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RESEARCH ARTICLE

Strategic Decision Making at a Steel Industry Assisted by Fuzzy Theory and Multicriteria Decision Making Model

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ABSTRACT Steel production is one of the major focuses of Vietnamese government's industrial development plans in the last few decades and the industry has experienced sustained growth where enterprises have made great strides in terms of scale, output, and technology. The growth and expansion of the steel industry, however, must be carefully evaluated due to the sizeable amount of waste, including wastewater, gas, and solid waste, as well as the significant emission of pollutants. Vietnamese steel companies are confronted with the difficulty of establishing sustainable practices to satisfy the sustainability requirements of stakeholders. Green suppliers evaluation and selection is a complex process where multiple quantitative and qualitative criteria must be considered. In this study, a Multicriteria Decision Making (MCDM) model is developed to support the green suppliers evaluation process in the steel manufacturing industry in Vietnam. The proposed model combines Fuzzy Analytic Hierarchy Process (Fuzzy AHP) and Tomada de Decisao Interativa Multicriterio (TODIM) methods to determine the most suitable suppliers based on relevant criteria. The main contribution of this study is to develop a Fuzzy MCDM model to support decision makers in the steel industry in green steel suppliers evaluation proceess. The proposed model is then applied to a case study in Vietnam to demonstrate its application feasibility. The results suggested that among the potential alternatives, Supplier 5 (Viet Uc Steel) is identified as the optimal supplier.

INDEX TERMS MCDM model, steel industry, fuzzy AHP, TODIM, sustainable.

I. INTRODUCTION

The steel industry plays a crucial role in the economic development of Vietnam. The country's steel output has seen significant growth from the year 2020 to the beginning of 2023. Vietnam has shown tenacity and made incredible progresses despite the obstacles presented by the worldwide epidemic and negative economics outlook (Fig. 1). Vietnam's steel production increased steadily over the years, reaching a total output of 29.34 million metric tons in 2022. Domestic steel demand remained robust due to continuing building and infrastructure development projects across the country. In addition, government initiatives to promote industrialization and urbanization boosted demand for steel and raised production. In 2021, production and export operations were seriously damaged by the rigorous lockdown restrictions and interrupted international supply lines due to the COVID-19 pandemic. However, the sector proved its resiliency by putting in place strict safety regulations, adjusting to fresh customer needs, raising operational effectiveness and has successfully maintained a high level of output as a consequence [1].

In 2022, the Vietnam steel industry had a minor decline due to a decline in global demand. According to the General Statistical Office of Vietnam, steel production output increased from the pre-pandemic level to 29.34 million tons.

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Even though demand generally has decreased, the industry's pace has been kept up primarily by increasing domestic construction activity, infrastructural improvements, and the resumption of foreign commerce. Maintaining production level required support from the government in the form of stimulus packages and infrastructure upgrades. Moving into early 2023, Vietnam's steel industry continues to exhibit positive momentum. The production output has been steadily increasing, meeting the growing demand for steel products both domestically and internationally. Investments in modernization and technology upgrades have enhanced the sector's productivity and competiveness.

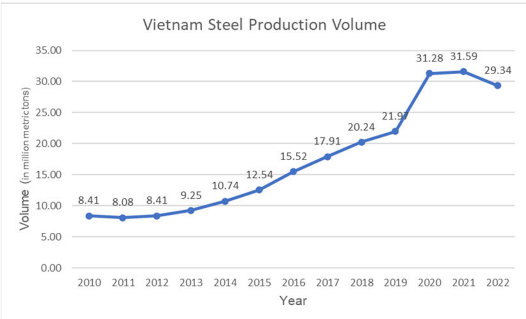

FIGURE 1. Vietnam steel production volume, 2010 – 2022 [2].

However, the steel sector still has to deal with issues including fluctuating raw material costs, international commerce instability, and environmental worries. To ensure long-term prosperity of the industry, the government's emphasis on sustainable development and the implementation of greener techniques in the steel production processes are essential. As such, sustainability has emerged as a critical consideration in the steel industry.

One of the key areas that can make help improving the sustainability of steel supply chains is supplier evaluation and selection process. The incoporation of sustainability dimensions has become neccessary for steel manufacturers. However, the evaluation and selection of sustainable sell suppliers is a complex process where the decision-makers must consider multiple quantitative and qualitative criteria. Multicriteria Decision Making (MCDM) approaches offer a powerful tool for informed decision-making and improving overall performance for such complex decision-making problems. The aim of this study is to develop a Fuzzy MCDM model utilizing Fuzzy Analytic Hierarchy Process (Fuzzy AHP) and Tomada de Decisao Interativa Multicriterio (TODIM) methods to support decision-makers in the sustainable supplier evaluation and selection process in the steel manufacturing industry of Vietnam. Supplier selection is frequently plagued with ambiguities, poor facts, and subjective judgments. The application of Fuzzy AHP with TODIM provides a systematic and well-structured approach for making supplier selection judgments. This enables decision-makers to comprehensively examine and rank supplier choices based on many criteria, resulting in better informed and robust decisions.

