Research Paper

A Combined Fuzzy AHP-Hybrid TOPSIS Methodology to Determine Smelter Project Selection

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Abstract

This study aims to give recommendations on smelter project selection based on three alternatives: the Alumina Processing Plant, the Pig Iron Processing Plant, and MHP HPAL Nickel Plant by using a hybrid decision-making method Fuzzy AHP and Hybrid TOPSIS. The method integrates both qualitative expert judgments and quantitative data to ensure objectivity of analysis. Expert input was collected through structured interviews and questionnaires, capturing a diverse range of perspectives from technical, operational, and management roles. The Pairwise Comparison questionnaire data are analyzed using Fuzzy AHP to calculate the weights of these criteria, addressing the ambiguity in human judgment through triangular fuzzy numbers. These fuzzy weights were then combined with quantitative performance data for each project using Hybrid TOPSIS, ensuring the final ranking accounted for both qualitative and quantitative factors. The results showed that the Alumina Project achieved the highest closeness coefficient of 0.6, making it the most feasible and strategic project for immediate development. The Pig Iron Project ranked second, reflecting its stable production capacity and technical maturity, though it faces challenges from environmental impacts and a limited domestic market for pig iron. The MHP Nickel Project ranked third due to its complex environmental footprint, high capital intensity, and current market volatility, despite its relevance to the EV battery sector.

Keywords: *Fuzzy AHP; Hybrid TOPSIS; Smelter, Refinery, Mining Extractive*

INTRODUCTION

The mineral extractive industry is central to the economic development of countries. As part of Indonesia's efforts to maximize value creation from its mineral wealth, the government has implemented policies. These policies have supported foreign direct investment (FDI) growth and the expansion of mineral processing facilities, including nickel, bauxite, and iron sand projects (Febrianto & Suparto, 2019; Nofrianto et al., 2021). This research focuses on selecting the most feasible project among three potential smelter developments: a MHP Nickel Plant, an Alumina Processing Plant, and a Pig Iron Processing Plant, which have the potential to strengthen Indonesia's mineral processing sector and support sustainable economic growth.

Despite the country's rich bauxite resources, the development of alumina refineries has been stagnant (Chen, 2023), prompting renewed government initiatives since 2022 to accelerate progress. Iron sand lacks domestic smelter facilities to transform it into value-added products like pig iron. Meanwhile, the development of HPAL technology aligns with Indonesia's ambitions to strengthen the electric vehicle (EV) battery supply chain, making it a key component in national green energy targets.

Previous studies have often used the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to rank project alternatives. While AHP is widely used to determine the relative importance of qualitative criteria, it can be sensitive to judgment bias in pairwise comparisons. To address this, the fuzzy AHP approach extends AHP by incorporating fuzzy numbers, which handle uncertainty in human judgment (Kabir & Sumi, 2012; Li & Zou, 2011). Similarly, the hybrid TOPSIS method has been applied to integrate

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quantitative performance data with qualitative assessments, enhancing decision-making accuracy.

Regardless of these advances, limitations persist, particularly the reliance on purely qualitative expert judgments. This research aims to overcome these limitations by incorporating quantitative data, such as project investment costs, expected profits, market share, and production capacity into the decision-making framework. The novelty of this research lies in combining the fuzzy AHP and hybrid TOPSIS methods to rank the three smelter project alternatives. This dual approach ensures a balanced and objective prioritization that reflects the complex nature of smelter project development in Indonesia. Despite these studies showing the potential of fuzzy AHP–hybrid TOPSIS, most did not integrate real operational data, limiting their objectivity.

LITERATURE REVIEW

Multi-Criteria Decision Making (MCDM) has become a widely adopted framework to address complex project selection challenges, particularly in capital-intensive and extractive industries. Among MCDM methods, the AHP and TOPSIS are frequently used to prioritize industrial projects and have been successfully applied in energy sector evaluations, infrastructure development, and mining projects, offering structured approaches to evaluate multiple conflicting criteria (Kabir & Sumi, 2012; Li & Zou, 2011). Recognizing the limitations of conventional AHP and TOPSIS in reliance on precise judgments, recent research has increasingly turned to hybrid approaches that integrate fuzzy logic. The fuzzy AHP–TOPSIS hybrid approach captures uncertainties, thus improving the reliability of decision-making processes (Zavadskas et al., 2016).

