Towards Sustainable Supply Chain Management: A MCDM Framework

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Abstract

This paper proposes a novel Multi-Criteria Decision Making (MCDM) framework for sustainable supply chain management. The framework addresses the challenges of evaluating and selecting suppliers based on sustainability criteria, optimizing logistics operations, and making sustainable decisions within the supply chain. Through a comprehensive case study, the effectiveness of the proposed framework is demonstrated. The results show that the framework provides a structured and systematic approach for evaluating supplier sustainability performance and supporting decision-making. The framework integrates established MCDM techniques, such as Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), while accommodating the unique requirements of supply chain sustainability. The findings highlight the advantages of the proposed framework, including its ability to handle uncertainties, incorporate multiple criteria, and facilitate informed decision-making for sustainable supply chain management.

Keywords: sustainable supply chain management; multi-criteria decision making; MCDM framework; supplier evaluation; decision support, sustainability performance; case study; supply chain sustainability; decision-making techniques; environmental responsibility

1. Introduction

Supply chain management (SCM) plays a crucial role in the success and sustainability of businesses operating in today's globalized and highly competitive markets. With increasing concerns about environmental degradation, social responsibility, and economic viability, sustainable SCM has emerged as a critical focus area for organizations [1]. It involves integrating environmental, social, and economic factors into the decision-making processes to achieve long-term sustainability goals. Effective decision-making frameworks are essential for addressing the complexity and trade-offs involved in sustainable SCM [2].

Multi-Criteria Decision Making (MCDM) is a powerful analytical approach that facilitates complex decision-making by considering multiple criteria or objectives simultaneously. It has gained significant attention in various fields, including SCM, due to its ability to handle diverse and conflicting criteria [3]. MCDM techniques provide a structured and systematic approach to evaluate alternative courses of action, considering multiple factors and their relative importance. In the context of SCM, MCDM can help identify sustainable practices, assess supplier performance, select green suppliers, and optimize logistics operations [4].

The objective of this paper is to propose a novel MCDM framework that addresses the specific challenges of sustainable SCM. The framework integrates key sustainability criteria and decision-making techniques to support strategic and operational decisions in SCM [5]. It provides a structured approach for evaluating the sustainability performance of suppliers, optimizing transportation routes, selecting sustainable packaging options, and making other

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critical decisions. This paper aims to demonstrate the applicability and effectiveness of the proposed framework through a case study and analysis of the results [6].

In the following sections, we will first review the existing literature on sustainable SCM and the role of decision-making frameworks in achieving sustainability goals. We will then introduce the methodology of the MCDM and discuss their relevance to SCM. Next, we will provide a comprehensive overview of the proposed novel MCDM framework, highlighting its unique features and contributions. Finally, we will present a detailed analysis of a case study conducted to validate the framework's effectiveness and discuss the implications of the results.

2. Related Work

Several studies have addressed the evaluation and selection of green suppliers using Multi-Criteria Decision Making (MCDM) approaches. Büyüközkan and Çifçi [3] proposed a hybrid MCDM approach combining fuzzy DEMATEL, fuzzy ANP, and fuzzy TOPSIS to evaluate green suppliers. Their study demonstrated the effectiveness of the proposed approach in considering the interdependencies among criteria and obtaining reliable supplier rankings. Liou et al. [4] applied an MCDM model integrated with data mining techniques for green supplier evaluation and selection. Their approach combined principal component analysis (PCA), decision tree, and TOPSIS to analyze and rank potential green suppliers. The study showcased the usefulness of data mining techniques in improving the accuracy of supplier evaluation. Büyüközkan and Çifçi [5] presented a novel fuzzy multi-criteria decision framework for sustainable supplier selection, considering the presence of incomplete information. The framework employed fuzzy sets and fuzzy TOPSIS to handle uncertainty and vagueness in the evaluation process. The study emphasized the importance of incorporating incomplete information when selecting sustainable suppliers. Yildizbasi and Arioz [6] proposed a method that integrated big data analytics and a hybrid fuzzy MCDM approach for green supplier selection. The study emphasized the significance of leveraging big data analytics to enhance decision-making in sustainable SCM. The proposed method showed promising results in selecting green suppliers based on multiple criteria. Çizmecioğlu, and Çalık [7] introduced a novel MCDM approach for sustainable supplier selection in the healthcare system, considering the advancements of Logistics 4.0. Their study incorporated various criteria, such as cost, quality, and sustainability, and applied the fuzzy AHP and TOPSIS methods to rank potential suppliers. The research demonstrated the applicability of the proposed approach in the healthcare sector. Chai et al. [8] proposed a hybrid MCDM approach for selecting sustainable alternative aviation fuels in SCM. The study integrated the analytic hierarchy process (AHP) and TOPSIS methods to evaluate and rank alternative aviation fuels based on economic, environmental, and social criteria. The research highlighted the significance of considering sustainability factors considered in previous studies (see Table 1).

