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Article

Lean and Sustainable Supplier Selection in the Furniture Industry

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Abstract: The furniture manufacturing sector faces intricate challenges in pioneering sustainable supply chains, particularly with lean and sustainable supplier selection. This study focused on integrating key performance indicators (KPIs) associated with lean philosophy and sustainability into multi-criteria decision-making (MCDM) methodologies. The study methodically evaluated 18 criteria spanning economic, environmental, and social dimensions to discern supplier suitability in both leanness and sustainability realms. Through the ENTROPY method, weights were systematically assigned to these criteria. Subsequently, Fuzzy ARAS and Fuzzy TOPSIS methods were adeptly employed to comparatively assess supplier options. Noteworthy findings included the paramount importance of the distance to the customer and labor practices in supplier selection. The quality level, however, carried the least weight, mainly due to comparable performance scores among alternatives. Consistently, Fuzzy ARAS and Fuzzy TOPSIS results converged to pinpoint Supplier 2 as the optimal choice, reflecting its superior K_i and CC_i metrics. Central to this research was the introduction of a structured and holistic framework for lean and sustainable supplier selection, a significant leap forward that promises to be an invaluable asset for practitioners and scholars in the furniture industry, supply chain management, multi-criteria decision-making, and policymaking.

Keywords: multi-criteria decision-making; supplier selection; sustainability; lean management; furniture industry

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1. Introduction

Sustainability is a global megatrend that has drastically changed how industries operate [1–3]. Sustainability is a concept where economic, social, and environmental indicators are holistically considered [4]. With this megatrend, not only economic prosperity is emphasized, but environmental and social consciousness have also been further awakened in people. This topic has been gaining importance because of some critical factors, such as the rapid depletion of natural resources, increasing population, and climate change. To enable future generations to sustain their lives with what is left of rapidly depleting natural resources, a shift towards a more sustainable lifestyle is necessary.

Sustainable supply chains refer to the management of products, services, and information from the raw material stage to the end consumer, intending to balance economic, social, and environmental sustainability. In recent years, the concept of sustainability has gained significant importance in the business world, as consumers and companies have become more conscious of the impact of their actions on the environment and society.

One of the critical benefits of sustainable supply chains is that they could lead to cost savings through improved efficiency and reduced waste [5,6]. For example, by implementing sustainable practices in transportation and logistics, companies could reduce emissions and save on fuel costs [7–9]. Additionally, sustainable supply chains could improve brand reputation, as consumers are more likely to choose products and services from companies committed to sustainability [10,11].

However, implementing sustainable supply chains could also be challenging, as it often requires significant changes to existing systems and processes. Companies need to consider a range of factors, including the environmental impact of their suppliers, the conditions of workers in their supply chain, and the use of sustainable materials.

In the contemporary business landscape, supplier selection transcends cost and quality to encompass more nuanced and critical aspects such as lean processes and sustainability. Key performance indicators (KPIs) related to lean processes and sustainability have therefore emerged as indispensable metrics in the evaluation of suppliers. These KPIs address a gamut of considerations ranging from resource efficiency and waste reduction to environmental stewardship and social responsibility. By adopting a systematic approach to measure and track these KPIs, organizations could make informed, holistic decisions that align economic viability with environmental and social objectives. Hence, this study aims to contribute to both theoretical and practical dialogues by proposing a robust supplier selection framework that incorporates lean and sustainable KPIs as integral components of the evaluation criteria.

Despite the challenges regarding the sustainability transformation of business, sustainable supply chains are becoming increasingly important as companies and consumers become more conscious of the impact of their actions on the environment. While implementing sustainable supply chains could be challenging, the benefits of improved efficiency, cost savings, and improved brand reputation make it a worthwhile investment for companies.

Such challenges and opportunities exist within any industry. One of these industries is the wood furniture industry, whose outputs, as an element, have a history spanning over 5000 years. The significance it held in the past is something that it will continue to maintain in the present and future [12]. Like every other sector, the wood furniture industry strives to sustain its existence optimally by staying open to evolving technology and all innovations. Among these innovations, leanness- and sustainability-focused developments are among the ones with primary importance and are expected to remain relevant. One fact separates this industry from others; a high proportion of raw material input of the wood furniture industry is a renewable resource with a natural carbon sequestration potential. Once the procurement, production, and delivery activities are carried out sustainably and efficiently, this industry could transform into one of the most sustainable industries.

When efficiency improvement is the concern, Lean Management is the first modern management technique that comes to mind. It is more than just a production method; it is a culture. It first emerged with Toyota's efforts to improve efficiency by doing more with less. It was developed by Taiichi Ohno, the father of the Toyota Production System, in the late 1970s [13]. The philosophy of Lean Management aims to increase efficiency by minimizing all sorts of waste. Since then, Lean Management principles have been expanded to cover and transform supply chain operations. When implemented successfully, businesses could gain a significant competitive advantage by taking advantage of opportunities in the business environment as a function of increased leanness and flexibility, reduced costs, and maximized profits.

One of the most critical activities within a supply chain is the procurement activities, which involve crucial decisions such as supplier selection, lot-size determination, logistics management, and warehousing. The proper supplier selection in supply chain management could be a "success or failure" decision for a business. The supplier selection problem is one of the multi-criteria decision-making problems that consist of defining methods and models to analyze and measure a series of suppliers' performance to enhance the competitive power of organizations. The diversity of quantitative and qualitative criteria varies depending on the characteristics of the encountered problem, making supplier selection a complex decision [14]. The methodology used to solve the supplier selection and a series of similar complex problems is called Multi-Criteria Decision Making (MCDM).

Multi-Criteria Decision Making (MCDM) methods are used to make the most accurate decision by considering multiple criteria. The use of these methods helps businesses make more informed decisions in their supplier selection process. MCDM methods could be used across all complex decision-making processes, regardless of the sector. They are employed in various sectors, from automotive [15] to textile, and from textile [16] to health [17]. With MCDM methods, many decision-making criteria could be used to evaluate multiple alternatives. Given the inherently complex nature of supplier selection problems, they could be solved using MCDM methods. However, there are situations in which uncertainty comes into play in using MCDM methods. When such a situation is encountered, solutions should be produced using MCDM methods in a fuzzy environment [18,19]. MCDM methods solved with fuzzy numbers perform better where quantitative data are insufficient, and there are more linguistic data and uncertainty. Therefore, many techniques with fuzzy numbers have been introduced into the literature for this purpose [20–22].

Not only for the furniture industry but in all businesses, companies that apply lean supplier selection in supply chain management aim to adopt a model that allows both the company and the supplier to profit while meeting customer needs. At the same time, sustainable supplier selection presents a robust and holistic selection model in terms of economic, social, and environmental indicators [23]. Businesses combining the lean philosophy developed by Ohno with sustainability concepts could achieve true sustainability more quickly and easily and gain a competitive advantage [24].

Literature Review

Upon reviewing academic studies conducted in past years, it has been observed that lean management, sustainability, and Multi-Criteria Decision Making (MCDM) have been used in numerous sectors and very different combinations. Both empirical and review studies were included in the review. The primary focus was to explore and understand the current state-of-the-art in terms of variety, quantity, and practicality of the criteria and to identify the research gap in the intersection of MCDM, supply chain management, and Lean and Sustainability Performance.

Aouadni et al. (2019) carried out a literature review on supplier selection and order allocation problems in their study. They reviewed studies published on the subject matter from 2000 to 2017. The studies under review were examined from three different perspectives: summaries of existing evidence on the problems, identifying gaps in current research to help identify areas that may require further research, and positioning new research activities. Overall, this paper provides valuable insights and guidance for researchers in the field of supplier selection and order allocation, helping them to position their research and contribute to the advancement of knowledge in this area [25].

Pınar (2020) studied the Multi-Criteria Decision-Making (MCDM) methods used in supplier selection. By examining 153 academic studies conducted over the last 20 years, it was determined that the most commonly used methods in supplier selection are AHP and Fuzzy TOPSIS. Moreover, it was observed that the interest in fuzzy methods has increased in recent years. The article highlights the importance of effective supplier selection in an efficient supply chain and its impact on product quality, cost reduction, flexible production, and customer satisfaction [26].

Schramm et al. (2020) reviewed 82 articles on sustainable supplier selection published in the last thirty years in their study. The reviewed articles were classified into two categories: (1) approaches based on single methods, (2) approaches based on co-employment of techniques. The methods used in both categories were MCDM methods and their variations. The results indicated that one or more methods could yield satisfactory results. The integration of multiple techniques has been a trend in this field, but the fundamental differences among the methods should be well understood before integrating them to avoid inconsistent results. Additionally, the paper emphasized the need for more research on the applicability of these approaches to real-life supplier selection problems, particularly in terms of the cognitive effort required from decision makers and their confidence in the recommendations provided by the approaches [27].

Naqvi and Amin (2021) conducted a literature review on supplier selection and order allocation in their study, regardless of the sector. Ninety-two articles between 2015 and 2020 were analyzed and classified according to operational research methods used in the study. The classifications were made under the titles of literature reviews, deterministic optimization, and uncertain optimization. The practical implications of this study included the identification of practical challenges in applying the various methods, the suggestion of case studies to demonstrate the applications of MCDM methods, and the exploration of new methods for special circumstances such as COVID-19. The study also highlighted the potential use of advanced forecasting techniques such as machine learning, deep learning, and neural networks to estimate parameters in optimization models [28].

In their study, Abdollahi et al. (2015) chose lean- and agile-focused evaluation criteria for supplier selection. The weights of these criteria were calculated using the ANP method. Later, twenty suppliers were evaluated using the DEA method with the calculated criterion weights. The DEA score obtained through this approach served as a surrogate for the overall competence and capability of a supplier, providing a comprehensive evaluation that could not have been easily discerned through traditional supplier audits. The framework also allowed for the identification of strategically important suppliers and provided benchmarks for improving the operations of poorly performing suppliers [29].

In their study, Zulqarnain and Dayan (2017) analyzed a problem involving the selection of the best alternative for an automotive company using four criteria and five alternatives, using the Intuitionistic Fuzzy TOPSIS (IF-TOPSIS) method. They determined that the A3 alternative provided the best result. The study proposed and validated a technique that could improve decision-making processes by taking into account the uncertain nature of linguistic evaluations, which could be valuable in various industries, including the automotive sector [30]. In another study, Oztel et al. (2018) utilized the entropy-based TOPSIS method to evaluate the annual sustainability performances of an energy company. The sustainability performance of seven years was evaluated with fourteen criteria. The paper was observed to be part of the broader academic discussion on corporate sustainability and its relationship with organizational culture. It added to the understanding of how corporate sustainability could be integrated into business strategies and decision-making processes [31].

Buyukozkan and Gocer (2018) focused on the supplier selection problem for the digital supply chain in their study. They utilized the IVIF AHP method to calculate the weights of the five main and 16 sub-criteria selected for the problem, and the IVIF ARAS method was used to evaluate eight alternatives. The ease of use and ability to extend the proposed methodology to an IVIF environment overcame the limitations of classical Multiple Criteria Decision Making (MCDM) methodologies, making it a practical and accessible tool for organizations. The study also suggested future research directions, such as exploring the use of classical fuzzy logic and comparing its results with sensitivity analysis, integrating other MCDM methods with fuzzy or IF sets, and applying the proposed model to different MCDM problems [32]. Abdullah et al. (2019) focused on green supplier selection using the PROMETHEE method in their work. They attempted to solve the identified decision-making problem with seven evaluation criteria and four alternatives based on the input of 5 decision-makers. The paper demonstrated the use of different preference functions in evaluating and comparing green suppliers based on seven economic and environmental criteria. The results showed that despite the differences in preference functions used, supplier A1 consistently emerged as the most preferred alternative. This suggested that the choice of preference function may not significantly impact the final preference for green suppliers [33].