Overview of Smelter Development in Indonesia

Indonesia has implemented policies to strengthen its downstream mineral processing sector. Development in bauxite refining and iron sand smelting has lagged, creating opportunities for new projects to support national economic growth. While the industrial benefits are evident, researchers have also noted the importance of managing its broader impacts. A study by Sangadji and Ginting (2023) emphasizes the need for stronger governance to ensure environmental protection, fair labor practices, and equitable value distribution. Complementing this view, Guberman et al. (2024) highlight Indonesia's success in increasing export value and production capacity following the ban, while also underscoring the long-term challenge of aligning mineral processing with international sustainability standards. Together, these perspectives suggest that while the export ban has been effective in driving industrial growth.

However, the current progress is not as smooth as Nickel downstreaming development; some challenges and issues remain unsolved and become constraint for investors to continue the project development for other commodities. Indonesia's nickel sector has thrived, contributing over 40% of global production, while other commodities like bauxite have struggled, largely due to investment hesitancy and policy impacts following the 2014 export ban (Firmanto et al., 2025). As of 2024, Indonesia has only three alumina refineries and one aluminum smelter in operation (Chen, 2023), highlighting the slower progress compared to nickel downstreaming. This constraints underscores the need to understand commodity-specific dynamics, as demonstrated by a comparison with the Philippines, where differing development strategies have led to divergent mining sector outcomes.

Several factors constrain the effectiveness of the bauxite export ban in Indonesia, including that global demand for bauxite is lower than that for nickel, and Indonesia lacks sufficient domestic smelting and refining capacity to accommodate the redirected bauxite supply. Investors are hesitant to develop new alumina refinery projects due to high capital costs, long development timelines, and market uncertainties. Global buyers can easily source bauxite from alternative suppliers like Australia and Guinea (Chen, 2023). These structural differences suggest that, unlike the nickel sector, Indonesia's bauxite policy may only disrupt exports in the short term without driving the same level of long-term industrial transformation.

The outlook for smelting development in Indonesia reflects a mix of strong potential and systemic challenges. While the country's abundant mineral resources and downstream industrialization goals present clear opportunities, the overall competitiveness of the smelter industry remains weak due to structural and policy limitations. Hanafi et al. (2019) identify key barriers that include inconsistent regulations, insufficient infrastructure, unreliable energy supply, and limited support for investment feasibility, particularly in high capital expenditure.

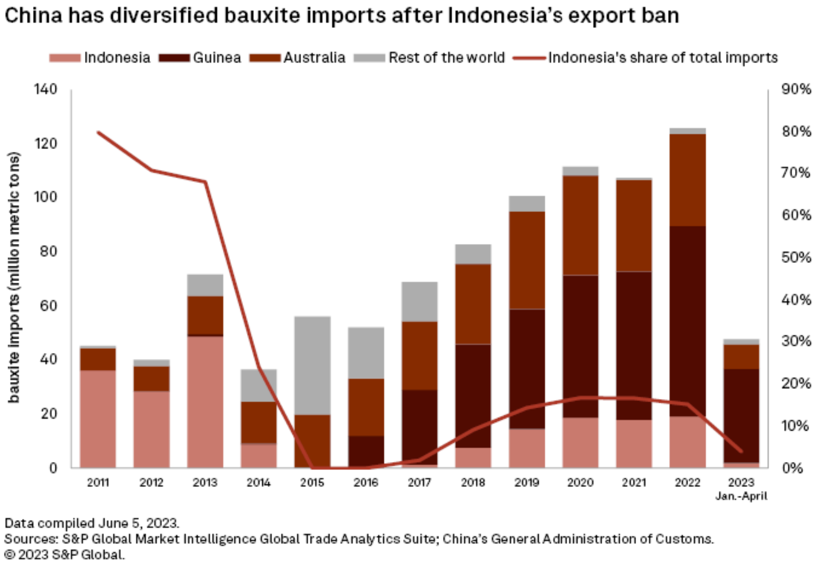

Figure 1. China, which stands as the primary consumer of Indonesian bauxite, shows diversified bauxite imports, with substantial volumes originating from Australia and Guinea (Chen, 2023).

