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Enhancing Supplier Selection for Sustainable Raw Materials: A Comprehensive Analysis Using Analytical Network Process (ANP) and TOPSIS Methods

Ilyas Masudin [1,*], Isna Zahrotul Habibah [1], Rahmad Wisnu Wardana [1], Dian Palupi Restuputri [1] and S. Sarifah Radiah Shariff [2]

[1] Industrial Engineering Department, Universitas Muhammadiyah Malang, Malang 65144, Indonesia; isnazahraa23@gmail.com (I.Z.H.); rahmadwisnu78@umm.ac.id (R.W.W.); restuputri@umm.ac.id (D.P.R.)
[2] Malaysia Institute of Transport (MITRANS), Universiti Teknologi MARA, Shah Alam 40450, Malaysia; shari990@uitm.edu.my
* Correspondence: masudin@umm.ac.id

Abstract: *Background:* This research endeavors to enhance supplier selection processes by combining the Analytic Network Process (ANP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methodologies, with a specific focus on sustainability criteria. *Method:* Initially comprising 21 sub-criteria derived from prior research, the selection criteria are refined to 17, eliminating redundant elements. The core principle guiding this refinement is the comprehensive coverage of economic, social, and environmental dimensions, essential for sustainable supplier evaluation. *Results:* The study's outcomes underscore the paramount importance of economic criteria (0.0652) in supplier selection, followed by environmental (0.0343) and social dimensions (0.0503). Key sub-criteria contributing significantly to this evaluation encompassed consistent product quality, competitive raw material pricing, proficient labor capabilities, recycling potential, punctual delivery performance, and effective waste management practices. *Conclusions:* These sub-criteria are thoughtfully integrated into the sustainable assessment framework, aligning seamlessly with the economic, environmental, and social criteria.

Keywords: sustainable; supplier selection; ANP; TOPSIS; decision-making

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1. Introduction

Supplier selection holds a crucial role within a company, ensuring the availability of necessary raw materials and impacting both profitability and overall maintenance. However, contemporary societal concerns have compelled businesses to integrate sustainable attributes encompassing social, economic, and environmental aspects into their supply chain operations [1]. Choosing sustainable suppliers poses a challenging decision. Yet, it can enhance profit stability for the company and yield resources aligning with market demands. While economic and environmental performance have long been factors in sustainable supplier selection, considering a company's social and ethical stance has gained prominence more recently [2]. Corporations actively embracing sustainability in their strategy may need to augment selection criteria and performance metrics to assess supplier sustainability [3].

The assessment and choice of an optimal sustainable supplier involve numerous criteria. Issues with suppliers, such as subpar raw material quality, delayed deliveries, and distance from the company, lead to delays in meeting consumer orders, incurring penalty costs and hindering the production process, resulting in inconsistent product quality. Thus, sustainability becomes pivotal as a diagnostic tool for evaluating and aligning sustainability performance with the supply chain [4]. Supplier activities significantly impact downstream firms in achieving sustainable and collaborative competitive advantages [1]. In addition to the criteria mentioned above, another crucial factor in assessing sustainable suppliers is their commitment to environmental and social responsibility. Suppliers that prioritize eco-friendly production processes, ethical labor practices, and community engagement not only contribute to a company's sustainability goals but also enhance its brand reputation and customer loyalty [5]. Moreover, Vachon and Klassen [6] found that collaborating with such suppliers can lead to a positive ripple effect, fostering a culture of sustainability throughout the supply chain and ultimately benefiting both the company and the broader society. Therefore, the selection of an optimal sustainable supplier extends beyond operational efficiency to encompass a holistic approach that considers the broader impact of supplier activities on the environment, society, and the company's long-term competitiveness.

In the realm of supplier selection, the landscape is richly diverse with methodologies ranging from the well-established Analytical Hierarchy Process (AHP) and Analytical Network Process (ANP) to innovative approaches like Simple Additive Weighting (SAW), Weighted Product (WP), and ELECTRE (Elimination Et Choix Traduisant la Realité). However, it is the convergence of these methodologies with contemporary sustainability paradigms that ushers in a new era of novelty. The seminal study by Govindan et al. [7] illuminates the path towards sustainable material selection in construction, where factors like recyclability and reuse potential are pivotal in decision-making, spotlighting brick wool as a beacon of eco-consciousness. Equally transformative is the investigation by Hadiguna [8] unveiling the intricacies of performance-based risk in Indonesian sustainable palm oil supply chains, underscoring the delicate balance between economic viability and environmental integrity. This narrative finds its backbone in the discipline of Multi-Criteria Decision Making (MCDM) as expounded by Saaty [9], a navigational compass for deciphering intricate decision matrices. The fusion of economic, social, and environmental dimensions within the framework of supplier selection, as espoused by Sen et al. [10], represents a bold stride toward holistic sustainability. In the pioneering work of Lu et al. [11], as they lead the way in integrating environmentally friendly principles into multi-objective decision-making, the field echoes with the well-established insights of the Analytical Network Process (ANP) and the impartial objectivity of TOPSIS. This combination of methods not only guides the selection of optimal raw material suppliers but also sets the stage for a sustainable future in supplier selection, where innovation and responsibility come together in compelling harmony.

While existing research has explored the complexities of sustainable supplier selection, there is a notable gap in understanding the practical implementation of diverse methodologies within the contemporary sustainability paradigm. Although studies by Govindan et al. [7] and Hadiguna [12] have focused on specific industries and regions, a comprehensive framework that integrates various multi-criteria decision-making techniques with evolving sustainability principles is missing. Furthermore, while the theoretical foundations provided by Saaty [9] and the methodological advancements highlighted by Sen et al. [10] offer valuable insights, empirical studies validating these frameworks in real-world supplier selection scenarios are limited. There is also a need to investigate the dynamic nature of supplier relationships within sustainability, considering factors such as long-term collaboration, supplier development, and the impact of supplier selection decisions on broader supply chain dynamics. Future research should address these gaps by conducting empirical studies that validate the effectiveness of multi-criteria decision-making methodologies in sustainable supplier selection across diverse industries and geographical contexts, and by exploring the dynamic nature of supplier relationships and their implications for sustainability in the supply chain ecosystem.

The organization of this article is outlined as follows: In Section 2, we examine the evaluation criteria and the technique employed to assess suppliers. In this section, we also provide a more detailed explanation of our suggested methodology. Section 3 explores the conversion of numerical values to fuzzy terms and the stability of rankings, along with contrasting the outcomes achieved via various approaches. The considerations regarding real-world applications and theoretical significance are deliberated in Section 4, and the paper is concluded in Section 5.

2. Related Works and Methods

2.1. Supplier Selection

Suppliers can be defined as organizations that furnish the necessary resources to fulfill the requirements and desires of customers, encompassing both tangible elements like products and intangible aspects such as services. The role of suppliers transcends mere material provision, delving into a complex web of factors that impact a company's operational efficacy, economic stability, environmental responsibility, and social contributions [13]. The blend of traditional SCM and sustainable supply chain approach forms a comprehensive framework for supplier selection that holds the potential to shape industries and foster responsible business practices [14,15]. Within a company's operational framework, the components supplied by these entities, whether they are physical materials or essential raw materials, constitute pivotal elements in the intricate production process. The process of selecting suppliers assumes paramount significance as it ensures the seamless functioning of production operations. The chosen supplier must possess the capabilities to deliver products of superior quality, maintain competitive pricing, and adhere to stipulated delivery timelines. Although suppliers may appear homogeneous at first glance, they do possess distinct characteristics that set them apart. Supply Chain Management (SCM) entails a meticulous evaluation of certain criteria for effective supplier selection, including aspects like cost, pricing, quality assurance, and punctual delivery. This viewpoint is supported by Govindan et al. [16]. They believed that sustainability encompasses a supplier's commitment to eco-friendly processes, reducing carbon footprint, and ensuring that their operations align with environmental regulations. This not only reflects positively on a company's corporate social responsibility but can also mitigate risks associated with supply chain disruptions due to environmental issues.

