Logistics performance (Table 4).

Table 4
Total and final criteria weights

	C1	C2	C3	C4
$\tilde{s}_j$	0.792, 0.921, 0.975	0.887, 1.017, 1.070	0.941, 1.071, 1.119	0.867, 0.996, 1.069
$\widetilde{w}_j$	0.069, 0.087, 0.106	0.078, 0.096, 0.116	0.082, 0.101, 0.122	0.076, 0.094, 0.116
	C5	C6	C7	C8
$\tilde{s}_j$	0.728. 0.857. 0.963	0.935. 1.065. 1.101	0.935, 1.065, 1.101	0.815, 0.945, 1.050
$\widetilde{w}_j$	0.064. 0.081. 0.105	0.082. 0.100. 0.120	0.082, 0.100, 0.120	0.071, 0.089, 0.114
	C9	C10	C11	
$\tilde{s}_j$	0.789, 0.919, 1.005	0.610, 0.740, 0.851	0.905, 1.034, 1.107	
$\widetilde{w}_j$	0.069, 0.086, 0.109	0.053, 0.070, 0.092	0.079, 0.097, 0.120	

Once the weights of the criteria have been established, the suppliers' ranking is ascertained. This process utilizes the steps outlined in the fuzzy CORASO method. The initial step of this method involves assessing suppliers based on the chosen criteria (Table 5). In this step, companies evaluated generic suppliers against the selected criteria. Subsequently, the linguistic values are converted in a manner similar to that of the criteria. Following this, the collective decision-making matrix is determined. This decision matrix is created by computing the average fuzzy numbers for all companies involved. By adhering to this principle, all companies are equally engaged in the supplier assessment.

Table 5
Total and final criteria weights Table 5. Evaluation of suppliers using linguistic values

Company 1	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
SUP1	G-O	V-G	V-G	E-Q	V-G	V-G	G-O	V-G	V-G	M-G	V-G
SUP2	M-G	V-G	G-O	E-Q	V-G	V-G	E-Q	V-G	V-G	V-G	G-O
SUP3	V-G	V-G	V-G	V-G	V-G	V-G	V-G	V-G	V-G	E-Q	E-Q
SUP4	E-Q	M-G	E-Q	E-Q	V-G	V-G	V-G	V-G	V-G	V-G	M-G
Company 2	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
SUP1	M-B	M-B	G-O	E-Q	V-G	V-G	V-G	V-G	V-G	V-G	V-G
SUP2	M-G	E-Q	M-G	M-G	V-G	V-G	V-G	V-G	M-G	G-O	G-O
SUP3	E-Q	M-G	V-G	V-G	V-G	G-O	G-O	G-O	E-Q	G-O	M-B
SUP4	M-B	M-B	M-G	E-Q	V-G	V-G	V-G	V-G	G-O	G-O	G-O
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Company 7	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
SUP1	E-Q	E-Q	E-Q	E-Q	E-Q	E-Q	E-Q	E-Q	E-Q	M-G	M-G
SUP2	E-Q	M-G	M-G	M-G	M-G	M-G	M-G	M-G	M-G	M-G	E-Q
SUP3	M-G	M-G	E-Q	M-G	M-G	M-G	E-Q	E-Q	M-G	M-G	E-Q
SUP4	G-O	G-O	G-O	M-G	M-G	M-G	M-G	M-G	G-O	G-O	M-G

Once the collective decision-making matrix has been established, alternative solutions are identified. These solutions essentially reflect the highest values for suppliers based on specific criteria, or the lowest values for suppliers based on specific criteria. The subsequent step involves normalizing this decision-making matrix. Unlike the normalization process utilizing fuzzy SiWeC, the fuzzy CORASO method involves division by the maximum value of the fuzzy number corresponding to each individual criterion (equation (5)). Following this, the normalized data is weighted, where these values are multiplied by the respective weights of the criteria (equation (6)).

The subsequent step involves calculating the aggregate value of the alternatives. In this step, the individual values of complex fuzzy numbers are summed for each alternative, which includes both the maximum and minimum alternative solutions (equation (7)). Next, the calculation of deviations from the alternative solutions is performed. To compute the deviation from the maximum alternative solution, the individual values are divided by the values of this solution (equation (8)). In determining the deviation from the minimum alternative solution, the values of this alternative are divided by the values of all other alternatives (equation (9)). Following this, the defuzzification of these deviations is carried out (equation (10) and (11)), and ultimately, the final value of the fuzzy CORASO method is computed (equation (12)). The findings from this approach indicate that the highest-ranked supplier is SUP4, which is an international large supplier with certifications, followed by supplier SUP2, a national manufacturer of construction materials, while the lowest-ranked supplier is SUP3, a local supplier of recycled construction materials (Table 6).