Application of MCDM in The Industry Sector

Multi-Criteria Decision Making (MCDM) is adapted for various applications, including project selection, resource allocation, and policy analysis (Vargas, 2010). MCDM allows decision makers to evaluate multiple conflicting selections of choices that involve both quantitative and qualitative considerations (Wang & Elhag, 2005). In Capital-Intensive industry, problem solving using the MCDM method is widely used, particularly as these decisions often have complex features like inherent uncertainties (Al-Mohamed et al., 2023).

Among the most applied methods is the AHP, which decomposes complex decisions into a hierarchical structure and uses pairwise comparisons to derive criteria weights. It is widely appreciated for its transparency and consistency checks and has been effectively used in infrastructure and energy planning (Algarin et al., 2017). TOPSIS is frequently employed due to its ability to rank options based on proximity to an ideal solution, offering a straightforward and logical output (Behzadian et al., 2012). VIKOR provides compromise solutions based on ideal and regret measures (Opricović & Tzeng, 2003), and PROMETHEE, which offers visual and preference-based ranking outputs. Previous studies conducted by Brans and Mareschal (2006) are also applied in complex prioritization settings such as transportation, sustainability, and energy transition.

Overall, combining several methods in MCDM can complement each other, such as integrating AHP with TOPSIS and including fuzzy calculations. This integration helps to handle interdependencies between criteria and provides a more accurate weighing method and has been successfully applied in various sectors to support decision-making under complex, uncertain, and multi-criteria conditions. In project prioritization, particularly within capital-intensive and extractive industries, these methods are effective in integrating both financial and non-financial criteria.

However, these techniques are not without limitations, as the applicability of MCDM is constrained by the subjectivity involved in assigning weights to the criteria, which may not accurately reflect the preferences of all stakeholders, and it is also computationally intensive (Freire et al., 2018). Decisions often involve ambiguity and subjective judgments, leading to the integration of fuzzy logic into AHP. Fuzzy AHP addresses this by allowing expert input through linguistic terms, making it highly suitable for evaluating strategic industrial investments with qualitative criteria (Önüt et al., 2008; Rivero-Iglesias et al., 2023). Fuzzy TOPSIS, its fuzzy counterpart, extends the TOPSIS model by incorporating uncertain or imprecise data, making it particularly applicable in evaluating industrial projects where expert judgment is dominant and precise quantification is limited (Akintayo et al., 2023; Wang & Elhag, 2005).

Fuzzy AHP – Hybrid TOPSIS

Integrating Fuzzy AHP with other MCDM techniques, such as Hybrid TOPSIS, has proven to be an effective strategy for handling complex project prioritization tasks, particularly in capital-intensive sectors like smelting. One of the primary limitations of traditional AHP is its inability to accommodate imprecise or vague input from experts—a challenge that fuzzy logic is well-suited to address (Afolayan et al., 2020). By incorporating fuzzy sets, Fuzzy AHP allows for a more accurate representation of subjective expert judgments, enabling the assignment of differentiated weights to multiple indicators, even under uncertainty (Alghassab, 2022; Gao & Li, 2018). Once the criteria weights are established, Hybrid TOPSIS is employed to rank alternatives by evaluating their relative closeness to ideal and anti-ideal solutions and mixed-polarity indicators (Aljohani, 2023; Demircan & Yetilmezsoy, 2023; Wicaksono, 2021).

This hybrid approach reduces bias in qualitative assessments by transforming linguistic variables into quantitative calculations, resulting in a more robust and defensible decision output (Kannan et al., 2013; Karataş et al., 2018). Comparative studies have shown that this combination performs more consistently than single-method MCDM tools or alternative hybrids such as the Best Worst Method–TOPSIS model, especially in prioritizing projects with interrelated technical, environmental, and financial dimensions (Rivero-Iglesias et al., 2023; Tırkolaee et al., 2019). The method is not without limitations, such as sensitivity to subjective membership function design and potential inconsistency in expert input. These can be mitigated by involving diverse expert panels, validating outputs through sensitivity analysis, and adopting real-time data where applicable (Cheng et al., 2025).

