Empowering sustainable practices: actionable insights for navigating green supply chains in uncertainty

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Abstract. This research demonstrates how Green Supply Chain Management (GSCM) can boost organizational performance and mitigate environmental risks in uncertain environments. The critical role of supplier selection in building resilient supply chains is a central focus. We employ the Fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to uncover and evaluate the most influential factors in GSCM criteria. This quantitative approach helps us identify crucial criteria by assessing supplier performance. While limitations in generalizability and potential biases are acknowledged, the study emphasizes the strategic necessity of supplier selection in GSCM. It provides actionable insights for managers, enhancing decision-making and contributing to sustainable supply chain practices. **Keywords:** Sustainable supply chain management; Fuzzy decision-making; DEMATEL analysis; Supplier performance assessment; Mitigation of environmental risks.

1 Introduction

Modern manufacturing faces escalating environmental challenges, prompting the integration of sustainable practices into business strategies. The electronics industry requires green technical capabilities to address these concerns effectively. GSCM plays a pivotal role in aligning business goals with environmental considerations [1].

Scholars and practitioners emphasize the intricate link between supplier product quality, environmental performance, and their influence on global customer perceptions, highlighting the need for efficient operational management [2]. GSCM considerations span the entire product life cycle, making it a strategic imperative for businesses. This approach offers opportunities for profitability, market share growth, reduced environmental risks, and enhanced efficiency [3-4].

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GSCM involves integrating environmental thinking into all aspects of supply chain management, including product design, material sourcing, manufacturing processes, product delivery, and end-of-life management [5]. A critical aspect is selecting suppliers aligned with environmental goals. Establishing strategic partnerships with suppliers during the early stages of product research and development is crucial [6]. Supplier selection is recognized as a key function contributing to cost savings and competitive advantage [7]. Enterprises assess suppliers' environmental performance, ensuring adherence to measures for product and process quality [8].

Implementing GSCM practices enables firms to choose from diverse suppliers, optimizing resources to mitigate environmental impacts [9, 10]. However, traditional methods like interviews and surveys used to evaluate GSCM can be limited by incomplete information, subjective biases, and linguistic uncertainties [11]. This study addresses these challenges by employing the DEMATEL method, providing insights into complex causal relationships influencing GSCM performance criteria.

The primary objectives include evaluating drivers impacting GSCM implementation, understanding interactions among identified drivers, and discerning managerial implications. The study structure encompasses a literature survey on GSCM implementation, the research methodology for developing and validating GSCM criteria, empirical results, and discussions on implications and conclusions.

1.1 Green Supply Chain Management (GSCM): A Critical Review and the Role of Supplier Selection

GSCM has evolved significantly since its early focus on minimizing unforeseen environmental impacts within organizations and supply chains [12-14]. Today, GSCM encompasses various aspects, including product design, production processes, material sourcing, supplier impact, and strategies for achieving environmental sustainability [15, 16]. Buyer requirements play a crucial role in shaping green supply chains and fostering collaborative partnerships with environmentally responsible suppliers [17].

Research by Jo & Kwon [18] defines GSCM as the direct involvement of firms with suppliers and customers, collaborating to minimize the environmental footprint of production processes and products. This involves collaborative efforts in environmental management, knowledge sharing, and setting mutual environmental improvement goals. Such collaborations strengthen cooperation among stakeholders, leading to reduced environmental impacts associated with material flows throughout the supply chain [19].

The critical role of supplier selection in GSCM is well established. Enterprises often expect their suppliers to exceed environmental compliance by implementing green practices like efficient product design and life cycle assessments [20-21]. Robust supplier selection, incorporated into performance evaluations, allows firms to optimize internal resources and mitigate environmental impacts [22].

Various ways of demonstration and methods have been employed to analyze and understand the complex relationships among GSCM criteria:

• Fishbone diagrams: utilized as a visual tool to demonstrate various factors affecting the performance of green suppliers, such as process, people, equipment, environment, and management [23].

• Interpretive Structural Modeling (ISM) and Analytic Hierarchy Process (AHP): Employed to analyze and select green suppliers based on environmental performance [24].

• Hybrid Multi-Criteria Decision-Making Models: Used to explore qualitative and quantitative measurements of environmental practices in knowledge management [25].

While these methods offer valuable insights, few studies have effectively demonstrated the relationships between factors influencing GSCM performance. This research addresses this gap by pioneering the use of the DEMATEL method to identify appropriate GSCM criteria for enterprises. The strength of the DEMATEL method lies in its ability to unveil direct and indirect relationships between factors, providing a comprehensive understanding of their influence on each other [26].

Chen et al., [27] explored qualitative and quantitative measurements of environmental practice in knowledge management capability using a novel hybrid multi-criteria decision-making model, addressing dependence relationships through the integration of the Analytical Network Process and DEMATEL. Additionally, Walter et al., [28] based on interviews conducted at seven different private and public sector organizations, identified both internal and external drivers, such as the challenge of selecting suppliers. According to [29], conventional GSCM criteria, along with environmental criteria, need to be incorporated into a comprehensive model to identify the most suitable supplier. Despite these efforts, few studies have effectively illustrated the interconnectedness of factors impacting SCM performance. Considering this, our study utilizes the DEMATEL method to identify GSCM criteria suitable for enterprises, leveraging its capacity to unveil relationships among factors [30].

While previous studies have made strides in applying DEMATEL and hybrid methods across various domains, our research aims to build upon and contribute to this body of literature by providing unique insights into the drivers of GSCM implementation and their relationship with environmental management. Drawing inspiration from previous implementations, we acknowledge both the gains and critiques observed in the literature.

One notable gain observed in prior research, as exemplified by Zhu et al., [1], is the utilization of DEMATEL to understand the diffusion of green innovations and its relationship with organizational improvement. Similarly, studies such as Huang et al., [2] and Raman et al., [3] have demonstrated the effectiveness of hybrid methods in enhancing supply chain capability, resilience, and their alignment with UN Sustainable Development Goals.