In the context of cultivating a sustainable supply chain, the parameters for supplier selection become more comprehensive, encompassing economic, environmental, and social dimensions. This holistic approach is undertaken to enable companies to establish long-standing business sustainability and resilience. The selection of suppliers under this framework becomes adaptable to various industries and individual company circumstances. Bai and Sarkis [17] introduced a groundbreaking model that interweaves the supplier selection predicament with sustainability considerations. These factors account for the intricate balance between economic viability, ecological impact, and societal well-being. Within this sustainable paradigm, recycling, reusability, and resource reduction have emerged as pivotal criteria, as highlighted by Su et al. [18].

2.2. Sustainable Supplier Selection

Sustainability has emerged as a comprehensive discipline aimed at fostering collaboration between practitioners and scientists across all dimensions of sustainability. It encompasses a holistic perspective that strives to recognize the intricate interplay between systems and their broader environmental context. A significant subset within sustainability is Sustainable Supply Chain Management (SSCM), which represents a form of environmentally conscious supply chain management. It transcends mere economic and environmental considerations by also incorporating social criteria in its design and operation [19,20]. Acknowledging the growing significance of sustainability for businesses, it has become a vital diagnostic tool for evaluating and harmonizing sustainability performance with the intricacies of supply chain operations [4,21]. This is particularly notable as the activities of suppliers play a pivotal role in enabling downstream companies to attain sustainable and competitive advantages through collaboration [1]. The foundational framework of sustainability is often delineated by three pillars: economic, social, and environmental [22]. Each pillar introduces distinct considerations and challenges that have profound implications for decision-makers and researchers alike. These challenges are not insignificant, as they underscore the complexity involved in striving for sustainability and sustainable development in various contexts. We delve into the pillars in more depth below.

a. Economy

The economic pillar spotlights the necessity of fostering enduring economic growth and preserving the financial stability of companies. Supply chain managers are tasked with devising strategies that incorporate profitable sustainable supply chain activities, allowing for sustained success over time [20,23]. Unlike short-term corporate planning, the principle of economic sustainability strives for consistent returns over the long haul [24]. Realizing economic sustainability entails addressing critical factors such as collaborative relationships, efficient logistics support, and profitability [25]. The suppliers' role becomes pivotal, as their contributions to ensuring affordable, high-quality raw materials can significantly impact a company's economic outlook.

b. Environment

The environmental pillar encompasses a broad spectrum of concerns centered on safeguarding ecosystems against avoidable harm [26]. Companies are expected to guide their suppliers toward adopting sustainable practices, including prudent resource utilization, ethical labor practices, reduction of greenhouse gas emissions, and more [24]. This dimension involves a multitude of factors spanning green packaging distribution, warehouse and transportation optimization, conservation efforts, carbon footprint reduction, and adherence to environmental standards [27]. The interconnectedness of ecosystems underscores the global impact of local environmental damage, underscoring the imperative of maintaining functional ecosystems to sustain various ecosystem services.

c. Social

With social sustainability, organizations grapple with the intricacies of managing diverse stakeholders, each with their unique goals and perspectives [28]. This pillar extends the sustainability paradigm to individual, community, and societal levels, emphasizing the need for a sustainable way of life [24]. Key considerations encompass well-being, diversity, democracy, engagement, and security. A noteworthy facet is the evaluation of labor competence in supplier selection, recognizing its centrality to smooth production processes [28]. Training emerges as a fundamental component, ensuring the efficacy of workers and the overall production cycle.

2.3. Identification of Criteria and Sub-Criteria

The process of selecting suitable criteria holds paramount significance for businesses during their decision-making endeavors [1,29]. When companies engage in evaluating potential suppliers, they do so by taking into account specific benchmarks and situational factors. In this intricate process, the initial step involves pinpointing the precise set of criteria that will guide the selection of suppliers, with a special emphasis on sustainability-focused considerations. This selection is not haphazard; instead, it is an outcome of meticulous literature reviews and extensive consultations with industry experts, as highlighted by [30]. Natalia et al. [30] advocated that these criteria are not arbitrarily derived but are extracted from a comprehensive analysis of existing literature and in-depth dialogues with specialists. The meticulous curation of these criteria ensures a well-informed and robust approach to supplier selection, which is paramount in today's complex business landscape. As outlined by Natalia et al. [30], the comprehensive compilation of data and expert insights culminates in a list of 17 sustainable criteria, meticulously identified through a thorough review of relevant literature. The culmination of these criteria is visually represented in Table 1, offering a clear overview of the multi-faceted considerations that underlie the supplier selection process.

Table 1. Identification of criteria and sub-criteria.

Criteria	Sub-Criteria	Code	Sources
Economy (E)	Price	E1	Memari et al. [31]
	Product defect rate	E2	Amiri et al. [32]
	Discount on quantity	E3	Puska et al. [33]
	Distance	E4	Amindoust [34]
	On-time delivery	E5	Puska et al. [33]
	Consistent quality	E6	Khulud et al. [35]
	Warranty and claims	E7	Hana and Nurcahyo [36]
Social (S)	Labor competency	S1	Restuputri et al. [37]
	Labor satisfaction	S2	Memari et al. [31]
	Communication fluency	S3	Amiri et al. [32]
	Flexible work arrangements	S4	Restuputri et al. [38]
	Use of safety equipment	S7	Sukmawati et al. [26]
	Compliance with labor regulations	S8	Hermawan et al. [39]
Environment (E)	Environmentally friendly materials	L1	Dzikriansyah et al. [40]
	Recycling potential	L2	Memari et al. [31]
	Eco-friendly certification	L3	Hana and Nurcahyo [36]
	Waste	L4	Masudin et al. [41]

Table 1 presents a comprehensive set of criteria for evaluating suppliers based on economic, social, and environmental factors. Each main criterion is broken down into specific sub-criteria, reflecting various aspects crucial to supplier selection. For instance, economic criteria include price, product defect rate, discounts on quantity, distance, on-time delivery, consistent quality, and warranty and claims. These factors highlight the importance of cost efficiency, product quality, logistical considerations, and reliability in the supplier selection process [42].

Social criteria focus on aspects related to the workforce and communication within the supplier's organization. Sub-criteria such as labor competency, labor satisfaction, communication fluency, flexible work arrangements, use of safety equipment, and compliance with labor regulations emphasize the significance of human resources and ethical practices [43]. These factors are essential for ensuring that suppliers can meet quality and logistical standards and maintain a positive and safe working environment, which can affect overall performance and sustainability.

Environmental criteria assess the supplier's commitment to sustainability and eco-friendly practices. Sub-criteria include the use of environmentally friendly materials, recycling potential, eco-friendly certification, and waste management [44]. These factors are increasingly important as organizations strive to reduce their environmental footprint and comply with regulatory requirements. By incorporating these criteria, the table underscores the growing importance of sustainability in supplier selection, reflecting a holistic approach that balances economic, social, and environmental considerations.