The following research gaps may be addressed by this study:

Integration of Fuzzy Decision-Making: Many supplier selection studies have typically relied on crisp, deterministic data, which frequently fails to represent the inherent uncertainties and ambiguities of supplier evaluation. This study bridges the gap by using Fuzzy AHP, allowing for the representation of ambiguous data and judgments in the decision-making process.

Multicriteria Decision-Making that is Interactive: While there are standard multicriteria decision-making approaches, the introduction of TODIM, an interactive methodology, is a novel contribution in the context of supplier selection. It responds to the need for a more interactive and transparent supplier evaluation process that includes stakeholders in decision-making.

The combination of Fuzzy AHP-TODIM is an innovative methodology that can be adapted to meet supplier selection challenges in a variety of sectors. It helps to enhance decision-making approaches, especially in situations characterized by ambiguity and the requirement for participatory decision-making.

This study is critical in resolving the complexity of supplier selection in the steel industry through the use of advanced approaches such as Fuzzy AHP-TODIM. By combining fuzzy logic and adding an interactive decision-making process, it closes a research gap. Its unique contributions include its practical applicability, methodological innovation, and the potential to improve supplier selection methods in the steel sector and beyond.

In summary, the paper's objectives revolve around the application of advanced decision-making methodologies to choose a steel supplier, with a focus on robustness, inclusivity, and the practical relevance of the findings in the steel industry. Its scope encompasses the complexities of supplier selection (6 steel suppliers in Viet Nam, taking into account multiple criteria(12 sub-criteria) and the challenges associated with fuzzy data and interactive decision-making.

II. LITERATURE REVIEW

MCDM Multiple Criteria Decision Making (MCDM) techniques have gained significant attention in various industries, including the steel industry, as a means to support complex decision-making processes. MCDM methods provide a structured framework to evaluate and prioritize alternatives based on multiple criteria, taking into account diverse and often conflicting objectives. In the context of the steel industry, MCDM approaches have been widely applied to address various challenges and optimize decision-making in areas such as production planning, supplier selection, technology adoption, and sustainability.

Some case studies applying MCDM in supplier selection such as Ghamari et al. [3] Interpretive Structural Modelling (ISM), Best-Worst Method (BWM), and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) were used to create a framework for choosing sustainable suppliers in the Iranian steel industry. The framework for choosing a green supplier was presented by Lu et al. [4] using a cloud-based model, possibility degree, and Fuzzy AHP. AHP method is one of the most used analytical methods in the MCDM model when this method can be combined with many other methods to give optimal results [5], [6], [7], [8], [9], [10]. One of the first studies to apply the AHP method was done by Yahya and Kingsman [11] the study used the AHP method to determine the preference in supplier selection.

Some of the highlighted research about MCDM in steel such as Wang et al. [12] used a hybrid model of Fuzzy AHP and Fuzzy TOPSIS to identify the most effective green supplier of steel manufacturing in Vietnam, Monteiro Gomes et al. [13] demonstrates the use of the Choquet-extended TODIM method as well as the classic TODIM approach. These methods are used to compare suppliers of certain materials and products, which is important for the steel sector in the Brazilian state of Rio de Janeiro. Govindan et al. [14] employed the best-worst method (BWM) in the first phase to generate KPI weights, the TODIM technique in the second phase for supplier evaluation, and a supplier classification grid in the third phase to analyze the impact of each selection strategy to be applied.

Amiran et al. [15] introduced performance evaluation indices that were chosen via expert questionnaires. Also, the chosen evaluation indexes' relative weights are determined using the Fuzzy AHP method. Each criterion's weights are expressed in language phrases that can be represented by triangular fuzzy numbers. According to three case studies as empirical examples, the Fuzzy TOPSIS method, one of the analytical tools used in Multiple Criteria Decision Making (MCDM), is used to rank the performance of three mills by simultaneously calculating the distances to both the Fuzzy Positive-ideal solution and Fuzzy Negative-ideal solution. Almasi et al. [16] employed a multiperiod mathematical model to choose and assign orders to a sustainable supplier in the Iranian automotive sector. Zindani et al. [17] proposed the robustness and applicability of the TODIM method in addressing material selection issues demonstrated by a sensitivity study demonstrating the impact of different values of the attenuation factor of the losses on the rankings of the candidate materials. Sharma et al. [18] compared the rankings of the materials using four different Multicriteria Decision Making Techniques (MCDM) to determine which material is best for railway wagons among three steel and three aluminum-based materials. Chakraborty et al. [19] mentioned a set of alternative suppliers are ranked using a relatively new MCDM technique known as Measurement Alternatives and Rating According to Compromise Solution (MARCOS). Jain et al. [20] suggested the iron and steel industry's supplier selection. Weights have been assigned to the criteria using the Analytical Hierarchy Process, and suppliers have been ranked using the weighted Aggregated Sum Product Assessment (WASPAS) approach.