However, critiques have also emerged regarding the implementation of DEMATEL and hybrid methods. For instance, some studies, such as Srivastava [4] and Rupa & Saif [5], have pointed out challenges related to the overlap of criteria and the relevance of certain factors in supplier selection processes. Moreover, issues regarding the selection method and the background of expert groups have been raised, as highlighted by Diabat & Govindan [24], and Govindan et al., [26], emphasizing the need for transparency and rigor in research methodologies.

Informed by these gains and critiques, our study takes a rigorous approach to evaluate the drivers of GSCM implementation. We address concerns regarding the selection method by carefully defining our evaluation criteria based on insights from a diverse set of experts. Additionally, we ensure transparency and robustness in our methodology by providing detailed information about the background of the expert groups, including their educational backgrounds, industrial experiences, and working years.

Furthermore, to mitigate concerns about criterion overlap, we conducted a thorough literature review and engaged in extensive discussions with domain experts to refine and validate our criteria. Additionally, we provide a rationale for the relevance of each criterion, including internal service excellence (C7), which contributes to the overall efficiency and effectiveness of supplier interactions, as highlighted by Shuib et al., [31], and Stanley & Wisner [32].

In summary, while drawing upon previous implementations, we have endeavored to address key critiques and incorporate best practices to enhance the robustness and validity of our research findings. Recognizing the profound impact of supplier selection on the GSCM relationship, this research employs a fuzzy DEMATEL approach to assess the issue and enhance GSCM performance through prudent supplier selection.

This research uniquely evaluates GSCM drivers within the context of environmental management, recognizing the pivotal role of supplier selection [17]. Acknowledging the potential of collaborative efforts highlighted by [33], we employ a fuzzy DEMATEL approach to assess and enhance GSCM performance through prudent supplier selection.

Collaborative decision-making strategies are increasingly adopted by organizations to tackle complex challenges. In this context, group decision-making involves seeking consensus through the interaction of multiple experts, ultimately leading to a collectively acceptable solution [6].

1.2 Introduction to Fuzzy Set Theory

Fuzzy set theory provides a framework for incorporating linguistic information into decision-making processes. In this context, a fuzzy set is used to represent the degree of membership of an element in a set. In simpler terms, it allows us to express uncertain or subjective evaluations using linguistic terms like "low influence" or "very high influence", instead of relying solely on numerical values.

Many organizations have embraced collaborative decision-making strategies to tackle real decision-making challenges. Group decision-making involves seeking consensus through the interaction of multiple experts, resulting in a collectively acceptable resolution. Let Z represent the universe of discourse, denoted as $Z = \{z_1, z_2, \dots, z_n\}$. In this context, a fuzzy set $\tilde{B}$ of Z consists of ordered pairs $\{z_1, f_{\tilde{B}}\ (z_2)\}$, where $f_{\tilde{B}}: Z \to [0,1]$ serves as the membership function of $\tilde{B}$, and $f_{\tilde{B}}\ (z_i)$ denotes the membership degree of z_i in $\tilde{B}$.

Table 1 presents the fuzzy linguistic scale used in this study, associating linguistic terms with corresponding numerical values represented by triangular fuzzy numbers. The linguistic variable column specifies the linguistic terms used to express the evaluations of GSCM influencing factors. The corresponding triangular fuzzy numbers column indicates the numerical values associated with each linguistic term, represented in triangular fuzzy number format. This scale allows experts to express their evaluations with greater nuance and flexibility, facilitating the assessment of GSCM factors in uncertain environments.

Table 1. Fuzzy linguistics Scale for evaluating GSCM factors

Linguistic variable	**Corresponding triangular fuzzy numbers**
No influence	(0, 0.1, 0.3)
Very low influence	(0.1, 0.3, 0.5)
Low influence	(0.3, 0.5, 0.7)
High influence	(0.5, 0.7, 0.9)
Very high influence	(0.7, 0.9, 1.0)

Source : [52]

Each linguistic term is associated with a triangular fuzzy number representing a range of numerical values. For instance, in the case of "low influence," the corresponding triangular fuzzy number is (0.3, 0.5, 0.7). This format signifies a range of possible values, with the lower bound being 0.3, the midpoint being 0.5, and the upper bound being 0.7.

To convert these linguistic terms into crisp values, we utilize the midpoint of the triangular fuzzy number. For instance, for "low influence," the midpoint value of 0.5 is considered the crisp numerical equivalent. This approach allows us to capture the essence of each linguistic term while providing a specific numerical value for analysis. By employing this method, we ensure that the evaluations of GSCM influencing factors are translated into precise numerical representations, enabling a more nuanced assessment of their impact in uncertain environments.

The conversion of linguistic terms into crisp values involves extracting the mid-point from the triangular fuzzy number associated with each term. This process allows us to maintain the flexibility and nuance of linguistic expressions while providing numerical equivalents for analysis and decision-making.

Group decision-making offers a valuable approach to address this challenge. Leveraging the collective knowledge and diverse perspectives of multiple experts facilitates the development of consensus-based solutions that are more likely to be comprehensive and effective. However, when dealing with uncertainty within the decision-making process, traditional methods might fall short. This study utilizes fuzzy set theory, allowing experts to express their evaluations using linguistic terms rather than solely relying on numerical scores. This approach provides a more nuanced and flexible way to capture subjective assessments in the presence of uncertainty.