Furthermore, Table 1 provides a comprehensive overview of the definitions and explanations for the criteria that have been meticulously employed in the process of selecting sustainable suppliers. This table serves as an invaluable reference tool, shedding light on the fundamental concepts and considerations that underpin the assessment of potential partners in the realm of sustainability. Each criterion is thoughtfully elucidated to ensure clarity and understanding, thereby enabling a transparent and informed decision-making process.

Economic aspects:

- Price: This criterion evaluates the cost of the raw materials provided. The company seeks high-quality raw materials at the lowest possible cost.
- Raw material defect rate: This aspect examines how frequently received raw materials exhibit defects, such as fabric holes, weak thread connections leading to blemishes, stubborn stains, etc.
- Quantity-based discounts: This factor gauges the discounts offered by suppliers to the company when the order quantities increase.
- Proximity: Evaluated by considering the distance between the company and its suppliers.
- Timely delivery: This parameter assesses the punctuality of raw material deliveries from suppliers.
- Material suitability: This criterion considers whether the delivered raw materials align with the required specifications, encompassing aspects like color, material type, and thickness.
- Warranty and vlaims: Assessed through post-transaction services offered in cases where received raw materials are damaged.

Social aspects:

- Workforce competence: This element evaluates the skill level of the workforce, which directly impacts the company's productivity.
- Employee satisfaction: This factor assesses the contentment of employees with their work, which can contribute to a smoother workflow.
- Effective communication: This aspect gauges the quality of communication between supervisors and employees, fostering harmony and facilitating clear information flow for streamlined production.
- Flexibility in work arrangements: This criterion examines the ability to adjust work hours based on company orders.
- Safety equipment utilization: This parameter is measured by observing whether employees adhere to safety protocols, reducing the occurrence of workplace accidents.
- Compliance with labor regulations: This factor assesses whether the supplier's labor practices align with established standards.

Environmental aspects:

- Use of environmentally friendly materials: This criterion evaluates the utilization of raw materials that do not harm the environment, including elements like fabric dyes.
- Recyclability potential: This aspect assesses whether generated waste can be repurposed or appropriately disposed of.
- Eco-certifications: This parameter examines whether the company possesses certifications related to environmental responsibility.
- Waste management: This criterion assesses how waste is handled, ensuring it follows regulations and guidelines.

3. Results

Several approaches can be employed for the selection of suppliers, such as the Analytical Hierarchy Process (AHP), Simple Additive Weighting (SAW), Weighted Product (WP), and ELECTRE, among others. However, researchers commonly utilize a combination of the Analytical Network Process (ANP) and TOPSIS methods, as these two approaches complement each other effectively. The ANP technique focuses on determining the weight of various criteria, while the TOPSIS method is geared towards establishing a preference order. In this particular study, the research pertains to garment suppliers and involves the evaluation of four distinct suppliers. The study incorporates insights from three key participants: the logistics manager, the head of purchasing, and the production manager. These stakeholders hold pivotal roles within the company, especially in significant activities related to material procurement that caters to the production process [45]. The assessment of supplier performance encompasses four distinct questionnaires. The primary purpose of the initial questionnaire is to assess both criteria and sub-criteria (Table 2). This evaluation employs the Cut Off Point method, which aids in selecting criteria for decision-making. The assigned importance values range from 1 (Not Important) to 5 (Very Important) (Table 3). Additionally, this method helps narrow down the key criteria to a select few [46].

Table 2. ANP scale.

Intensity of Interest	Description
1	Both elements are equally important
3	One element is slightly more important than the others
5	One element is more important than another
7	One element is clearly more absolutely essential than the others
9	One element is absolute over another
2,4,6,8	Values between two adjacent consideration values

Table 3. Likert scale.

Scale Value	Description
1	Very low/Bad
2	Low/Bad
3	Medium
4	High/Good
5	Very high/Very good

3.1. Analytical Network Process (ANP)

ANP, a theory of decision-making, operates within a mathematical framework and is also categorized as a Multi-Criteria Decision Making (MCDM) technique devised by Thomas L. Saaty [9]. This approach, known as the ANP method, possesses the ability to effectively address intricate multi-criteria challenges. By revealing connections and interdependencies between numerous performance metrics, ANP offers a more accurate evaluation of metric rankings [9]. In contrast to the AHP method, ANP is characterized by its simplicity, rendering it suitable for various qualitative case studies like assessment, visualization, prediction, and decision-making. ANP boasts an advantage over AHP by establishing an interconnected criteria network [47]. Being more comprehensive than AHP, which is confined to multi-criteria decision analysis, ANP employs a network-based approach instead of the hierarchical structure found in AHP. Unlike AHP's tiered levels of objectives, criteria, sub-criteria, and alternatives, ANP utilizes clusters termed "nodes" without the need for predefined levels [48].

The Analytical Network Process (ANP) is employed to resolve challenges reliant on choices and criteria. This analytical technique involves making pairwise comparisons between alternatives and project criteria. The conversion of qualitative data into quantitative information in ANP relies on a scale outlined by Saaty [9]. There are several stages in solving decision-making using the Analytical Network Process (ANP) technique which is implemented in the following manner:

1. Developing a network framework. The process of building the model relies on pre-existing issues, demanding a lucid depiction for structuring a network. It becomes essential to outline control benchmarks and referral criteria, facilitating the assessment of alternative options. Consequently, this phase facilitates the interconnection of individual elements.
2. Formulating a matrix for pairwise comparisons. Effective decision-making involves evaluating the significance of elements across various tiers. This evaluation leads to

the creation of a matrix A, where the value a_{ij} signifies the relative importance of each element. The comparison matrix is defined as follows:

$$A = \begin{pmatrix} \frac{W1}{W1} & \frac{W1}{W2} & \cdots & \frac{W1}{Wn} \\ \frac{W2}{W1} & \frac{W2}{W2} & \cdots & \frac{W2}{Wn} \\ \cdots & \frac{Wn}{W2} & \cdots & \frac{Wn}{Wn} \end{pmatrix} = \begin{pmatrix} 1 & a12 & \ldots & a1n \\ a21 & 1 & \ldots & a2n \\ an1 & an2 & \ldots & 1 \end{pmatrix} \quad (1)$$

3. Determining the weight of elements. When the comparisons between pairs are fully completed, the priority vector "w", also known as the eigenvector, is computed using the following equation:

$$\text{A}.w = \lambda\text{max}.w \quad (2)$$

4. Calculating the consistency ratio.

In the practical consistency matrix $\lambda max = n$, the Consistency Index (CI) is given as follows:

$$CI = \alpha max - n \quad (3)$$

If the results of the CI (Consistency Index) value have been obtained, the calculation of the consistency ratio can be found using the following formula:

$$CR = \frac{CI}{RI} \quad (4)$$

The requirement is for the CR figure to be below 10%, ensuring a consistent comparison between the two criteria. If the results go beyond ten percent, this indicates a lack of consistency in establishing the comparative significance between a pair of criteria. In such a situation, it can be affirmed that the ANP solution lacks meaningful interpretation for the researcher.

