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AN INTEGRATED MULTIPLE CRITERIA DECISION-MAKING MODEL FOR GREEN SUPPLIER SELECTION IN STEEL MANUFACTURING INDUSTRY: A CASE STUDY IN VIETNAM

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ABSTRACT

The problem of global warming caused by manufacturing activities has received a lot of attention recently. Along with an increasing worldwide awareness of the environment, green manufacturing is a major challenge for almost all companies and will determine a manufacturer's long-term sustainability. A performance evaluation method for green suppliers thus is critical for determining the potential of suppliers to collaborate with the company. Thus, multi- criteria decision-making (MCDM) models are a useful tool for resolving complicated selection problems involving multiple criteria and alternatives, especially in relation to qualitative factors. Thus, the author presents an MCDM model that combines the analytic hierarchy process (AHP) and the data envelopment analysis (DEA) approach to assess and choose the best green supplier in the steel manufacturing industry. The criteria are created for the evaluation of potential suppliers based on previous literature and expert interviews. The AHP model specifies the weight based on the opinion of an expert and the DEA is used to rank suppliers at a final stage. For criteria weighting results, "product cost", "supplier's reputation", "lead time", "warranty" and "green policies" with weights of 0.637, 0.669, 0.750, 0.731 and 0.512, respectively, were found as the most significant sub-criteria. The final ranking suggests GS-01 (KKC Metal JSC), GS-04 (Vnsteel-Vicasa JSC), GS-05 (Vietnam Germany Steel Pipe JSC), and GS-08 (Hoa Sen Group) are indicated to be the top four most suitable green suppliers. With the suggested approach, manufacturers can better understand the performance of their suppliers and can evaluate and choose the most appropriate green supplier for cooperation.

Keywords: Supplier's reputation; product cost; analytic hierarchy process; steel production; supply chain management.

1. INTRODUCTION

"As Vietnam's economy improves and people's living standards rise, the demand for steel in industries such as buildings, transportation, and household appliances is also increasing. The rapid growth of steel demand has attracted many steel companies to invest in new

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steel production facilities in Vietnam. Therefore, selecting the proper supplier is essential for businesses at this time" [1]. "The necessity for a firm to engage closely with its supply chain partners to enhance its business operations is increasingly recognized. The selection of providers is one of the most important components of the buying function, which is crucial for improving competitiveness and customer satisfaction in an organization" [2]. "With increased government regulation and public awareness of environmental preservation, businesses cannot afford to disregard environmental concerns if they want to compete in the global market. Firms must implement plans to voluntarily minimize the environmental consequences of their goods. In certain countries, environmental regulations apply to the sale of items. A pressing matter in business" today is the combination of environmental, economic, and social performance to achieve sustainable development [3]. Hence, today many businesses and organizations are paying close attention to green practices in order to gain a competitive edge in the global marketplace [4].

However, green supply management is not widely implemented, and awareness of environmental sustainability principles related to supply chain management (SCM) operations remains limited [5]. Therefore, further study is needed to determine how firms conduct green supplier selection while considering both environmental and economic factors [6]. Despite the rising interest in green SCM, most existing research focuses on decision-making approaches involving complex mathematical computational models in the supplier selection problem [7]. "Decision-making is based on supplier estimates by using quantitative and qualitative criteria. Choosing the supplier can require searching for a new supplier or selecting from available providers. As a result, businesses should use the appropriate supplier selection model to find the proper partners and keep their competitive advantage through the globalization process" [1]. "Multi-criteria decision-making (MCDM) is a useful tool for resolving complicated selection problems with numerous criteria and alternatives, particularly for qualitative factors. Qualitative criteria frequently contain ambiguous features that are difficult to describe precisely, making it difficult to synthesize evaluation findings. The MCDM approach will assist decision-makers to define qualitative criteria, determine the overall score of the assessment subjects based on the weight of each criterion, and provide a more reliable foundation for selections" [8].

In this study, an MCDM framework is proposed using a combination of the analytic hierarchy process (AHP) and the data envelopment analysis (DEA) model to find the best suitable provider among 10 potential suppliers in Viet Nam for the steel manufacturing industry. To explain, the authors intend to use the AHP method in the first stage to rate the selected criteria and the various alternatives (suppliers) but the selection of numerous providers is practically limited due to the number of pairwise comparisons being conducted, and a disadvantage of the AHP method is that the input data depends on subjective opinions through the experience of experts. Thus, DEA analysis is proposed to rank the suppliers in the final stage. In addition, the DEA is provided to confirm the results as a systematic approach and to address the shortcomings of the AHP model as previously indicated. In the first step, the weights of five specified evaluation criteria (price, quality, delivery, service, environment criteria) and 15 sub-criteria affecting the supplier selection were established and used to prioritize the suppliers by ranking their final weights. In step 2, DEA analysis is conducted based on three inputs including total asset, liability, and operating expenses, while profit and AHP model findings are applied as the quality benefits of the DEA's output factor for various suppliers. For this purpose, Charnes–Cooper–Rhodes (CCR) and Banker–Charnes–Cooper (BCC), the slacks-based measure (SBM) model, and the epsilon-based measure (EBM) model in DEA, were proposed.