Criteria, Sub-Criteria and Alternatives Selection

Selecting appropriate criteria, sub-criteria, and alternatives is crucial for the success of any MCDM framework. Saaty (1980) explains that breaking down a complex problem into hierarchical levels of goal, criteria, sub-criteria, and alternatives helps decision-makers understand the nature of the decision and all elements involved. These criteria should represent the various dimensions relevant to the decision problem, while sub-criteria provide a more detailed breakdown of each criterion. In smelter project evaluations, typical top-level criteria include economic feasibility, environmental impact, social considerations, technological aspects, (Rivero-Iglesias et al., 2023), political, and market (Saaty & Vargas, 2012).

Table 1. Factors that Affected the Project Development in Capital-Intensive

Parameter	Type	Sub Parameter	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
Economic	quantitative	investment cost	✓	✓	✓	✓	✓	✓	✓	✓
	quantitative	operation and maintenance cost	✓	✓	✓	✓	✓			
	quantitative	technology cost	✓					✓		✓
	qualitative	resource potential	✓					✓	✓	
	quantitative	payback period	✓				✓			✓
	quantitative	net present	✓							
Technical	qualitative	efficiency	✓	✓		✓	✓			
	qualitative	technology maturity	✓		✓		✓		✓	✓
	qualitative	risk	✓					✓		✓
	qualitative	safety	✓			✓				
	quantitative	production capacity	✓			✓				
	qualitative	reliability	✓		✓	✓	✓			
	qualitative	ability to respond to demand	✓		✓			✓		
	quantitative	resources availability	✓		✓	✓	✓		✓	
Environment	quantitative	land use	✓		✓	✓	✓			
	qualitative	impact on environment	✓						✓	
	qualitative	potential for reduction of ghg	✓						✓	
	quantitative	water consumption	✓		✓	✓	✓			
	quantitative	enviro external costs	✓	✓						
	qualitative	force majeure risk	✓							
Social	qualitative	social acceptability	✓	✓	✓	✓	✓	✓	✓	✓
	qualitative	job creation	✓	✓	✓	✓	✓			
	qualitative	social benefits	✓			✓	✓			
Political	qualitative	policy in project country						✓	✓	✓
	qualitative	political instability						✓	✓	
	qualitative	political acceptance								✓
Market	quantitative	market share						✓		
	quantitative	demand of the product						✓		
	qualitative	competitive advantage of the product						✓	✓	

Conceptual Framework

The conceptual framework for this study integrates both qualitative and quantitative factors to prioritize the three smelter projects. Qualitative data from structured interviews with high-level management and experts are used to determine the relative importance of various criteria and sub-criteria, while quantitative project data, such as investment costs, expected profitability, and production capacity, enhance the objectivity of the evaluation. By balancing these inputs, the framework addresses the challenges of potential bias in decision-making and provides a comprehensive basis for determining the most feasible project.

This study aims to improve upon previous research by combining these quantitative data with fuzzy numbers, which help to reduce potential biases in qualitative research. This research hypothesis that integrating quantitative data with fuzzy weighting will provide more reliable and objective results in project prioritization, offering a significant improvement over previous studies that relied solely on qualitative inputs.