5. Creating a supermatrix.

The supermatrix emerges from priority rankings obtained by comparing clusters, criteria, and alternative options. This supermatrix comprises three main phases: the unweighted supermatrix, the weighted supermatrix, and the limiting supermatrix. The subsequent equation represents the unweighted supermatrix:

$$\begin{array}{cc} & \begin{array}{cccc} C1 & C2 & \ldots & Cn \end{array} \\ A = \begin{array}{c} \text{C1} \\ \text{C2} \\ \text{C3} \end{array} & \begin{bmatrix} a_{11} & a_{12} \cdots & a_{1n} \\ a_{12} & a_{22} \ldots & a_{2n} \\ a_{n1} & a_{n2} \cdots & a_{nn} \end{bmatrix} \end{array} \quad (5)$$

The weighted supermatrix is obtained by using the following the equation:

$$Ta = \begin{bmatrix} t_{11}^{\propto} & t_{1j}^{\propto} & t_{1n}^{\propto} \\ t_{i1}^{\propto} & t_{ij}^{\propto} & t_{in}^{\propto} \\ t_{n1}^{\propto} & t_{nj}^{\propto} & t_{nn}^{\propto} \end{bmatrix} \quad (6)$$

In Equation (6), the T matrix is combined with α and forms a new matrix, $T\alpha$. In addition, in the T matrix, if the value is less than α, the value will be reset to 0. Furthermore, Equation (7) is used to determine the number in each row.

$$c_i = \Sigma_{j=1}^{n} t_{ij}^{\propto} \quad (7)$$

Dividing the T∝ matrix by c_i will form a normalization matrix, Ts.

$$\text{Ts} = \begin{bmatrix} t^{\propto}_{11/d1} & t^{\propto}_{1j/d1} & t^{\propto}_{1n/d1} \\ t^{\propto}_{i1/di} & t^{\propto}_{ij/di} & t^{\propto}_{in/di} \\ t^{\propto}_{n1/d3} & t^{\propto}_{nj/d3} & t^{\propto}_{nn/d3} \end{bmatrix}$$
$$\text{Ts} = \begin{bmatrix} t^{s}_{11} & t^{s}_{1j} & t^{s}_{1n} \\ t^{s}_{i1} & t^{s}_{ij} & t^{s}_{in} \\ t^{s}_{n1} & t^{s}_{nj} & t^{s}_{nn} \end{bmatrix} \tag{8}$$

The result of this Ts matrix will be multiplied by matrix A, thus forming a weighted supermatrix (Aw).

$$\text{A}w = \begin{bmatrix} t^{s}_{11}\ x\ a_{11} & t^{s}_{1j}\ x\ a_{12} & \dots & t^{s}_{1n}\ x\ a_{1n} \\ t^{s}_{i1}\ x\ a_{12} & t^{s}_{ij}\ x\ a_{22} & \dots & t^{s}_{in}\ x\ a_{2n} \\ t^{s}_{n1}\ x\ a_{n1} & t^{s}_{nj}\ x\ a_{n2} & \dots & t^{s}_{nn}\ x\ a_{nn} \end{bmatrix} \tag{9}$$

When the weights in each column have the same value, the limiting supermatrix has been obtained.

$$\lim_{k \to \infty} W^{k}_{w} \tag{10}$$

The sustainable criteria in the supplier selection process utilizes these supermatrix equations to structure and analyze complex decision-making scenarios. The unweighted supermatrix, as shown in Equation (5), represents initial priority rankings without adjusting for the relative importance of the clusters. The transition to the weighted supermatrix, detailed in Equation (6), involves scaling the initial values by a factor α (alpha), ensuring that values below this threshold are set to zero. This scaling reflects the relative significance of each element within the matrix. Equation (7) calculates the sum of the weighted elements for normalization purposes. The resulting matrix Ts, as given in Equation (8), standardizes these values, preparing them for multiplication with the original matrix A to form the weighted supermatrix Aw in Equation (9). Finally, by iteratively applying these weights, the limiting supermatrix is obtained, as indicated in Equation (10), where all columns converge to uniform weights, signifying a stable state in the decision-making process. This comprehensive approach ensures that the most sustainable supplier is selected based on a rigorous, multi-criteria decision analysis [49].

3.2. TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution)

The TOPSIS technique is utilized to handle problems that involve multiple criteria. As detailed by Marbun and Sinaga [50], this technique provides a solution by evaluating various choices in a specific problem context. These alternatives are assessed and ranked, with one being the most beneficial and another being the least desirable. In the TOPSIS methodology, alternatives are assessed based on how closely they resemble an ideal solution. The positive ideal solution represents the best possible values for all attributes, while the negative ideal solution embodies the worst values for each attribute. After evaluation, these alternatives act as benchmarks for decision-making, assisting in the selection of the optimal solution. This approach is commonly employed in real-world decision-making due to its simplicity, clarity, computational efficiency, and ability to evaluate the performance of different alternatives [47], and is outlined below.

a. Create a decision matrix

Decision-making X is based on m alternatives to be evaluated with n criteria. The decision matrix X can be seen below:

$$X = \begin{matrix} a1 \\ a2 \\ \vdots \\ am \end{matrix} \begin{pmatrix} x1 & x2 & \ldots xn1 \\ x11 & x12 & \ldots xn1 \\ x12 & x22 & \ldots xn2 \\ \vdots & \vdots & \vdots \\ xm1 & xm2 & \ldots xmn \end{pmatrix} \quad (11)$$

b. Create a normalized decision matrix
The equation used to transform each element Xij is:

$$rij = \frac{Xij}{\sqrt{\sum_{i=1}^{m} X^2 ij}} \quad (12)$$

with i = 1,2,3 . . . , m: and j = 1,2,3 . . . , n.

c. Create a weighted normalized decision matrix

With weight wi = (w1, w2, w3, . . . , wn), where w_j is the weight of the jth value and $\sum_{i=1}^{n} wj$ =1, then normalize the weight matrix V as follows:

$$\text{Vij} = \text{Wi} \times r_{ij} \quad (13)$$

d. Determine the value of positive ideal solutions and negative ideal solutions. The positive ideal solution is denoted A+ while the negative ideal solution is denoted A. The equation for determining the ideal solution can be seen as follows:

$$A+ = (y1+, y2+, \ldots\ldots yn+) \quad (14)$$

$$A- = (y1-, y2-, \ldots\ldots\ldots yn-) \quad (15)$$

e. Determine the distance between the value of each alternative with the positive ideal matrix and the negative ideal solution matrix which can be referred to as the separation measure. The following is the mathematical equation of S^+ and S.
The distance of alternative Si+ to the positive ideal solution is formulated as:

$$Si^+ = \sqrt{\sum_j^n = 1\left(v_{ij} - v_j^+\right)} \quad (16)$$

The distance of alternative Si^- to the negative ideal solution is formulated as:

$$Si^- = \sqrt{\sum_j^n = 1\left(v_{ij} - v_j^-\right)} \quad (17)$$

f. Calculate the preference value of each alternative The preference value of each alternative can be calculated with the equation:

$$Ci^+ = \frac{Si^-}{\left(Si^- + Si^+\right)} \quad (18)$$

Ranking supplier alternatives. Each alternative starts from the largest C^+ to the smallest. The alternative that has the largest C^+ value is the alternative that has the best solution.