Tasdemir and Gazo (2019) and Tasdemir et al. (2020) developed and validated a holistic sustainability benchmarking tool by incorporating modern management philosophies such as Lean Management and Six Sigma with sustainability to assess the true sustainability performance of companies and supply chains. The study involved a complex assessment mechanism with 33 key performance indicators stratified under three hierarchical levels. The authors emphasized that the synergies between Lean Management and sustainability could be harnessed to achieve true sustainability. The authors' motivation for the study included the wood products industry's failure to become a frontier of innovation and sustainability, its relatively low profit margins, the potential benefits of triple bottom line sustainability investments, the need to assess and benchmark the sustainability performance of the value-added wood products industry and SMEs, and the true sustainability potential of the wood products industry due to the renewable, recyclable, and biodegradable nature of wood. The study also focused on a small-sized manufacturing operation to demonstrate the benefits of sustainability initiatives for SMEs [24,34].

In their study, Hosseini and Khaled (2019) addressed the supplier selection decision for a firm in the USA that manufactures water and sewer plastic pipes. The study proposed a hybrid ensemble-AHP to calculate potential suppliers' resilience based on absorptive, adaptive, and restorative capacities. Eight contributors to supplier resilience were identified, analyzed, and ranked using the proposed community method. Five suppliers with higher resilience values were selected based on robustness, reliability, and redirection. The proposed approach successfully aided the decision-making process of the resilient supplier selection problem under investigation. Shandong (China) supplier was the best supplier [35].

In the study by Zulqarnain et al. (2020), the TOPSIS method based on fuzzy set theory was used to evaluate five candidates applying to work at a bank, and the best two candidates were selected. The bank's head office determined five criteria for the selection of the candidates and calculations were made in accordance with the methodology. The best two selected candidates were Y1 and Y5. The study contributed to the research field by providing a practical technique for decision-making and expanding the knowledge and application of fuzzy set theory [36]. In another 2020 study, Zulqarnain et al. used the TOPSIS method to solve a problem involving the selection of a clinic for emergency illness diagnosis, based on four criteria and four alternatives. The best alternative, H1, was determined in accordance with the methodology. This study contributed to the field of medical decision-making and aids health professionals in making informed choices for emergency illness diagnosis [37].

Rouyendegh et al. (2020) addressed a green supplier selection problem aiming for the selection of the most lean, agile, environmentally sensitive supplier that prioritized sustainability and resilience. To reduce the impact of uncertainty and indecisiveness on the problem, the Intuitive Fuzzy TOPSIS approach was employed. The problem consisted of ten criteria and four alternative suppliers. The problem was successfully tackled with the fuzzy approach, and the A2 alternative was selected as the best-performing supplier in regard to leanness, agility, sustainability, and resilience. The paper contributed to the field of supply chain management by addressing the problem of green supplier selection (GSS) and its importance in enhancing competitive pressure and meeting environmentalist attitudes [38].

Fei (2020) focused on the supplier selection decision in his study. In this decision-making problem, a choice was made among three alternative suppliers using six evaluation criteria and the D-ANP and D-AHP MCDM methods for the selection. The paper extended the traditional Analytic Network Process (ANP) method using D numbers, which allowed for the management of dependencies and interactions at different levels. This extension overcame the limitations of the Analytic Hierarchy Process (AHP) and provided more flexibility, rationality, and credibility [39]. In another study, Li et al. (2020) dealt with the lean and agile supplier selection problem in the textile sector in China. The evaluation criteria were selected through a literature review and analyzed using the DEMATEL method. The study emphasized the importance of quality as a conventional criterion for enhancing competitive advantage, while market sensitivity holds less influence [40].

Ecer (2021) proposed a model for solving sustainable supplier selection decision-making problems within the automotive spare parts sector. This model included 12 criteria across three sustainability dimensions and was used to evaluate five alternative suppliers. The FUCOM method was used to calculate the criteria weights, while the MAIRCA method was used to rank the supplier alternatives [41]. Kaya and Ayçin (2021) worked on the proper supplier selection in the textile sector during the Industry 4.0 era. The study utilized an integrated Interval Type 2 Fuzzy AHP and GOPRAS-G methodology. The Interval Type 2 Fuzzy AHP method was used to determine the weights of the supplier evaluation criteria, and the Gray GOPRAS method was applied subsequently to evaluate the alternative suppliers. The paper provided insight into how Industry 4.0 strategies influence supplier selection, aiming to benefit both practitioners and researchers [42].

In another study, Fallahpour et al. (2021) developed a new integrated model involving various sustainability- and Industry 4.0-related criteria for supplier selection within the textile industry. The proposed method employed the Fuzzy Best-Worst Method (FBWM) and two-stage Fuzzy Inference System (FIS) in supplier selection. The paper aimed to address the concept of Industry 4.0 and its integration with Sustainable Supply Chain Management (SSCM) [43].

Rahimi et al. (2021) used the Intuitive Fuzzy ENTROPY method to rank and select suppliers according to their qualifications. The main supplier to provide the necessary materials for a company's production line in Iran was chosen using five criteria among five alternatives. The paper contributed by introducing a new intuitionistic fuzzy entropy measure for selecting suppliers. It built on the work of Burillo and Bustince, who defined interval-valued fuzzy sets and IFSs and introduced the distance measure between IFSs using entropy measures [44].

In their study, Sonar et al. (2022) developed the LARGS paradigm for lean, agile, flexible, green, and sustainable supplier selection, determining twenty-two selection criteria. Using the ISM approach, they also created a hierarchical structure between the chosen twenty-two criteria. The paper tried to fill a research gap by being the first of its kind to identify supplier selection criteria in the LARGS paradigm and develop hierarchical relationships between them using the ISM approach [45].

In his study, Baki (2022) developed a decision-making approach using Structural Equation Modeling (SEM) and Fuzzy Additive Ratio Assessment (ARAS) techniques for ranking in the green supplier selection process. Eight main and twenty-seven sub-criteria were determined, and six alternative suppliers were evaluated considering these criteria. The new approach was successfully used to conclude that Supplier 1, which demonstrated the best performance, should be chosen as the vendor. The approach developed in the study could be used for effective and impartial strategic decision-making, especially in challenging situations like GSS where conflicts of opinion could be intense [46].

Afrasiabi et al. (2022) followed a hybrid MCDM approach to address the sustainable, resilient supplier selection problem in their studies. The best-worst method was used to determine criteria weights. The Fuzzy Gray Relational Analysis and TOPSIS methods were used to evaluate suppliers. Sixteen evaluation criteria were divided into four main categories: economic, environmental, social, and flexible. Six alternative suppliers were evaluated with the determined criteria, and it was concluded that Supplier A6 was the best. The results were then examined with other MCDM methods, namely F-WASPAS, F-MOORA, and F-VIKOR, confirming the accuracy of the outcome. By presenting an evaluation framework for supplier selection that considers the resilience concept and the three pillars of sustainability (economy, society, and environment) simultaneously, and by boosting the use of the Fuzzy Best-Worst Method (FBWM) to assign weights to criteria in real-life situations involving ambiguous and uncertain data, the study made significant contributions to the field [47].

Nasri et al. (2022) delivered a solution to the sustainable supplier selection problem in the oil industry by integrating Fuzzy DEMATEL, ANP, Data Envelopment Analysis, and the Anderson–Peterson rating model. The paper presented a novel procedure for solving the sustainable supplier selection problem, allowing decision-makers to prioritize suppliers based on their performance [48]. In another recent study, Menon and Ravi (2022) used an integrated AHP-TOPSIS approach for sustainable supplier selection. In their study, the authors added the ethical dimension to sustainability's economic, environmental, and social dimensions. Four main and 16 sub-criteria were determined. These selected criteria were used to evaluate six suppliers. AHP was used to calculate criteria weights, while the TOPSIS method was utilized to evaluate suppliers. The fifth alternative was chosen as the best supplier. Overall, the paper contributed to the field of sustainable supplier selection in the electronic industry by providing a comprehensive and practical approach to address the complex decision-making process involved in selecting sustainable suppliers [49].

Çalık (2022) focused on the supplier selection problem in his study. The model created for the supplier selection problem included two main, eight sub-criteria, and ten alternative suppliers. The Fuzzy AHP was used to determine criteria weights, and the Fuzzy ARAS method was utilized to evaluate alternative suppliers. Fuzzy MCDM methods were effectively used in the presence of uncertainty. The findings of the study highlighted the importance of resilience in supplier selection, with factors such as supplier flexibility and responsiveness being crucial within the resilience factor [50].

The comprehensive review of the extant literature on sustainable supplier selection demonstrates both academic and industrial significance. From a scientific standpoint, the integration of various fuzzy and original MCDM methods like TOPSIS, ARAS, AHP, DEMATEL, MAIRCA, VIKOR, and MOORA reveals a growing interest in tackling the multifaceted nature of decision-making under uncertainty. Such advancements broaden the methodological toolkit for researchers and indicate the maturation of the field. Additionally, the focus on incorporating resilience and ethics into sustainability criteria sets a new precedent for future academic inquiries. From a practical perspective, these studies offer valuable insights for businesses across sectors, from oil to textile, in making informed, impartial, and effective supplier selection decisions. They also enhance the resilience and competitiveness of supply chains by allowing for a holistic evaluation that encompasses economic, environmental, and social dimensions. However, it was noted that the furniture industry, particularly wood furniture manufacturing, is underrepresented in current literature, signifying a pertinent avenue for immediate research focus. This is especially crucial given the current global emphasis on sustainability and lean operations.

Based on the comprehensive review of the state-of-the-art, it could be concluded that a business's supplier selection decision is a typical MCDM problem. When the objective is lean and sustainable supplier selection, which considers lean, environmental, economic, and social aspects simultaneously, the problem becomes more complex and uncertain.

While various studies have engaged in the evaluation of sustainable supplier selection using Multiple-Criteria Decision-Making (MCDM) methods, such as TOPSIS, ARAS, AHP, DEMATEL, MAIRCA, VIKOR, and MOORA, across sectors like oil, textiles, and electronics, a conspicuous gap exists when it comes to the wood furniture manufacturing industry. Despite this industry's ongoing transformation toward sustainability, there is a paucity of research focused on the integration of both lean and sustainability metrics in supplier selection. Moreover, based on the literature in the field, fuzzy MCDM methods performed well in the presence of a lack of data availability and increased uncertainty. Furthermore, the integrated use of fuzzy MCDM methods made a more informed decision-making process possible through comparative discussions of the results.

Furthermore, existing literature has largely neglected to establish a standardized set of criteria that assess suppliers' leanness and sustainability performance concurrently, regardless of firm size. In today's evolving world, investing in sustainability is not an option but a necessity. On the other hand, the competition within the sectors shifted from the company level to the supply chain level. Moreover, resource scarcity, tightening profit margins, and elevated supply chain interruptions across all sectors have been forcing companies to do more with less by increasing their efficiency. Due to such dynamic industrial conditions, with every passing day, an increasing number of companies are seeking sustainable options in all areas of operations, including supplier selection. Therefore, this study tried the answer the research question of "is it possible to simultaneously address lean and sustainable supplier selection problem with help of fuzzy MCDM methods?" and sought to bridge this gap by proposing an integrated, systematic approach for supplier selection in the wood furniture manufacturing sector. As part of the proposed systematic methodology, the study also aimed to develop and deploy a set of valid criteria that could be utilized to assess the leanness and sustainability performance of suppliers across diverse operational scales.