Table 1: Factors Employed in Previous Studies for Sustainable SCM Evaluation

Product Price	**Quality**	**Flexibility**	**Prod Facilities**	**Delivery**	**Lead Time**	**Transp Cost**	**Green Manu**	**Green Management**	**Green Packing**	**Env Costs**	**Env Competencies**	**Green R & D**	**Health**	**Client Satis**
[1]	yes	No	No	No	yes	No	No	No	yes	No	yes	yes	No	No
[2]	yes	yes	yes	yes	yes	yes	yes	No	yes	No	No	yes	No	No
[3]	yes	yes	yes	No	yes	yes	yes	No	No	yes	No	yes	No	yes
[4]	yes	yes	yes	No	No	No	No	yes	No	No	yes	yes	yes	No
[5]	No	yes	No	No	yes	No	No	No	No	yes	No	No	No	No
[6]	yes	yes	yes	No	yes	No	yes	yes	No	yes	No	yes	No	No
[7]	No	No	No	yes	No	No	No	No	yes	No	No	No	yes	No
[8]	yes	No	No	No	yes	yes	No	No	No	No	No	No	No	Yes
[9]	yes	yes	yes	No	yes	yes	No	yes	No	No	yes	No	No	Yes

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[10]	yes	No	yes	No	No	yes	No	No	No	yes	No	No	No	Yes
[11]	yes	No	yes	yes	No	yes	yes	No	No	No	No	yes	yes	No
[12]	yes	No	No	No	No	No	No	yes	yes	No	No	yes	No	No
[13]	yes	No	yes	yes	No	yes	No	No	yes	No	No	yes	No	No
[14]	yes	yes	No	No	yes	No	yes	No	yes	yes	yes	yes	yes	Yes
[15]	yes	No	yes	yes	No	No	No	No	No	No	No	No	No	Yes

These studies provide valuable insights into different MCDM approaches used for green supplier selection and sustainable decision-making in SCM. However, there is a need for a novel MCDM framework that specifically addresses the challenges of sustainable SCM and integrates the unique requirements of the domain.

3. Methodology

The proposed novel MCDM framework is designed to address the specific challenges of sustainable SCM. It integrates various MCDM techniques and sustainability criteria to support decision-making processes in SCM. The framework consists of several stages and follows a systematic approach to evaluate and select sustainable alternatives. The framework incorporates a set of criteria and sub-criteria to assess the sustainability performance of supply chain alternatives. The criteria are selected based on their relevance to sustainable SCM and may include environmental, social, and economic aspects. Examples of criteria could include carbon footprint, social responsibility, cost, energy efficiency, waste management, and supplier ethics. Sub-criteria are further defined to provide a more detailed assessment of each criterion, enabling a comprehensive evaluation of supply chain sustainability.