Hence, the major contribution of this study is the development of an MCDM approach for selecting green suppliers in the steel manufacturing industry. After analyzing businesses' requirements in supplier selection, the study provides the main criteria and sub-criteria for green supplier selection, which can assist organizations in identifying weak areas for improving green suppliers. The suggested method provides a framework for combining cost, quality, delivery, service, and environment criteria to reflect actual the needs of green supplier selection. This helps to reduce the potential risk of choosing the wrong provider. To our knowledge, the research that investigates the issue of choosing green suppliers for steel manufacturers is still limited, so the authors want to expand the scope of the study by integrating AHP and DEA models. Moreover, there have been no previous studies investigating the issue of green supplier selection for steel manufacturers in Vietnam using an approach integrating AHP and DEA models. The proposed approach has been effectively implemented in a case where a company selected the best green supplier and analyzed the most suitable alternative green supplier. The findings of this study will help managers understand the nature of green supplier selection criteria. Besides, the suggested approach has the potential to be extensively employed as a structural model for selecting green suppliers.

The remainder of this paper is organized as follows. In section 2, an overview of the literature is presented. Analytic hierarchy process (AHP), DEA models (BBC, CCR, SBM, EBM) are explained in Section 3. A case study of Viet Nam is demonstrated in section 4. Section 5 contains the results and discussion. Finally, the conclusions and future work are discussed in the last section.

2. LITERATURE REVIEW

In the present business environment, purchasing is essential to determine a product's value-added content and to ensure the profitability and survival of a firm. When environmental concerns are included, the purchase process becomes more difficult. This is because, in addition to traditional criteria such as prices, quality, lead-time, and flexibility, green purchasing must include the supplier's environmental responsibilities. Environmental compliance-focused supplier management is insufficient; a more proactive plan is needed. The literature included studies that evaluate many individual modeling approaches to solve MCDM problems in the area of green supplier selection such as analytic hierarchy process (AHP), analytic network process (ANP), mathematical programming, and other techniques as the fuzzy multi-agent decision-making, the fuzzy inference method [9-13]. MCDM methods are effective tools in supplier selection problems because they consider multiple conflicting criteria and decision-maker preferences. For example, Boran et al. [14] used the TOPSIS method in combination with an intuitionistic fuzzy set to pick a respective provider in group decisions. Parkouhi et al. [15] proposed "the fuzzy analytic network process (FANP) and VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR) strategies for selecting suppliers". As an example of Khouzestan Steel business, Javad et al. [16] used the best-worst method (BWM) and fuzzy TOPSIS to choose green suppliers for particular steel industries. Guo and Tsai [17] investigated the criteria for assessing green suppliers using the decision-making trial and evaluation laboratory (DEMATEL). Kuo et al. [18] explored a combination of artificial neural networks (ANN), multi-attribute decision analysis (MADA), data envelopment analysis (DEA), and ANP to evaluate the performance of a green supplier. Kuo and Lin [19] used an integrated ANP and DEA technique to evaluate green suppliers. Users can use this technique to limit weights according to their own weight criteria. The fuzzy TOPSIS is an evaluation approach based on a range of criteria. The fuzzy TOPSIS is an approach for evaluating alternative providers based on a set of criteria. Boran et al. [14,20,21] are among the notable researchers that used the fuzzy TOPSIS to solve supplier selection difficulties. Yan [22] proposed an integrated strategy to assess and select the use of the genetic algorithm and AHP for green suppliers. The integrated modified model TOPSIS, BMW, and FMOLP was developed by Lo et al. [23] to resolve difficulties with green selection and order assignment in a small electronic business. Entezaminia et al. [24] laid down a multi-objective approach to deal with the problems of green supply chain planning multi-product, multi-term and multi-site aggregations. Environmental impact reduction measures have been developed as a new competitive tool for companies seeking to improve their reputation and market competitiveness. By using a green provider evaluation approach, organizations can identify critical factors that improve supply chain sustainability. Also, managers can choose and evaluate the most sustainable supplier performance. This study recognizes the importance of selecting suppliers and is the first effort to develop a framework for the green supplier selection of Vietnam's steel company. In this study, we offer a two-stage approach on supplier selection in Vietnam using AHP and DEA techniques, depending on the green capabilities of suppliers.

Since its creation, the analytic hierarchy process is an efficient tool for policymakers and researchers and is one of the MCDM most commonly utilized [25]. AHP has been applied in various fields such as planning, choosing the best alternatives, resource allocations, optimization, etc., as well as digital extensions of AHP [26]. For the green supplier selection problem, AHP is a prominent MCDM approach that has been used in various studies. For example, Asamoah et al. [27] used the AHP technique to evaluate and choose suppliers at a pharmaceutical manufacturing business in Ghana. Chucheep et al. [28] used AHP to choose the optimum replacement brush cutter blades. For the green supplier selection problem, Humphreys et al. [29] used AHP to assess different providers' relative importance and performance concerning environmental variables. A knowledge-based decision support system was then built up to include environmental issues in the selection process for the supplier. Humphreys, et al. [30] presented a hierarchical fuzzy system with scalable fuzzy membership functions that are supported by the incorporation of environmental characteristics to choose suppliers. Using fuzzy AHP, Lu et al. [31] developed the green supply chain management multi-objective decision-making method for managers to assess and measure supply chain management's success. But most of the above studies focused only on environmental factors and neglected other crucial non-environmental aspects. In a complete green supplier selection model, all traditional considerations, as well as environmental concerns, must be considered to identify the most potential supplier who excels in all critical respects. Therefore, a suitable green supplier selection model is proposed in this research.