2. Materials and Methods

This study tackled the lean and sustainable supplier selection problem of a large-size wood-panels-based furniture manufacturer through a systematic approach. The firm was located in one of the Mid-Western states of the U.S. The firm has been going through a lean and sustainability transformation and, therefore, was looking for ways to improve sustainability performance by partnering with lean and sustainable suppliers. Wood-based panels such as medium-density fiberboard (MDF) and particleboard were the primary raw materials fed into the production system. A significant portion of procurement activities were related to these raw materials and were reported to form more than 95% of any finished goods sold by the company. Therefore, the study focused on the wood-panels suppliers of the firm. A systematic supplier selection process was initiated by identifying the potential suppliers (Phase 1). Since the firm was a big player and was willing to work with wood-panel producers in the U.S., only three potential suppliers could meet the company's purchase volume. Throughout the study, the names of the company and the suppliers were not shared since a confidentiality agreement was signed between the company and the researchers, and the suppliers were referred to as Supplier 1, Supplier 2, and Supplier 3. Once the supplier alternatives were identified, a team of experts consisting of three furniture industry experts, three purchasing managers from three furniture companies, and three academics was formed. Subsequently, the researchers and experts created an agreed-upon set of lean and sustainability performance criteria through Delphi Technique (Phase 2) [51,52]. The team of experts decided to follow and adapt from Global Reporting Initiative's Sustainability Reporting Guidelines to develop the criteria to assess the leanness and sustainability performance of the three suppliers [53].

Therefore, all criteria were grouped under three pillars of sustainability: Economic, Environmental, and Social. Key performance indicators (KPIs) designed to capture the level of leanness of the suppliers were placed under the category of Economic criteria. A total of eighteen criteria—seven Lean-Infused Economic, six Environmental, and five Social criteria—have been put forth for the problem of lean and sustainable supplier selection. Lean-Infused Economic Performance Criteria involved Distance to Customer (km), Value-Added Time Per Unit (h/unit), Value-Added Cost Ratio per Unit (%/unit), Customer Service Level (%), Rate of Returns on Costs (%), Net Profit Margin (%), and Quality Level (%) while the Environmental Performance Criteria consisted of Sustainable Sourcing (%), Global Warming Potential ($kgCO_2$/unit), Water Footprint per Unit (L/unit), Energy Footprint per Unit (kwh/unit), Solid Waste Generation (kg/unit), and Recycled Raw Material Ratio (%). The Social Performance category of the criteria set was comprised of Employee Satisfaction Rate (%), Contribution to Society ($/year), Absenteeism Ratio (%), Gender Bias Ratio (%), and Labor Practices (%). The definitions of the criteria were provided in Appendix A. Each criterion was assigned an identifier based on its occurrence order in Table 1, starting with C1 and ending with C18. The criteria were developed with a dual focus. Firstly, they were deeply rooted in the specific challenges and needs of the furniture manufacturing sector, which was the primary context of the study. Through an analysis of current practices and a keen understanding of this sector's unique demands, it was ensured that the criteria resonate with the experimental context. However, their significance extends beyond this sector. Grounded in core principles of leanness and sustainability, these criteria could be broadly applicable. They could serve industries beyond furniture manufacturing, facing similar supplier selection challenges, with minimal adjustments. Furthermore, the proposed criteria emphasized the critical overlap between lean and sustainability practices, a synergy widely acknowledged in the literature. By highlighting elements like waste reduction, efficient resource use, and long-term value creation, it was aimed to bridge the divide between these two vital paradigms. Therefore, while the study's primary focus was the furniture manufacturing sector, the foundational leanness and sustainability principles behind the criteria ensured their wider relevance.

Table 1. Decision matrix used to determine criteria weights.

Criteria Category	Criteria Code	Criteria	Alternatives			Industry Average
			Supplier 1	Supplier 2	Supplier 3	
Lean-Infused Economic Performance Criteria	C-1	Distance to Customer (km)	75	130	48	No Benchmark
	C-2	Value-Added Time per Unit * (h/unit)	2.5	1.8	2.2	No Benchmark
	C-3	Value-Added Cost Ratio per Unit * (%/unit)	2.11	2.25	2.6	2.5–3
	C-4	Customer Service Level (%)	91.5	93	95.2	95.00%
	C-5	Rate of Returns on Costs (%)	9.7	8	5.5	10.00%
	C-6	Net Profit Margin (%)	5.5	5.3	4.2	5.00%
	C-7	Quality Level (%)	99.91	99.93	99.9	99.00%
Environmental Performance Criteria	C-8	Sustainable Sourcing (Wood Chips) (%/unit)	72	55	63	80–90%
	C-9	Global Warming Potential (kgCO_2/unit)	551	633	518	568.82
	C-10	Water Footprint per Unit * (L/unit)	1820	1550	1730	1500 L
	C-11	Energy Footprint per Unit * (kwh/unit)	731	749	711	734
	C-12	Solid Waste Generation per Unit * (kg/unit)	17.5	13.88	19	15.5
	C-13	Recycled Raw Material Ratio per Unit * (%)	27	21	30	20.00%
Social Performance Criteria	C-14	Employee Satisfaction Rate (%)	75	82	78	65%
	C-15	Contribution to society ($/year)	120,000	125,000	135,000	No Benchmark
	C-16	Absenteeism Ratio (%)	3.3	5.2	4.7	4.50%
	C-17	Gender Bias Ratio (%)	11	16	14	17.00%
	C-18	Labor Practices (%)	21	37	15	20.00%

* The functional unit: 1 m^2 of defect-free, shipment-ready wood panel.

In Phase 3, the decision-making firm contacted potential suppliers and asked for information regarding the eighteen criteria. The data gathering took approximately one and a half weeks with back-and-forth communications. The performance data of the suppliers reflect their operational performance for the year of 2022. The industry averages were also identified through expert opinion to set reference values for each criterion. The data on eighteen criteria, which was the input for the analyses, were presented in Table 1. In the next phase (Phase 4), criteria weights were determined using the ENTROPY method. In the last phase of the study (Phase 5), the team of experts, excluding the researchers, independently scored the three suppliers' leanness and sustainability performance using fuzzy language evaluation scales. Then, the researchers combined those scores and computed the analysis as per the methodology of Fuzzy TOPSIS and Fuzzy ARAS methods. The schematic of the phases constituting the lean and sustainable supplier selection problem of the furniture manufacturer was given in Figure 1.

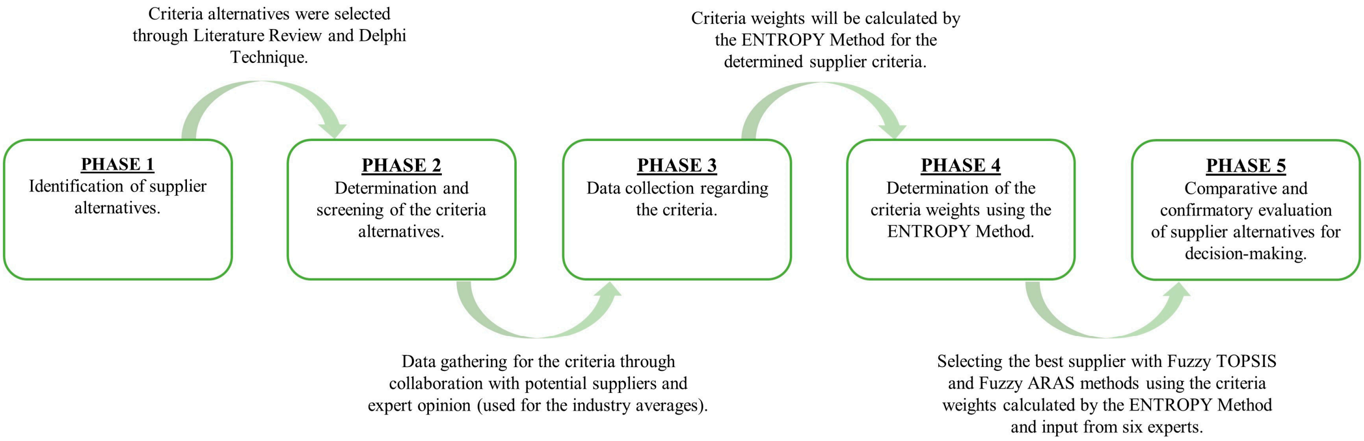

Figure 1. Phases-based systematic approach of the study.

The study design was aimed to opt for methods that provide a comprehensive and robust evaluation, especially given the challenges posed by integrating leanness and sustainability KPIs, in addressing the lean and sustainable supplier selection problem. Among the wide array of available fuzzy methods, Fuzzy ARAS and Fuzzy TOPSIS stood out due to their inherent ability to manage the uncertainty and vagueness often encountered when assessing qualitative and subjective lean and sustainable criteria. Their strengths in comparative evaluations further allowed the researchers to deeply analyze suppliers against multiple criteria, a vital aspect when considering the potential trade-offs between leanness and sustainability. It is also worth noting that while many fuzzy methods have been employed for supplier selection in past research, they often focused predominantly on either leanness or sustainability, not both. Some of these methods are particularly suited for scenarios where criteria weights or decision-makers' preferences were explicitly stated upfront. However, this study aimed to bridge this gap by co-integrating lean and sustainability KPIs, and the selected methods seemed to align best with this objective. On the topic of complexity, while some fuzzy methods could be intricate, Fuzzy ARAS and Fuzzy TOPSIS were able to strike a balance between rigorous analysis and practical applicability, making them more accessible to practitioners in the furniture industry. Finally, the consistency observed in the results obtained from both Fuzzy ARAS and Fuzzy TOPSIS bolstered the confidence in the methods' robustness for this specific problem. To conclude, methodological choices made in the study, while among several available options, were made to best address the unique intricacies of the lean and sustainable supplier selection problem in the furniture industry, and we believe they significantly enhance both the theoretical and practical understanding of this complex decision-making arena.

Detailed methodology of the ENTROPY, Fuzzy TOPSIS, and Fuzzy ARAS methods were laid out in the following parts of the study.

2.1. ENTROPY Method

The concept of ENTROPY first emerged in information theory. ENTROPY is a statistical parameter that measures, on average, how much information is produced for each letter of a text in a certain sense and language. Information theory provides a constructive criterion for forming probability distributions based on partial information. Additionally, ENTROPY is helpful in information theory when measuring the expected information content of a particular message. In short, entropy is seen as a measure of uncertainty. ENTROPY is a convenient method for determining the weights of criteria [31,54].

The ENTROPY method could be summarized as follows:

Step 1: Creating the decision matrix.

$$D = \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_i \\ \vdots \\ A_n \end{matrix} \begin{bmatrix} x_{11} & x_{12} & \ldots & x_{1j} & \ldots & x_{1n} \\ x_{21} & x_{22} & \ldots & x_{2j} & \ldots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{i1} & x_{i2} & \ldots & x_{ij} & \ldots & x_{in} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \ldots & x_{mj} & \ldots & x_{mn} \end{bmatrix} \quad (1)$$

x_{ij} is the success (performance) value of the ith alternative according to the jth criterion, where $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$.

Step 2: Creation of the normalized decision matrix.

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}, \ i = 1, 2, \ldots, m, \ j = 1, 2, \ldots, n \quad (2)$$

By utilizing Equation (2), the normalized decision matrix, effectively standardizing the values, $R = [r_{ij}]_{m\times n}$ was obtained.

Step 3: Calculation of the entropy values.

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m} r_{ij}\ln r_{ij} \quad (3)$$

Step 4: Calculating the weights.

$$W_j = \frac{1 - e_j}{\sum_{j=1}^{n} 1 - e_j}, \ j = 1, 2, \ldots, n \quad (4)$$

where; W_j is the weight of the jth criterion, and it satisfies the condition $\sum_{j=1}^{n} W_j = 1$.