Table 6
Results of supplier ranking using the fuzzy CORASO method

	$\tilde{S}_j$	$\tilde{R}_j$	$\widetilde{R'}_j$	$R_{j\,def}$	$R'_{j\,def}$	Q_i	Rank
SUP1	0.60, 0.87, 1.17	0.49, 0.93, 1.78	0.49, 0.96, 1.88	0.998	1.033	-0.017	3
SUP2	0.63, 0.90, 1.22	0.51, 0.97, 1.85	0.47, 0.92, 1.79	1.039	0.991	0.024	2
SUP3	0.60, 0.87, 1.17	0.49, 0.93, 1.78	0.49, 0.96, 1.88	0.998	1.034	-0.018	4
SUP4	0.64, 0.92, 1.22	0.52, 0.98, 1.86	0.47, 0.91, 1.77	1.050	0.978	0.036	1
MAX AS	0.66, 0.93, 1.24						
MIN AS	0.57, 0.83, 1.14						

Once a supplier is chosen that aligns most closely with the research objectives, a sensitivity analysis is conducted. Sensitivity analysis serves as a mechanism to identify potential errors in the computation of weight coefficients [25-26]. The primary aim is to assess the extent to which the ranking of alternatives (suppliers) is influenced by variations in the weight coefficients of the criteria [27]. It is anticipated that significant changes in the ranking of alternatives will occur with substantial modifications to the weight coefficients; however, generally, drastic changes are not expected [28]. Considerable shifts in the ranking of alternatives may signal a possible issue with the selection of the optimal alternative, necessitating the use of alternative analytical methods or potentially restarting the entire process of defining weight coefficients [29]. Modifications to weight coefficients are typically executed through changes in the coefficients themselves [30-31]; however, they may also be applied through alternative methods depending on the employed techniques [32-33]. In this study, 33 scenarios were analyzed (figure 2). The results indicated that the rankings for suppliers SUP4 and SUP2 remained unchanged. They consistently held the first and second positions in the ranking hierarchy, demonstrating a significant deviation from the other two suppliers, as the adjustments in the weight of the criteria did not influence the ranking order of these suppliers. The sensitivity analysis revealed that the ranking order of suppliers SUP3 and SUP1 is affected by changes in the weights of the criteria. In 15 scenarios, supplier SUP3 achieved a superior ranking compared to SUP1. Consequently, supplier SUP4 must enhance 5 criteria to surpass supplier SUP1. For other suppliers to outperform SUP4, they must focus on improving their products and the materials they provide to significantly enhance their offerings, thereby becoming a more favorable option for construction companies engaged in the modular housing construction.