DEA is a method for mathematical programming to assess the relative efficiency of various decision-making units (DMUs) with different inputs and outputs. Charnes et al. [32] created the first DEA model, often used in decision-making issues [33]. The two most well-known models in supplier selection are provided in DEA, CCR, and BCC. Banker, Charnes, and Cooper (BCC) developed the BCC model, which is an improved version of the CCR model [34]. The objective of the CCR model is to detect general inefficiency and to differentiate scale and technique from the BCC model. In 2001, Tone created a slack-based measure (SBM) of DEA efficiency [35]. The SBM explicitly deals with the input excess and output deficit, as opposed to the CCR and BCC stages, which rely on the proportional reduction of input vectors. In 2010, the epsilon-based measure (EBM) model was developed by K. Tone and Tsutsui to address the problem of radial and non-radial variation in input and output variables [36]. For supplier selection problems, the DEA has been utilized to prioritize the nominated supplier as a reliable optimization technique. For example, Wu [37] provided a hybrid approach that includes data envelopment analysis, decision trees (DTs), and neural networks (NNs). Toloo [38] suggested the most effective supplier of new integrated DEA models when cardinal and ordinal data are available. Hasan et al. [39] proposed the synergistic integration of two technologies, the ANP and DEA in a multi-phase supplier selection approach. In this study, the DEA is used to aggregate data to provide ratings of providers. In addition, DEA is also widely used in the selection of green suppliers. For example, Dobos and Vörösmarty [40] used a combination of DEA and an integrated indicator technique to rank green suppliers based on their long-term performance indicators. Wen and Chi [41] used DEA in the assessment process to ensure that the suggested approach could handle the bigger size problem. The authors attempt to overcome the method's limitations and present a thorough guide to green supplier selection problems.

3. METHODOLOGY

3.1 Analytic Hierarchy Process (AHP)

The analytical hierarchy process (AHP) was originally established by Saaty [42]. “It is a method designed to quantify managerial assessments of the relative relevance of each of several independent criteria employed in the decision-making process. In this approach, a comparison matrix for each level of the hierarchy is used to establish priorities using a relative scale of relevance as indicated in Table 1” [43].

Table 1. Scale of relative significance

Intensity of importance	**Definition**
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values

The step-by-step process of AHP is as follows:

- Step 1: List the general goal, criteria, decision options, and establish the hierarchical tree as Fig. 1 below:

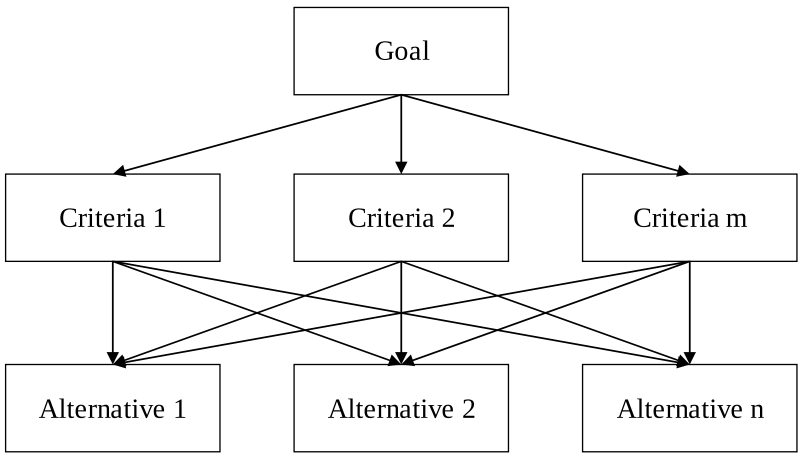

Fig. 1. A structure of the hierarchical tree

- Step 2: Create matrices for pairwise comparisons.

In the pairwise comparison matrix, the significant level of criteria and sub-criteria are assessed by experts. There are k rows and k columns in the k-by-k matrix. The a_{ij} element indicates the relative meaning of the index row i in comparison to the index column j.

$$A = (a_{ij})_{k\times k} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1k} \\ a_{21} & 1 & \cdots & a_{2k} \\ \vdots & \vdots & \vdots & \vdots \\ a_{k1} & a_{k2} & \cdots & 1 \end{bmatrix} \quad (1)$$

- Step 3: Create normalized matrices.

Divide each number in a matrix column by the total column.

- Step 4: Create a priority vector.

Averages row values in the normalized matrix are the priority vector (*f*).

- Step 5: Determine consistency ratio.

In this step, the appropriate priorities are given by the priority vector (*f*) that matches the largest eigenvalue (λ_{max}).

$$[A]f = \lambda_{max} f \quad (2)$$

The consistency index (*CI*) is calculated using the eigenvector with the largest eigenvalue (λ_{max})and the number of criteria (*n*).

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

The consistency ratio (*CR*) is calculated by dividing the consistency index (*CI*) and the random index (*RI*), i.e., as shown in Table 2.

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

If $CR \le 0.1$, the findings are good. Otherwise, the pairwise comparison matrix must be reconsidered.

- Step 6: Calculate the total weight of the objective function.

$$Function\ 1 = F_{11} \times w_1 + F_{12} \times w_2 + \cdots + F_{1u} \times w_u$$

$$Function\ v = F_{v1} \times w_1 + F_{v2} \times w_2 + \cdots + F_{vu} \times w_u \quad (5)$$

where w_u stands weight of *u-th* criteria, F_{vu} stands weight of *v-th* item according to u-th criteria.