2.2. Fuzzy ARAS Method

The ARAS method, introduced by Turskis and Zavadskas (2010), not only determines the performance of the alternatives but also calculates the ratio of each alternative to the ideal alternative [55,56]. The fundamental steps of the Fuzzy ARAS method, developed by Turskis and Zavadskas (2010), are provided below:

Step 1: The fuzzy decision matrix for the alternatives was created by following Equation (5).

$$A = \begin{bmatrix} \tilde{x}_{01} & \tilde{x}_{02} & \cdots & \tilde{x}_{0j} & \cdots & \tilde{x}_{0n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \tilde{x}_{i1} & \tilde{x}_{i2} & \cdots & \tilde{x}_{ij} & \cdots & \tilde{x}_{in} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mj} & \cdots & \tilde{x}_{mn} \end{bmatrix} \quad (5)$$

In this matrix, the fuzzy performance value of the ith alternative according to the jth criterion is represented by the expression of $\tilde{x}_{ij}$ $(i = 0, 1, \ldots, m \ ve \ j = 0, 1, \ldots, n)$. The $\left(\tilde{x}_{0j}\right)$ located in the first row of this matrix denotes the optimal value for the jth criterion.

For the j criterion, whose optimal value was unknown:

$$\tilde{x}_{0j} = \max \tilde{x}_{ij} \ j \in B \quad (6)$$

$$\widetilde{x}_{0j} = \min \widetilde{x}_{ij}\ j \in C \tag{7}$$

In Equation (6), *B* represents the benefit (maximizing) criteria set, and in Equation (7), *C* signifies the cost (minimizing) criteria set. The triangular fuzzy numbers used for linguistic evaluations of suppliers were given in Table 2.

Table 2. Linguistic terms used to evaluate supplier performance.

Linguistic Term	Triangle Fuzzy Number
Very Poor (VP)	(0, 1, 2)
Poor (P)	(1, 2, 3)
Medium Poor (MP)	(2, 3.5, 5)
Fair (F)	(4, 5, 6)
Medium Good (MG)	(5, 6.5, 8)
Good (G)	(7, 8, 9)
Very Good (VG)	(8, 9, 10)

Step 2: The initial values of all criteria were normalized. The normalized fuzzy decision-making matrix was calculated using Equation (8).

$$\overline{\widetilde{X}} = \begin{bmatrix} \overline{\widetilde{x}}_{01} & \overline{\widetilde{x}}_{02} & \ldots & \overline{\widetilde{x}}_{0n} \\ \overline{\widetilde{x}}_{11} & \overline{\widetilde{x}}_{12} & \ldots & \overline{\widetilde{x}}_{1n} \\ \vdots & \vdots & \ldots & \vdots \\ \overline{\widetilde{x}}_{m1} & \overline{\widetilde{x}}_{m2} & \ldots & \overline{\widetilde{x}}_{mn} \end{bmatrix} i = 0,\ 1,\ \ldots, m \text{ and } j = 0,\ 1,\ \ldots,\ n \tag{8}$$

Preference values for the criteria maximizing benefits, i.e., benefit criteria, were normalized using Equation (9), while those minimizing preference values, i.e., cost criteria, were normalized using Equation (10).

$$\overline{\widetilde{x}}_{ij} = \frac{\widetilde{x}_{ij}}{\sum_{i=0}^{m} \widetilde{x}_{ij}} \tag{9}$$

$$\widetilde{x}_{ij} = \frac{1}{\widetilde{x}_{ij}^{*}};\ \overline{\widetilde{x}}_{ij} = \frac{\widetilde{x}_{ij}}{\sum_{i=0}^{m} \widetilde{x}_{ij}} \tag{10}$$

Step 3: The weighted fuzzy decision matrix was calculated using Equation (11).

$$\overline{\widetilde{X}} = \begin{bmatrix} \overline{\widetilde{x}}_{01} & \overline{\widetilde{x}}_{02} & \ldots & \overline{\widetilde{x}}_{0n} \\ \overline{\widetilde{x}}_{11} & \overline{\widetilde{x}}_{12} & \ldots & \overline{\widetilde{x}}_{1n} \\ \vdots & \vdots & \ldots & \vdots \\ \overline{\widetilde{x}}_{m1} & \overline{\widetilde{x}}_{m2} & \ldots & \overline{\widetilde{x}}_{mn} \end{bmatrix} i = 0,\ 1,\ \ldots, m \text{ and } j = 0,\ 1,\ \ldots,\ n \tag{11}$$

The normalized weighted values of all criteria were calculated as in Equation (12).

$$\widetilde{\hat{x}}_{ij} = \overline{\widetilde{x}}_{ij} \otimes \widetilde{W}_j,\ i = 0,\ 1,\ \ldots,\ m \tag{12}$$

where $\tilde{W}_j$ represents the weight (level of importance) of the jth criterion; x_{ij} is the normalized value of the jth criterion.

Step 4: The fuzzy optimality function values $\left(\overset{\sim}{\overline{S}}_i\right)$ were calculated.

$$\overset{\sim}{\overline{S}}_i = \sum_{j=1}^{n} \overset{\sim}{\hat{x}}_{ij}\,,\ i = 0,\ 1,\ \ldots,\ m \tag{13}$$

Step 5: $\overset{\sim}{\overline{S}}_i$ values were subjected to defuzzification.

$$S_i = \frac{1}{3}(S_{il} + S_{im} + S_{iu}) \tag{14}$$

Step 6: Alternatives were arranged in ascending order based on K_i (the degree of benefit of the ith alternative), and the alternative with the highest K_i value was selected.

$$K_i = \frac{S_i}{S_0},\ i = 0,\ 1,\ \ldots,\ m \tag{15}$$

2.3. Fuzzy TOPSIS Method

The Fuzzy TOPSIS methodology was adapted and employed from the methodology outlined in the work of El Alaoui, M. (2021) [57–59]. The set consisting of N decision-makers was expressed as $E = KV_1, KV_2, \cdots, KV_N$. Once the committee of decision-makers was established, the existing alternatives were defined as $E = A_1, A_2, \cdots, A_m$, and the criteria to be used in evaluating these alternatives were defined as $E = K_1, K_2, \cdots, K_n$. Subsequently, the decision-makers evaluated the alternatives and criteria using linguistic variables. Evaluations made by decision-makers using linguistic variables were then expressed in the form of fuzzy numbers. The corresponding triangular fuzzy numbers for these linguistic variables are shown in Tables 3 and 4.

Table 3. Linguistic terms used in determining the importance weights of the criteria.

Linguistic Terms	Triangle Fuzzy Number
Very Low (VL)	(0, 0, 0.1)
Low (L)	(0, 0.1, 0.3)
Medium Low (ML)	(0.1, 0.3, 0.5)
Medium (M)	(0.3, 0.5, 0.7)
Medium High (MH)	(0.5, 0.7, 0.9)
High (H)	(0.7, 0.9, 1)
Very High (VH)	(0.9, 1, 1)

Table 4. Linguistic terms used in evaluation of alternatives.

Linguistic Term	Triangle Fuzzy Number
Very Poor (VP)	(0, 0, 1)
Poor (P)	(0, 1, 3)
Medium Poor (MP)	(1, 3, 5)
Fair (F)	(3, 5, 7)
Medium Good (MG)	(5, 7, 9)
Good (G)	(7, 9, 1)
Very Good (VG)	(9, 10, 10)

Equation (16) was used to combine the evaluations of N decision-makers for alternatives and criteria to a single value.

$$\tilde{x}_{ij} = \frac{1}{N}\left[\tilde{x}_{ij}^{1}(+)\tilde{x}_{ij}^{2}(+)\cdots(+)\tilde{x}_{ij}^{N}\right] \tag{16}$$

where $\tilde{x}_{ij}^{N}$ represents the evaluation of the Nth decision maker.

To consolidate the weights determined by N decision-makers for each criterion into a single value, $\tilde{W}_{j}^{N}$ was calculated using Equation (17).

$$\tilde{W}_{j} = \frac{1}{N}\left[\tilde{W}_{j}^{1}(+)\tilde{W}_{j}^{2}(+)\cdots(+)\tilde{W}_{j}^{N}\right] \tag{17}$$

where $\tilde{W}_{j}^{N}$ represents the weight of the Nth decision-maker.

Once a single value was created for all criteria and alternatives, the decision problem was represented in a matrix format as follows.

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ x_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \quad \tilde{W} = \left[\tilde{W}_1, \quad \tilde{W}_2, \quad \wedge \quad \tilde{W}_n\right] \tag{18}$$

where $\tilde{x}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ and $\tilde{W}_{ij} = (W_{j1}, W_{j2}, W_{j3})$ are triangular fuzzy numbers, where $\tilde{D}$ represents the fuzzy decision matrix, and $\tilde{W}$ represents the fuzzy weights matrix.

The step following the creation of the decision matrix was the normalization of this matrix. The fuzzy decision matrix was normalized using Equations (20) and (21), resulting in the normalized fuzzy decision matrix, $\tilde{R}$, which was given in Equation (19).

$$\tilde{R} = \left[\tilde{r}_{ij}\right]_{m\times n} \quad i = 1,\ 2,\cdots,m \quad j = 1,\ 2,\cdots,n \tag{19}$$

where r_{ij} represents the normalized triangular fuzzy numbers, $(\forall, j)$, and B and C denote the benefit and cost criteria, respectively.

$$\tilde{r}_{ij} = \left(\frac{l_{ij}}{u_j^+}, \frac{m_{ij}}{u_j^+}, \frac{u_{ij}}{u_j^+}\right), \quad j \in B, \quad u_j^+ = max u_{ij} \tag{20}$$

$$\tilde{r}_{ij} = \left(\frac{l_j^-}{u_{ij}}, \frac{l_j^-}{m_{ij}}, \frac{l_j^-}{l_{ij}}\right), \quad j \in C, \quad l_j^- = min l_{ij} \tag{21}$$

After the formation of the normalized fuzzy decision matrix, considering that each decision criterion may have a different weight of importance, the weighted normalized fuzzy decision matrix was created as follows.

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{m\times n}, \quad i = 1,\ 2,\cdots,m \quad j = 1,\ 2,\cdots,n \tag{22}$$

where

$$\tilde{V}_{ij} = \tilde{r}_{ij}(.)\tilde{W}_{j} \tag{23}$$

After the construction of the weighted normalized fuzzy decision matrix, the fuzzy positive ideal solution $(FPIS,\ A^{+})$ and the fuzzy negative ideal solution $(FNIS,\ A^{-})$ were defined with the help of Equations (24) and (25).

$$A^{+} = \left(\tilde{v}_1^{+}, \tilde{v}_2^{+}, \cdots, \tilde{v}_n^{+}\right) \tag{24}$$

$$A^{-} = \left(\tilde{v}_1^{-}, \tilde{v}_2^{-}, \cdots, \tilde{v}_n^{-}\right) \tag{25}$$

Subsequently, the distances of each alternative to the positive ideal solution (A^{+}) and the negative ideal solution (A^{-}) were computed as demonstrated in Equations (26) and (27).

$$d_i^{+} = \sum_{j=1}^{n} d_v\left(\tilde{v}_{ij}, \tilde{v}_j^{+}\right), \qquad i = 1,\ 2, \ldots,\ m \qquad j = 1,\ 2,\ \ldots,\ n \tag{26}$$

$$d_i^{-} = \sum_{j=1}^{n} d_v\left(\tilde{v}_{ij}, \tilde{v}_j^{-}\right), \qquad i = 1,\ 2, \ldots,\ m \qquad j = 1,\ 2,\ \ldots,\ n \tag{27}$$

where $d_v(a,b)$ represents the distance between two fuzzy numbers, which was determined using the Vertex Method as provided in Equation (28). Following the calculation of distances, the closeness coefficients (CC_i) corresponding to each alternative were determined. The closeness coefficient considers the distance to the fuzzy positive ideal solution (A^{+}) and the fuzzy negative ideal solution (A^{-}) concurrently.

$$(a,b) = \sqrt{\frac{1}{3}\left[(l_a - l_b)^2 + (m_a - m_b)^2 + (u_a - u_b)^2\right]} \qquad d(a,b) \in R^{+} \tag{28}$$

The closeness coefficient for each alternative was calculated as presented in Equation (29). The closer the closeness coefficient is to 1, the higher the likelihood of the alternative being preferred.

$$C_i = \frac{d_i^{-}}{d_i^{+} + d_i^{-}}, \qquad i = 1,\ 2,\ \ldots,\ m \tag{29}$$

3. Results and Discussion

The hierarchical structure created for the lean- and sustainability-focused supplier selection problem of the furniture manufacturer was provided in Figure 2.