Through fuzzy aggregation methods, such as the one proposed by Abassi et al., [34], the linguistic evaluations from different experts are combined into a single, crisp score for each factor influencing GSCs. This allows for a more robust and quantifiable analysis of the factors' relative importance. To amalgamate diverse evaluator opinions, this research embraces the synthetic value notation for aggregating subjective judgments provided by w evaluators, given by Equation 1.

$$\tilde{Y}_j = \frac{1}{w}\left(\tilde{y}_{ij}^1 + \tilde{y}_{ij}^2 + \tilde{y}_{ij}^3 + \cdots + \tilde{y}_{ij}^k\right) \tag{1}$$

Where:

$\tilde{Y}_j$: represents the synthesized value or aggregated score for factor j, which influences GSCs. It's the outcome of the fuzzy aggregation process and serves as a single, crisp score that quantifies the overall importance of factor j.

w: denotes the number of evaluators or experts providing subjective judgments on the importance of factor j. It acts as a weighting factor in the aggregation process, reflecting the diversity and quantity of opinions considered.

$\tilde{y}_{ij}^1 + \tilde{y}_{ij}^2 + \tilde{y}_{ij}^3 + \cdots + \tilde{y}_{ij}^k$: are the linguistic evaluations provided by each evaluator i for factor j. They represent the subjective assessments or ratings given by different experts regarding the importance of factor j to GSCs. The superscript indices (1, 2, ..., k) indicate the evaluations provided by each evaluator, contributing to the overall aggregation process. The fuzzy aggregation method combines these linguistic evaluations to derive a consensus score for factor j, reflecting the collective expert opinion on its significance in GSCs.

1.3 General discussion of the DEMATEL Method

The practical application of the DEMATEL method has been demonstrated in diverse contexts, including various aspects of supply chain management [35, 36, 37]. This study leverages this method to analyze the interconnectedness of factors influencing GSCM and gain valuable insights into their interdependent nature.

This section outlines the core principles of the DEMATEL method. It involves considering a system with a set of GSCM criteria (denoted as $C = \{c_1, c_2, \ldots, c_n\}$), and establishing pairwise relations for mathematical modeling. The procedural steps encompass generating the direct-relation matrix in the first step, normalizing it in the second step, deriving the total relation matrix in the third step, creating a causal diagram in the fourth step, and finally obtaining the dependence matrix in the fifth step. The normalization method ensures that the sum of each column in the total relation matrix equals 1, facilitating the acquisition of the dependence matrix.

The analysis procedures of the fuzzy DEMATEL method are outlined as follows:

Step 1: Identifying Decision Goal: The initial step involves clearly defining the objectives of the analysis. This includes gathering relevant information to evaluate potential solutions and monitor progress toward achieving the set goals. To ensure comprehensive knowledge and diverse perspectives, two expert committees are formed to contribute their collective expertise. These expert groups encompass individuals with varied educational backgrounds, including but not limited to disciplines such as supply chain management, environmental science, engineering, and business administration. Additionally, members of these committees possess extensive industrial experiences spanning various sectors, such as manufacturing, logistics, retail, and consulting. The working years of the experts within these groups range from mid-career professionals to seasoned veterans, ensuring a balanced mix of fresh insights and seasoned expertise.

Step 2: Developing Evaluation Criteria and Survey Instrument: Establishing a comprehensive set of criteria for evaluation is crucial. The fuzzy DEMATEL method excels at handling situations with complex interrelationships between these criteria. By applying this method, we aim to develop a structural model that categorizes the criteria into cause-and-effect groups. To gather reliable information on the influences and directions of relationships among these criteria, two expert groups are consulted to validate the developed survey instrument. The members of these expert groups bring diverse perspectives and expertise from their respective fields, contributing to the robustness and validity of the evaluation criteria.

Step 3: Interpreting Linguistic Information: This step involves utilizing linguistic information, such as "low influence" or "very high influence," provided by the experts. Through defuzzification and aggregation techniques, these linguistic assessments are converted into crisp values (numerical equivalents) for further analysis.

Step 4: Analysing Criteria into Causal and Effect Diagram: Utilizing the crisp values obtained from the initial direct relation matrix, the analysis proceeds to categorize the criteria into a causal and effect diagram. This visual representation (refer to Table 3) provides valuable insights into the dominant and dependent factors within the GSCM system.

2 Materials and Method

The identification of key factors vital for the effective adoption of GSCM practices is a complex undertaking that encompasses a comprehensive literature review and collaborative input from a decision-making team consisting of industry experts. The criteria listed in Table 2 were generated through a comprehensive process involving several key steps:

- Extensive Literature Review: we conducted an in-depth review of existing literature on GSCM practices to identify commonly discussed factors influencing the selection of suppliers.
- Expert Consultation: we consulted with industry experts and professionals in the field of GSCM to gather insights and perspectives on the most critical factors for supplier selection.
- Decision-Making Framework: these criteria were further refined and selected based on their relevance, importance, and impact on the overall success of GSCM initiatives, as determined through a structured decision-making framework.

Table 2 details the fundamental criteria explored in this study, along with the corresponding sources that inform their inclusion. This table serves as a valuable tool for understanding the significant factors that influence successful GSCM implementation.

Table 2. Key Factors Influencing GSCM Implementation: Overview of Criteria and Sources

Criteria	Sources
(1) Environmental Partnership with Suppliers	[16, 38, 39]
(2) Synergistic Design-Supplier Collaboration for Waste Reduction	[40-41]
(3) Proximity in Supplier Relationships	[42-43]
(4) Customer-Centric Fulfillment	[44-45]
(5) Product Quality Adherence	[46]
(6) Supplier Flexibility	[47, 48]
(7) Internal Service Excellence	[49-50]
(8) Innovative Green Design Practices	[51]
(9) Sustainable Procurement Practices	[52-53]
(10) ISO 14000 Compliance	[54]
(11) Strategic Internal Green Production Planning	[55]
(12) Innovation Level in R&D for Green Product Development	[56-57]