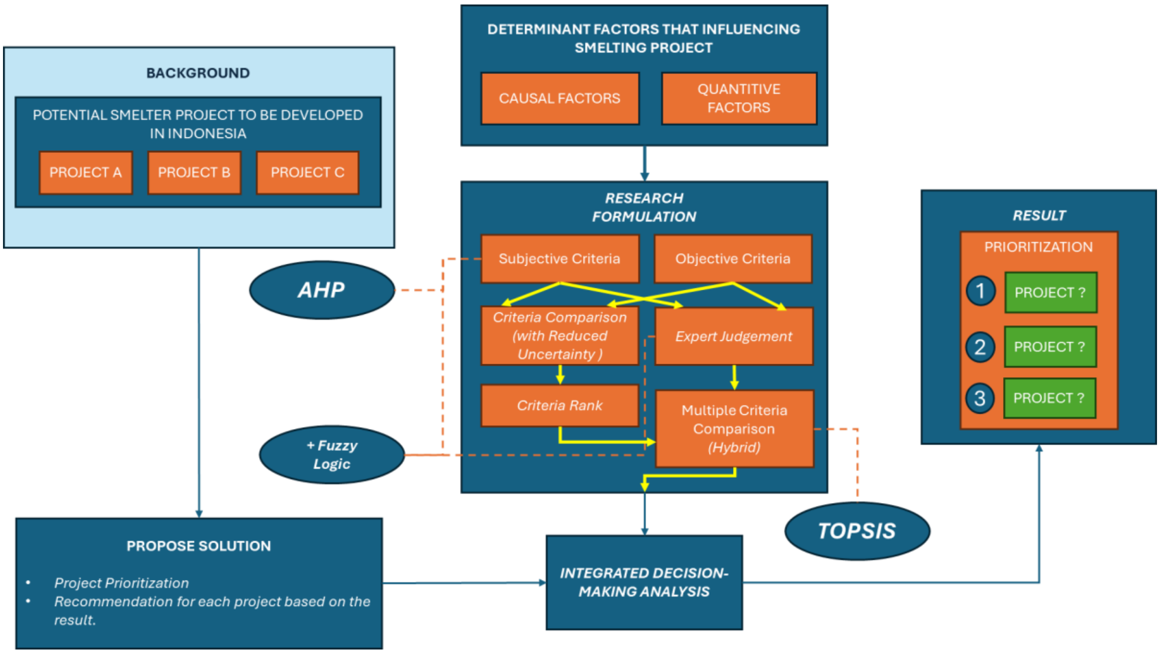

Figure 2. Conceptual Framework of the Study

To be able to determine the best project to be selected, knowing what factors influence the project will be crucial, especially in Capital-intensive projects and in developing country like Indonesia. AHP Process will help a complex decision matrix by breaking down the problem into a hierarchical structure and combining with Fuzzy numbers to manage uncertainty due to subjective judgement. Hybrid TOPSIS is then used to combine the qualitative input and quantitative factors and analyze the result based on the distance to the ideal solution. The result will give insight into which alternatives are recommended to be selected.

RESEARCH METHOD

The research design of this study explains how the overall process is used to solve the issues, starting from problem identification and data gathering to final recommendations. It shows how this study aims to reflect the real-world conditions that influence project viability, including the global market changes and Indonesia's industrial policies. This study uses primary and secondary data to support the analysis. The data is collected by interviews and involves assessment from experts. Both qualitative and quantitative data were gathered to ensure that the study covers all relevant aspects, including economic, social-political, market, environmental, and technical factors. Using a combination of qualitative data for sub-criteria, with the addition of quantitative data for sub-criteria, helps to give a more objective score for each project, reducing potential bias in expert judgment.

Finally, the data will be analyzed using the combination of Fuzzy AHP and Hybrid TOPSIS. This method combines the ability of AHP to calculate the relative importance of criteria with the ranking capability of TOPSIS and addresses the subjectivity in expert opinions by using fuzzy logic. The use of quantitative data together with this combined method ensures that the final ranking and recommendations are as objective and reliable as possible. This research also contributes to the existing studies on decision-making by showing how combining fuzzy AHP and hybrid TOPSIS can be applied to capital-intensive projects like smelting, giving clearer insights for prioritizing the project.

Research Design

This study develops a structured and reliable methodology to prioritize three potential project alternatives: an Alumina Processing Plant, a Pig Iron Processing Plant, and a MHP HPAL plant. The prioritization process considers both qualitative and quantitative factors, which are shaped by global, national, and internal conditions. Using a case study approach, the research focuses on the practical application of the hybrid Fuzzy AHP–Hybrid TOPSIS method to rank these projects, supported by data from literature, expert interviews, and project feasibility documents.