The ENTROPY Method was utilized to calculate the weights of the evaluation criteria with the help of the decision matrix presented in Table 5.

Table 5. Decision matrix.

Alternatives	CRITERIA																	
	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15	C-16	C-17	C-18
Supplier 1	75	2.5	2.11	91.5	9.7	6.5	99.91	72	551	1820	731	17.5	27	75	120,000	3.3	11	21
Supplier 2	130	1.8	2.25	93	8	5.3	99.93	55	633	1550	749	13.88	21	82	125,000	5.2	16	37
Supplier 3	48	2.2	2.6	95.2	5.5	4.2	99.9	63	518	1730	711	19	30	78	135,000	4.7	14	15

Then, the decision matrix provided in Table 5 was subjected to a normalization process. The data obtained from this operation were presented in Table 6.

The ENTROPY values of each criterion were calculated based on the normalized values shown in Table 6. The calculated entropy values are given in Table 7.

Table 6. Normalized decision matrix.

	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15	C-16	C-17	C-18
Supplier 1	0.296	0.385	0.303	0.327	0.418	0.406	0.333	0.379	0.324	0.357	0.334	0.347	0.346	0.319	0.316	0.250	0.268	0.288
Supplier 2	0.514	0.277	0.323	0.332	0.345	0.331	0.333	0.289	0.372	0.304	0.342	0.276	0.269	0.349	0.329	0.394	0.390	0.507
Supplier 3	0.190	0.338	0.374	0.340	0.237	0.263	0.333	0.332	0.304	0.339	0.325	0.377	0.385	0.332	0.355	0.356	0.341	0.205

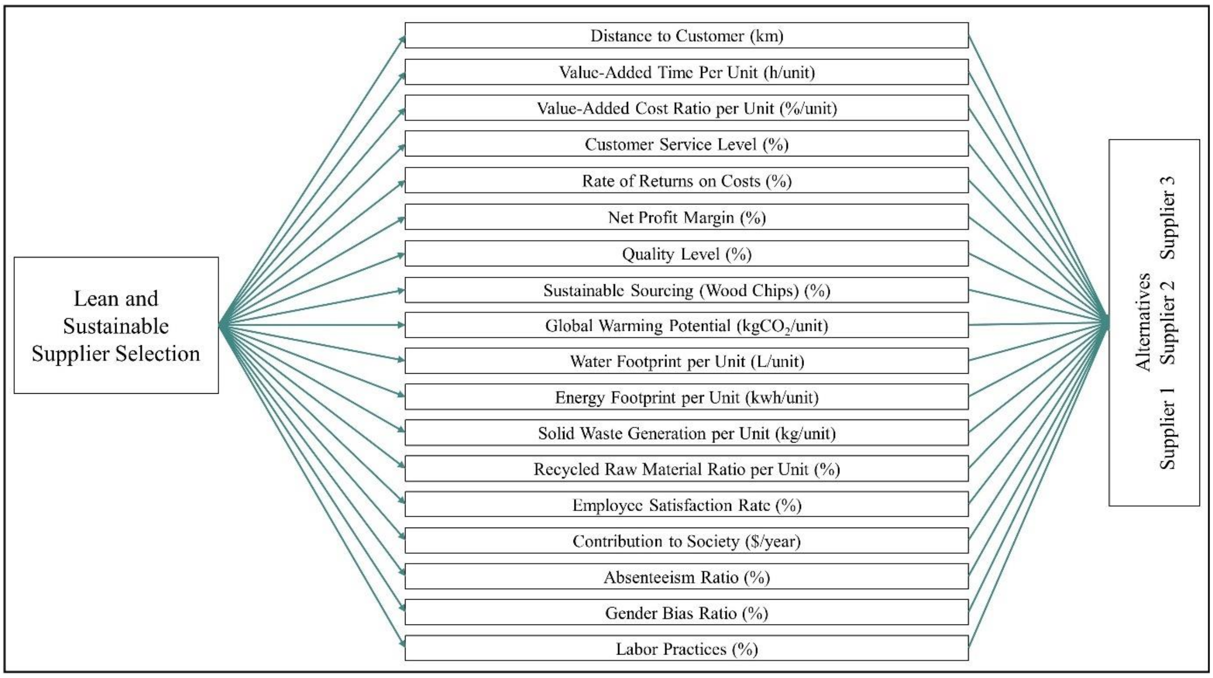

Figure 2. Hierarchical structure of lean and sustainable supplier selection problem.

Table 7. ENTROPY values.

	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15	C-16	C-17	C-18
Supplier 1	−0.36	−0.37	−0.36	−0.37	−0.36	−0.37	−0.37	−0.37	−0.37	−0.37	−0.37	−0.37	−0.37	−0.36	−0.36	−0.35	−0.35	−0.36
Supplier 2	−0.34	−0.36	−0.37	−0.37	−0.37	−0.37	−0.37	−0.36	−0.37	−0.36	−0.37	−0.36	−0.35	−0.37	−0.37	−0.37	−0.37	−0.34
Supplier 3	−0.32	−0.37	−0.37	−0.37	−0.34	−0.35	−0.37	−0.37	−0.36	−0.37	−0.37	−0.37	−0.37	−0.37	−0.37	−0.37	−0.37	−0.33
e_j	0.93	0.99	1.00	1.00	0.98	0.99	1.00	0.99	1.00	1.00	1.00	0.99	0.99	1.00	1.00	0.98	0.99	0.94

After the criteria weights were calculated, the next phase was having the alternatives scored by the experts using the linguistic variables of the Fuzzy ARAS and the Fuzzy TOPSIS methods. The evaluation of suppliers through Fuzzy ARAS and Fuzzy TOPSIS methods was carried out independently. To ensure consistency and comparability between the results of the methods used for supplier selection, the weights of criteria calculated with the ENTROPY method were used in both (Table 8).

Table 8. Weights of supplier selection criteria.

	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15	C-16	C-17	C-18
W_j	0.302	0.033	0.015	0.001	0.096	0.058	2.9E-08	0.023	0.013	0.008	0.001	0.031	0.040	0.003	0.005	0.065	0.043	0.264

In the Fuzzy ARAS method, which was the first of the selected methods for comparison, each alternative supplier was evaluated by three company owners and three purchasing managers using linguistic variables, and these evaluation results were provided in Table 9.

Table 9. Expert evaluation results for the Fuzzy ARAS method.

	S1	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
C-1	G	F	MG	F	VP	VG	MG	MP	G	MG	MP	G	F	MG	VG	MG	F	G
C-2	G	VG	G	G	P	MG	G	F	G	G	MP	MG	MG	F	MG	G	F	G
C-3	G	F	MP	F	MG	G	MG	MG	G	MP	F	G	F	F	MG	G	MG	F
C-4	P	MP	F	P	MP	F	G	G	G	MG	MG	G	MG	MG	G	VP	P	P
C-5	MG	F	MP	G	MG	MP	G	G	P	G	MG	MP	MG	MG	G	G	F	P
C-6	F	MP	MP	F	P	VP	G	MG	F	MG	MG	F	G	G	MG	F	F	MP
C-7	MG	G	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG
C-8	MP	F	MP	VG	MG	G	MG	F	MP	F	MP	F	MG	F	F	MP	P	MP
C-9	P	F	MG	F	MP	MG	F	MG	G	F	MP	MG	MG	F	MG	F	P	F
C-10	F	MG	F	MG	VP	G	MG	G	MG	F	G	F	MP	MG	MP	VP	MP	VP
C-11	MG	F	G	MP	P	G	MG	F	G	MG	F	G	MG	MG	MG	MG	MG	G
C-12	MP	F	P	P	G	VP	MG	MP	G	F	MG	MP	F	G	MP	MP	G	MP
C-13	MG	F	G	MP	P	F	G	F	G	VG	G	VG	VG	G	VG	MG	F	G
C-14	P	MP	P	P	F	P	MG	G	MG	G	VG	G	G	G	G	MP	F	MP
C-15	F	F	MG	G	G	G	MG	MG	G	MG	MG	G	MP	MP	MP	F	F	F
C-16	MG	MP	F	VG	P	MP	G	F	MG	VG	MP	F	G	F	MG	VG	F	MG
C-17	VP	P	P	VP	VP	VP	F	G	G	F	G	MG	F	MG	MG	P	F	F
C-18	F	G	P	MP	G	P	F	G	MP	G	VG	MG	G	VG	MG	MG	VG	MP
	EXPERT-1			EXPERT-2			EXPERT-3			EXPERT-4			EXPERT-5			EXPERT-6		

The computational analysis process was initiated by converting the linguistic variables into corresponding triangular fuzzy numbers and calculating the arithmetic mean of expert evaluation results in Table 9. Since no ideal values existed in the decision matrix, the selection criteria were primarily divided into cost and benefit categories. Then, for each benefit-based criterion, the maximum value across all alternatives was determined as the ideal value, while for each cost-based criterion, the minimum value was determined as the ideal value. The decision matrix formed in this way was given in Table 10.

Table 10. Fuzzy ARAS method decision matrix.

CRITERIA		**Supplier 1**			**Supplier 2**			**Supplier 3**			**Ideal Value**		
		l	**m**	**u**	**l**	**m**	**u**	**l**	**m**	**u**	**l**	**m**	**u**
COST	C-1	5.000	6.250	7.333	2.833	4.083	5.833	7.000	8.083	9.167	5.000	6.250	7.333
BENEFIT	C-2	6.667	7.750	8.833	3.833	4.917	6.000	6.000	7.167	8.500	6.667	7.750	8.833
BENEFIT	C-3	4.833	6.000	7.167	4.500	5.750	7.000	5.333	6.500	7.667	4.833	6.000	7.167
BENEFIT	C-4	3.167	4.333	5.500	3.667	5.000	6.333	5.000	6.000	7.000	3.167	4.333	5.500
BENEFIT	C-5	6.333	7.500	8.667	5.000	6.250	7.500	2.500	3.750	5.000	6.333	7.500	8.667
BENEFIT	C-6	5.167	6.250	7.333	4.000	5.250	6.500	2.833	4.083	5.333	5.167	6.250	7.333
BENEFIT	C-7	7.500	8.583	9.667	7.833	8.833	9.833	8.000	9.000	10.000	7.500	8.583	9.667
BENEFIT	C-8	4.333	5.667	7.000	3.333	4.500	5.667	3.500	4.750	6.000	4.333	5.667	7.000
COST	C-9	3.667	4.750	5.833	3.000	4.250	5.500	5.167	6.500	7.833	3.667	4.750	5.833
COST	C-10	3.333	4.583	5.833	4.333	5.583	6.833	3.667	4.833	6.000	3.333	4.583	5.833
COST	C-11	4.500	6.000	7.500	3.833	5.000	6.167	6.667	7.750	8.833	4.500	6.000	7.500
COST	C-12	3.000	4.250	5.500	5.333	6.500	7.667	2.333	3.583	4.833	3.000	4.250	5.500
BENEFIT	C-13	5.833	7.083	8.333	4.500	5.500	6.500	6.833	7.833	8.833	5.833	7.083	8.333
BENEFIT	C-14	3.833	5.000	6.167	5.333	6.417	7.500	3.833	5.000	6.167	3.833	5.000	6.167
BENEFIT	C-15	4.500	5.750	7.000	4.500	5.750	7.000	5.333	6.500	7.667	4.500	5.750	7.000
COST	C-16	7.167	8.250	9.333	2.833	4.000	5.167	4.167	5.500	6.833	7.167	8.250	9.333
BENEFIT	C-17	2.167	3.167	4.167	4.000	5.083	6.167	3.667	4.833	6.000	2.167	3.167	4.167
BENEFIT	C-18	4.833	6.000	7.167	7.500	8.500	9.500	2.667	4.000	5.333	4.833	6.000	7.167

The fuzzy decision matrix in Table 10 was normalized to maximize the benefits of selection criteria and minimize costs, forming the normalized fuzzy decision matrix shown in Table 11.