The criteria outlined in Table 2 encompass a comprehensive framework for understanding the drivers crucial to successful GSCM implementation. Environmental Partnership with Suppliers denotes the establishment of collaborative relationships with suppliers committed to environmental sustainability. It involves mutual efforts to reduce carbon footprint, minimize waste generation, and promote eco-friendly practices throughout the supply chain. Synergistic Design-Supplier Collaboration for Waste Reduction focuses on joint efforts between companies and suppliers to integrate sustainable design principles aimed at minimizing waste generation. It entails collaborative product development processes that prioritize resource efficiency, recycling capabilities, and the reduction of material waste at every stage of production. Proximity in Supplier Relationships emphasizes the importance of geographical closeness between companies and suppliers to enhance logistical efficiency, reduce transportation-related emissions, and foster stronger communication and collaboration in implementing sustainable practices. Customer-centric Fulfilment underscores the significance of aligning supply chain practices with customer preferences and sustainability expectations. It involves tailoring products and services to meet evolving consumer demands for environmentally responsible offerings, thereby enhancing customer satisfaction and loyalty. Product Quality Adherence emphasizes the maintenance of high standards in product manufacturing processes while integrating sustainable practices. It involves ensuring that sustainable initiatives do not compromise product quality, reliability, or safety, thereby preserving customer trust and brand reputation. Supplier Flexibility refers to the ability of suppliers to adapt to changing market dynamics, consumer preferences, and regulatory requirements while maintaining sustainable practices. It involves fostering agility and responsiveness within the supply chain to address emerging sustainability challenges and opportunities effectively. Internal Service Excellence focuses on optimizing internal processes and capabilities to support the effective implementation of sustainable practices. It entails fostering a culture of continuous improvement, employee empowerment, and knowledge sharing to drive innovation and efficiency in sustainability initiatives. Innovative Green Design Practices highlights the adoption of innovative design practices aimed at reducing environmental impact throughout the product lifecycle. It involves incorporating sustainable materials, technologies, and processes into product design and development to enhance resource efficiency, minimize waste, and promote circularity. Sustainable Procurement Practices entail the integration of environmental, social, and ethical considerations into the sourcing and procurement processes. It involves selecting suppliers and materials based on their environmental and social performance, promoting fair labor practices, and minimizing adverse impacts on ecosystems and communities. ISO 14000 Compliance refers to adherence to the international standards for environmental management systems. It involves implementing systematic approaches to identify, monitor, and mitigate environmental impacts, ensuring regulatory compliance, and continually improving environmental performance across the supply chain. Strategic Internal Green Production Planning emphasizes the strategic alignment of production processes with sustainability goals and objectives. It involves integrating environmental considerations into production planning, resource allocation, and capacity management to optimize resource efficiency, minimize waste, and reduce environmental footprint. Innovation Level in Research & Development (D&R) for Green Product Development assesses the level of innovation in research and development (R&D) activities aimed at green product development. It involves investing in R&D initiatives to develop sustainable products, technologies, and solutions that address environmental challenges, meet market demands, and drive competitive advantage. Each criterion contributes to a holistic approach to GSCM, promoting environmental responsibility and competitive advantage.

This section advocates for the incorporation of linguistic information into complex evaluation systems used in managing Green Supply Chains (GSC). By decomposing the intricate evaluation environment into smaller subsystems, the analysis of variations and measurement scores becomes more straightforward. The proposed hybrid approach utilizes linguistic expressions and generates a visual map to facilitate informed strategic decision-making in GSCs.

GSCM involves intricate relationships between various factors, making it crucial to identify and understand these interconnections for effective implementation.

The DEMATEL method emerges as a valuable tool in this context. Its strength lies in visualizing complex causal relationships among system elements through matrices or digraphs [54]. Each numerical value within these matrices represents the strength and direction of influence between a pair of factors. By transforming these cause-and-effect relationships into a clear and structured model, the DEMATEL method enhances our understanding of the system's dynamics.

By following the comprehensive steps of the fuzzy DEMATEL method, the fuzzy DEMATEL method offers a systematic and effective approach for analyzing the interconnectedness of factors influencing GSCM in uncertain environments. This approach empowers stakeholders to make informed decisions and navigate the complexities of the GSCM. To further explore the fuzzy DEMATEL research method within the realm of uncertainty, the analysis procedures are elucidated as follows:

Table 3. Matrix of Crisp Values for Analyzing Interconnectedness of GSCM Factors

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
C1	0.075	0.058	0.040	0.022	0.040	0.040	0.040	0.040	0.059	0.040	0.059	0.059
C2	0.075	0.074	0.040	0.040	0.058	0.058	0.058	0.040	0.040	0.059	0.059	0.040
C3	0.059	0.058	0.079	0.040	0.040	0.522	0.040	0.058	0.075	0.040	0.059	0.059
C4	0.040	0.058	0.040	0.022	0.058	0.709	0.040	0.040	0.059	0.059	0.059	0.075
C5	0.075	0.040	0.059	0.040	0.040	0.522	0.058	0.040	0.040	0.059	0.059	0.040
C6	0.059	0.074	0.040	0.022	0.058	0.709	0.040	0.058	0.059	0.075	0.075	0.059
C7	0.040	0.074	0.059	0.040	0.058	0.709	0.040	0.040	0.040	0.075	0.059	0.075
C8	0.075	0.040	0.040	0.022	0.040	0.058	0.040	0.058	0.059	0.059	0.059	0.059
C9	0.045	0.040	0.059	0.040	0.058	0.058	0.058	0.040	0.040	0.059	0.059	0.022
C10	0.059	0.059	0.040	0.040	0.058	0.040	0.058	0.040	0.040	0.059	0.059	0.059

C11	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.058	0.040	0.059	0.059	0.040
C12	0.075	0.040	0.040	0.058	0.040	0.040	0.040	0.040	0.075	0.059	0.075	0.040

Table 3 presents a matrix of crisp values derived from the fuzzy DEMATEL analysis, depicting the relationships and interdependencies among GSCM factors. Each cell in the matrix represents the strength of influence between two factors, providing insights into the extent of their impact on each other. The crisp values facilitate a deeper understanding of the complex dynamics within GSCM, aiding stakeholders in decision-making processes.