Jin et al. [21], [22] proposed the rejoice-regret probabilistic linguistic multiplicative DEA cross efficiency assessment approach for a two stage system to overcome the psychological and behavioral problems of evaluators. More than that Jin et al. [23] studied about the Large-scale group decision-making (LSGDM) deals with complex decision-making problems which involve a large number of decision makers (DMs). This study presented a novel consensus based linguistic distribution LSGDM (CLDLSGDM) strategy that attempts to produce accepted solutions. It is built on a statistical inference principle that takes into account the psychological aspects of DMs' regret aversion utilizing regret theory. In particular, the CLDLSGDM technique uses the consensus matrix and modified decision-making matrices to solve the decision-making problem by applying the statistical inference principle to the consensual knowledge acquired during the consensus process. This allows for the determination of the weights of DMs and characteristics. Next, the comprehensive perceived utility values of the alternatives are computed and ranked using regret theory.

An explanation of the set of criteria used for this document is referenced by several authors as following Table 1:

In order to improve the supplier selection process as well as tackle the inherent uncertainty and complexity of this decision-making task, Fuzzy AHP and ToDIM are being applied to the steel supplier selection process. Here are some main justifications for selecting these techniques: The steel industry often deals with imprecise or uncertain data due to fluctuating market conditions, variable supplier performance, and changing customer demands. When choosing a supplier, a number of factors must be taken into account, including price, capacity, quality, delivery, sustainability,... Fuzzy AHP provides a structured approach to handle the hierarchy of criteria. It enables you to rank and balance factors in the supplier selection process based on their relative significance. This is particularly useful when some factors like quality or dependability have a greater influence on the choice. Pairwise comparisons of criteria and alternatives are made easier by Fuzzy AHP. This makes it possible to compare providers consistently and quantitatively by evaluating their performance in relation to each criterion in a methodical manner. Conversely, TODIM is very helpful in combining the different preferences and criteria into a single score for supplier selection. It emphasizes the idea of ideal and anti-ideal solutions, assisting in the selection of the supplier who most closely resembles the ideal profile. Because FAHP and TODIM are flexible and can handle a range of preferences and decision-making situations, there is flexibility in the supplier selection process.

In conclusion, the kind of data that is available and the nature of the decision problem will determine which of these approaches is best. Fuzzy AHP and TODIM were selected to build the proposed Fuzzy MCDM model. When choosing a

TABLE 1. Definitions of the criteria used.

Criteria	Sub-Criteria	Definition
Product	Price	The sum that must be paid in order to purchase the goods that the supplier is offering [3,24]
	Quality	Program for continuous improvement, corrective and preventative measures, documentation and self-inspection, inspection and control, installation of the ISO quality system, quality shipping, and certification of the quality. [24]
	Capacity	Guaranteed in terms of product quantity continuously, without interruption, product shortage.[25]
	Quantity discount	If the amount grows, the supplier will offer a percentage discount. [25,26]
Service	Reliability	Communication, dedication, and trust are all components of a secure communication system. Over a long working life, easy communication might have an impact on the connection between supplier and management. Language, morals, and customs differ from one country to the next. Suppliers must provide communication systems that are easier and more successful than their competitors in order to have a strong connection. [25]
	Warranty	Product warranty is clear [3,26]
	Technology	Current manufacturing facilities / capacities, supplier technology development to satisfy current and future resource needs, R&D capabilities, and supplier new product design to meet current and future needs of an organization, technology, interoperability, and supplier growth.[26]
	On-time delivery	The supplier must meet shipping conditions including location and time for shipping. [3]
Environmental	CO2 emissions	CO2 emissions from furnace the combustion process, sintering, and pelletizing.[26,27,34]
	Sustainability	Meeting the needs of the present does not affect the ability of future generations to meet their own needs, including three pillars: economic, environmental, and social.[20,29,34]
	Wastewater generation	The process to treat industrial wastewater before being discharged into lakes, rivers, … [29,30]
	Resource recycling	Recovery and recycling of scrap products. [29,36,39]

steel supplier, the information at hand is frequently ambiguous or imprecise, as such, it is necessary to apply fuzzy logic in building the model. The combination of Fuzzy AHP and TODIM allows a flexible decision-making procedure that can successfully handle the ambiguity in the input data. Furthermore, while TODIM operates based on the decision space and calculates the relative values of alternatives, Fuzzy AHP can use model knowledge to set the weights of criteria. These two methods can be combined to integrate model knowledge and information about the decision space, resulting in a final decision that is based on both particular information and expert knowledge.

TODIM gives simple rankings, making it simple for decision-makers to grasp why one alternative is ranked higher or lower. This facilitates decision-making communication and persuasion. TODIM compares each alternative to the ideal answer, which aids in expressing the degree of similarity to the evaluation criteria. This is useful for making decisions that necessitate taking into account both similarity and dissimilarity across alternatives. TODIM can be used to a variety of data kinds, including numeric and qualitative or fuzzy data, making it applicable to a variety of decision scenarios.