In the context of sustainable supplier selection, we integrate these mathematical formulations into a systematic decision-making process. Initially, we create a decision matrix X where mmm alternatives are evaluated against n criteria. This matrix captures the performance of each supplier across the specified criteria. To facilitate comparison, we normalize this decision matrix using Equation (12), transforming each element Xij into a dimensionless value rij. The next step involves constructing a weighted normalized decision matrix V by multiplying the normalized values rij with their respective criteria weights wj, as shown in Equation (13). This weighted matrix reflects the relative importance of each criterion in the decision-making process. Subsequently, we identify the positive ideal solution A+ and the negative ideal solution A− using Equations (14) and (15), representing the best and worst possible values for each criterion, respectively. To evaluate each supplier's performance, we calculate the separation measures Si^{+} and Si^{-} from these ideal solutions using Equations (16) and (17). These measures quantify the distance of each supplier from the optimal and worst scenarios. Finally, we determine the preference value Ci^{+} for each alternative using Equation (18), which provides a composite score indicating the relative desirability of each supplier. The suppliers are then ranked based on their Ci^{+} values, with the highest value indicating the most suitable supplier according to the sustainable criteria. This method ensures a comprehensive and objective evaluation of suppliers, aligning the selection process with sustainability goals [51].

4. Discussion

4.1. Criterion Relationship Results

Following the completion of the questionnaire, a set of 17 sub-criteria was derived from interviews and prior research. The determination of the number of sub-criteria resulted from applying the cut-off point method, which aims to streamline or minimize less significant criteria. The acquired data serves the purpose of establishing connections between criteria and sub-criteria. These connections culminate in a linkage network, forming the foundation of an Analytic Network Process (ANP) model. The primary objective of this model is to facilitate a comparative analysis of the criteria employed as indicators for supplier assessment. In this methodology, the identification of linkage relationships is imperative. The ANP linkage relationship model employs clusters and nodes, as delineated in Table 4. The table explicates relationships between sub-criteria in terms of influence and being influenced. Interactions among criteria exist both within clusters and between clusters. For instance, within the economic criteria cluster, the level of product defects (Ek2) maintains a relationship with the warranty and claims sub-criteria (Ek7), exemplifying an intra-cluster relationship. Conversely, the sub-criteria of smooth communication (So3) and on-time delivery (Ek5) exhibit an inter-cluster relationship.

Table 4. The ANP linkage relationship between criteria and sub-criteria.

Criteria		**Economy (E)**							**Social (S)**						**Environment (L)**			
		E1	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**S1**	**S2**	**S3**	**S4**	**S7**	**S8**	**L1**	**L2**	**L3**	**L4**
Economy (E)	E1		√	√	√		√								√			
	E2						√	√	√		√	√			√	√		√
	E3	√					√											
	E4	√				√			√		√							
	E5				√		√		√	√	√	√	√					
	E6	√	√	√		√		√	√	√	√	√	√	√	√			√
	E7		√				√		√		√			√	√			

Table 4. *Cont.*

Criteria		**Economy (E)**							**Social (S)**						**Environment (L)**			
		E1	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**S1**	**S2**	**S3**	**S4**	**S7**	**S8**	**L1**	**L2**	**L3**	**L4**
Social (S)	S1	√			√	√	√	√		√	√	√	√	√	√	√		
	S2		√				√		√		√	√	√	√			√	
	S3		√		√	√	√			√								√
	S4		√			√	√		√	√	√			√				
	S7						√		√					√			√	
	S8										√	√	√					
Environment (L)	L1	√						√	√	√						√	√	√
	L2		√						√						√			√
	L3														√			√
	L4		√					√					√			√		

Based on the analysis of the connection between sub-criteria within the evaluation of supplier performance, three distinct types of relationships have been identified: inner dependence, outer dependence, and feedback. The inner dependence relationship pertains to the connection among elements within the same cluster. For instance, within the economic aspect (illustrated in Table 4), an inner dependence exists between price and discount in each cluster. The outer dependence relationship refers to the linkages between elements located in separate clusters. Conversely, feedback represents a mutual relationship connecting one cluster to another. An example is seen in each cluster, where the economic cluster influences the social cluster and vice versa. Following the pairwise comparisons conducted on all criteria and sub-criteria involving three participants, the subsequent step involves aggregating the values from these comparisons. To integrate these values into the super decision software, a single value is needed. However, since the three respondents have provided diverse inputs, it becomes necessary to calculate the geometric mean manually using Microsoft Excel (https://www.microsoft.com/zh-hk/microsoft-365/excel?market=hk accessed on 17 April 2024). This process is demonstrated in Table 5.

Table 5. Geometric mean.

Criteria	**Sub Criteria 1**	**Sub Criteria 2**	**R1**	**R2**	**R3**	**G-Mean**
Economic	Price	Product defect rate	2	3	4	2.884
		Discount on quantity	1	2	2	1.587
		Distance	2	2	2	2.000
		On-time delivery	1	3	3	2.080
		Consistent quality	3	2	1	1.817
		Warranty and claims	2	0.50	2	1.260
	Product defect rate	Discount on quantity	2	2	3	2.289
		Distance	1	2	3	1.817
		On-time delivery	2	1	2	1.587
		Consistent quality	0.50	2	4	1.587
		Warranty and claims	1	4	3	2.289
		Discount on quantity	2	2	3	2.289

Table 5. *Cont.*

Criteria	Sub Criteria 1	Sub Criteria 2	R1	R2	R3	G-Mean
Economic	Discount on quantity	Distance	2	1	1	1.260
		On-time delivery	1	2	2	1.587
		Consistent quality	3	1	0.50	1.145
		Warranty and claims	2	0.33	1	0.874
	Distance	On-time delivery	0.50	2	2	1.260
		Consistent quality	2	1	0.50	1.000
		Warranty and claims	1	0.33	1	0.693
	On-time delivery	Consistent quality	0.33	2	3	1.260
		Warranty and claims	0.50	4	2	1.587
	Consistent quality	Warranty and claims	2	3	0.50	1.442
Social	Workforce competency	Labor satisfaction	3	1	2	1.817
		Communication fluency	0.50	4	2	1.587
		Flexible work arrangements	3	0.50	2	1.442
		Use of safety equipment	2	0.50	2	1.260
		Compliance with labor regulations	3	0.33	2	1.260
	Labor satisfaction	Communication fluency	2	4	3	2.884
		Flexible work arrangements	1	0.50	1	0.794
		Use of safety equipment	2	2	4	2.520
		Compliance with labor regulation	1	3	3	2.080
	Communication fluency	Flexible work arrangements	2	3	4	2.621
		Use of safety equipment	1	3	0.50	1.145
		Compliance with labor regulations	2	2	1	1.587
	Flexible work arrangement	Use of safety equipment	2	1	4	2.000
		Compliance with labor regulations	1	2	2	1.587
	Use of safety equipment	Compliance with labor regulations	2	0.50	2	1.260
Environment	Friendly materials environment	Recycling potential	1	2	0.50	1.000
		Eco-friendly certification	2	0.50	1	1.0000
		Waste	0.50	2	2	1.260
	Recycling potential	Eco-friendly certification	2	0.33	2	1.101
		Waste	2	0.33	1	0.874
	Friendly certification environment	Waste	1	1	0.50	0.794

Table 6 shows that the highest weight is in the price sub-criteria with a weight of 0.0922 followed by consistent quality with a weight of 0.083, and the lowest weight value is in the labor satisfaction sub-criteria with a weight of 0.012.