3.2 Data Envelopment Analysis (DEA)

The mathematical models of the data envelopment (DEA), including CCR-I, BCC-I, SBM-I-C, and EBM-I-C, are presented in this section. The list of the symbols and annotation utilized in the model, which are described as follows:

n: number of decision-making units (DMUs)

DMU*i*: the *i-th* DMU, $i = 1, 2, \dots, n$

DMU*0*: the DMU target

$a_0 = (a_{01}, a_{02}, \dots, a_{0p})$: input vector of DMU*0*
$b_0 = (b_{01}, b_{02}, \dots, b_{0q})$: output vector of DMU*0*
$a_i = (a_{i1}, a_{i2}, \dots, a_{ip})$: input vector of DMU*i*, $i = 1, 2, \dots, n$
$b_i = (b_{i1}, b_{i2}, \dots, b_{iq})$: output vector of DMU*i*, $i = 1, 2, \dots, n$
$u \in R^{p\times 1}$: weight-input vector
$v \in R^{q\times 1}$: weight-output vector

3.2.1 Charnes-Cooper-Rhodes Model (CCR)

The CCR model is the first DEA model, and it is specified as follows [44-46]. The multiplier model of the CCR input-oriented (CCR-I) is shown as follows.

$$Max\,\gamma = \sum_{r=1}^{q} u_r b_{r0} \quad (6)$$

such that

$$\sum_{r=1}^{q} u_r b_{re} - \sum_{i=1}^{p} v_i b_{ie} \le 0$$

$$\sum_{i=1}^{p} v_i a_{i0} = 1$$

$$u_r, v_i \ge \beta > 0$$

3.2.2 Banker-Charnes-Cooper Model (BCC)

The BBC input-oriented (BBC-I) techniques are introduced as follows [47,48]. In a linear model (7), BBC input-oriented (BBC-I) is depicted as follows.

Table 2. The values of random index (*RI*)

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54	1.56	1.57	1.59

$$\underset{u,v,v_0}{Max}\, \xi = v^T b_0 - v_0 \tag{7}$$

such that

$$u^T a_0 = 1$$
$$v^T b_e - u^T a_e - v_0 \leq 0, e = 1, 2, \ldots, n$$
$$u \geq 0, v \geq 0$$

3.2.3 Slacks-Based Measure Model (SBM)

The Slacks-Based Measure model (SBM) is introduced by Tone, i.e., which is also referred to by Pastor et colleagues [35,49]. Under the premise of continuous returns-to-scale, SBM input-oriented (SBM-I-C). As can be seen in model (8), the linear model is displayed:

$$\omega_{In}^* = \underset{\alpha, s^-, s^+}{Min}\, 1 - \frac{1}{p}\sum_{i=1}^{p} \frac{s_i^-}{a_{i0}} \tag{8}$$

such that

$$\sum_{e=1}^{n} a_{ie}\alpha_e = a_{i0} - s_i^-, i = 1, 2, \ldots, p$$
$$\sum_{e=1}^{n} b_{re}\alpha_e = b_{r0} + s_r^+, r = 1, 2, \ldots, q$$
$$\alpha_e \geq 0, e = 1, 2, \ldots, n$$
$$s_i^- \geq 0, i = 1,2, \ldots, p$$
$$s_r^+ \geq 0, r = 1,2, \ldots, q$$

3.2.4 Epsilon-Based Measure model (EBM)

The epsilon-based measure (EBM) was presented by Tone and Tsutsui [36] as a remedy to the shortcomings of CCR and SBM models. There are n DMUs $(j = 1, 2, \ldots, n)$ in the EBM model, with m inputs $(i = 1, 2, \ldots, m)$ and s outputs $(r = 1, 2, \ldots, s)$. $X = \{x_{ij}\} \in R^{m\times n}$ and $Y = \{y_{rj}\} \in R^{s\times n}$ define input and output matrices, respectively. In which X and Y are non-negative matrices. The input-oriented model with a constant return to scale (EBM-I-C) is displayed, as can be seen in model (9).

$$\delta^* = \underset{\theta, \lambda, s^-}{Min}\, \theta - \varepsilon_x \sum_{i=1}^{m} \frac{w_i^- s_i^-}{x_{io}} \tag{9}$$

such that

$$\sum_{j=1}^{n} x_{ij}\lambda_j = \theta x_{io} - s_i^-, i = 1, .., \mathrm{m}$$
$$\sum_{j=1}^{n} y_{rj}\lambda_j \geq y_{ro}, r = 1, .., \mathrm{s}$$
$$\lambda_j \geq 0, j = 1, 2, \ldots, n$$
$$s_i^- \geq 0, i = 1,2, \ldots, \mathrm{m}$$

where λ_j indicates the intensive vector of DMU, the subscript "o" shows that the DMU is being evaluated, s_i^- and w_i^- represent the amount of slack and weight in the $i^{t□}$ input, a parameter ε_x which depends on the dispersion of the inputs, and θ represents the radial properties.

4. CASE STUDY

This research proposed models that integrate quantitative and qualitative MCDM integrated models to determine the potential green supplier of steel manufacturers in Viet Nam. The authors collected 10 suppliers (DMUs), which are shown in Table 3.

Table 3. List of suppliers and their revenue in 2020 (million USD)

No.	Supplier	Hose	DMUs	Revenue
1	KKC Metal JSC	KKC	GS-01	19.611
2	Tung Kuang Industrial JSC	TKU	GS-02	36.403
3	Dai Thien Loc Corporation	DTL	GS-03	85.228
4	Vnsteel Vicasa JSC	VCA	GS-04	93.761
5	Vietnam Germany Steel Pipe JSC	VGS	GS-05	288.941
6	Pomina Steel Corporation	POM	GS-06	426.628
7	Nam Kim Steel JSC	NKG	GS-07	501.230
8	Hoa Sen Group	HSG	GS-08	1,198.272
9	Viet Nam Steel Corporation	TVN	GS-09	1,371.243
10	Hoa Phat Group JSC	HPG	GS-10	3,939.366