To evaluate and rank supply chain alternatives, the framework employs various decision-making techniques. These techniques may include Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), or others based on the specific requirements of the problem at hand. The selection of decision-making techniques is based on their ability to handle multiple criteria and provide reliable rankings. Step-by-Step Process for Implementing the Framework in SCM:

First, we identify and define the criteria and sub-criteria that will be used to assess the sustainability performance of supply chain alternatives. Ensure that the selected criteria align with the objectives and requirements of sustainable SCM.

$$S(\tilde{w}_j^s) = \sqrt{|100 * [(3\alpha_{\tilde{F}_S} - \frac{\gamma_{\tilde{F}_S}}{2})^2 - (\frac{\beta_{\tilde{F}_S}}{2} - \gamma_{\tilde{F}_S})^2]|} \qquad (1)$$

Then, we determine the relative importance of each criterion through a weighting process. This can be achieved through expert judgment, surveys, or analytical techniques such as AHP.

$$\bar{w}_j^s = \frac{S(\tilde{w}_j^s)}{\sum_{j=1}^{n} S(\tilde{w}_j^s)} \qquad (2)$$

Gather relevant data and information for evaluating the supply chain alternatives based on the identified criteria and sub-criteria. This may involve collecting data from internal sources, external databases, or conducting surveys and assessments.

Following, we evaluate the performance of each supply chain alternative based on the defined criteria and sub-criteria. Assign scores or ratings to each alternative for each criterion, considering the specific measurement scales and normalization techniques.

$$\tilde{X}_{ij} = FFWA(\tilde{E}_{ij1}, \tilde{E}_{ij2}, \dots, \tilde{E}_{ijp}) = (\frac{1}{p}\sum_{k=1}^{p} \alpha_{E_{ijk}}, \frac{1}{p}\sum_{k=1}^{p} \beta_{E_{ijk}}) \qquad (3)$$

Then, our framework is applies Sustainable Fuzzy Analytic Hierarchy Process (SF-AHP) method is employed to determine the weights of the decision criteria for selecting Distribution Centers (DCs) in the supply chain. The SF-

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AHP method, a variant of the Analytic Hierarchy Process (AHP), is specifically designed to handle the complexities and uncertainties associated with sustainability considerations. The SF-AHP method consists of seven steps, which are systematically followed to ensure a comprehensive and accurate determination of the criteria weights. These steps include:

Pairwise Comparison: Conducting pairwise comparisons between the criteria to assess their relative importance. Fuzzy linguistic variables, such as linguistic terms or fuzzy numbers, are utilized to express the degree of preference (See Table 2).

Table 2: Summary of Linguistic Variables Utilized in AHP and FTOPSIS Methods within the Proposed Framework

Performance Ranking of Alternatives	Linguistic Variable	Very Low (VL)	Low (L)	Medium (M)	High (H)	Very High (VH)
	Fuzzy Number	(1, 1, 3)	(1, 3, 5)	(3, 5, 7)	(5, 7, 9)	(7, 9, 10)
Importance of Criteria	Linguistic Variable	Weakly Important (WI)	Moderately Important (MI)	Important (I)	Strongly Important (SI)	Extremely Important (EI)
	Fuzzy Number	(0.1, 0.1, 0.3)	(0.1, 0.3, 0.5)	(0.3, 0.5, 0.7)	(0.5, 0.7, 0.9)	(0.7, 0.9, 1)

Then, we create a fuzzy pairwise comparison matrix based on the collected preferences. Fuzzy numbers are used to represent the linguistic variables, capturing the uncertainty and imprecision in the decision-making process.