The most significant emphasis is placed on the economic factor, serving as a pivotal measure for supplier evaluation. In an earlier study by Luthra et al. [43], environmental factors held the greatest importance due to their heightened priority in terms of costs. In contrast, our research assigns secondary significance to the environment, following economic criteria. This is rooted in the fundamental notion that economic considerations consistently take precedence in supplier selection, as asserted by Chaharsooghi and Ashrafi [44]. Moreover, social criteria are equally integral, given the inherent interconnectedness of all three indicators. Upon entering the questionnaire responses into the system and analyzing their correlation, the disparity score for individual sub-criteria within each aspect/criterion becomes apparent. When the disparity score registers below 0.1, it is possible to deduce that the questionnaire responses exhibit coherence. Table 7 shows the inconsistency value for each sub-criterion.

Table 6. The ANP model weighting.

Criteria	Code	Sub-Criteria	Final Priority Weight	Cluster Normalized Priority Weight
Economy (0.0652)	E1	1. Price	0.0922	0.2695
	E2	2. Product defect rate	0.0418	0.1221
	E3	3. Discount on quantity	0.0293	0.0856
	E4	4. Distance	0.0229	0.0669
	E5	5. Timely delivery	0.0820	0.0447
	E6	6. Consistent quality	0.0832	0.2430
	E7	7. Warranty and claims	0.0576	0.1682
Social (0.0343)	S1	1. Labor competency	0.0862	0.3137
	S2	2. Labor satisfaction	0.0127	0.0463
	S3	3. Smoothness of communication	0.0425	0.1545
	S4	4. Flexible work arrangements	0.0232	0.0843
	S7	7. Use of safety equipment	0.0284	0.103
	S8	8. Compliance with labor regulations	0.0153	0.2979
Environment (0.0503)	L1	1. Environmentally friendly materials	0.0568	0.2440
	L2	2. Recycling potential	0.0747	0.3205
	L3	3. Eco-friendly certification	0.0380	0.1629
	L4	4. Waste	0.0635	0.2725

Table 7. The ANP linkage and inconsistency value.

Criteria	Code	Linkage Relationship	Inconsistency Value
Economy	E1	E2, E3, E4, E5, E6, E7 L1, L2, L3, L4	0.0176 0.0454
	E2	E1, E3, E4, E5, E6 L1, L4 S1, S2, S3, S4, S7, S8	0.0195 0.0000 0.0350
	E3	E1, E2, E4, E5, E6	0.016
	E4	E1, E2, E3, E5, E6	0.0202
	E5	E1, E2, E3, E4, E7	0.0202
	E6	E1, E2, E3, E4, E5, E7 L1, L2, L3, L4 S1, S2, S3, S4, S7, S8	0.0184 0.0454 0.0357
	E7	E1, E2, E3, E4, E5, E6, L1, L2, L3, L4	0.0200 0.0454

Table 7. *Cont.*

Criteria	Code	Linkage Relationship	Inconsistency Value
Social	S1	E1, E2, E6 S2, S3, S4, S7, S8 L2, L4	0.0085 0.0000 0.0260
	S2	E2, E6 S1, S3, S4, S7, S8	0.0000 0.0326
	S3	E2, E6 S1, S2, S4, S7, S8	0.0000 0.0460
	S4	E2, E6 S1, S2, S3, S7, S8 L1, L2	0.0000 0.0530 0.0000
	S7	E2, E6 S1, S2, S3, S4, S8	0.0000 0.0270
	S8	E2, E6, E7 S1, S2, S3, S4, S7 L1, L2, L3, L4	0.0080 0.0454 0.027
Environment	L1	E1, E6, E7 L2, L3, L4	0.051 0.051
	L2	E1, E2, E6, E7 S1, S4, S8	0.026 0.051
	L3	E1, E6, E7 L1, L2, L4 S4, S8	0.051 0.051 0.000
	L4	E1, E2, E6, E7 L1, L2, L3 S1, S8	0.026 0.051 0.000

4.2. Network-Based ANP Model

The majority of contemporary studies aimed at tackling the intricate issue of sustainable supplier selection mainly concentrate on assessing suppliers based on three sustainability dimensions. Nevertheless, a significant drawback present in this research field is the use of evaluation criteria that are inherently broad, challenging to precisely measure, and fraught with differing levels of uncertainty. Consider, for example, factors like the presence of an "environmental management framework", the assessment of "environmental expenditures", or the dedication to "ethical commerce". These factors, as illuminated by the research of Govindan et al. [7], Luthra et al. [52], and Bai and Sarkis [17], respectively, pose formidable challenges when it comes to objective measurement and evaluation.

In contrast, our study has taken a different approach by strategically selecting indicators that lend themselves to accurate and straightforward measurement. We have predominantly relied on ratios that are commonly encountered within the context of supplier sustainability assessment. This pragmatic choice has allowed us to streamline the evaluation process, ensuring that our model can efficiently and effectively assess suppliers against sustainability criteria. Given this meticulous selection of easily measurable indicators, we conclude that the integration of the Analytic Network Process (ANP) method with fuzzy or rough set theory would not yield significant improvements to our model. While these advanced methodologies hold value in addressing complex and uncertain decision-making problems, their incorporation into our already precise and robust framework may not yield substantial benefits. Instead, our model's strength lies in its ability to provide a clear and straightforward means of sustainable supplier evaluation, making it a practical and effective tool for businesses striving to make responsible and sustainable supplier selections.

The subsequent content presents the outcomes of the criteria weighting process, which was conducted using the ANP method and finalized using the super decision software. As depicted in Table 1, the data processed through the super decision software is deemed consistent, as the inconsistency value for each criterion remains below 0.1. The ensuing section reveals the outcomes of the weighting procedure facilitated by the ANP method.

In Figure 1, we utilized the Analytic Network Process (ANP) method in conjunction with the powerful super decision software to undergo a comprehensive re-evaluation of criteria weights. This rigorous analysis has allowed us to gain a deeper understanding of the factors influencing our decision-making process.

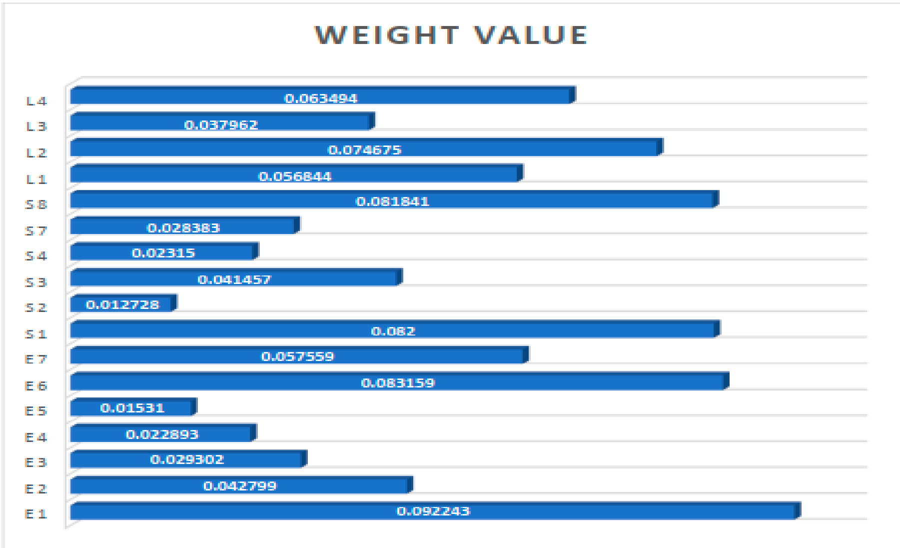

Figure 1. Recapitulation of ANP weight value results.