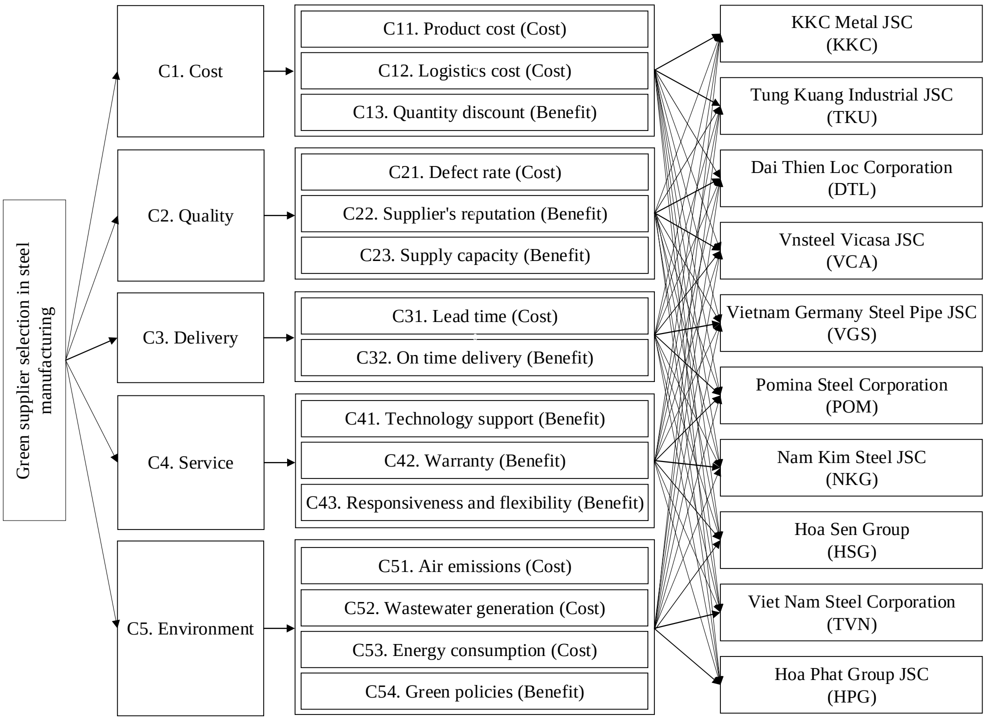

Fig. 2. The hierarchical tree to select green suppliers

Table 4. Descriptions of criteria and sub-criteria

Criteria and Sub-criteria	Descriptions
C1. Cost	
C11. Product cost	The amount paid to buy the products offered by the supplier
C12. Logistics cost	Fixed transportation cost for the supply of the products
C13. Quantity discount	The supplier will give a percentage discount if quantity increases
C2. Quality	
C21. Defect rate	The percentage of products that did not meet a quality target
C22. Supplier's Reputation	The supplier information is clear, transparent in cooperation, and in compliance with the law
C23. Supply capacity	The ability of supplier to provide products over predetermined periods of time
C3. Delivery	
C31. Lead time	How long it takes a supplier to deliver a product
C32. On time delivery	How many times supplier deliver product on premised date
C4. Service	
C41. Technology support	Technology capabilities, information security, tracking and tracing ability
C42. Warranty	How long supplier offer warranty of delivered product
C43. Responsiveness and Flexibility	The ability of the supply chain to respond intentionally to consumer demands and within a reasonable period
C5. Environment	
C51. Air emissions	The quantity control and handling of hazardous emission, such as SOx, NHx, COx
C52. Wastewater generation	The quantity control and the treatment of wastewater
C53. Energy consumption	The control of energy consumption used to carry out production activities of the enterprise such as electricity, gas
C54. Green policies	The commitment to sustainability and environmental management that business makes such as green packaging, green production, green R & D project.

In this stage, AHP is applied to choose the best supplier for selection of green supplier in the steel manufacturing industry in Viet Nam using the list of five criteria (i.e., price, quality, delivery, service, environment) and 15 sub-criteria which are shown in the hierarchical tree, as can be seen in Fig. 2. These criteria and sub-criteria, i.e., including qualitative and quantitative aspects, are based on the experiences of the relevant experts and preferences from the previous research. In addition, the descriptions of these criteria and sub-criteria are explained in Table 4.

The processes below show an example of how to calculate the main criteria (C1) cost, (C2) quality, (C3) delivery, (C4) service, and (C5) environment, as well as other factors using the same methodology. After evaluating all critical criteria and sub-criteria, interviewing experts in the area of the steel industry in Vietnam, i.e., Equation (21), is used to create pairwise comparison matrices among main criteria, as shown in Table 5.

In order to obtain the standardized pair matrix by dividing each value into a column in the matrix by its total column, the weight of the main criteria is established. Moreover, the priority vector (i.e., weight of the main criteria) as indicated in Table 6 is produced by averaging row elements in the standard matrix.

This step is used in order for the consistency index (*CI*), the random index (*RI*), and the consistency ratio (*CR*), i.e., to be determined, that is, the largest eigenvalue (λ_{max}). Using values in the two Tables above to construct Eq. (1):

$$\begin{bmatrix} 1 & 3 & 5 & 5 & 3 \\ 1/3 & 1 & 5 & 5 & 3 \\ 1/5 & 1/5 & 1 & 1/3 & 1/3 \\ 1/5 & 1/5 & 3 & 1 & 1/3 \\ 1/3 & 1/3 & 3 & 3 & 1 \end{bmatrix} \begin{bmatrix} 0.430 \\ 0.281 \\ 0.053 \\ 0.086 \\ 0.150 \end{bmatrix} = \begin{bmatrix} 2.417 \\ 1.567 \\ 0.274 \\ 0.437 \\ 0.803 \end{bmatrix}$$

$$\begin{bmatrix} 2.417/0.430 \\ 1.567/0.281 \\ 0.274/0.053 \\ 0.437/0.086 \\ 0.803/0.150 \end{bmatrix} = \begin{bmatrix} 5.615 \\ 5.569 \\ 5.172 \\ 5.093 \\ 5.367 \end{bmatrix}$$

Five main criteria are considered in this research. We get $= 5$. Thus, λ_{max} and CI are calculated as follows.

$$\lambda_{max} = \frac{5.615 + 5.569 + 5.172 + 5.093 + 5.367}{5} = 5.365$$

$$CI = \frac{\lambda_{max} - n}{n-1} = \frac{5.365 - 5}{5-1} = 0.091$$

In which $n = 5$, we get $RI = 1.12$, the consistency ratio (CR) is determined as follows.

$$CR = \frac{CI}{RI} = \frac{0.091}{1.12} = 0.081$$

From the result, $CR = 0.081 < 0.1$, therefore, the matrix of pairwise comparison is consistent, with satisfactory results.