3 Results and discussion

GSCM faces the challenge of selecting suppliers who contribute positively to environmental sustainability. This study employs the fuzzy DEMATEL method to analyze and prioritize a set of 12 critical evaluation criteria for GSCM supplier selection.

The fuzzy DEMATEL method offers a robust framework for evaluating the interconnectedness and relative importance of criteria in uncertain environments. This approach is particularly well-suited for GSCM, where subjective assessments and complex relationships between criteria are prevalent.

This study utilizes a four-phase approach to analyze the data and construct a cause-and-effect model for GSCM supplier selection:

Phase 1: Establishing the Direct-Relation Matrix

The initial stage involves collecting data from experts and constructing a direct-relation matrix (presented in Table 4). This matrix captures the perceived influence of each criterion on all others, laying the foundation for further analysis. Each cell in the matrix contains a numerical value representing the perceived influence of one criterion on another. The calculation involves aggregating expert opinions and assigning values based on the strength of influence, considering factors such as expertise, experience, and relevance to GSCM supplier selection.

The formula used in this phase is the following:

$$D_{ij} = \frac{1}{n} \sum_{k=1}^{n} d_{ijk} \tag{2}$$

Where D_{ij} represents the direct influence between criteria i and j, and d_{ijk} represents the influence value provided by expert k.

Table 4. Direct-Relation Matrix for GSCM Supplier Selection

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
C1	0.075	0.058	0.040	0.022	0.040	0.040	0.040	0.040	0.059	0.040	0.059	0.059
C2	0.075	0.074	0.040	0.040	0.058	0.058	0.058	0.040	0.040	0.059	0.059	0.040
C3	0.059	0.058	0.079	0.040	0.040	0.522	0.040	0.058	0.075	0.040	0.059	0.059
C4	0.040	0.058	0.040	0.022	0.058	0.709	0.040	0.040	0.059	0.059	0.059	0.075
C5	0.075	0.040	0.059	0.040	0.040	0.522	0.058	0.040	0.040	0.059	0.059	0.040
C6	0.059	0.074	0.040	0.022	0.058	0.709	0.040	0.058	0.059	0.075	0.075	0.059
C7	0.040	0.074	0.059	0.040	0.058	0.709	0.040	0.040	0.040	0.075	0.059	0.075
C8	0.075	0.040	0.040	0.022	0.040	0.058	0.040	0.058	0.059	0.059	0.059	0.059
C9	0.045	0.040	0.059	0.040	0.058	0.058	0.058	0.040	0.040	0.059	0.059	0.022
C10	0.059	0.059	0.040	0.040	0.058	0.040	0.058	0.040	0.040	0.059	0.059	0.059

C11	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.058	0.040	0.059	0.059	0.040
C12	0.075	0.040	0.040	0.058	0.040	0.040	0.040	0.040	0.075	0.059	0.075	0.040

Table 4 showcases the pairwise relationships between criteria in GSCM supplier selection. Each cell in the matrix represents the perceived influence of one criterion on another, providing insights into the direct connections and dependencies within the decision-making process. This matrix serves as a crucial tool for identifying key factors and prioritizing criteria in GSCM supplier selection.

Phase 2: Converting Triangular Fuzzy Numbers to Crisp Values

Building upon the direct-relation matrix from Phase 1 (Table 4), this phase focuses on converting the linguistic assessments provided by experts into numerical values. These linguistic assessments, often expressed as triangular fuzzy numbers (e.g., "low influence"), represent the perceived influence of each criterion on the others.

This conversion process, known as defuzzification, translates fuzzy numbers into crisp values, denoted as $\tilde{Y}_{ij}$ (see Table 5). These crisp values allow for further quantitative analysis and construction of the cause-and-effect model. We used the formula:

$$C_{ij} = \frac{a+2b+c}{4} \tag{3}$$

Where C_{ij} represents the crisp value for the influence between criteria i and j, and $a, b,$ and, c represent the lower, middle, and upper bounds of the triangular fuzzy number.

Table 5. Triangular Fuzzy Matrix for Converting Linguistic Assessments to Crisp Values Positioning

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
C1	1.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C2	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C3	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C4	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C5	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C6	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000
C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
C8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000
C9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000
C10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000
C11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000
C12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000

Table 5 showcases the conversion process of linguistic assessments provided by experts into crisp values. Each cell in the matrix represents the crisp value obtained from defuzzification, indicating the perceived influence of one criterion on another in GSCM supplier selection. This matrix serves as a crucial intermediary step in the analysis, facilitating the transition from qualitative linguistic assessments to quantitative crisp values.

Phase 3: Deriving the Total Relation Matrix

Following the conversion of individual assessments to crisp values in Phase 2, this phase involves aggregating the information from all experts. This aggregation process aims to capture the collective perspective on the interrelationships between the GSCM criteria.

The result of this phase is the total relation matrix (presented in Table 6). This matrix depicts the direct and indirect influences between each pair of criteria, providing a more comprehensive understanding of the system's dynamics. Aggregation of crisp values from the direct-relation matrix to derive the total relation matrix. The equation (4) could involve summing up the individual values contributed by each expert to obtain the total influence between criteria.

$$T_{ij} = \sum_{k=1}^{n} C_{ijk} \quad (4)$$

Where T_{ij} represents the total influence between criteria i and j, and C_{ijk} represents the crisp value provided by expert k.