Table 11. Normalized fuzzy decision matrix.

Criteria	Supplier 1			Supplier 2			Supplier 3			Ideal Value		
	l	**m**	**u**	**l**	**m**	**u**	**l**	**m**	**u**	**l**	**m**	**u**
C-1	0.048	0.050	0.052	0.081	0.073	0.063	0.033	0.037	0.041	0.048	0.050	0.052
C-2	0.078	0.072	0.069	0.048	0.049	0.049	0.071	0.068	0.067	0.078	0.072	0.069
C-3	0.056	0.056	0.056	0.056	0.057	0.057	0.063	0.062	0.060	0.056	0.056	0.056
C-4	0.037	0.040	0.043	0.046	0.049	0.052	0.059	0.057	0.055	0.037	0.040	0.043
C-5	0.074	0.070	0.068	0.062	0.062	0.061	0.030	0.035	0.039	0.074	0.070	0.068
C-6	0.060	0.058	0.057	0.050	0.052	0.053	0.034	0.039	0.042	0.060	0.058	0.057
C-7	0.087	0.080	0.075	0.098	0.087	0.080	0.095	0.085	0.079	0.087	0.080	0.075
C-8	0.050	0.053	0.055	0.042	0.044	0.046	0.041	0.045	0.047	0.050	0.053	0.055
C-9	0.065	0.065	0.065	0.076	0.070	0.067	0.044	0.047	0.048	0.065	0.065	0.065
C-10	0.072	0.068	0.065	0.053	0.053	0.054	0.062	0.063	0.062	0.072	0.068	0.065
C-11	0.053	0.052	0.051	0.060	0.060	0.060	0.034	0.039	0.042	0.053	0.052	0.051
C-12	0.080	0.073	0.069	0.043	0.046	0.048	0.098	0.084	0.077	0.080	0.073	0.069
C-13	0.068	0.066	0.065	0.056	0.054	0.053	0.081	0.074	0.070	0.068	0.066	0.065
C-14	0.045	0.047	0.048	0.067	0.063	0.061	0.045	0.047	0.049	0.045	0.047	0.048
C-15	0.052	0.054	0.055	0.056	0.057	0.057	0.063	0.062	0.060	0.052	0.054	0.055
C-16	0.033	0.038	0.041	0.081	0.075	0.071	0.055	0.055	0.055	0.033	0.038	0.041
C-17	0.025	0.030	0.032	0.050	0.050	0.050	0.043	0.046	0.047	0.025	0.030	0.032
C-18	0.056	0.056	0.056	0.094	0.084	0.077	0.032	0.038	0.042	0.056	0.056	0.056

Each selection criterion was multiplied by the criterion weight calculated with the ENTROPY method, thereby constructing the weighted normalized fuzzy decision matrix, as shown in Table 12.

Then, the fuzzy function value $\left(\tilde{S}_i\right)$ was calculated for each alternative. This calculation was made by summing all the criterion values for alternatives. The calculated S_i values were provided in Table 13. Subsequently, since the S_i values obtained were fuzzy numbers, they were subjected to a defuzzification process. As a result of the defuzzification process, the S_i value of each alternative was compared with the ideal performance degree (S_0), and the benefit degrees (K_i) of the alternatives were determined. The S_i and K_i values were given in Table 14.

According to the S_i and K_i values given in Table 14, the alternative with the largest K_i value, i.e., the benefit degree, was the best option, while the alternative with the smallest K_i value was the worst option. In short, according to the result of the ENTROPY-based Fuzzy ARAS Method, the best alternative was Supplier 2 with a K_i value of 1.260, followed by Supplier 1 and Supplier 3 with K_i values of 1.000 and 0.792, respectively.

Table 12. Weighted normalized fuzzy decision matrix for Fuzzy ARAS method.

Criteria	Supplier 1			Supplier 2			Supplier 3			Ideal Value		
	l	m	u	l	m	u	l	m	u	l	m	u
C-1	0.01445	0.01499	0.01560	0.02440	0.02206	0.01906	0.00983	0.01130	0.01231	0.01445	0.01499	0.01560
C-2	0.00258	0.00240	0.00228	0.00159	0.00161	0.00162	0.00236	0.00225	0.00222	0.00258	0.00240	0.00228
C-3	0.00082	0.00082	0.00081	0.00082	0.00083	0.00083	0.00092	0.00090	0.00088	0.00082	0.00082	0.00081
C-4	0.00002	0.00002	0.00002	0.00002	0.00002	0.00003	0.00003	0.00003	0.00003	0.00002	0.00002	0.00002
C-5	0.00708	0.00672	0.00648	0.00598	0.00593	0.00587	0.00284	0.00341	0.00378	0.00708	0.00672	0.00648
C-6	0.00351	0.00340	0.00333	0.00291	0.00303	0.00309	0.00196	0.00225	0.00245	0.00351	0.00340	0.00333
C-7	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C-8	0.00114	0.00119	0.00123	0.00094	0.00100	0.00104	0.00093	0.00101	0.00106	0.00114	0.00119	0.00123
C-9	0.00088	0.00088	0.00087	0.00103	0.00094	0.00090	0.00059	0.00063	0.00064	0.00088	0.00088	0.00087
C-10	0.00059	0.00056	0.00054	0.00044	0.00044	0.00044	0.00051	0.00052	0.00051	0.00059	0.00056	0.00054
C-11	0.00004	0.00004	0.00004	0.00005	0.00005	0.00005	0.00003	0.00003	0.00004	0.00004	0.00004	0.00004
C-12	0.00250	0.00229	0.00216	0.00135	0.00144	0.00151	0.00307	0.00265	0.00243	0.00250	0.00229	0.00216
C-13	0.00270	0.00262	0.00258	0.00223	0.00216	0.00210	0.00321	0.00294	0.00276	0.00270	0.00262	0.00258
C-14	0.00011	0.00012	0.00012	0.00017	0.00016	0.00015	0.00011	0.00012	0.00012	0.00011	0.00012	0.00012
C-15	0.00024	0.00024	0.00025	0.00025	0.00026	0.00026	0.00028	0.00028	0.00027	0.00024	0.00024	0.00025
C-16	0.00217	0.00245	0.00264	0.00526	0.00485	0.00463	0.00356	0.00358	0.00356	0.00217	0.00245	0.00264
C-17	0.00109	0.00127	0.00140	0.00215	0.00216	0.00216	0.00187	0.00197	0.00203	0.00109	0.00127	0.00140
C-18	0.01488	0.01480	0.01476	0.02473	0.02221	0.02047	0.00834	0.01001	0.01110	0.01488	0.01480	0.01476

Table 13. Fuzzy function values.

	Supplier 1			Supplier 2			Supplier 3			Ideal Value		
$\left(\tilde{S}_i\right)$	0.05480	0.05481	0.05512	0.07430	0.06915	0.06422	0.04044	0.04386	0.04620	0.05480	0.05481	0.05512

Table 14. S_i and K_i values.

Alternatives	S_i	K_i	Ranking
Supplier 1	0.05491	1.000	2
Supplier 2	0.06922	1.260	1
Supplier 3	0.0435	0.792	3
Ideal Value	0.05491	1	Optimal

After applying the Fuzzy ARAS Method, the Fuzzy TOPSIS method was applied to the same decision matrix. Each of the three company owners and three purchasing experts submitted their evaluation of the alternatives according to the selection criteria, and the evaluations made by the experts using the linguistic variables converted into triangular fuzzy numbers. Then, the arithmetic mean of these evaluations was taken to form a fuzzy decision matrix. The linguistic evaluations made by the experts were given in Table 15, and the resulting decision matrix was given in Table 16.

Table 15. Expert evaluation results for the Fuzzy TOPSIS method.

	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
C-1	G	F	MG	F	VP	VG	MG	MP	G	MG	MP	G	F	MG	VG	MG	F	G
C-2	G	VG	G	G	P	MG	G	F	G	G	MP	MG	MG	F	MG	G	F	G
C-3	G	F	MP	F	MG	G	MG	MG	G	MP	F	G	F	F	MG	G	MG	F
C-4	P	MP	F	P	MP	F	G	G	G	MG	MG	G	MG	MG	G	VP	P	P
C-5	MG	F	MP	G	MG	MP	G	G	P	G	MG	MP	MG	MG	G	G	F	P
C-6	F	MP	MP	F	P	VP	G	MG	F	MG	MG	F	G	G	MG	F	F	MP
C-7	MG	G	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG
C-8	MP	F	MP	VG	MG	G	MG	F	MP	F	MP	F	MG	F	F	MP	P	MP
C-9	P	F	MG	F	MP	MG	F	MG	G	F	MP	MG	MG	F	MG	F	P	F
C-10	F	MG	F	MG	VP	G	MG	G	MG	F	G	F	MP	MG	MP	VP	MP	VP
C-11	MG	F	G	MP	P	G	MG	F	G	MG	F	G	MG	MG	MG	MG	MG	G
C-12	MP	F	P	P	G	VP	MG	MP	G	F	MG	MP	F	G	MP	MP	G	MP
C-13	MG	F	G	MP	P	F	G	F	G	VG	G	VG	VG	G	VG	MG	F	G
C-14	P	MP	P	P	F	P	MG	G	MG	G	VG	G	G	G	G	MP	F	MP
C-15	F	F	MG	G	G	G	MG	MG	G	MG	MG	G	MP	MP	MP	F	F	F
C-16	MG	MP	F	VG	P	MP	G	F	MG	VG	MP	F	G	F	MG	VG	F	MG
C-17	VP	P	P	VP	VP	VP	F	G	G	F	G	MG	F	MG	MG	P	F	F
C-18	F	G	P	MP	G	P	F	G	MP	G	VG	MG	G	VG	MG	MG	VG	MP
	EXPERT-1			EXPERT-2			EXPERT-3			EXPERT-4			EXPERT-5			EXPERT-6		

Table 16. Fuzzy TOPSIS method decision matrix.

Criteria	Supplier 1			Supplier 2			Supplier 3		
	l	m	u	l	m	u	l	m	u
C-1	4.667	6.667	8.500	2.167	3.833	5.667	7.330	9.000	9.833
C-2	6.667	8.667	9.833	3.167	4.833	6.500	6.000	8.000	9.500
C-3	4.333	6.333	8.000	4.000	6.000	8.000	5.000	7.000	8.500
C-4	2.833	4.167	5.833	3.167	5.000	6.833	4.500	6.333	7.833
C-5	6.333	8.333	9.667	4.667	6.667	8.500	1.670	3.333	5.167
C-6	4.667	6.667	8.333	3.500	5.333	7.167	2.170	3.833	5.667
C-7	8.333	9.500	9.833	8.667	9.833	10.000	9.000	10.000	10.000
C-8	4.000	5.833	7.500	2.500	4.333	6.333	2.670	4.667	6.500
C-9	2.833	4.667	6.667	2.167	4.000	6.000	5.000	7.000	8.833
C-10	2.833	4.500	6.333	5.667	7.500	8.833	3.170	4.833	6.500
C-11	4.333	6.333	8.333	3.167	5.000	7.000	7.330	9.167	10.000
C-12	2.167	4.000	6.000	5.000	7.000	8.500	1.670	3.167	4.833
C-13	6.000	7.667	8.833	3.833	5.667	7.333	7.000	8.667	9.500
C-14	3.333	5.000	6.667	5.000	6.833	8.167	3.330	5.000	6.667
C-15	4.000	6.000	7.833	4.000	6.000	7.833	5.000	7.000	8.500
C-16	7.667	9.167	9.833	1.833	3.667	5.667	3.67	5.667	7.667
C-17	1.500	2.667	4.333	3.667	5.167	6.667	3.33	4.833	6.500
C-18	4.333	6.333	8.000	8.000	9.500	10.000	2.000	3.667	5.667

The fuzzy decision matrix provided in Table 16 was normalized to maximize the benefits of the selection criteria and minimize their costs, resulting in the normalized fuzzy decision matrix presented in Table 17.