Table 5. Matrix of pairwise comparisons for criteria

Criteria	C1	C2	C3	C4	C5
C1	1	3	5	5	3
C2	1/3	1	5	5	3
C3	1/5	1/5	1	1/3	1/3
C4	1/5	1/5	3	1	1/3
C5	1/3	1/3	3	3	1
Sum	2	19/4	17	43/3	23/3

Table 6. Normalized matrix of pairwise comparisons

Criteria	C1	C2	C3	C4	C5	Weight
C1	0.484	0.634	0.294	0.349	0.391	0.430
C2	0.161	0.211	0.294	0.349	0.391	0.281
C3	0.097	0.042	0.059	0.023	0.043	0.053
C4	0.097	0.042	0.176	0.070	0.043	0.086
C5	0.161	0.070	0.176	0.209	0.130	0.150
Sum	1	1	1	1	1	1

A similar procedure is used to compute other factors. The priorities and synthesized priorities of criteria and sub-criteria are shown in Table 7 and visualised in Fig. 3. Among the five main criteria shown in the table below, Cost (C1) has the highest priority (0,443). Product cost (C11), supplier's reputation (C22), lead time (C31), warranty (C42), green policies (C54) are the most important sub-criteria in their set.

The pairwise comparison matrix was built by completing a questionnaire based on how the hierarchical structure was constructed. The gathered data is then used to determine the weight of the criteria of the supplier and to check the accuracy of the accepted inconsistency rate and other restrictions.

"According to the research framework, in the second stage, the qualitative models-DEA models are used to select some potential suppliers from the list of top 10 steel manufacturers in Viet Nam. In the last few decades, the DEA model has been used to evaluate the performance of DMUs through their efficiency scores in many research fields. DEA can be used for multiple input and output factors" [50]. Based on the expert interviews and literature review, this paper examines three inputs including total assets, liability, and operating expenses. The findings of the AHP model for the ranking of various suppliers on qualitative characteristics are used as qualitative benefits in the output of the DEA model [51,52]. Hence, qualitative benefits and profit are considered as output factors in this paper.

Table 7. The priorities and synthesized priorities of criteria and sub-criteria

Criteria	Sub-criteria	Priorities	Rank	Synthesized Priorities	Synthesized Rank
C1. Cost	C11	0.637	1	0.282	1
(0.443)	C12	0.258	2	0.114	3
	C13	0.105	3	0.047	7
C2. Quality	C21	0.088	3	0.025	10
(0.282)	C22	0.669	1	0.189	2
	C23	0.243	2	0.069	5
C3. Delivery	C31	0.750	1	0.038	9
(0.050)	C32	0.250	2	0.013	14
C4. Service	C41	0.188	2	0.015	11
(0.079)	C42	0.731	1	0.058	6
	C43	0.081	3	0.006	15
C5. Environment	C51	0.100	3	0.015	12
(0.145)	C52	0.295	2	0.043	8
	C53	0.093	4	0.013	13
	C54	0.512	1	0.074	4

