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Enhancing Supply Chain Sustainability in Modern Manufacturing

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Abstract

In the dynamic landscape of modern manufacturing, optimizing supply chain sustainability has emerged as a paramount concern for companies seeking to balance profitability with environmental and social responsibility. This multifaceted challenge involves processes, stakeholders, and resources required in sourcing, production, and distribution across global supply chains. As industries strive to reduce carbon footprints, minimize waste, and maintain ethical standards, the need for effective strategies to navigate these complexities becomes increasingly pressing. In this context, our analysis aims to explore and evaluate a range of strategies aimed at enhancing supply chain sustainability within the manufacturing sector. Through a comprehensive examination of criteria analyzed from the existing literature, we seek to prioritize strategic approaches as drivers of operational efficiency while promoting long-term sustainability across the supply chain ecosystem. To achieve this goal, we propose a Multi-Criteria Decision-Making (MCDM) procedure to identify the most effective strategies for enhancing supply chain sustainability, accounting for trade-offs under the considered criteria. Leveraging expert-based insights, our framework aims to represent a flexible procedure for different manufacturing contexts, empowering organizations to advancing sustainability goals.

Keywords

Manufacturing; Sustainability; Supply Chain; Multi-Criteria Decision-Making

1. Introduction

In the realm of manufacturing, sustainability within supply chain operations stands as a crucial pillar dictating the trajectory of industries. Its significance transcends mere operational efficiency, extending into the realms of environmental preservation, social equity, and economic resilience. Every link of global supply chains holds the potential for profound impact, be it on natural ecosystems, local communities, or the bottom line of business organizations. By promoting sustainable practices in supply chain operations, manufacturers take the commitment to reducing their ecological footprint, striving to minimize resource depletion, pollution, and carbon emissions inherent in traditional industrial practices. Moreover, such initiatives refer to the aspect of social responsibility, including fair labor practices, ethical sourcing, and community engagement. The role of sustainability in supply chains arises from pragmatic considerations as well, as embracing sustainable practices improves operational efficiency while protecting businesses from such risks as those posed by volatile commodity prices, regulatory shifts, and disruptions in the global marketplace. Furthermore, in an era where consumer preferences increasingly skew towards environmentally and socially conscious products, sustainability emerges as an effective driver of market differentiation and brand loyalty.

1.1. Objectives and structure

The general goal of this research consists in exploring and evaluating strategies aimed at enhancing supply chain sustainability within the manufacturing sector, prioritizing operational efficiency and long-term sustainability. To such an aim, we will be pursuing the following intermediate goals.

- Conducting an examination of criteria related to supply chain sustainability, drawn from existing literature.
- Identifying a range of strategies for enhancing supply chain sustainability within the manufacturing sector considered as effective in literature.
- Proposing a Multi-Criteria Decision-Making (MCDM) approach based on expert experience to systematically assess and rank the identified strategies on the basis of the defined criteria.

- Providing structured recommendations for organizations in advancing sustainability goals through the adoption of the supply chain strategy emerged as the best trade-off.

The present research is organized as follows. Section 2 reports a comprehensive literature review culminating in the identification of criteria and strategies. Section 3 describes methodological details. Section 4 develops the practical application. Conclusions are reported in Section 5.