However, TODIM can grow complicated when dealing with multiple criteria and options. Pairwise comparisons and the determination of ideal and anti-ideal solutions are involved in the calculation process, which can be time-consuming and labor-intensive. TOPSIS is primarily concerned with estimating the distance between each alternative and the ideal and anti-ideal solutions, but it does not explicitly examine their dissimilarity. If the ideal and anti-ideal solutions are not symmetric, this can result in asymmetric results.

Finally, Fuzzy AHP-TODIM excels at offering an intuitive ranking based on similarity to the ideal answer. Both approaches provide solid solutions to the problems posed by fuzzy or inaccurate data in multi-criteria decision-making.

III. METHODOLOGY

A. THE FUZZY ANALYTIC HIERARCHY PROCESS

Fuzzy AHP is a fuzzy MCDM method [32] that allows decision-makers to evaluate and prioritize alternatives based on a criterion hierarchy. The method entails decomposing a complex decision problem into a hierarchical structure of criteria and sub-criteria, then comparing alternatives based on pairwise comparisons of criteria using linguistic terms such as "very important," "important," "moderately important," "less important," and "not important." Based on the linguistic terms, the fuzzy AHP computes the priority weights of criteria, sub-criteria, and alternatives. This method is commonly used in renewable energy studies to evaluate and select renewable energy solutions based on a variety of criteria, including economic, environmental, service, and social factors, …

The difference and relationship between the proposed Fuzzy AHP and AHP lie in their approaches to handling uncertainty and imprecision in decision-making. Here's a breakdown of the key distinctions and the connection between the two:

1) TREATMENT OF UNCERTAINTY AND FUZZINESS

AHP: In its conventional form, AHP presumes that decision-makers convey their preferences and judgments by providing clear, non-fuzzy values. It doesn't naturally deal with the problem of ambiguity or imprecision.

Fuzzy AHP: Fuzzy AHP was created especially to deal with fuzziness and uncertainty in the decision-making process. Decision makers can describe the degree of ambiguity in their decisions by using fuzzy logic and fuzzy numbers to represent imprecise or uncertain information. Because of this, Fuzzy AHP works effectively in scenarios where the data is ambiguous or unpredictable by nature.

2) PAIRWISE COMPARISONS

AHP: The relative relevance of criteria and alternatives is determined by pairwise comparisons in AHP. Numerical numbers expressed in crisp form are usually used in these comparisons.

Fuzzy AHP: Similar to AHP, FAHP compares criteria and options pairwise to ascertain their relative relevance. Fuzzy numbers or linguistic variables are used in FAHP comparisons in order to account for the imprecise nature of decision-makers' assessments.

3) FUZZY SETS AND MEMBERSHIP FUNCTIONS

AHP: AHP does not inherently employ fuzzy sets or membership functions in its traditional form. Instead, it relies on crisp values and consistency checks based on the eigenvector method.

Fuzzy AHP: Fuzzy AHP makes extensive use of fuzzy sets and membership functions to handle the fuzziness in data. Decision-makers can assign membership degrees to elements, indicating the degree to which they belong to a particular set.

4) RELATIONSHIP

Fuzzy AHP can be considered an extension of AHP. While AHP deals with crisp data and preferences, Fuzzy AHP expands on the AHP framework by accommodating fuzzy data, allowing for more flexible and robust decision-making in situations where information is vague or uncertain.

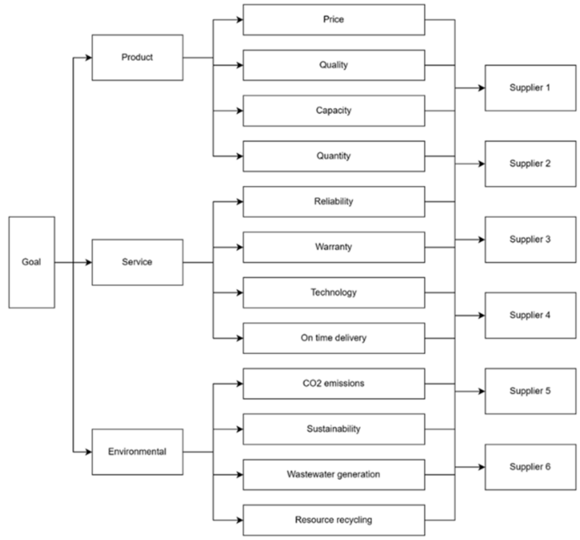

FIGURE 2. Proposed fuzzy analytic hierarchy process model structure.

TABLE 2. The fuzzy linguistics scale.

Fuzzy set	Meaning	Triangular fuzzy numbers
$\tilde{1}$	Equal level	(1,1,1)
$\tilde{2}$	Light level	(1,2,3)
$\tilde{3}$	Weak level	(2,3,4)
$\tilde{4}$	Preferable level	(3,4,5)
$\tilde{5}$	Importance level	(4,5,6)
$\tilde{6}$	Fairly level	(5,6,7)
$\tilde{7}$	Highly level	(6,7,8)
$\tilde{8}$	Strongly level	(7,8,9)
$\tilde{9}$	Extremely level	(9,9,9)

In practice, the choice between AHP and FAHP depends on the nature of the decision problem. If there is a high degree of uncertainty or imprecision in the data, FAHP is a more appropriate choice. However, if the decision can be made with crisp, precise data, AHP can still be an effective tool.