At the forefront of our considerations is the cost of raw materials, which commands the highest weight of 0.0922. This factor holds a pivotal role in our evaluations, as it directly impacts the economic aspects of our operations. Following closely behind, with substantial influence, are criteria such as consistent quality (0.083), labor proficiency (0.082), and adherence to labor regulations (0.081). These criteria underscore the significance of maintaining high standards in our production processes and ensuring compliance with labor-related legalities. Additionally, we must not overlook the importance of sustainability and responsible practices. Recycling potential (0.074), waste management (0.063), and the handling of warranty and claims (0.057) are critical aspects of our decision framework. These criteria highlight our commitment to environmental stewardship and customer satisfaction.

In the realm of materials and production, we also consider the utilization of environmentally friendly materials (0.0566) and product defect rate (0.042) as crucial factors. These underscore our dedication to sustainable sourcing and product excellence. Effective communication (0.0414) plays a pivotal role in our evaluation, ensuring that information flows seamlessly within our organization. Eco-friendly certification (0.037) also holds a noteworthy position, reflecting our commitment to meeting recognized environmental standards. In the realm of economics and logistics, we take into account quantity discounts (0.029) as a factor influencing our decisions. Safety equipment utilization (0.028) is another critical consideration to ensure the well-being of our workforce. Geographical distance (0.0228) and flexible work arrangements (0.021) have their roles in our decision-making process, reflecting the importance of location and workforce flexibility. Lastly, punctual delivery (0.0153) is a factor we consider carefully to meet customer expectations. Labor satisfaction (0.0127), while carrying the least weight, is not overlooked, as it is essential to maintaining a harmonious and productive work environment.

4.3. Prioritization of Alternative Suppliers Based on TOPSIS

Figure 2 serves as an illuminating visual depiction of the supplier performance preferences that have been meticulously derived through the rigorous TOPSIS evaluation methodology. This graphic offers a comprehensive insight into the comparative evaluation of four distinct suppliers, scupulously scrutinizing their performance across seventeen carefully chosen sub-criteria. In this visual representation, we observe that Supplier 2 undeniably emerges as the unrivaled frontrunner, showcasing an outstanding score of 73%. This remarkable score highlights their exceptional performance in meeting the specified sub-criteria, setting them apart as the preferred choice among the suppliers under assessment. The compelling data presented in Figure 2 underscores the robustness of Supplier 2's performance across the spectrum of evaluated criteria. It is evident that their consistent excellence in addressing these sub-criteria positions them as the supplier of choice, reaffirming their status as a valuable partner for our organization. This visual representation not only simplifies the complex evaluation process but also reinforces the importance of supplier performance in our decision-making processes.

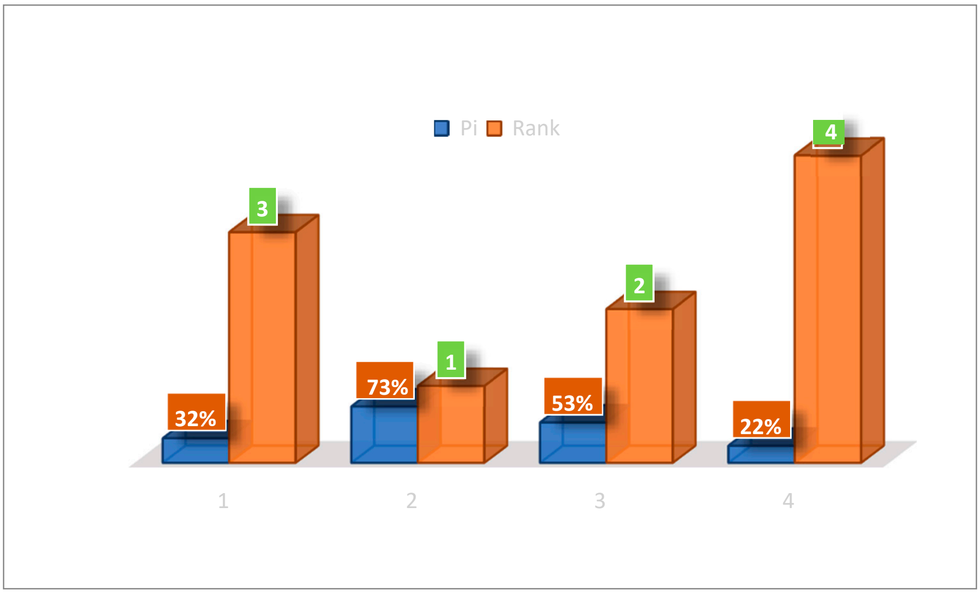

Figure 2. Ranking with TOPSIS.

In the intricate landscape of supplier performance evaluation, the data depicted in Figure 2 serves as a valuable compass, guiding decision-makers toward optimal supplier selection and strategic procurement decisions. The meticulous examination of these seventeen sub-criteria has unveiled Supplier 2 as the pinnacle of performance excellence, a testament to their commitment to quality and efficiency.

Figure 2 not only illustrates the selection of sustainable suppliers but also highlights the effectiveness of the proposed method in achieving remarkable outcomes. It becomes evident that Supplier 2 emerges as a standout performer, showcasing a multitude of sustainable criteria already encompassed within a single supplier. This is a testament to the robustness of our approach in identifying and fostering partnerships with suppliers who not only meet but exceed sustainability expectations. The comprehensive range of sustainable practices embodied by Supplier 2 underscores the potential for long-term collaboration and mutual benefits that can be harnessed through strategic supplier selection.

These findings underscore the importance of a thorough and data-driven supplier assessment process, providing stakeholders with actionable insights for enhancing supply chain efficiency, reducing risks, and ultimately bolstering organizational success. In the ever-evolving realm of supplier management, the prominence of Supplier 2 in Figure 2 serves as a beacon of excellence to emulate and a foundation upon which to build lasting and mutually beneficial supplier relationships. One of the primary benefits of a data-driven supplier assessment process is the enhancement of supply chain efficiency [53]. By identifying underperforming suppliers or bottlenecks in the supply chain, organizations can take targeted actions to streamline operations and reduce costs. As an illustration, when data indicates that a specific supplier consistently fails to meet delivery deadlines, organizations have two options: they can collaborate with the supplier to enhance their performance or explore other supplier options to guarantee on-time deliveries. Moreover, this approach also contributes significantly to risk mitigation. With real-time data on supplier performance and compliance, companies can proactively identify potential risks, such as supply disruptions, quality issues, or regulatory violations [54]. This allows for the development of contingency plans and risk mitigation strategies, ultimately safeguarding the organization's operations and reputation.

4.4. Comparison between the ANP and TOPSIS Methods Based on the Results

The Analytic Network Process (ANP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methods offer distinct approaches for evaluating supplier performance, each with its strengths. ANP, combined with super decision software, allows for a detailed weighting of criteria, ensuring consistency and precision in the evaluation process. For example, the highest weight in the ANP evaluation was assigned to the cost of raw materials (0.0922), highlighting its critical impact on economic considerations. Other significant criteria included consistent quality (0.083), labor proficiency (0.082), and adherence to labor regulations (0.081). This method emphasizes a comprehensive understanding of various factors influencing decision-making, including sustainability aspects like recycling potential and waste management. In contrast, the TOPSIS method provides a straightforward comparison of suppliers by calculating their relative performance against an ideal solution [55]. The results, depicted in Figure 2, revealed Supplier 2 as the top performer with a score of 73%, demonstrating its exceptional ability to meet sustainability and performance criteria. TOPSIS's visual representation simplifies complex evaluations, making it easier for decision-makers to identify the best supplier based on a range of sub-criteria. While ANP offers a nuanced and detailed assessment through precise criteria weighting, TOPSIS excels in providing a clear and direct comparison of suppliers, highlighting their overall performance [56]. Both methods underscore the importance of a data-driven approach in supplier evaluation, but their applications differ based on the need for detailed analysis versus straightforward performance ranking [57].