2. Literature Review

With the advent of industry 4.0 technologies, such as Internet of Things (IoT), Artificial Intelligence (AI), big data analytics, and automation, there is a significant potential to enhance sustainability practices throughout the manufacturing supply chain (Agarwal and Ojha, 2024). Sustainable supply chain management (SSCM) contemplates the integration of environmental, social, and economic considerations in solving complex optimization problems (Abualigah et al., 2023) at any stage of the supply chain, from sourcing raw materials to product disposal. Various scholars argue that SSCM can lead to cost savings (Kumar and Kumar, 2024), risk mitigation (Kähkönen et al., 2023), enhanced brand reputation, and transparency in regulatory compliance (Jestratijevic et al., 2024). Looking at the fusion of digital technologies with traditional manufacturing processes, several studies have explored how Industry 4.0 technologies can facilitate the implementation of sustainable practices in manufacturing supply chains. For instance, IoT sensors can track energy consumption and emissions in real-time, enabling companies to identify areas for improvement and reduce environmental impact. With this regard, Kumar et al. (2023) identify and prioritize enablers for IoT adoption in logistic by proposing a readiness model. The authors highlight as sustainability focus and technology maturity can inform strategic planning and efficient deployment methods. Furthermore, AI and machine learning algorithms can optimize production processes, minimizing waste and resource usage while maximizing efficiency. Gardas and Narwane (2024) examine critical factors influencing the adoption of machine learning technologies in manufacturing supply chains with the objective of guiding practitioners in understanding the relationships among these factors and devising effective implementation strategies. Despite the promises of Industry 4.0 for sustainable supply chain management, several challenges still make challenging a widespread adoption. These include strategic, economic, and transformation barriers, among others (Lahane et al., 2023). Additionally, there may be resistance to change within organizations accustomed to traditional manufacturing practices, something that underlines the need of establishing conceptual frameworks of industry 4.0 technologies-embedded SSCM (Liu et al., 2023). We analyzed several articles in the domain object of the present research, formalizing a set of main criteria for supply chain sustainability optimization in manufacturing, reported in Table 1. Subsequently, we analyzed related strategies, described in Table 2, that could support manufacturing companies in achieving their sustainability goals.

Table 1. Criteria for manufacturing supply chain sustainability optimization analyzed in literature

ID	Criterion	Description	Reference
C_1	Environmental impact	Understanding the ecological consequences of supply chain decisions, including their effects on carbon emissions, energy usage, waste generation, and water consumption.	Helo et al., 2024
C_2	Social responsibility	Evaluating the ethical and moral dimensions of supply chain practices, focusing on fair labor conditions, ethical sourcing standards, supplier diversity, and community engagement efforts.	Uttam et al., 2024
C_3	Economic feasibility	Assessing the financial viability and sustainability of supply chain strategies, considering factors such as cost-effectiveness, profitability, resource optimization, and operational efficiency.	Manco et al., 2023
C_4	Regulatory compliance and risk mitigation	Ensuring adherence to legal requirements and industry standards while proactively identifying and managing risks related to supply chain disruptions, compliance issues, and reputational damage.	Kumar et al., 2024; Hu et al., 2023

Table 2. Strategies to achieve sustainability goals analyzed from literature

ID	Strategy	Description	Reference
S_1	Local sourcing	Procure raw materials and components from local suppliers to minimize transportation emissions, support local economies, and reduce lead times.	Cui et al., 2021
S_2	Renewable energy adoption	Transition manufacturing facilities to renewable energy sources such as solar, wind, or hydroelectric power to reduce greenhouse gas emissions and dependence on fossil fuels.	Masoomi et al., 2023
S_3	Supplier sustainability assessments	Conduct comprehensive assessments of suppliers' sustainability practices, including environmental performance, labor standards, and social responsibility, to ensure alignment with sustainability goals.	Cinnirella et al., 2022
S_4	Green transportation	Utilize low-emission transportation methods such as electric vehicles, hybrid vehicles, or biodiesel-powered trucks for logistics and distribution to reduce carbon emissions in the supply chain.	Moh'd Anwer, 2022
S_5	Packaging optimization	Optimize packaging design and materials to reduce waste, minimize packaging volume, and increase recyclability or biodegradability to improve overall supply chain sustainability.	Ramanathan et al., 2023
S_6	Waste reduction initiatives	Implement waste reduction initiatives within manufacturing processes, such as lean manufacturing principles, circular economy practices, and waste-to-energy solutions, to minimize waste generation and maximize resource efficiency.	Niu et al., 2024
S_7	Sustainable logistics	Implement sustainable logistics practices, including route optimization, mode shifting to greener transportation modes, and consolidation of shipments to reduce emissions and improve efficiency in the transportation of goods.	Sadeghi and Abadi, 2024
S_8	Water conservation measures	Implement water-saving technologies and practices in manufacturing processes, such as water recycling systems, and process optimization, to minimize water usage and reduce environmental impact.	Lepawsky, 2024
S_9	Employee training and engagement	Provide training programs and engage employees in sustainability initiatives to raise awareness, promote behavior change, and foster a culture of sustainability within the organization.	Acquah et al., 2023
S_{10}	Continuous improvement and innovation	Foster a culture of continuous improvement and innovation to develop and implement new sustainable technologies, processes, and practices that drive efficiency, reduce environmental impact, and enhance supply chain sustainability.	Lyu et al., 2023