Table 6. DEMATEL Initial Direct-Relation Matrix for GSCM Criteria

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
0.905	(0.074)	(0.040)	(0.040)	(0.058)	(0.058)	(0.058)	(0.040)	(0.040)	(0.059)	(0.069)
(0.075)	0.922	(0.069)	(0.040)	(0.040)	(0.040)	(0.040)	(0.058)	(0.075)	(0.040)	(0.059)
(0.059)	(0.058)	0.940	(0.022)	(0.058)	(0.058)	(0.040)	(0.040)	(0.059)	(0.059)	(0.059)
(0.040)	(0.040)	(0.059)	0.940	(0.040)	(0.040)	(0.058)	(0.040)	(0.040)	(0.059)	(0.059)
(0.075)	(0.074)	(0.040)	(0.022)	0.922	(0.058)	(0.040)	(0.058)	(0.059)	(0.075)	(0.059)
(0.059)	(0.074)	(0.059)	(0.040)	(0.058)	0.922	(0.040)	(0.040)	(0.040)	(0.075)	(0.059)
(0.040)	(0.040)	(0.040)	(0.022)	(0.040)	(0.058)	0.940	(0.058)	(0.059)	(0.059)	(0.059)
(0.075)	(0.040)	(0.059)	(0.040)	(0.058)	(0.058)	(0.058)	0.940	(0.040)	(0.059)	(0.059)
(0.040)	(0.040)	(0.040)	(0.040)	(0.058)	(0.040)	(0.058)	(0.040)	0.940	(0.059)	(0.059)
(0.059)	(0.040)	(0.040)	(0.040)	(0.040)	(0.040)	(0.040)	(0.058)	(0.040)	0.921	(0.059)
(0.040)	(0.040)	(0.040)	(0.058)	(0.040)	(0.040)	(0.040)	(0.040)	(0.075)	(0.059)	0.905

Table 6 illustrates the direct and indirect influences between each pair of GSCM criteria. Each cell in the matrix represents the strength of influence, allowing stakeholders to identify key relationships and prioritize criteria in GSCM decision-making. This matrix serves as a crucial tool for understanding the interconnectedness of factors and guiding strategic interventions in GSCM processes.

Phase 4: Formulation of the Generalized Direct Relation Matrix

Table 7 showcases the direct relationships between all principal elements of the GSCM framework. Each cell in the matrix represents the strength of the relationship, offering insights into the influence of one criterion on another. This matrix facilitates a comprehensive analysis of GSCM dynamics, aiding stakeholders in strategic decision-making and intervention planning. Formula (4) is used to carry on the respective calculations.

$$G_{ij} = \frac{1}{m} \sum_{k=1}^{m} D_{ijk} \quad (5)$$

Where G_{ij} represents the generalized direct relation between criteria i and j, and D_{ijk} represents the direct influence value provided by expert k.

Table 7. Generalized Direct Relation matrix for comprehensive GSCM Analysis

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
C1	1.597	0.500	0.439	0.373	0.447	0.438	0.440	0.405	0.489	0.528	0.530	0.474

C2	0.598	1.482	0.457	0.374	0.430	0.419	0.424	0.422	0.503	0.510	0.529	0.492
C3	0.592	0.492	1.448	0.363	0.455	0.444	0.431	0.412	0.493	0.538	0.539	0.518
C4	0.520	0.430	0.426	1.347	0.397	0.389	0.410	0.376	0.435	0.491	0.491	0.440
C5	0.639	0.532	0.470	0.382	1.477	0.466	0.453	0.451	0.521	0.581	0.582	0.525
C6	0.610	0.524	0.481	0.393	0.469	1.459	0.445	0.426	0.495	0.571	0.557	0.434
C7	0.523	0.431	0.408	0.330	0.399	0.407	1.393	0.394	0.454	0.492	0.492	0.458
C8	0.576	0.449	0.442	0.360	0.432	0.423	0.426	1.391	0.452	0.511	0.511	0.438
C9	0.531	0.439	0.416	0.354	0.423	0.396	0.418	0.383	1.444	0.501	0.501	0.466
C10	0.528	0.421	0.399	0.341	0.390	0.381	0.385	0.386	0.426	1.481	0.482	0.429
C11	0.535	0.442	0.420	0.376	0.409	0.400	0.405	0.387	0.483	0.506	1.522	0.452
C12	0.588	0.480	0.432	0.368	0.440	0.412	0.417	0.398	0.480	0.501	0.521	1.484

Phase 5: Construction of the Total Relation Matrix

Table 8 presents the total relation matrix, derived from the generalized direct relation matrix. This matrix captures the direct and indirect influences between each pair of GSCM criteria.

By analysing the total relation matrix, we can gain valuable insights into the interconnectedness and relative importance of the GSCM criteria. Examining the rows of the matrix allows us to identify the total influence each criterion exerts on all other criteria while inspecting the columns reveals the total influence each criterion receives from all others. The calculations were performed using the formula (6).

$$R_{ij} = \sum_{k=1}^{n} G_{ik} \; x \; G_{kj} \qquad (6)$$

Where R_{ij} represents the total relation between criteria i and j, and G_{ik} and G_{kj} represent the generalized direct relations between criteria i and k, and j respectively.