4.5. Managerial and Theoretical Implications

Based on our previous discussions, it is crucial that we further explore the practical implications of our findings for the company. Our research highlights a pressing need for a fundamental change in our supplier selection criteria. Traditionally, we have primarily focused on factors like proximity and product quality, while overlooking vital sustainability aspects. The core of our proposed transformation centers on embracing a comprehensive and forward-looking perspective. We recommend organizing sustainable criteria into three key dimensions: economic, social, and environmental, to guide our supplier selection process effectively.

From the supplier perspective, economic sustainability in procurement entails a multifaceted approach to supplier evaluation. Beyond simply focusing on initial costs, it involves a broader perspective that factors in long-term cost-effectiveness. This includes considering elements such as lifetime costs, ongoing maintenance expenses, and the potential savings that can be achieved through sustainable practices over time [58]. Additionally, economic sustainability also encompasses the ability of suppliers to innovate and adapt to ever-evolving market trends and sustainability standards. Miceli, Hagen, Riccardi, Sotti, and Settembre-Blundo [59] and Amankou et al. [21] believed that this evaluation extends to their commitment to research and development in sustainable technologies, ensuring that they remain agile and responsive to the changing demands of a sustainable future. Moreover, social sustainability is a critical facet of responsible business practices, encompassing various dimensions. One crucial aspect involves monitoring labor practices within the supply chain, with a focus on ensuring fair employment standards [60]. This includes upholding principles of equal opportunity employment, maintaining safe and healthy working conditions, and providing fair wages to workers. Additionally, social sustainability extends to evaluating a supplier's commitment to community engagement. Businesses should assess their suppliers' involvement in local communities, philanthropic efforts, and the broader impact they have on the social fabric of their respective regions. Ratten and Babiak [61] argued that by addressing these key considerations, companies can contribute to a more socially sustainable and equitable global business environment.

The study emphasizes the critical importance of environmental sustainability in the supplier selection process. It outlines several key aspects that are evaluated to ensure that suppliers align with sustainability goals. These aspects include resource efficiency, carbon footprint measurement, sustainable materials, and production methods, as well as recycling and waste reduction practices. By incorporating these criteria into supplier selection, the organization not only reduces its environmental impact but also contributes positively to society. This approach demonstrates a commitment to corporate responsibility and positions the company favorably in an eco-conscious market, emphasizing environmental stewardship and alignment with sustainability objectives. The manufacturing industry could apply some strategies for environmental issues such as resource efficiency evaluation. Implementing a comprehensive assessment of potential suppliers to gauge their resource efficiency has been proven as an effective way for suppliers to apply sustainable criteria [62]. This assessment should encompass practices related to energy consumption, waste reduction, and water resource conservation. Suppliers with strong resource-efficient practices should be given preference.

From a theoretical perspective, this study goes beyond the traditional idea of endorsing a one-size-fits-all strategy, in which companies vigorously strive for excellence in all aspects of sustainability throughout their supplier network. Although the ideal scenario does envision such a comprehensive commitment, the harsh realities of the business world place specific constraints, particularly in terms of financial limitations and limited resources. The limitations imposed by practical considerations consistently compel decision-makers to make thoughtful selections, focusing their efforts on sustainability aspects that deliver immediate and measurable results. Giannakis et al. [4] believed that these chosen dimensions include, foremost, the critical task of evaluating and mitigating the risks stemming from suppliers' poor performance in the realm of social responsibility. Taking a proactive approach is crucial, not just to protect a company's image but also to guarantee ethical and fair business practices across the entire supply chain. Additionally, decision-makers are strongly encouraged to prioritize short-term economic considerations just as diligently [63]. This includes a prudent emphasis on minimizing turnover rates, which can significantly impact the stability and effectiveness of the supply chain. Equally important is the need to decrease expenses related to waste operations. This not only enhances a company's cost-effectiveness but also supports broader sustainability objectives by reducing the environmental impact of its activities.

This study calls for a paradigm shift in sustainable supplier selection methodologies. It encourages decision-makers to move beyond the limitations of isolated evaluations and vague metrics, opting instead for a methodological approach that appreciates and accounts for the intricate tapestry of interrelationships within sustainability metrics. The adoption of the ANP method, in this context, promises to be a transformative step towards a more sustainable and responsible supply chain management strategy. While the body of existing literature has made significant strides in the realm of sustainable supplier selection and performance evaluation, recurring limitations remains. Many studies continue to evaluate these criteria in isolation, neglecting the dynamic relationships that exist between them. Moreover, a common issue is the utilization of sustainability metrics that are often limited in scope and laden with ambiguity [64], thus lacking a comprehensive set of objectives.

This approach limits the holistic understanding of a supplier's sustainability performance, potentially leading to suboptimal choices in supplier selection. In contrast, the ANP approach advocated in this study offers a more nuanced and holistic perspective. By incorporating interdependencies among sustainability metrics, it provides decision-makers with a more accurate and comprehensive view of a supplier's sustainability performance. This, in turn, empowers organizations to make more informed choices when selecting suppliers and aligning their procurement strategies with broader sustainability goals.

5. Conclusions

In conclusion, this research has successfully integrated the ANP and TOPSIS methods to enhance the process of selecting sustainable suppliers. The study initially identified 21 sub-criteria, but through rigorous analysis, it narrowed these down to 17 essential sub-criteria, spanning economic, environmental, and social dimensions. Economic criteria emerged as the most crucial, followed by environmental and social considerations, underscoring the importance of a well-rounded approach to supplier selection. Despite its achievements, this research acknowledges limitations in the scope of criteria and sub-criteria defined by the company. To address these limitations, future studies could benefit from engaging in focus group discussions to refine the selection criteria further. Additionally, opportunities exist to enhance the ANP–TOPSIS method by incorporating complementary approaches for more robust solutions.

From a managerial perspective, this study underscores the importance of continuous skill development for staff involved in supplier selection and the need for policies that facilitate meaningful interaction between buyers and suppliers. These findings offer valuable insights for policymakers and practitioners seeking to improve supplier selection processes. Looking ahead, future research should focus on uncovering the optimal company-specific criteria and continually assessing and adapting these criteria to ensure the achievement of desired outcomes in sustainable supplier selection. This ongoing refinement and adaptation will be key to maintaining a competitive edge in a dynamic business environment driven by sustainability imperatives.

Future extensions of this study could explore the integration of product-specific services into the supplier selection framework, recognizing the increasing importance of service attributes alongside product quality. Additionally, international supplier selection based on tax implications offers a fertile area for research, as tax policies can significantly impact the overall cost-effectiveness and sustainability of global supply chains. By expanding the scope of supplier selection criteria to include these factors, future studies can provide more comprehensive and practical solutions for companies operating in an increasingly complex and interconnected global market.

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