In this context, embracing a MCDM perspective could represent a strategic approach, as manufacturers could systematically evaluate the sustainable strategies defined in Table 2 based on the fulfillment of the optimization criteria formalized in Table 1. Indeed, such an approach enables decision-makers to assess various factors simultaneously (Thakkar and Paliwal, 2024) to prioritize strategies in alignment with broader organizational goals and values. This would promote informed decision-making, allowing manufacturers to navigate complex trade-offs and select strategies that offer the most significant overall benefits while minimizing potential drawbacks. MCDM methods have been widely applied in literature to support a wide range of decision-making problem, something that confirms their usefulness and flexibility of application. Specifically, they have been successfully applied in the SSCM sector (Chai and Zhou, 2022), also in integration with AI-based technologies (Dohale et al., 2024). Among the various MCDM methods that could serve to the purpose of the present research, the VIKOR (Serbian acronym: VlseKriterijumska Optimizacija I Kompromisno Resenje) technique appears to be particularly useful. Reasons behind this choice will be illustrated in the next section, along with specifications about methodological details.

3. MCDM Method

The VIKOR method, first introduced by Opricovic (1998), is an established and well known MCDM method used to select the best compromise solution from a set of alternatives when there are conflicting criteria. Its suitability for the problem object of the present research can be summarized through the following points.

- Comprehensive evaluation. VIKOR allows for a comprehensive evaluation of alternatives by considering multiple criteria simultaneously (Chen, 2022). This ensures that decisions are made considering various aspects that are crucial for sustainable operations.
- Trade-off analysis. VIKOR facilitates trade-off analysis among conflicting criteria, enabling decision-makers to identify alternatives that offer the best compromise solution (Alhadidi and Alomari, 2024). This helps in balancing competing objectives and finding strategies that optimize across different dimensions of sustainability.
- Sensitivity analysis. VIKOR enables sensitivity analysis to assess the robustness of the selected strategies to changes in alternative performance or variations in criteria weights (Sarwar and Bashir, 2024). This helps in understanding the impact of uncertainties on the final decision, enhancing the reliability of the chosen strategies.
- Transparent decision-making. VIKOR provides a transparent decision-making process by quantitatively evaluating alternatives and generating clear rankings based on their performance against the selected criteria (Carpitella, 2024). This transparency fosters trust among stakeholders and facilitates communication regarding the rationale behind the chosen strategies.

3.1 VIKOR methodological steps

The methodology consists of the following methodological steps.

- Construction of the input decision matrix by considering the alternatives, criteria, and evaluations for each alternative under each criterion. Evaluations has to be quantitative and established according to a defined scale.

- Normalization of the input decision matrix. Input values have to be normalized to ensure comparability across criteria and establish uniformity in scale. Formula (1) can be employed to accomplish this step.

$$f_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \tag{1}$$

- Identification of optimal and suboptimal performance for each criterion. Ideal and anti-ideal solutions will have to be determined based on the preference directions of criteria. On the one hand, if criteria have to be maximized, formulas (2) and (3) will be used.

$$f_j^* = \max f_{ij}; j = 1 \dots m \tag{2}$$
$$f_j^- = \min f_{ij}; j = 1 \dots m \tag{3}$$

On the other hand, if criteria have to be minimized, formulas (4) and (5) will be used.

$$f_j^* = \min f_{ij}; j = 1 \dots m \tag{4}$$
$$f_j^- = \max f_{ij}; j = 1 \dots m \tag{5}$$

The ideal and anti-ideal solutions can be lastly formulated as:

$$f^* = \{f_1^*, f_2^*, \dots, f_m^*\} \tag{6}$$
$$f^- = \{f_1^-, f_2^-, \dots, f_m^-\} \tag{7}$$

- Computation of collective utility and individual regret. The alternative with associated highest group utility S_i and minimal individual regret R_i across criteria has to be identified by analyzing the following metrics:

$$S_i = \sum_{i=1}^{m} w_j \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \tag{8}$$
$$R_i = \max\left[w_j \frac{f_j^* - f_{ij}}{f_j^* - f_j^-}\right] \tag{9}$$

where w_j is the weight assigned to each criterion, reflecting considerations of mutual importance within the whole set of considered criteria.