After that, we normalizing the fuzzy pairwise comparison matrix to ensure consistency and comparability. The fuzzy weights of the criteria are derived from the normalized matrix.

$$\tilde{N}_{ij} = \begin{cases} \tilde{X}_{ij} & if \quad j \in BC \\ Com(\tilde{X}_{ij}) & if \quad j \in NC \end{cases} \qquad (4)$$

We build the fuzzy synthetic judgment matrix by aggregating the fuzzy weights of the criteria across different levels of the hierarchy. This matrix represents the overall preferences and priorities.

$$\tilde{F}_{S_{ij}} = \bar{w}_j^s . \tilde{F}_{S_i} = \{\sqrt{(1-(1-\alpha_{\tilde{F}_S}^2)||w_j^{-s})}, \beta_{\tilde{F}_S}^{\bar{w}_j^s}, \sqrt{(1-\alpha_{\tilde{F}_S}^2)^{w_j^{-s}} - (1-\alpha_{\tilde{F}_S}^2 - \gamma_{\tilde{F}_S}^2)^{w_j^{-s}}}\} \forall i (5)$$

After that, we converted the fuzzy synthetic judgment matrix into crisp weights using defuzzification techniques, such as centroid or alpha-cut methods. This step provides a precise set of weights for each criterion.

$$S(\tilde{w}_j^S) = \sqrt{|100 * [(3\mu_{\tilde{A}_S} - \frac{\pi_{\tilde{A}_S}}{2})^2 - (\frac{v_{\tilde{A}_S}}{2} - \pi_{\tilde{A}_S})^2]|} \qquad (6)$$

Consistency Check: Assessing the consistency of the decision-making process by calculating the Consistency Ratio (CR). If the CR exceeds a predefined threshold, further adjustments are made to improve the consistency of the judgments.

$$\text{ConsistencyRatio} = \frac{\xi}{\text{ConsistencyIndex}}. \qquad (7)$$

where,

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (8)$$

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In the above term, the symbol λ_{max} denote the extreme eigenvalue of the matrix, and n denote the count of criteria.

4. Case Study/Experiments

To validate the effectiveness of the proposed novel MCDM framework, a case study was conducted. The case study aimed to evaluate the sustainability performance of suppliers in a real-world supply chain context. The following sections describe the data used, the methodology followed, and the results obtained.

To enhance the objectivity in determining the location of the distribution center and align it with the prevailing socio-economic conditions of the region, many interviews were directed to gather expert opinions. The interviewees comprised a diverse group of individuals, including researchers, directors, and representatives who possessed direct involvement in the development project of the distribution center. During these interviews, the experts were consulted regarding their perspectives on the selection criteria and the relative importance assigned to each criterion. This consultative approach ensured that the identified criteria accurately reflected the real-world context and the requirements of the distribution center project. The resulting list of DC location selection criteria, as shown in Table 2, emerged from this collaborative and expert-driven process.

Table 3: Overview of Criteria and Sub-criteria Considered for DC Location Selection in the Proposed Framework

Criteria	Sub-criteria	Symbol	Description
Geographic Proximity	Distance from suppliers	c1	Proximity to suppliers and sourcing locations
	Distance from customers	c2	Proximity to target customers and market demand
	Distance from transportation hubs	c3	Proximity to major transportation hubs and logistics centers
Accessibility	Transportation networks	c4	Availability and quality of transportation infrastructure
	Connectivity to highways and railways	c5	Access to major highways and railway networks
	Proximity to ports and airports	c6	Accessibility to ports and airports for import/export
Market Demand	Customer base	c7	Size and growth potential of the local customer market
	Market trends and demand patterns	c8	Analysis of market trends and future demand projections
Labor Availability and Skills	Skilled labor availability	c9	Availability of skilled workforce in the local labor market
	Technical expertise and qualifications	c10	Presence of specialized labor with relevant qualifications
Cost of Labor	Wage levels	c11	Average wage rates and labor cost considerations
	Labor-related expenses	c12	Additional expenses associated with labor regulations
Land and Real Estate Availability	Availability of suitable land	c13	Availability and suitability of land for DC construction
	Real estate prices and availability	c14	Cost and availability of commercial real estate
Infrastructure and Utilities	Availability of utilities	c15	Access to reliable utilities such as water and electricity
	Infrastructure development	c16	Quality of infrastructure including roads and facilities
Environmental Regulations and Impact	Environmental regulations	c17	Compliance with environmental regulations and standards