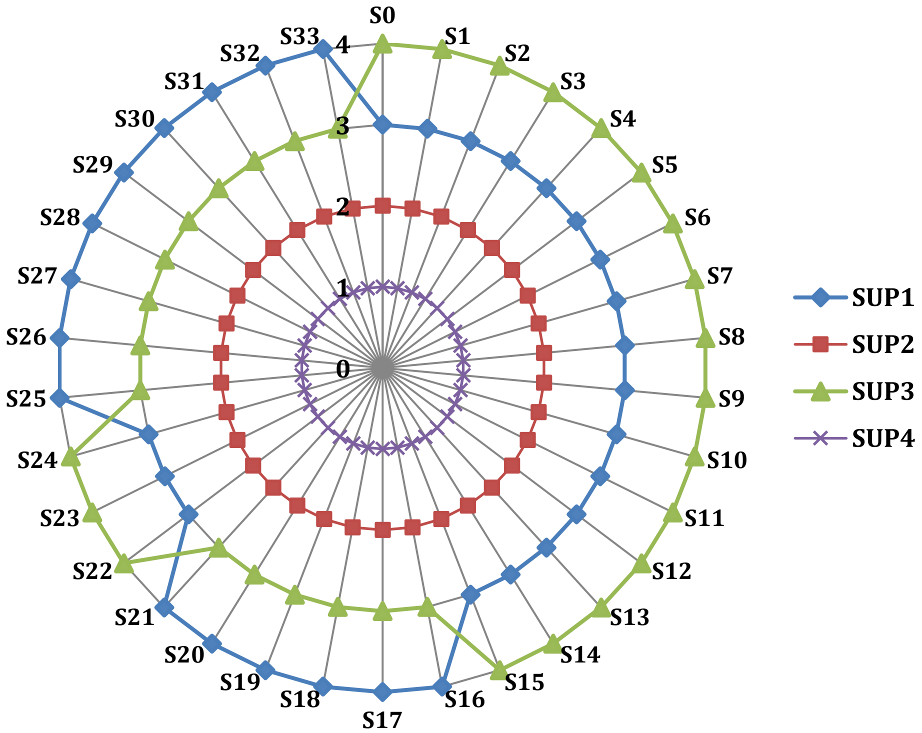

Fig. 2. Results of the sensitivity analysis

5. Discussion

This paper examined low carbon optimization within the supply chain, focusing specifically on supplier selection in the construction industry. Instead of evaluating individual suppliers, the analysis focused on a generic supplier from which construction companies could acquire construction materials or prefabricated modules for the production of modular homes. The unique aspect of modular homes is that construction companies either purchase or manufacture ready-made modules, which they subsequently transport and assemble according to the specific requirements of the customer. This approach allows the buyer to obtain a fully constructed house quickly, addressing housing needs effectively or providing a vacation residence. The demand for such homes in Zadar County is significant, as many individuals are seeking vacation properties, and this region boasts natural resources primarily associated with its coastal areas. In addition, it should be emphasized that buildings significantly affect global energy consumption and the effect of CO2 emissions, as they contribute to 30% of global energy consumption [34].

Companies engaged in the production of modular homes have the option to either acquire pre-fabricated modules from suppliers or to manufacture these modules independently, sourcing the necessary materials from suppliers. When opting for pre-fabricated modules, the focus shifts to the interior design of the homes [35]. These companies provide ready-made modules and make adjustments based on customer requirements. Alternatively, companies may choose to buy materials and raw components to create the modules themselves, thereby enhancing their production capabilities. In such instances, it is essential for the supplier to provide the requisite materials for the fabrication of these modules. The disadvantages associated with the construction of these houses include issues related to transportation and assembly, as well as the limited lifespan of these modules [36]. This means that since finished modules are delivered to the construction site, the challenge in building these houses lies in the transportation, which necessitates the use of truck transport for these modules, consequently increasing CO_2 emissions.

Therefore, it was essential to investigate which suppliers could assist in reducing emissions. The lifespan of these modules is constrained by the materials used. Consequently, the materials procured from suppliers must meet standards to ensure that the lifespan of these houses is extended, thereby enhancing customer satisfaction.

This research examines four types of suppliers, specifically: a local supplier of construction materials, a national manufacturer of construction materials, a local supplier of recycled materials, and an international large supplier. The suppliers were evaluated based on 11 criteria. These criteria were designed to focus on three key categories of sustainability. Consequently, this research incorporated a sustainable selection of suppliers with a particular emphasis on minimizing CO_2 emissions. Construction companies engaged in modular housing within Zadar County are part of this research. In total, seven companies participated as respondents in this research. Consequently, these companies participated in the research and completed a questionnaire concerning the significance of the research criteria and the extent to which these criteria were met by generic suppliers. They responded to this research by selecting one of the provided linguistic values, which ranged from very bad to very good.

To determine the significance of criteria and the ranking of suppliers, a fuzzy approach was employed. This approach is applicable when there is incomplete information that necessitates a decision or when linguistic values are utilized as ratings [37]. In the application of the fuzzy approach, a membership function is established to convert linguistic values into fuzzy numbers [38]. A similar approach was used in the study by Trang et al. [39], where the emphasis was on other methods. Subsequently, the importance of the criteria is assessed using suitable methods, and the alternatives are ranked accordingly. The Fuzzy SiWeC and CORASO methods were implemented in this research.

The fuzzy SiWeC method was employed to assess the significance of various criteria. The findings from this method indicate that the foremost criterion for companies involved in the production of modular houses is waste management and recycling. This criterion holds substantial importance for these companies as they procure materials and raw materials for their production processes. Consequently, they are obligated to ensure the complete utilization of these materials and raw materials; if complete utilization is not feasible, they should resort to recycling the resultant waste. Following this, the next most critical criteria for these companies include product quality and logistics performance. Naturally, to achieve the highest possible product quality, it is essential to utilize high-quality materials and raw materials, making it reasonable to expect quality products from suppliers. Given that these houses are constructed in modular forms, it is imperative to receive materials and raw materials precisely and punctually. Therefore, suppliers must demonstrate strong logistics performance to ensure accurate and timely delivery of products. It is also important to remember that deliveries must meet the quantity requirements set by the construction companies.