The processes for implementing an Fuzzy AHP model are outlined below.

Step 1: Fuzzy hierarchical tree formation (Fig. 2)

Step 2: After establishing the Fuzzy AHP structure, the criteria will be compared to one another. The relative importance of the two criteria is quantified on a scale of $\tilde{1}$- $\tilde{9}$ based on the given linguistic characteristics of TFNs. The tilde symbol (~) is placed above the parameter symbols to denote erroneous data. Table 2 show the fuzzy scale used:

Step 3: Clarify the pairwise comparison matrix of triangular fuzzy number as demonstrated below [34]:

$$R_{\alpha,\beta}(\bar{\alpha}_{ij}) = [\beta.FN_{\alpha}(L_{ij}) + (1-\beta). \times FN_{\alpha}(U_{ij})];\ 0 \leq \beta \leq 1, 0 \leq \alpha \leq 1 \quad (1)$$

If denotes an uncertain situation, ($\alpha = 0.5$, $\beta = 0.5$) demonstrates that the export's approach is reasonable.

$$FN_{\alpha}(L_{ij}) = (M_{ij} - L_{ij}).\alpha + L_{ij} \quad (2)$$

$$FN_{\alpha}(U_{ij}) = U_{ij} - (U_{ij} - M_{ij}).\alpha \quad (3)$$

If we replicate the diagonal portion of the matrix, we are given:

$$S_{\alpha,\beta}(\bar{\alpha}_{ij}) = \frac{1}{R_{\alpha,\beta}(\bar{\alpha}_{ij})};\ 0 \leq \beta \leq 1, 0 \leq \alpha \leq 1, i > j \quad (4)$$

A comparision matrix that of crisp values is obtained. This comparison is done between pairs of indicators, which are then integrated into a matrix of lines and columns (k is the number of indicators). The significance of indicator i when compared to the column criteria is calculated as:

$$Q = (t_{ij})_{k\times k} = \begin{bmatrix} 1 & t_{12} & \ldots & t_{1k} \\ t_{21} & 1 & \ldots & t_{2k} \\ \vdots & \vdots & \vdots & \vdots \\ t_{k1} & t_{k2} & \ldots & 1 \end{bmatrix} \quad (5)$$

Step 4: Calculate the highest individual value and look for the consistency index.

$$\lambda\,|Q - {}_{max}.I| = 0 \quad (6)$$

where:

$\lambda_{\max}$ is the maximum value of the matrix.

Q is the relative matrix of pairs of elements.

I is the unit matrix of the similar with matrix Q.

This ratio balances with the level of consistency with the data's (random) neutrality [33]:

$$\text{Critical Ratio (CR)} = \frac{\text{Consistency Index (CI)}}{\text{Random Index(RI)}} \quad (7)$$

$$\text{Consistency Index (CI)} = \frac{\lambda_{\max} - \text{t}}{\text{t} - 1} \quad (8)$$

where RI is obtained using Table 3:

CR ≤ 0.1 is acceptable; otherwise the Fuzzy AHP model must be reevaluated.

B. THE TOMADA DE DECISAO INTERATIVA MULTICRITERIO (TODIM) METHOD

The TODIM technique [31], which is based on prospect theory, takes into consideration the subjectivity of decision makers' behavior and can indicate the advantage of one choice over another using operational formulas. It is more concrete, sensible, and scientific in its application to the problem of multi-criteria decision making (MCDM). The TODIM processing as shown in:

TABLE 3. Index values are generated at random and correlate to indicators [2].

t	RI
1	0
2	0
3	0.52
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

Step 1: With $\boldsymbol{\vartheta} = (\boldsymbol{\vartheta_1, \vartheta_2, \ldots \vartheta_m})$ as a group of suppliers, establish a dicision matrix with m suppliers and n critetia:

$$\text{Normalize } \boldsymbol{\vartheta} = (\boldsymbol{a_{ij}})_{\boldsymbol{mxn}} \text{ into } \boldsymbol{\vartheta}' = (\boldsymbol{a'_{ij}})_{\boldsymbol{mxn}} \quad (9)$$