Table 8. Total Relation Matrix for Comprehensive Analysis of GSCM Criteria

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
C1	0.567	0.458	0.416	0.336	0.406	0.397	0.401	0.383	0.462	0.482	0.501	0.467
C2	0.597	0.500	0.439	0.373	0.447	0.437	0.440	0.405	0.489	0.528	0.530	0.474
C3	0.572	0.474	0.450	0.368	0.422	0.412	0.417	0.415	0.496	0.501	0.520	0.484
C4	0.563	0.482	0.440	0.356	0.446	0.436	0.423	0.405	0.488	0.528	0.529	0.509
C5	0.576	0.447	0.441	0.360	0.413	0.404	0.426	0.390	0.452	0.509	0.510	0.456
C6	0.613	0.524	0.463	0.375	0.469	0.459	0.445	0.444	0.513	0.572	0.574	0.517
C7	0.581	0.515	0.473	0.386	0.461	0.450	0.437	0.419	0.486	0.561	0.567	0.525
C8	0.579	0.449	0.424	0.343	0.415	0.423	0.409	0.408	0.470	0.510	0.511	0.475
C9	0.520	0.431	0.426	0.347	0.416	0.408	0.410	0.376	0.435	0.492	0.493	0.422
C10	0.561	0.448	0.424	0.361	0.431	0.405	0.426	0.391	0.453	0.510	0.511	0.475
C11	0.409	0.412	0.391	0.334	0.381	0.373	0.377	0.378	0.417	0.472	0.472	0.420
C12	0.591	0.460	0.435	0.389	0.425	0.415	0.421	0.401	0.409	0.524	0.541	0.489

Table 8 illustrates the direct and indirect influences between each pair of GSCM criteria. Each cell in the matrix represents the strength of influence, offering insights into the overall influence of one criterion on another. This matrix facilitates a comprehensive understanding of the dynamics within GSCM processes, aiding stakeholders in decision-making and intervention planning.

Phase 6: Identifying Prominent Factors and Cause-and-Effect Relationships

This phase of the analysis focuses on identifying prominent factors and cause-and-effect relationships within the GSCM criteria, building upon the Total Relation Matrix (Table 8). Table 9 presents the results of this phase, crucial for understanding the relative importance and interconnectedness of these criteria. The table includes the sum of row values (D) and the sum of column values (R), allowing for the identification of prominent factors and cause-and-effect relationships within the GSCM system. This information, presented in Table 9, is crucial for understanding the relative importance and interconnectedness of these criteria.

Here's how this phase works:

• The sum of row values (D): This value represents the total influence a specific criterion exerts on all other criteria in the system.

• The sum of column values (R): This value represents the total influence a specific criterion receives from all other criteria in the system.

By analyzing these values, we can identify:

Prominent factors: Criteria with high driving power (high sum of rows) and high dependence (high sum of columns) are considered dominant factors. They significantly influence other criteria and are also significantly influenced by others, indicating their central role in the GSCM system.

Cause-and-effect relationships: The relative differences between D and R values can reveal cause-and-effect relationships. A larger difference (D > R) suggests the criterion primarily acts as a cause, while a smaller difference (D < R) suggests it primarily acts as an effect.

Table 9. Prominent Factors and Cause-Effect Relationships Analysis for GSCM Criteria

	D	R	D+R	D-R
C1	5.28	6.73	12.01	(1.45)
C2	5.66	5.60	11.26	0.06
C3	5.53	5.22	10.75	0.31
C4	5.61	4.69	10.30	0.92
C5	5.39	4.69	10.08	0.70
C6	5.97	5.02	10.99	0.95
C7	5.86	5.03	10.89	0.83
C8	5.42	4.82	10.24	0.60
C9	5.18	5.57	10.75	(0.39)
C10	5.40	6.19	11.59	(0.79)
C11	4.84	6.26	11.10	(1.42)
C12	5.50	5.74	11.24	(0.24)

Figure 1 illustrates the D-R vs. D+R diagram, a visual representation used to analyze the influence and dependence of criteria within the GSCM system. Here, D represents the sum of column values, indicating the total influence exerted by a criterion, while R represents the sum of row values, representing the net influence received by a criterion. Thus, D+R reflects the total influence a criterion has on the system, encompassing both its direct influence and the influence it receives from other criteria. On the other hand, D-R signifies the net influence received by a criterion, accounting for the influence it receives from other criteria minus its influence on the system. Point C's position within this diagram provides insights into its relative importance and role within the GSCM system, with its location relative to other criteria indicating its level of influence and dependence. This visualization aids stakeholders in understanding the complex dynamics of cause-and-effect relationships within GSCM processes.

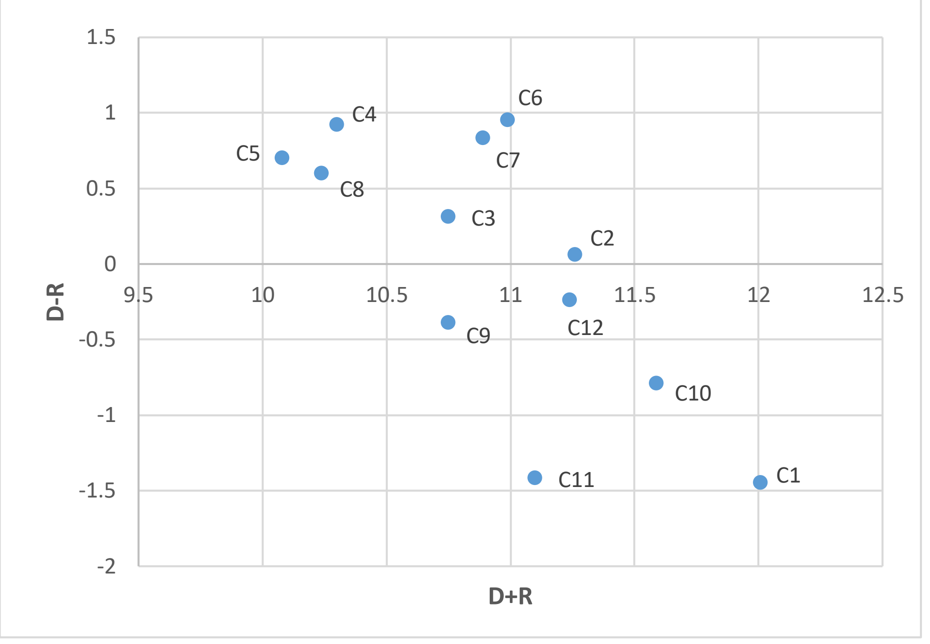

Fig. 1. Visualization of Point C's Location in D+R vs. D-R Diagram

The figure depicts the D+R vs. D-R diagram, where each point represents a criterion in the GSCM system. The horizontal axis (D+R) represents the total influence exerted by a criterion, while the vertical axis (D-R) represents the net influence received by a criterion. Point C's location within this diagram indicates its position relative to other criteria, providing insights into its importance and role within the GSCM system. This visualization aids stakeholders in understanding the dynamics of cause-and-effect relationships within GSCM processes.