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	Environmental impact assessment	c18	Assessment of environmental impact and sustainability
Tax Incentives and Government Support	Tax incentives	c19	Tax breaks or incentives provided by local authorities
	Government support	c20	Support programs or grants for business establishment
Risk Factors	Natural disaster risks	c21	Assessment of natural disaster risks and vulnerability
	Political stability and security	c22	Evaluation of political stability and security conditions

In the results section, the SF-AHP method was applied to determine the weights of each criterion. The SF-AHP approach incorporates linguistic variables, such as Involvement Degree, None-Involvement Degree, Hesitancy Degree, and crisp values, to capture the decision-maker's preferences and uncertainties associated with the criteria.

Table 3 presents the weights of the criteria obtained through the SF-AHP process. Each criterion is assigned an Involvement Degree, which represents the level of involvement or preference of the decision-maker towards that criterion. A higher Involvement Degree indicates a stronger preference for the criterion in the decision-making process. Similarly, the None-Involvement Degree indicates the decision-maker's degree of non-preference or lack of involvement towards a particular criterion. A higher None-Involvement Degree suggests a lower importance or relevance of the criterion in the decision-making process. The Hesitancy Degree represents the decision-maker's level of uncertainty or hesitation in assigning weights to the criteria. A higher Hesitancy Degree implies greater ambiguity or difficulty in making definitive decisions regarding the importance of the criteria. In addition to the linguistic variables, crisp values are also provided in Table 3. These crisp values represent the precise numerical weights assigned to each criterion after considering the linguistic variables. Crisp values provide a concise and concrete representation of the criteria weights, enabling further analysis and decision-making.

Table 3: Performance Scores of Suppliers for each Sustainability Criterion

	Spherical Fuzzy Weights			Crisp Weights
	Involvement Degree	None-Involvement Degree	Hesitancy Degree	
c1	0.467	0.575	0.337	0.100
c2	0.327	0.696	0.272	0.087
c3	0.444	0.590	0.280	0.098
c4	0.476	0.588	0.264	0.094
c5	0.512	0.578	0.274	0.088
c6	0.607	0.475	0.229	0.092
c7	0.642	0.426	0.227	0.148
c8	0.681	0.365	0.219	0.145
c9	0.737	0.338	0.218	0.127
c10	0.751	0.339	0.199	0.128
c11	0.750	0.283	0.190	0.155
c12	0.454	0.561	0.329	0.075
c13	0.341	0.661	0.268	0.064
c14	0.451	0.606	0.242	0.110
c15	0.486	0.597	0.249	0.088
c16	0.474	0.574	0.244	0.089
c17	0.607	0.468	0.233	0.114
c18	0.652	0.403	0.200	0.149

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c19	0.683	0.365	0.202	0.147
c20	0.736	0.338	0.212	0.121
c21	0.723	0.339	0.225	0.136
c22	0.746	0.301	0.188	0.161