Step 2: Determine the degree of dominance. As shown below, the preference index value is calculated as:

$$\mathbf{C}\,(\boldsymbol{\vartheta_i,\vartheta_t}) = \sum\nolimits_{j=1}^{n} \boldsymbol{\mu_j}(\boldsymbol{\vartheta_i,\vartheta_t});\ (\mathbf{i,t = 1, 2, \ldots, m}) \quad (10)$$

$$\boldsymbol{\mu_j}\,(\boldsymbol{\vartheta_i,\vartheta_t}) = \begin{cases} \sqrt{\dfrac{\boldsymbol{\varepsilon_{jk}}\,(\boldsymbol{d_{ij} - d_{tj}})}{\sum_{j=1}^{n}\boldsymbol{\varepsilon_{jk}}}} & \boldsymbol{If\ d_{ij} - d_{tj} > 0} \\ \mathbf{0} & \boldsymbol{If\,d_{ij} - d_{tj} = 0} \\ -\dfrac{\mathbf{1}}{\boldsymbol{\delta}}\sqrt{\dfrac{\left(\sum_{j=1}^{n}\boldsymbol{\varepsilon_{jk}}\right)(\boldsymbol{d_{ij} - d_{tj}})}{\boldsymbol{\varepsilon_{jk}}}} & \boldsymbol{If\,d_{ij} - d_{tj} < 0} \end{cases} \quad (11)$$

where δ specifies loss decay coefficient ($\delta > 0$). The default value of δ is 1 which expresses neutrality of the decision makers to losses. Finally, the dominance degree of each alternative is determined:

$$\mathbf{C}\,(\vartheta_i) = \frac{\sum_{t=1}^{m} \text{C}(\vartheta_i, \vartheta_t) - min\left\{\sum_{t=1}^{m} \text{C}(\vartheta_i, \vartheta_t)\right\}}{max\left\{\sum_{t=1}^{m} \text{C}(\vartheta_i, \vartheta_t)\right\} - min\left\{\sum_{t=1}^{m} \text{C}(\vartheta_i, \vartheta_t)\right\}} \quad (12)$$

Step 4: Rank the alternatives according to their $\mathbf{C}\,(\vartheta_i)$ values. The supplier with the highest value is the best option.

IV. CASE STUDY

The steel industry is facing many challenges because of competition and market prices. However, the demand for steel is in many fields such as construction (civil and industrial works), automobile manufacturing, ships, oil and gas pipelines, electronic equipment and household electrical goods, and many other fields. This demand is still growing gradually and is expected to continue to increase in the future because of the development of many industries and construction globally. This study proposes a set of criteria to help businesses choose the right supplier. This set of criteria includes 3 main criteria: economy, service, and environment [38] along with 12 sub-criteria. To test the set of criteria, this study selected six different suppliers to evaluate. The information of the six potential suppliers as shown in the Table 4:

TABLE 4. Potential suppliers' information.

Name of company	Alterniative code
Hoa Phat Group	Supplier 1
Hoa Sen Group	Supplier 2
Song Hau Corporation	Supplier 3
Pomina Steel Corporation	Supplier 4
Viet Uc Steel	Supplier 5
Nam Kim Steel	Supplier 6

A. THE FUZZY AHP MODEL

Criteria weighting results after applying the Fuzzy AHP model are the results of quantitative evaluation and analysis of the priority of criteria in a system or process. This result is calculated based on the importance of each criterion and gives corresponding weights for each criterion. The application of the Fuzzy AHP model helps to optimize the evaluation process and quantify the priority of the criteria by using mathematical methods to evaluate the importance of the criteria and calculate the corresponding weights. This result (Table 5) brings many benefits to the evaluation process, helping to improve operational efficiency and ensure fairness in the evaluation and prioritization of criteria.

B. THE TODIM MODEL

After the Fuzzy AHP model quantifies the weight of the criteria. The results of Fuzzy AHP will be used as input to the TODIM model, a weight-based multicriteria evaluation method. Specifically, the weighted results of the criteria will be presented in the form of a matrix and these values will be applied to TODIM to conduct the evaluation of optimal supplier selection. TODIM is a multicriteria evaluation method that uses information about the weight and priority of the criteria to determine the optimal supplier. The TODIM method's input setup information is shown in Table 6 where Profit criteria are those that have a positive impact, while Cost criteria are those that have a negative impact. Table 7 displays the TODIM method's initial matrix in this case, which contains expert assessments of how each alternative performed in relation to each criterion and criteria weights from the Fuzzy AHP method.

TABLE 5. Criteria weighting result.

Name	Normalized	Limiting
Air emissions (C1)	0.08739	0.043695
Capacity (C2)	0.0892	0.044599
On time delivery (C3)	0.10444	0.052222
Price (C4)	0.08263	0.041313
Quality (C5)	0.08948	0.044738
Quantity discount (C6)	0.10212	0.05106
Reliability (C7)	0.12675	0.063377
Resource recycle (C8)	0.07543	0.037717
Sustainability (C9)	0.06845	0.034225
Technology (C10)	0.07721	0.038605
Warranty (C11)	0.05494	0.027468
Wastewater generation (C12)	0.04196	0.020981

TABLE 6. Input setup information.

Guide to determine kind of criteria		
	profit	cost
Kind of criteria	1	-1
Number Of Suppliers	6	

Applying the TODIM formula from (9) - (12), we get the supplier ranking results as Tab.8.

To validate the performance of the proposed method, the input data is re-ran using a popular Fuzzy MCMD model that is Fuzzy AHP-TOPSIS. The results is shown in Table. 9. The results between the two model is extremely similar, with Supplier number 5 choosen as the most optimal supplier. This suggests that the proposed model is feasible and can identify the optimal supplier in this case.