- Calculation of the VIKOR index for each alternative. The VIKOR index Q_i will be calculated via formula (10) by considering both group utility and individual regret for each alternative.

$$Q_i = \gamma \frac{S_i - S^*}{S^- - S^*} + (1-\gamma)\frac{R_i - R^*}{R^- - R^*} \tag{10}$$

where $\gamma = 0.5$ refers to the maximum group utility, $S^* = \min\{S_i\}$, $S^- = \max\{S_i\}$, $R^* = \min\{R_i\}$, $R^- = \max\{R_i\}$.

- Prioritization of alternatives based on their S, R, and Q values. Three separate ranking lists will be derived and the values will be organized to ensure that the alternative with lowest VIKOR value receives highest rank.

- Recommendation of a compromise solution according to the conditions of acceptable advantage and acceptable stability, the last ones detailly described in (Carpitella, 2024). The alternative classified with the highest rank in the overall ranking will represent the most balanced compromise derived from the VIKOR procedure.

4. Results and Discussion

For the practical application of the described procedure, we involved an expert from a manufacturing company with a background in management engineering and sustainability. With years of experience in optimizing supply chains for manufacturing processes, the expert possesses a wide understanding of the industry's complexities and challenges, including such aspects as process optimization, waste reduction, and sustainable sourcing practices. The data collection process involved collaborative brainstorming sessions with the expert as well as iterative feedback exchange. The numerical values reported in Table 3 represent subjective evaluations of how well each strategy fulfills each criterion based on expert experience and knowledge. The scale used for evaluating strategies under each criterion ranges from 1 to 5, where higher values indicate better fulfillment of the criterion by the strategy, whereas lower values indicate less effective fulfillment. In leading the present application, we specify that the same mutual importance (i.e., weight) has been attributed to each criterion.

Table 3. Input matrix with evaluations of strategies under criteria

		C_1 Environmental Impact	C_2 Social Responsibility	C_3 Economic Feasibility	C_4 Regulatory Compliance
S_1	Local sourcing	3	4	2	3
S_2	Renewable energy adoption	5	4	3	4
S_3	Supplier sustainability assessments	2	3	4	2
S_4	Green transportation	4	3	2	3
S_5	Packaging optimization	3	2	3	2
S_6	Waste reduction initiatives	4	4	3	3
S_7	Sustainable logistics	4	3	3	3
S_8	Water conservation measures	2	3	4	2
S_9	Employee training and engagement	1	4	2	3
S_{10}	Continuous improvement and innovation	5	3	4	3

Table 4 reports values of group utility and minimal individual regret, respectively obtained via formulas (8) and (9) along with the VIKOR index for each alternative, the last one achieved via formula (10). The ranking list for each of these values is also specified in the same table. Results are graphically synthetized in Figure 1.

Table 4. Group utility (S_i), minimal individual regret (R_i), VIKOR index (Q_i) and related ranking lists

ID	S_i	**Rank in** S_i	R_i	**Rank in** R_i	Q_i	**Rank in** Q_i
S_1	0.500	5	0.250	3	0.800	5
S_2	0.125	1	0.125	2	0.000	1
S_3	0.562	6	0.250	3	0.850	6
S_4	0.562	6	0.250	3	0.850	6
S_5	0.750	8	0.250	3	1.000	8
S_6	0.312	3	0.125	2	0.150	3
S_7	0.438	4	0.125	2	0.250	4
S_8	0.562	6	0.250	3	0.850	6
S_9	0.625	7	0.250	3	0.900	7
S_{10}	0.250	2	0.125	1	0.100	2

The alternative with associated minimum VIKOR index Q_i (in our case, S_2) represents the most suitable compromise solution only if the condition of acceptable advantage and the condition of acceptable stability (Carpitella, 2024) are simultaneously met. As this is not the case, both alternatives S_2 and S_{10} (i.e., the alternative ranked second in the Q-based ranking list) are selected as compromise solutions to be prioritized. In other terms, within the set of considered strategies, S_2 and S_{10} represent the best trade-off when simultaneously maximizing criteria of environmental impact, social responsibility, economic feasibility, and regulatory compliance. This has interesting practical implications.