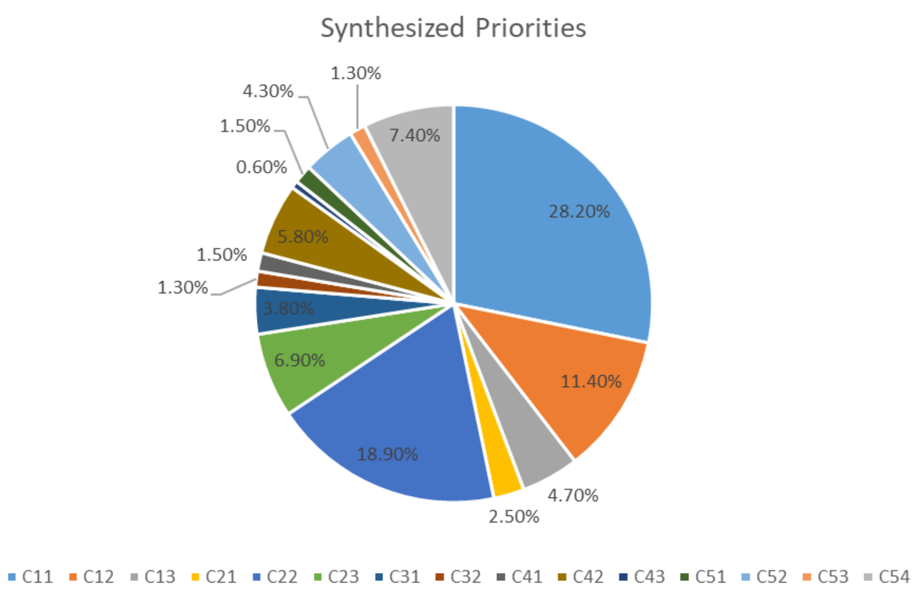

Fig. 3. The significant impact of sub-criteria

Table 8. The data set of 10 suppliers

No.	Hose	DMUs	(I1) Total Asset	(I2) Liability	(I3) Operating Expenses	(O1) Qualitative Benefits	(O2) Profit
1	KKC	GS-01	5.493	2.223	0.256	0.084	0.860
2	TKU	GS-02	42.498	19.976	1.818	0.083	6.181
3	DTL	GS-03	104.475	61.640	1.397	0.074	7.628
4	VCA	GS-04	13.507	3.948	1.402	0.078	3.698
5	VGS	GS-05	73.588	40.914	0.409	0.080	11.252
6	POM	GS-06	491.155	339.689	4.585	0.082	21.946
7	NKG	GS-07	325.560	188.270	3.967	0.071	37.513
8	HSG	GS-08	766.320	481.881	19.851	0.143	199.701
9	TVN	GS-09	959.114	525.288	29.128	0.072	73.591
10	HPG	GS-10	5,675.691	3,119.919	29.792	0.233	482.732

Table 9. The statistical data of input and output factors

Factors	Unit	Max	Min	Average	SD
(I1) Total asset	Mililion USD	5675.69	5.49	845.74	1641.14
(I2) Liability	Mililion USD	3119.92	2.22	478.37	900.57
(I3) Operating expenses	Mililion USD	29.80	0.26	9.26	11.47
(O1) Qualitative Benefits	%	0.23	0.07	0.10	0.05
(O2)Profit	Mililion USD	482.73	0.86	84.51	144.58

The definitions of input and output factors are as follows.

(I1) Total asset: The total assets owned by steel suppliers.

(I2) Liability: The total amount of debt and financial commitments owned by steel suppliers

(I3) Operating expenses: A cost incurred by steel suppliers through their ordinary business operations.

(O1) Qualitative benefit: The results of the AHP model for the ranking of various suppliers on qualitative characteristics.

(O2). Profit: Profit earned by suppliers after subtracting expenditures relating to the manufacture and sale of its
products.

Rather than using standard production efficiency assessment techniques, envision the inputs as the values decrease and the outputs as the value increases, which are anticipated to improve [51]. "Hence, the data set of input and output factors of 10 suppliers are collected" [53], as shown in Table 8. Furthermore, the statistics on input and output factors data, i.e., maximum, minimum, average, standard deviation, are given in Table 9 as follows.

5. RESULTS AND DISCUSSION

Global environmental concern is a reality, and green manufacturing in many industries is receiving more attention. Vietnamese steel manufacturers all claim to be working toward a "green steel industry" [54]. Hence, choosing green suppliers in the first place enables companies to both minimize environmental risks and cut manufacturing costs at the same time, thereby increasing their competitiveness. In addition, Vietnam's steel industry is one of the country's most important economic sectors. Overall, Vietnam's steel industry is still growing, and local steel production is struggling to keep up with demand. In 2018, Vietnam produced 14.1 million tons of crude steel, but demand for steel in the local market reached 22.31 million tons. Steel companies in Vietnam, meanwhile, have a small, unsustainable manufacturing scale and limited production technology [55]. In this regard, selecting the right supplier is one of the most critical decisions that have a significant impact on the product's quality. To solve the problem in its totality, two MCDM models were combined to consider all aspects related to green supplier selection decision-making in the steel manufacturing industry. In this context, ten major suppliers were selected to represent the steel industry in Viet Nam as a whole in this study.

5.1 AHP Results

The analytic hierarchy approach (AHP) is a powerful and adaptable decision-making process that helps individuals prioritize and pick the best green provider in a choice that is both qualitative and quantitative aspects. Hence, the set of criteria was considered as price, quality, delivery, service, environment, and 15 sub-criteria which are shown in the hierarchical tree, as can be seen in Fig. 1. To achieve reliable results, experts on the AHP's implementation were contacted. A similar procedure is used to compute other factors. The priorities and synthesized priorities of criteria and sub-criteria are shown in Table 5. According to experts' evaluations, the most important criterion is cost, with a priority of 0.443. The second significant criterion is quality, with a priority of 0.282, followed by the third place is environment criterion, and lastly, delivery, and service, consisting of 0.129 total priority criteria. Steel prices have lately risen considerably owing to rising raw material prices and shipping delays caused by the Covid-19 pandemic, according to the Ministry of Industry and Trade. Steel prices in the domestic market have risen by up to 45 percent in recent months [56]. However, according to the representative of Hoa Phat Group, to serve production stably, businesses have to buy goods even though the price is high, the price of any raw material also increases, but not buying quickly is not possible for goods to produce [57]. It proves that product prices play a very important role in supplier selection. A similar approach is used to determine the priority of the sub-criteria. Product cost (C11), supplier's reputation (C22), lead time (C31), warranty (C42), and green policies (C54) are the most important sub-criteria in their set. Specifically, under cost criteria, the most important sub-criterion is product cost (C11), with a priority of 0.637, followed by logistics cost (C12) and quantity discount, with priorities of 0.258 and 0.105, respectively. A comparison of all 15 sub-criteria reveals that product cost is the most relevant sub-criteria, with a synthesized priority of 0.282. The second through fourth factors is the supplier's reputation (0.189), logistics cost (0.114), and the green policies (0.074), respectively. Note that while the technique is developed for the evaluation of green suppliers, many sub-criteria that are not environmental factors also have high priority. Non-environmental criteria account for eight out of the top ten sub-criteria. This implies that not only environmental issues are considered, but traditional criteria also need to be considered when selecting green suppliers.

5.2 DEA Results

The relationship between input and output variables must be checked with the Pearson correlation coefficient before the DEA model is applied [58]. The correlation between input and output factors for a dataset in 2020 is shown in Table 10. All Pearson correlations of factors are larger than 0.6 (i.e., there is a positive linear relationship). As a result, these data can be included in the DEA model.