The research findings underscore the significance of seven criteria in assessing causation within GSCM: collaborative design supplier synergy for waste reduction (C2), proximity in supplier relationships (C3), customer-centric fulfillment (C4), adherence to product quality (C5), supplier flexibility (C6), internal service excellence (C7), and innovative green design practices (C8). These criteria demonstrate greater importance compared to others such as environmental partnership with suppliers (C1), sustainable procurement practices (C9), ISO 14000 compliance (C10), strategic internal green production planning (C11), and innovation level in R&D for green product development (C12). The causal diagram derived from the study identifies criteria establishing causal relationships, delineating two groups of cause and effect that elucidate the influence of criteria in GSCM.

According to the findings, several management implications emerge. Proactively controlling and emphasizing the cause group criteria becomes crucial due to their implications for influencing other criteria, while the effect group criteria signify the influenced criteria [58]. The total relation matrix results in Chart 6 reveal the evaluation criteria depicting causal relationships in GSCM supplier selection, derived from the fuzzy DEMATEL method. Seven of these criteria are identified as more important than others, demonstrating frequent interactive relations among them.

As illustrated in Fig. 1, the research offers valuable insights for making informed decisions. The varying degrees of influence among criteria are discerned, aiding in identifying key criteria for enhancing performance in GSCM based on the total matrix results (Table 6). The study findings unveil causal diagrams as follows: firstly, for an enterprise to achieve high performance in effect criteria, a proactive focus on "cause criteria" is essential. Criteria (C2, C3, C4, C5, C6, C7, and C8) are influential in dispatching evaluation criteria, impacting (C1, C9, C10, C11, and C12). To potentially enhance the effectiveness of specific criteria (e.g., C1, C9, C10, C11, and C12), it may be prudent to consider the influence of other criteria (e.g., C2, C3, C4, C5, C6, C7, and C8. However, it's important to note that these relationships are qualitative interpretations and may require further analysis to determine their significance. This could facilitate a company's identification of suitable suppliers based on the results [59].

Despite experts recognizing synergistic design-supplier collaboration for waste reduction (C2) as a highly significant criterion, this criterion frequently interacts with others. Conversely, while experts consider an environmental partnership with suppliers (C1) less important, it generally exhibits minimal interaction with other criteria. The cause diagram shows that supplier flexibility (C6) is a central criterion indirectly evaluating C1, C2, C3, C4, C5, C7, C8, C9, C10, C11, and C12. This underscores the importance and influence of supplier flexibility (C6), given its highest intensity of relationship with other criteria.

The study suggests that high-value criteria substantially influence other criteria in both directions. Moreover, the framework serves as an analytical tool for evaluating GSCM supplier selection, with evaluators prioritizing performance when selecting suitable green suppliers for GSCM activities.

4 Conclusions

In this study, the DEMATEL method was employed to assess the factors influencing the implementation of GSCM with a specific focus on evaluating and analyzing the selection of appropriate suppliers, a crucial aspect of the research. The findings underscore the importance for manufacturers to prioritize creating an environment and products aligned with supplier flexibility for effective supplier evaluation and selection, as this criterion significantly impacts other factors. Furthermore, the manufacturing industry often emphasizes in environmental partnerships with suppliers and strategic internal green production planning. While not the sole determinant of evaluation importance, these aspects can effectively assist companies in choosing GSCM providers. Analysis results reveal that the supplier flexibility criterion can directly or indirectly influence various factors, including environmental partnership with suppliers, collaboration between product designers and suppliers to reduce waste and eliminate environmental impact, proximity in supplier relationships, product conformity quality, flexibility of suppliers, internal service quality, green design, green purchasing, ISO 14000 compliance, internal green production plans. Furthermore, attention should be given to collaboration between product designers and suppliers, proximity in supplier relationships, meeting customer needs, product quality adherence, customer-centric fulfillment, internal service excellence, innovative green design practices, and the degree of innovation in R&D for green product development.

While our analysis sheds light on the intricate interdependencies within GSCM criteria, it is essential to acknowledge certain limitations in our study. Firstly, the scope of our research was delimited to a specific set of criteria, which may not encompass all potential factors influencing green supply chain practices. Future studies could explore additional dimensions and external factors to provide a more comprehensive understanding of GSCM dynamics. Additionally, the generalizability of our findings may be constrained by the specific context and industry sector examined. Conducting comparative analyses across diverse sectors and geographic regions could enhance the robustness and applicability of our conclusions.

Looking ahead, several avenues for future research warrant exploration. Firstly, there is a need to delve deeper into the external impacts of GSCM criteria on overall supply chain sustainability and resilience. By considering both internal dependencies and external influences, researchers can identify the most influential factors driving positive environmental outcomes. Moreover, incorporating stakeholder perspectives and employing mixed-method approaches could enrich our understanding of the complex interactions shaping GSCM practices. Furthermore, longitudinal studies tracking the evolution of GSCM frameworks over time could offer valuable insights into emerging trends and best practices in sustainable supply chain management.

In conclusion, while our study provides valuable insights into the factors shaping GSCM implementation and supplier selection, there remain avenues for further exploration and refinement. By addressing these limitations and embracing future research directions, we can advance the discourse on sustainable supply chain management and contribute to the development of effective strategies for fostering environmental stewardship and organizational resilience.

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