The fuzzy CORASO method was employed to evaluate and rank generic suppliers. The findings from this method indicated that a large international supplier most effectively fulfilled the established research criteria. This is primarily due to the fact that this supplier possesses certifications that ensure high module quality. Furthermore, this supplier benefits from significant economies of scale, allowing for the production of a substantial quantity of cost-effective modules that comply with all specified standards. However, a notable drawback of this supplier is its considerable distance from the construction companies situated in Zadar County. This distance contributes to increased carbon dioxide emissions, as it necessitates a more complex supply chain for the delivery of these products to the companies. This supply chain predominantly involves the transportation of products to the construction companies. Consequently, it is essential to focus on the implementation of ecological transportation solutions to mitigate this issue [40].

The results indicated that the subsequent supplier selection involves opting for a national manufacturer of building materials [41]. The primary advantage of this choice over the top-ranked supplier is its location within the same country as these companies, resulting in a more straightforward supply chain and reduced carbon dioxide emissions during the transportation of these products. Nevertheless, to effectively compete with the international supplier, it is essential to lower production costs to enhance the competitiveness of its product, thereby making it more appealing to construction companies. Furthermore, this research revealed that the lowest-ranked local supplier of recycled building materials is significantly disadvantaged. This is primarily attributed to the limited availability of products from this supplier, whose quality fluctuates based on the type of recycled material used [42]. The transition to renewable energy sources, i.e. the reduction of CO2 emissions, contributes to the conservation of natural resources, stimulates economic growth, creates new jobs and contributes to the creation of a more sustainable and functional energy system [43]. Based on this, the importance of this research is emphasized and the application of MCDM methods [44].

5.1. Research implications

The research conducted has both theoretical and practical implications that contribute to a deeper understanding of the research topic. Firstly, this research established the theoretical underpinnings necessary for comprehending supply chains within the construction industry, particularly focusing on supplier selection. This decision-making challenge has not been adequately addressed thus far, especially regarding its role in mitigating carbon dioxide emissions. The standards imposed on the construction industry are becoming increasingly stringent to curb the carbon dioxide emissions associated with these companies. A significant issue arises in the transportation of products from manufacturers to construction companies. Consequently, this paper outlines fundamental approaches to addressing this challenge in a practical context. In practice, this research demonstrated that, despite international suppliers having a more substantial impact on carbon dioxide emissions, they were still selected as the optimal choice. Based on these findings, domestic suppliers are required to undertake specific activities to certify their products before addressing costs to enhance profitability for construction companies. The practical implication of this research indicates that suppliers should engage as extensively as possible in the operations of construction companies. By offering ready-made solutions, they simplify the assembly process of these structures. It is essential for them to tailor their products to meet the needs of construction companies, enabling these companies to lower their finishing costs and improve their market competitiveness. The ultimate aim is to foster collaboration and cultivate partnership relations between companies and suppliers.

6. Conclusions

This research encompassed a range of generic suppliers from companies involved in the manufacturing of modular homes. Four suppliers were selected and assessed by seven companies based on 11 established criteria. The fuzzy approach, utilizing fuzzy SiWeC and CORASO methods, was employed. The results indicated that the most significant criterion, as per the evaluations of the companies, is waste management and recycling, with the highest performance attributed to a large international supplier. These findings were corroborated by the sensitivity analysis conducted.

This research, similar to other studies employing MCDM methods, has specific limitations concerning the selection of criteria and suppliers. It is important to highlight that this topic has not been extensively explored in practice to date, resulting in an underdeveloped theoretical framework. Consequently, this research lays the groundwork for identifying which criteria and suppliers should be considered in subsequent studies. Naturally, it will be essential to incorporate additional criteria and various generic suppliers in future investigations. An additional limit of this research is the use of seven construction companies, so it is necessary to increase the number of companies in future research to generalize the results, for example for the entire territory of the Republic of Croatia and not just one county. Furthermore, future research may utilize alternative MCDM methods to assess the significance of criteria and rank suppliers accordingly. Based on the results of this research, guidelines are given on how construction companies can improve their operations while reducing CO_2 emissions.

The research conducted indicated that selecting a supplier requires a more comprehensive evaluation approach that incorporates fundamental sustainability considerations. Consequently, it is essential to integrate greater ecological factors into the supplier selection process to contribute to the reduction of carbon dioxide emissions, particularly within the construction industry, which significantly contributes to this form of pollution.

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Conflicts of Interest
The authors declare no conflicts of interest.

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