The results of the ranking of suppliers using the TODIM model have shown that Viet Uc Steel is the most suitable supplier. However, in a volatile market, Nam Kim Steel and Pomina Steel Corporation could also be considered as alternative choices.

The TODIM model considers multiple criteria and evaluates each supplier based on their performance in these criteria. In this case, Viet Uc Steel's performance was the best overall, but the model recognizes that in certain situations, other suppliers may also be viable options.

V. SENSITIVITY ANALYSIS

A. CRITERIA WEIGHTS

A sensitivity analysis is carried out to analyze the outcome of the suggested method. One sort of robust testing and

TABLE 7. Initial matrix.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Weights of criteria	0.0874	0.0892	0.1044	0.0826	0.0895	0.1021	0.1268	0.0754	0.0685	0.0772	0.0549	0.042
Kind of criteria	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1
Supplier 1	4	8	2	4	2	7	2	2	9	2	5	5
Supplier 2	7	4	5	7	3	5	3	6	7	2	7	8
Supplier 3	9	5	3	7	5	4	5	3	5	6	4	3
Supplier 4	5	7	5	8	4	6	6	4	6	7	8	9
Supplier 5	3	5	7	9	4	4	7	5	4	9	8	6
Supplier 6	3	9	8	5	4	3	5	8	6	5	6	3

TABLE 8. The ranking results by FAHP-TODIM method.

Alternatives	Global Dominance G(i)	Relative Overall Value V(i)	Ranking
Supplier 1	-26.9668	0.5039	4
Supplier 2	-37.5194	0	6
Supplier 3	-29.455	0.3851	5
Supplier 4	-21.7558	0.7528	3
Supplier 5	-16.5783	**1**	**1**
Supplier 6	-18.3886	0.9136	2

TABLE 9. The ranking results by fuzzy AHP-TOPSIS method.

Alternatives	Si+	Si-	Ci	Ranking
Supplier 1	0.08429	0.074232	0.468274	4
Supplier 2	0.082058	0.043727	0.347633	6
Supplier 3	0.078223	0.056833	0.420809	5
Supplier 4	0.049033	0.075227	0.6054	2
Supplier 5	0.050489	0.091952	**0.645542**	**1**
Supplier 6	0.062198	0.081725	0.567839	3

sensitivity analysis involves computing the final ranking of alternatives when changing the weight of a particular criterion. The approach established by Alinezhad [36] is used for the sensitivity analysis where the weight of each criterion is removed one by one and then re-calculate the final ranking.

According to the results of sensitivity analysis, re-weighting (Table. 10) and supplier evaluation results (Table. 11). In most cases, supplier number 5 and 6 are the top 2 suppliers with slight changes in ranking between them in some cases, however their performance scores are closed in those cases. This suggests that the proposed model's is relatively robust and effective in finding optimal suppliers.

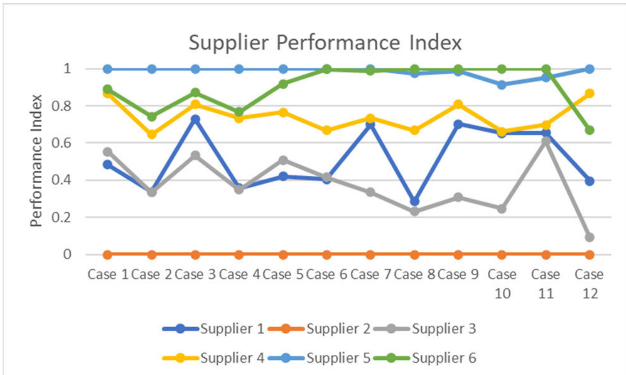

FIGURE 3. Suppliers' performance in each case.

In case number 12, supplier number 4 overtakes supplier number 6 as the second best supplier. This is because supplier number 4 performs extremely poor in waste generation criterion (C12) while supplier 6 is one of the best performers when consider this criterion. Therefore the result of case 12 suggests that the model performed as expected when there are changes to the criteria weights.

B. LOSS DECAY COEFFICIENT

Another sensitivity analysis can be performed to check the robustness of the results by alternating the loss decay coefficient (δ) of the TODIM model. If $\delta > 1$, the losses are attenuated; if $\delta < 1$, the losses are increased. As a result, this parameter allows decision makers to rank the alternatives based on their gains and: for big values of δ, the best alternatives provide more gains; while for small values of δ the best alternatives, the best alternatives provide little losses.

In this case, the TODIM model is re-ran for three cases: $\delta = 0.1$, $\delta = 1$, and $\delta = 2.5$. The final results is shown in Table. 12:

In all three cases, the ranking results are unchanged. This suggests that the case study results are robust against the sensitivity to losses of the decision makers.