Considering that each selection criterion carries different importance weights for each decision-maker, the weighted normalized fuzzy decision matrix was derived and was provided in Table 18.

Table 17. Normalized fuzzy decision matrix.

	Supplier 1			Supplier 2			Supplier 3		
C-1	0.255	0.325	0.464	0.382	0.565	1.000	0.220	0.241	0.295
C-2	0.678	0.881	1.000	0.322	0.492	0.661	0.610	0.814	0.966
C-3	0.510	0.745	0.941	0.471	0.706	0.941	0.590	0.824	1.000
C-4	0.362	0.532	0.745	0.404	0.638	0.872	0.570	0.809	1.000
C-5	0.655	0.862	1.000	0.483	0.690	0.879	0.170	0.345	0.534
C-6	0.560	0.800	1.000	0.420	0.640	0.860	0.260	0.460	0.68
C-7	0.833	0.950	0.983	0.867	0.983	1.000	0.900	1.000	1.000
C-8	0.533	0.778	1.000	0.333	0.578	0.844	0.360	0.622	0.867
C-9	0.325	0.464	0.765	0.361	0.542	1.000	0.250	0.310	0.433
C-10	0.447	0.630	1.000	0.321	0.378	0.500	0.440	0.586	0.895
C-11	0.380	0.500	0.731	0.452	0.633	1.000	0.320	0.345	0.432
C-12	0.278	0.417	0.769	0.196	0.238	0.333	0.340	0.526	1.000
C-13	0.632	0.807	0.930	0.404	0.596	0.772	0.740	0.912	1.000
C-14	0.408	0.612	0.816	0.612	0.837	1.000	0.410	0.612	0.816
C-15	0.471	0.706	0.922	0.471	0.706	0.922	0.590	0.824	1.000
C-16	0.186	0.200	0.239	0.324	0.500	1.000	0.240	0.324	0.500
C-17	0.225	0.400	0.650	0.550	0.775	1.000	0.500	0.725	0.975
C-18	0.433	0.633	0.800	0.800	0.950	1.000	0.200	0.367	0.567

Table 18. Weighted normalized fuzzy decision matrix for Fuzzy TOPSIS method.

	Supplier 1			Supplier 2			Supplier 3		
C-1	0.077	0.098	0.14	0.115	0.171	0.302	0.07	0.073	0.089
C-2	0.022	0.029	0.033	0.011	0.016	0.022	0.02	0.027	0.032
C-3	0.007	0.011	0.014	0.007	0.01	0.014	0.01	0.012	0.015
C-4	2×10^{-4}	3×10^{-4}	4×10^{-4}	2×10^{-4}	3×10^{-4}	4×10^{-4}	0	4×10^{-4}	5×10^{-4}
C-5	0.063	0.083	0.096	0.046	0.066	0.084	0.02	0.033	0.051
C-6	0.033	0.047	0.058	0.024	0.037	0.05	0.02	0.027	0.04
C-7	2×10^{-8}	3×10^{-8}	3×10^{-8}	3×10^{-8}	3×10^{-8}	3×10^{-8}	0	3×10^{-8}	3×10^{-8}
C-8	0.012	0.018	0.023	0.008	0.013	0.019	0.01	0.014	0.02
C-9	0.004	0.006	0.01	0.005	0.007	0.013	0	0.004	0.006
C-10	0.004	0.005	0.008	0.003	0.003	0.004	0	0.005	0.007
C-11	3×10^{-4}	4×10^{-4}	6×10^{-4}	4×10^{-4}	5×10^{-4}	8×10^{-4}	0	3×10^{-4}	4×10^{-4}
C-12	0.009	0.013	0.024	0.006	0.007	0.01	0.01	0.017	0.031
C-13	0.025	0.032	0.037	0.016	0.024	0.031	0.03	0.036	0.04
C-14	0.001	0.002	0.002	0.002	0.002	0.003	0	0.002	0.002
C-15	0.002	0.003	0.004	0.002	0.003	0.004	0	0.004	0.005
C-16	0.012	0.013	0.016	0.021	0.033	0.065	0.02	0.021	0.033
C-17	0.01	0.017	0.028	0.024	0.033	0.043	0.02	0.031	0.042
C-18	0.115	0.167	0.211	0.211	0.251	0.264	0.05	0.097	0.15

Subsequently, the distances of the alternatives to the fuzzy positive ideal solution and the fuzzy negative ideal solution were calculated and were displayed in Table 19.

Table 19. Distance to positive and negative ideal.

	d_i^+			d_i^-		
	Supplier 1	**Supplier 2**	**Supplier 3**	**Supplier 1**	**Supplier 2**	**Supplier 3**
C-1	0.89528598	0.80776919	0.92390284	0.10833479	0.21105755	0.07674660
C-2	0.97170630	0.98370327	0.97358272	0.02864551	0.01694147	0.02686834
C-3	0.98932426	0.98970628	0.98827514	0.01098459	0.01067227	0.01198328
C-4	0.99972885	0.99968307	0.99960560	0.00028209	0.00033083	0.00040376
C-5	0.91958820	0.93450613	0.96646544	0.08165250	0.06743771	0.03650861
C-6	0.95418021	0.96273297	0.97283599	0.04706150	0.03876628	0.02899565
C-7	0.99999997	0.99999997	0.99999997	0.00000003	0.00000003	0.00000003
C-8	0.98266993	0.98683988	0.98617299	0.01786219	0.01398407	0.01461393
C-9	0.99304388	0.99148545	0.99557541	0.00738286	0.00925539	0.00454767
C-10	0.99429893	0.99670935	0.99473812	0.00600914	0.00334799	0.00549324
C-11	0.99954594	0.99941206	0.99969162	0.00047046	0.00061872	0.00031114
C-12	0.98470966	0.99197263	0.98046399	0.01663114	0.00822876	0.02140769
C-13	0.96868321	0.97657954	0.96496774	0.03170320	0.02418729	0.03530996
C-14	0.99846745	0.99795656	0.99846745	0.00158839	0.00208190	0.00158839
C-15	0.99684597	0.99684597	0.99637423	0.00326192	0.00326192	0.00370501
C-16	0.98644083	0.96065282	0.97699074	0.01363783	0.04369867	0.02409480
C-17	0.98172632	0.96665740	0.96845541	0.01978351	0.03429986	0.03266710
C-18	0.83647973	0.75804942	0.90102133	0.16916401	0.24332243	0.10742314

Following the calculation of negative and positive distances, the d_i^+ and d_i^- distances for each selection criterion within each alternative were added up. Based on these distances, the closeness coefficients (CC_i) for each alternative were calculated, and the results were presented in Table 20.

Table 20. Fuzzy TOPSIS rankings.

	Supplier 1	**Supplier 2**	**Supplier 3**
d_i^+	17.453	17.301	17.588
d_i^-	0.564	0.731	0.433
CC_i	0.031	0.041	0.024
Ranking	2	1	3

According to the results given in Table 20, Supplier 2 was identified as the best supplier with a CC_i value of 0.041, followed by Supplier 1 and Supplier 3 with CC_i values of 0.031 and 0.024, respectively. The results of Fuzzy ARAS and Fuzzy TOPSIS MCDM methods were parallel and pointed out Supplier 2 as the best-performing alternative in leanness and sustainability.

The above-detailed documentation proved that the systematic approach and evaluation criteria proposed in this study could be effectively used to tackle lean and sustainable supplier selection problems within the furniture industry.

This study was expected to have significant scientific, practical, and managerial implications, detailed in the following sub-section. The study limitations were also discussed in the following sub-section of the study.

3.1. Implications and Limitations of the Study

One of many scientific implications of the study was its methodological contribution: Combining the ENTROPY method with Fuzzy ARAS and Fuzzy TOPSIS for supplier selection presented a unique methodological fusion. As proven effective, this could pave the way for similar integrations in other Multi-Criteria Decision-Making (MCDM) studies. Next, this study contributed to the body of knowledge on applying fuzzy logic in decision-making contexts. Understanding how fuzziness could be incorporated effectively into practical decision models expands the scope and adaptability of fuzzy logic theories. In addition, the research presented empirical evidence on the use of the ENTROPY method to assign weights to leanness and sustainability criteria. This demonstrates a practical application of a theoretical concept, enriching the current academic discourse around weight allocation techniques in decision-making problems. Moreover, the study also acted as a validation agent for the effective and multi-purpose use of GRI guidelines by utilizing criteria adapted and altered from the GRI's sustainability guidelines for supplier selection. The study provided a context-specific validation of these guidelines. The effectiveness and relevance of the GRI criteria in this context might motivate other industries to explore similar applications. Furthermore, since the proposed methodology was proven successful within the target industry, it could serve as a benchmark for other sectors looking to integrate lean practices with sustainability initiatives.

On the other hand, the work was unique with its holistic evaluation framework. Most studies in supplier selection tend to focus either on efficiency (leanness) or sustainability but rarely both. This study offered a holistic evaluation framework that could be explored and refined in subsequent research. This study was also a successful example of interdisciplinary research. The study tried to bridge operations management, sustainability sciences, and decision-making methodologies, promoting interdisciplinary collaboration. This kind of work could inspire future researchers to think beyond traditional disciplinary boundaries.

Another scientific implication of the study could be seen when the importance of replicability of the scientific propositions is considered. Since the proposed system demonstrated its efficacy in the furniture sector, researchers might be encouraged to test its applicability in other industries. Such replicability studies are crucial for generalizing the findings. Moreover, the study underscored the importance of making decisions under uncertainty. This could inspire further research into other methodologies or adaptations that account for uncertainty in decision-making scenarios.

Last but not least, by employing different fuzzy MCDM approaches, the study provided an opportunity for comparative analysis. Future studies could delve deeper into the pros and cons of each method or explore hybrid approaches that might offer better results. The researchers could also focus on exploring the optimization of the number of criteria used and the ability of criteria to snapshot actual leanness and sustainability performance of the suppliers. Moreover, different MCDM methods could be integrated to both assign criteria weights and assess the alternatives. In sum, this study's methodological innovations, interdisciplinary nature, and holistic approach hold the potential to shape future research directions in supplier selection, lean practices, and sustainability sciences.

This study also had various practical implications. Firms, especially in the wood furniture industry, could use the developed model as a decision-making tool to select suppliers that align with both lean and sustainable practices. Moreover, the ENTROPY method was used to eliminate any subjective bias in criteria weightage. Such an approach gives firms a systematic method of evaluating the importance of different criteria. Next, with the combined use of Fuzzy ARAS and Fuzzy TOPSIS, companies could evaluate supplier alternatives under uncertain and ambiguous conditions. The fuzzy nature captures the imprecision and vagueness inherent in human evaluations. Another strong implication of the study was its size-agnostic evaluation. The developed criteria and evaluation methods could be used by both large corporations and SMEs, offering a scalable solution. Adopting criteria based on GRI guidelines ensured that suppliers were evaluated based on internationally accepted sustainability metrics.

As for the managerial implications, strategic supplier relationships, brand reputation and corporate social responsibility (CSR), risk management, resource allocation, continuous improvement, competitive advantage, and stakeholder engagement could be deemed as the main aspects that could benefit from the study. Managers could now prioritize suppliers who not only offer cost or efficiency advantages (lean) but also align with sustainable practices. This could lead to longer-term, strategic partnerships with suppliers. Companies could enhance their CSR profiles by aligning supplier selection with GRI guidelines. This could lead to improved brand reputation and trust among consumers who are increasingly conscious of sustainable practices.