Table 10. The correlation between input and output factors

	Total Asset	**Liability**	**Operating Expenses**	**Qualitative Benefits**	**Profit**
Total Asset	1	0.99958	0.73139	0.92510	0.95823
Liability	0.99958	1	0.73509	0.92936	0.96178
Operating Expences	0.73139	0.73509	1	0.66278	0.78025
Qualitative Benefits	0.92510	0.92936	0.66277	1	0.97728
Profit	0.95823	0.96178	0.78025	0.97728	1

Table 11. DEA models results

No.	**Companies**	**DMUs**	**BBC-I**	**CCR-I**	**SBM-I-C**	**EBM-I-C**
1	KKC Metal JSC	GS-01	1	1	1	1
2	Tung Kuang Industrial JSC	GS-02	0.7274	0.6413	0.59682	0.632102
3	Dai Thien Loc Corporation	GS-03	0.40963	0.40422	0.38777	0.401536
4	Vnsteel-Vicasa JSC	GS-04	1	1	1	1
5	Vietnam Germany Steel Pipe JSC	GS-05	1	1	1	1
6	Pomina Steel Corporation	GS-06	0.2951	0.2585	0.23377	0.251353
7	Nam Kim Steel JSC	GS-07	0.70976	0.61409	0.60738	0.613852
8	Hoa Sen Group	GS-08	1	1	1	1
9	Viet Nam Steel Corporation	GS-09	0.3320	0.3198	0.2952	0.315743
10	Hoa Phat Group JSC	GS-10	1	1	0.56947	0.580364

In order to select the potential suppliers, DEA models consisting of CCR-I, BCC-I, SBM-I-C, and EBM-I-C are proposed in this stage. Table 11 shows the list of potential steel suppliers based on DEA results. There are four potential DMUs, which are KKC Metal JSC (GS-01), Vnsteel-Vicasa JSC (GS-04), Vietnam Germany Steel Pipe JSC (GS-05), and Hoa Sen Group (GS-08). Meanwhile, Hoa Phat Group JSC (GS-10) only achieved the ranking score of 1 of two models BBC and CCR. As a result, future research should focus on improving or reviewing data inputs to provide appropriate outputs and keep suppliers productive, the future study should involve improving or reviewing data inputs. Because of its efficiency and intricacy, this integration approach allows a large number of company decisions to choose the most suitable supplier exactly.

6. CONCLUSION AND FUTURE WORKS

"The green supplier selection is presently attracting a great deal of attention because of the growing international interest in natural resource depletion, environmental pollution, and global warming. Besides, the green supplier selection also improves productivity and customer satisfaction by providing consumers with solutions to decrease their environmental impact, conserve resources, and save prices" [59]. To achieve enterprise perpetuity, a company must prioritize environmental preservation and green production as an important component of its social duty. In a highly competitive and regulated market, an appropriate green supplier selection model can assist a company in reducing environmental and legal risks while boosting its competitiveness.

The proposed two MCDM models DEA and AHP help decision-makers in ranking their choices among multiple suppliers and selecting the best green supplier in the steel manufacturing industry. In the first stage, the AHP model was proposed to assess the criteria for suppliers' selection and set a priority to identify essential criteria that have a direct effect on the profitability of the firm. AHP can be used to evaluate providers but there is a problem that the input data is dependent on the experience of decision-makers, which gives its subjective, qualitative significance. Several DEA models are therefore given for ranking suppliers throughout the final stage. The DEA model is suitable for the best supplier ranking for multiple suppliers, with multiple input and output data of a quantitative significance. The AHP-DEA integration model helps a lot to make business decisions when picking precisely the most suitable supplier. Finally, this research will provide a list of possible suppliers that have been conditioned to meet the companies' green supply requirements. After using the recommended two-phase technique, suppliers GS-01 (KKC Metal JSC), GS-04 (Vnsteel-Vicasa JSC), GS-05 (Vietnam Germany Steel Pipe JSC), and GS-08 (Hoa Sen Group) were identified as the top four optimal greenest suppliers among the ten suppliers. Based on the scores of fifteen sub-criteria, some of these sub-criteria such as C13, C21, C32, C43, C53 were found to have very low scores across all supplies. This shows that the supplier should consider reducing the cost of raw materials if the order quantity increases further, reducing the defect rate, increasing the ability to deliver on time, being responsible and flexible in all situations, and importantly, quickly solving the pollution caused by consumed energy. That suggests that suppliers need to focus more on these problems. Besides, to push the efficiency of green suppliers, the environment criteria should be integrated into the supplier assessment strategy to support them in improving their environmental care and management process. Furthermore, suppliers must be trained on sustainability to develop a sustainable supply chain. Through the sustainable development of products and services according to the green supplier selection criteria, suppliers can enhance their chances of becoming the top green supplier.

"While it is thought that the proposed approach gives operational benefit in the green supplier section, there are numerous limitations to this study. The psychological behaviors of the decision-makers, which are essential factors, were not taken into account in the suggested technique. Another significant limitation is that we did not take into account potential interactions and connections between the criteria. We recommend considering these criteria in future research for creating a more effective green supplier selection. Besides, the proposed method might be useful for a variety of MCDM problems, such as management challenges (e.g., location selection and project management, flexible manufacturing systems) and marketing challenges (e.g., new product creation and promotion activities) when available data are imprecise and uncertain by nature. Other MCDM methods (i.e., FAHP, FANP, VIKOR)" [60,61] "can also be considered to develop a fuzzy group decision support system to green supplier selection management decision problems in order to get the robust result. Futhermore, the scale efficiency calculation should be discussed in the future studies" [62].

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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