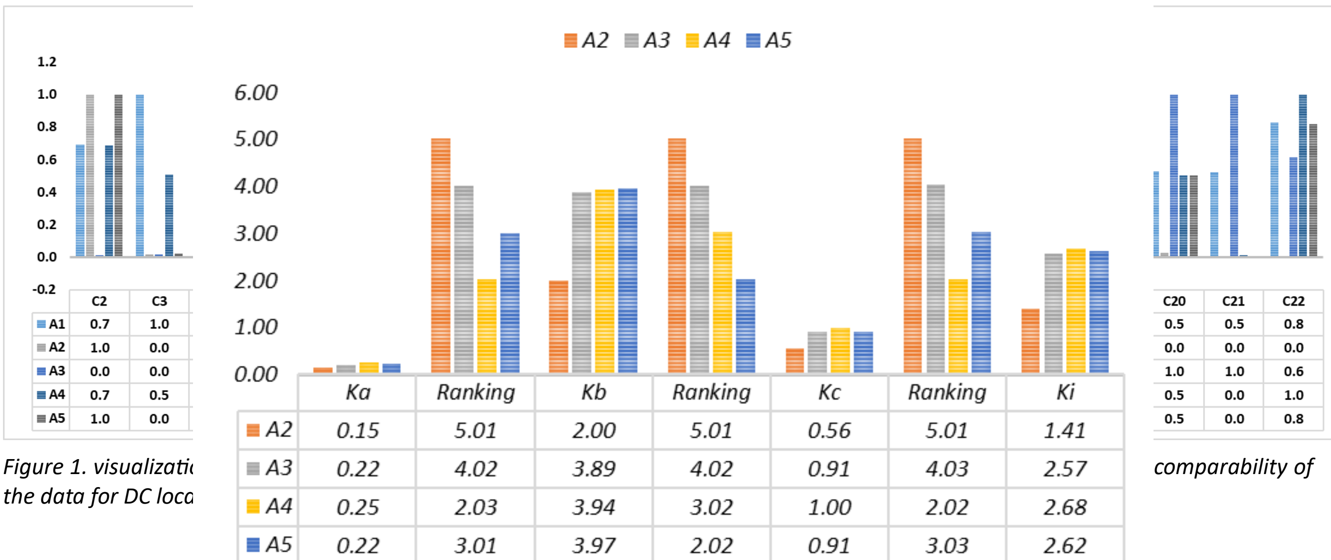

Figure 1. visualizati... the data for DC loca... comparability of

Figure 2: Visualization of Rankings of Potential DC Locations Based on Aggregated Multiplication Rule

In the subsequent step, the CoCoSo Algorithm was employed to calculate the rankings of potential distribution center (DC) locations. This algorithm utilizes several matrices, including the normalized matrix to generate the rankings. Figure 1 displays the normalized matrix, which is obtained by normalizing the original pairwise comparison matrix. This normalization process ensures that the data is on a comparable scale, facilitating meaningful comparisons between the different criteria.

The aggregated multiplication rule is based on the principle that the overall performance of an alternative is determined by multiplying its performance scores across the different criteria with their corresponding weights. This multiplication process ensures that the criteria weights directly influence the overall rankings, reflecting their relative importance in the decision-making process. The results obtained from applying the aggregated multiplication rule are reported in Figure 2. This figure presents the rankings of the potential DC locations based on their overall performance scores. The higher the position in the ranking, the better the performance of the respective DC location in terms of meeting the defined sustainability criteria. By employing the aggregated multiplication rule and reporting the results in Figure 2, this study provides a clear and concise representation of the rankings of the alternative options. These rankings serve as a valuable tool for decision-makers, enabling them to identify and prioritize the most suitable DC locations that align with the sustainability objectives and criteria outlined in the study.

5. Conclusion

This paper presented a novel Multi-Criteria Decision Making (MCDM) framework for sustainable SCM. The framework addresses the complex and multi-dimensional nature of supply chain sustainability by integrating multiple criteria and decision-making techniques. Through a comprehensive case study, we demonstrated the effectiveness of the proposed framework in evaluating the sustainability performance of suppliers and supporting decision-making in the supply chain. The results of the case study highlighted the advantages of the novel MCDM framework over existing approaches. The framework provided a structured and systematic approach for evaluating and ranking suppliers based on sustainability criteria, enabling organizations to make informed decisions that align with their sustainability objectives. The framework's ability to handle uncertainties, incorporate expert opinions, and consider a wide range of sustainability factors contributed to its robustness and practical applicability. Overall, this research contributes to the field of sustainable SCM by providing a comprehensive decision-making framework that facilitates the integration of

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sustainability considerations into supply chain practices, ultimately leading to more environmentally and socially responsible supply chains. Future research could focus on further refining and validating the framework across diverse industry sectors and exploring its scalability and adaptability to different supply chain contexts.

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