Moreover, using a systematic method to assess suppliers minimizes the risk of associating with suppliers who might have questionable practices that could harm the company's image or lead to disruptions in day-to-day operations. Furthermore, by integrating leanness and sustainability into supplier selection, managers could ensure a more effective allocation of resources by collaborating with efficient, responsible, and accountable suppliers. The integrated procedure also provides a framework for continuous improvement. Managers could periodically review and refine the criteria and their weights to align with changing business objectives or industry trends. Similarly, adopting such a comprehensive supplier selection procedure could become a source of competitive advantage, leading to better quality products, fewer supply chain disruptions, and more efficient operations. Last, shareholders, customers, and even employees have been increasingly demanding sustainable practices. Managers could better address these stakeholders' expectations by adopting a lean and sustainable supplier selection process. To summarize, as executed effectively, this study demonstrated the potential to revolutionize supplier selection in the furniture industry by merging the principles of leanness, sustainability, and multi-criteria decision-making. It provides actionable insights for both practitioners on the ground and managers making strategic decisions.

As for the implications for policy makers, the research emphasized the increasing demand for sustainable products with traceable and accountable supply chains. Policy makers could develop regulations and incentives that promote transparency and sustainability in the furniture industry's supply chains, thereby ensuring ethical and environmental standards are maintained. Given the significant weight attributed to the 'Distance to Customer' criterion, policies could be designed to incentivize local sourcing and production. This could reduce carbon footprints associated with transportation and promote local economic growth. Moreover, the prominence of 'Labor Practices' as a criterion was a strong reminder of the need for stricter regulations and standards regarding labor conditions in the furniture manufacturing industry. Policy makers could work to ensure that workers' rights are protected, and decent working conditions are upheld. Additionally, the systematic approach used in this study for supplier selection could serve as a benchmark for the industry. Policy makers could consider this framework or a more expanded version of it when setting industry standards for supplier evaluations, ensuring a balanced emphasis on both lean and sustainable practices. From the perspective of promoting research and development, the study's use of advanced MCDM methods for supplier selection could pave the way for further technological and methodological advancements in the industry. Policy makers could encourage R&D in these areas, potentially leading to more efficient and sustainable decision-making tools in the future. Furthermore, the shift from win-win partnerships to all-wins partnerships underscores the importance of collaboration. Policies could be formulated to promote collaboration between stakeholders, ensuring collective growth and mutual benefits.

The study also has implications for policymaking in regard to of educational initiatives. Given the intricate decision-making processes highlighted in the research, there is a clear need for skilled professionals that are adept at such methodologies. Policy makers could introduce educational initiatives or training programs to equip professionals in the industry with these skills. Last but not least, the study showcased the importance of considering economic, environmental, and social criteria in decision-making. Policies could be designed to ensure businesses consider this triad in their operations, leading to more holistic and sustainable outcomes. Incorporating above-stated implications into policymaking could not only foster a more sustainable and efficient furniture manufacturing industry but could also set a precedent for other sectors to follow a similar path.

On the other hand, this study had some limitations like any other research study. All three MCDM methods primarily used the data obtained from the suppliers. Even though all suppliers pledged to provide the most accurate and current data regarding their performance, such a situation could make the proposed approach prone to subjectivity if any biased, inaccurate, and incorrect reporting occurred. This could be avoided if the performance data of the suppliers were measured and reported by third-party independent organizations. However, due to time and resource constraints, such a process was not feasible.

The criteria proposed in this study were adapted and altered from GRI guidelines to ensure validity and applicability. However, the criteria selection and screening process was the product of six experts who carried out the process by considering the problem at hand. Moreover, based on the interpretations made during the literature review process, the experts were asked to limit the number of criteria to eighteen since measuring too much could have been as damaging as measuring too little. Therefore, the ability to capture the leanness and sustainability performance of the criteria set could be limited. Furthermore, the ENTROPY method determines the criteria weights based on the relative difference among performances of all alternatives for each criterion. Therefore, the decisiveness level of the criterion was case-specific and could not be generalized.

3.2. Future Research Directions

Based on the provided information and discussions in the context of the furniture manufacturing industry, lean practices, sustainability, and multi-criteria decision-making, several potential avenues for future research emerge. One promising direction could be exploring the system's efficacy not just in the furniture sector but also extending its applicability to other industries such as textiles or electronics manufacturing. The highlighted challenges of making decisions under uncertainty pave the way for delving deeper into methodologies or adaptations specifically addressing this uncertainty. Furthermore, using various fuzzy MCDM approaches in the study opens the door for an in-depth exploration and comparison, potentially yielding insights into each method's relative advantages and disadvantages under particular scenarios.

Moreover, there is an affluent area in researching how to optimize the number of criteria used in such analyses. By ensuring that these criteria adequately capture leanness and sustainability performance, one could ensure more precise and efficient supplier evaluations. The hint at possible hybrid approaches in the study also suggests a line of inquiry: could there be a way to integrate different MCDM methods to assign criteria weights and evaluate alternatives in a superior fashion?

From a broader societal perspective, given the research's implications for policymakers, a dedicated study to gauge the effect of existing policies on sustainable and lean practices in the furniture industry would be enlightening. This could further open doors to propose nuanced policy adjustments based on the study's insights. Another angle to consider is the interface between corporate social responsibility and brand reputation. Analyzing how aligning supplier selection with sustainability guidelines directly affects a brand's reputation could prove informative, especially in understanding the translation of these practices into consumer perception and loyalty.

It is notable how the 'Labor Practices' criterion was emphasized in the findings. Therefore, a focused exploration of labor practices' direct and indirect impacts on the broader supply chain and final product quality could be invaluable. This ties in with the 'Distance to Customer' criterion, suggesting a deep dive into the benefits, challenges, and feasibility of local sourcing and production in the furniture industry would be worth undertaking.

The intricacies of the decision-making processes highlighted also flag the potential for evaluating the effectiveness of educational initiatives tailored to train professionals in these methodologies. Lastly, the study's touch on the shift from win-win to all-wins partnerships in the supply chain alludes to a broader area of investigation: understanding the long-term implications and tangible benefits of such partnerships, potentially offering insights into collaborative growth strategies in the industry.

In summary, these directions, derived from the study and its implications, present promising avenues for augmenting the existing body of knowledge in the domain of lean practices, sustainability, and multi-criteria decision-making, specifically in the furniture industry and potentially extending to other sectors.

4. Conclusions

Integrating lean and sustainable principles in supplier selection constitutes a multi-faceted decision-making challenge. This complexity is accentuated as the number of alternatives and evaluation criteria proliferate. Nonetheless, Multi-Criteria Decision Making (MCDM) methodologies facilitate informed determinations concerning supplier selection. Engaging with a supplier proficient in delivering the requisite quantity in a timely manner is intrinsically linked to the resilience of production systems. Moreover, it substantively augments the aggregate performance and profitability of the overarching supply chain. Eliminating time and quantity ambiguities does not solely drive contemporary global markets. A burgeoning demand exists for sustainable products derived from transparent and accountable supply chains. Consequently, corporate frameworks have a discernible paradigm shift towards genuine sustainability, transitioning partnerships from a dyadic win-win model to a more encompassing "all-wins" perspective. The present research delineates the confluence of leanness and sustainability Key Performance Indicators (KPIs) within the MCDM framework, aiming to bolster lean and sustainable supplier selection within the furniture manufacturing sector.

Conclusive remarks of this study could be summarized as follows.

- The joint evaluation of suppliers on both leanness and sustainability metrics introduced additional intricacies. Yet, with the aid of MCDM, these complexities are proven navigable.
- The ENTROPY method has demonstrated efficacy in weight allocation for leanness and sustainability criteria. Subsequent to weight determination, these could be incorporated into various Fuzzy MCDM methodologies for a juxtaposed evaluation of potential alternatives.
- Among the established criteria, Distance to Customer (km) (C1) received the preeminent weight of 0.302, succeeded by Labor Practices (C18). Conversely, Quality Level (%) (C7) was accorded the least significance, evidenced by its weight of 2.9×10^{-8}.
- Pertaining to the studied problem, the determinants Distance to Customer (km) and Labor Practices emerged as paramount among the eighteen criteria.
- Both Fuzzy ARAS and Fuzzy TOPSIS methodologies concurred in ranking Supplier 2 as the optimal choice, characterized by superior K_i and CC_i values. This convergence in outcomes solidified the supplier hierarchy as Supplier 2 > Supplier 1 > Supplier 3.
- The problem was dissected using 18 criteria: seven economic, six environmental, and five social. The ENTROPY method facilitated the derivation of criterion weights. A juxtaposition between Fuzzy ARAS and Fuzzy TOPSIS was undertaken for alternative evaluation, underpinned by the stipulated criterion weights.

In conclusion, while the current study explicitly tackled a supplier selection challenge within furniture manufacturing, emphasizing leanness and sustainability tenets, its structured approach and consequential insights have broader applicability. These insights could serve as a lodestar for analogous intricate decision-making challenges, rendering the research invaluable for practitioners and academicians vested in furniture manufacturing, supply chain management, multi-criteria decision-making, and policymaking.

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Appendix A

Table A1. Definitions of the Lean and Sustainable Supplier Selection Criteria.

Criteria Code	Criteria	Definition
	Lean-Infused Economic Performance Criteria	
C-1	Distance to Customer (km)	The distance between the supplier and the customer (the decision-maker firm) in km.
C-2	Value-Added Time per Unit * (h/unit)	The value-added time spent for the production of 1 m^2 of wood panel.
C-3	Value-Added Cost Ratio per Unit * (%/unit)	The total cost associated with the value-added activities occurred during the production of 1 m^2 of wood panel.
C-4	Customer Service Level (%)	The percentage of all orders delivered on schedule.
C-5	Rate of Returns on Costs (%)	The ratio between net income (in the last fiscal year) and investment (cost associated with the production in the last fiscal year) expressed as a percentage.
C-6	Net Profit Margin (%)	The ratio of net profits to total revenues of the company in the last fiscal year expressed as a percentage.
C-7	Quality Level (%)	Achieved Six-Sigma quality level expressed as a percentage in the last six months.
	Environmental Performance Criteria	
C-8	Sustainable Sourcing (Wood Chips) (%/unit)	The percentage of raw material going into 1 m^2 of wood panel sourced from sustainably managed resources and/or deemed sustainable.
C-9	Global Warming Potential ($kgCO_2$/unit)	The amount of carbon dioxide emitted into the atmosphere during the production of 1 m^2 of wood panel.
C-10	Water Footprint per Unit * (L/unit)	The amount of water withdrawn from the source during the production of 1 m^2 of wood panel.
C-11	Energy Footprint per Unit * (kwh/unit)	The amount of electricity consumed during the production of 1 m^2 of wood panel.
C-12	Solid Waste Generation per Unit * (kg/unit)	The amount of solid waste generated and disposed of during the production of 1 m^2 of wood panel.

Table A1. *Cont.*

Criteria Code	Criteria	Definition
C-13	Recycled Raw Material Ratio per Unit * (%)	The percentage of the recycled raw material amount in 1 m^2 of wood panel.
	Social Performance Criteria	
C-14	Employee Satisfaction Rate (%)	The percentage of total employees feeling satisfied with their job and work environment.
C-15	Contribution to society ($/year)	The amount of money spent (directly or through intermediaries) by the company in the last year in order to contribute to the development of the local community in which their manufacturing facility is located.
C-16	Absenteeism Ratio (%)	The ratio of the total number of employee days lost to job absence and the total number of employee days expressed as a percentage.
C-17	Gender Bias Ratio (%)	The ratio of women employees to men employees within the organization.
C-18	Labor Practices (%)	The percentage of employees getting paid above the industry average for their assigned job title.

* The functional unit: 1 m^2 of defect-free, shipment-ready wood panel.

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