TABLE 10. Criteria weights in analysed cases.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12
C1	0.0000	0.0960	0.0976	0.0953	0.0960	0.0973	0.1001	0.0945	0.0938	0.0947	0.0925	0.0912
C2	0.0977	0.0000	0.0996	0.0972	0.0980	0.0993	0.1022	0.0965	0.0958	0.0967	0.0944	0.0931
C3	0.1144	0.1146	0.0000	0.1138	0.1147	0.1163	0.1196	0.1129	0.1121	0.1131	0.1105	0.1090
C4	0.0905	0.0907	0.0922	0.0000	0.0907	0.0920	0.0946	0.0893	0.0887	0.0895	0.0874	0.0862
C5	0.0981	0.0983	0.0999	0.0976	0.0000	0.0997	0.1025	0.0968	0.0961	0.0970	0.0947	0.0934
C6	0.1119	0.1121	0.1140	0.1113	0.1121	0.0000	0.1169	0.1104	0.1096	0.1106	0.1080	0.1066
C7	0.1389	0.1392	0.1416	0.1382	0.1393	0.1412	0.0000	0.1371	0.1361	0.1374	0.1342	0.1324
C8	0.0826	0.0828	0.0842	0.0822	0.0828	0.0840	0.0863	0.0000	0.0809	0.0817	0.0798	0.0787
C9	0.0751	0.0752	0.0765	0.0747	0.0752	0.0763	0.0784	0.0741	0.0000	0.0742	0.0725	0.0715
C10	0.0846	0.0848	0.0862	0.0842	0.0848	0.0860	0.0884	0.0835	0.0829	0.0000	0.0817	0.0806
C11	0.0602	0.0603	0.0613	0.0598	0.0603	0.0611	0.0629	0.0594	0.0589	0.0595	0.0000	0.0573
C12	0.0460	0.0461	0.0469	0.0458	0.0461	0.0468	0.0481	0.0454	0.0451	0.0455	0.0444	0.0000

TABLE 11. Supplier performance.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12
Supplier 1	0.4849	0.3374	0.7293	0.3568	0.4210	0.4055	0.6995	0.2857	0.7016	0.6538	0.6550	0.3969
Supplier 2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Supplier 3	0.5540	0.3342	0.5325	0.3488	0.5090	0.4162	0.3359	0.2306	0.3088	0.2465	0.6089	0.0914
Supplier 4	0.8673	0.6459	0.8078	0.7351	0.7652	0.6691	0.7344	0.6682	0.8078	0.6622	0.6988	0.8680
Supplier 5	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9759	0.9860	0.9143	0.9525	1.0000
Supplier 6	0.8893	0.7420	0.8708	0.7668	0.9178	0.9988	0.9893	1.0000	1.0000	1.0000	1.0000	0.6683

TABLE 12. Supplier performance and ranking with different loss decay coefficients values.

Case	δ = 0.1		δ = 1		δ = 2.5	
	Performance Index	Ranking	Performance Index	Ranking	Performance Index	Ranking
Supplier 1	0.7016	4	0.5039	4	0.4800	4
Supplier 2	0.0000	6	0.0000	6	0.0000	6
Supplier 3	0.3361	5	0.3851	5	0.3910	5
Supplier 4	0.7022	3	0.7528	3	0.7589	3
Supplier 5	1.0000	1	1.0000	1	1.0000	1
Supplier 6	0.8912	2	0.9136	2	0.9163	2

VI. DISSCUSION AND CONCLUSION

In recent years, the push for steel production to satisfy domestic and international demand has increased significantly in Vietnam, along with increasing requirements in various aspects of the production process. The steel industry continues to face challenges such as shifting prices for raw materials, unstable global trade, and environmental concerns. This has pressured steel purchasers to better analyse and optimize their operations. Sustainable procurement therefore has become one the focus the industry. However, sustainable supplier evaluation and selection process can be complicate as it involves multiple quantitative and qualitative criteria.

For companies within the steel manufacturing industry, the results from the case study can provide useful insights. The weighting results of the evaluation criteria can be used to prioritize important criteria. Specifically, Reliability (C7) and On time delivery (C3) are identified as the most two most important criteria in this case study which suggests that companies should focus on these aspects of their businesses. The results of this study, practicularly the supplier ranking, can also be a useful resource for potential procurers who are looking for buying steel from Vietnam.

Futhermore, while Fuzzy AHP and TODIM are relatively easy to use and understand, the use of this model still necessitates basic knowledge and experience in MCDM model development and implementation. As a result, businesses should develop adequate guidance and instruction to aids with the application process. The model also has to be updated and re-evaluated frequently to guarantee its viability and efficacy in supplier selection.

The limitations of this study are that it solely takes into account local steel producers and does not provide a thorough comparison with popular Fuzzy MCDM models. Future research can extend from this study by expanding the pool of potential suppliers and criteria, or developing Fuzzy AHP-TODIM models to solve complex decision-making problems in different industries. Comparision study can also be done to analyse the proposed model performance to that of common methods. The proposed model can also be applied in combination with Multi-objectives decision making (MODM) models to solve supplier order allocation problems.

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