- S_2, renewable energy adoption. Adopting such a strategy offers several advantages to manufacturing companies for sustainable supply chain management, such as long-term cost savings, environmental benefits, and energy security. The implementation process encompasses conducting thorough energy audits, making strategic investments in renewable technologies, forging partnerships with energy providers, educating employees, and implementing rigorous performance monitoring mechanisms to ensure enduring success in supply chain sustainability.

- S_{10}, continuous improvement and innovation. Adopting such a strategy holds significant promise for sustainable supply chain management from manufacturing companies, offering enhanced operational efficiency, product quality, and market competitiveness. This approach requires the establishment of a culture of innovation throughout the whole organization, implementing systematic processes for continuous improvement, investing in research and development, empowering employees to contribute ideas, as well as investing on new technologies. Through this strategic focus on innovation and improvement, manufacturing companies can achieve sustained success in optimizing their supply chain operations while meeting evolving customer demands and market trends (Figure 1).

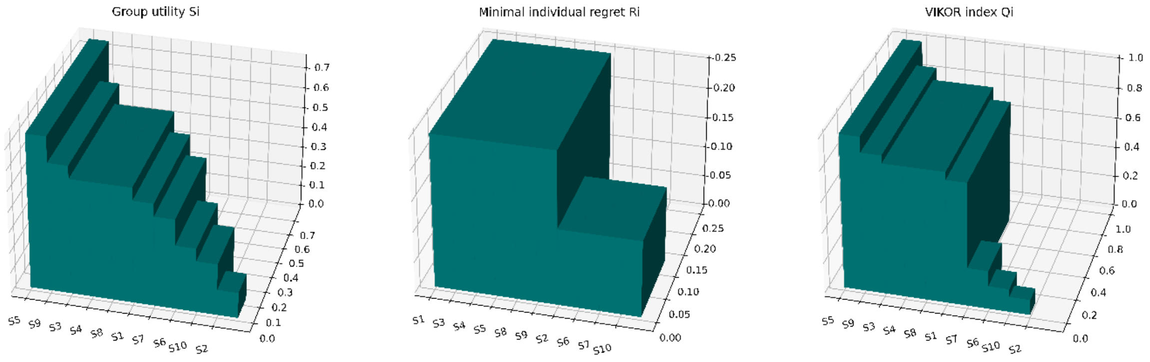

Figure 1. Results derived from the VIKOR procedure

5. Conclusions and Future Research

In contemporary manufacturing, optimizing supply chain sustainability is paramount for achieving numerous critical objectives. Through a thorough analysis of criteria and sustainable strategic alternatives drawn from existing literature, this paper proposes an MCDM approach to rank these alternatives by identifying those that predominantly enhance operational efficiency across the supply chain ecosystem. To achieve this aim, we employ the VIKOR technique, which facilitates reaching a final solution based on specified criteria: environmental impact, social responsibility, economic feasibility, and regulatory compliance. Findings of this study highlight the potential of renewable energy adoption and continuous improvement and innovation for sustainable supply chain management within manufacturing firms, offering noticeable enhancements in operational efficiency, product quality, and market competitiveness. The proposed MCDM-based approach is adaptable to various manufacturing contexts, empowering organizations to pursue sustainability goals tailored to their specific needs. It is important to note that results derived from the application of the VIKOR technique have been obtained by quantitatively translating subjective evaluations of input provided by an expert in the field. Therefore, outcomes may vary depending on different stakeholders. In future research, we aim to broaden the decision-making panel by including experts from diverse backgrounds to minimize subjectivity in input data. Additionally, sensitivity analyses could be implemented by varying criteria weights, or integrating another MCDM approach for more precise weight calculation.

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Biographies

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