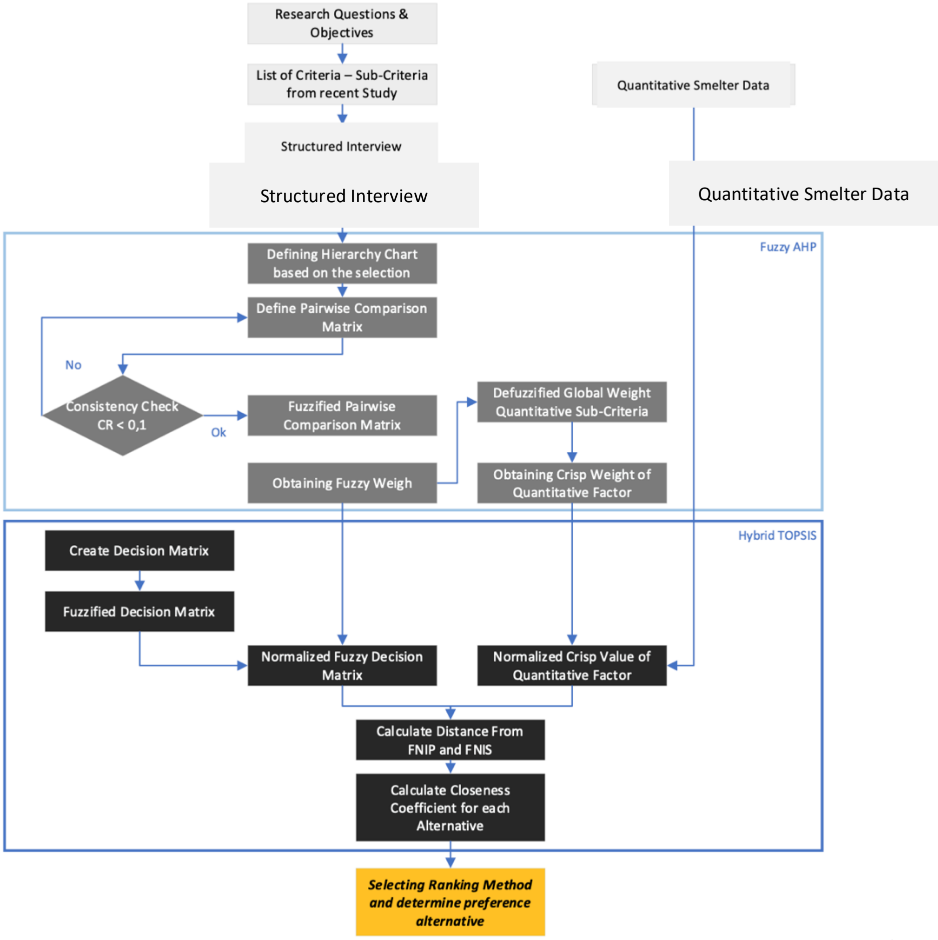

Figure 3. Research design of the study

Data Collection Method

The initial stage involved a comprehensive literature review and the gathering of smelter quantitative data to identify relevant decision factors. A key experience leader in a smelting company was interviewed to validate and refine the selected criteria and sub-criteria.

After establishing the criteria structure and project alternatives, the researchers conducted primary data collection for the Fuzzy AHP analysis. The sampling strategy is Purposive sampling where the judgement is already selected based on the expertise in the smelter industry and capital-intensive project development, to give valuable information for the study. This involved distributing questionnaires to a panel of eleven experts, including both internal stakeholders and external industry professionals. The questionnaires utilized linguistic scales to capture the expert judgments in pairwise comparisons between the criteria and sub-criteria. For the Hybrid TOPSIS component, the researchers extracted quantitative data from the technical and financial feasibility studies of each project alternative. This data provided the necessary input values for constructing the decision matrix, such as cost, production volume, and project timelines.

Table 2. Experts' Background and Data Collection Method

No	Key Persons Title	INITIAL	Company Background	Data Collection method
1	President Director	Experts A	Holding Company (for Smelter Industry)	Brainstorming (for Factors Selection) and Rating Scale (used for TOPSIS)
2	Director	Experts B	Holding Company (for Smelter Industry)	Rating Scale (used for TOPSIS)
3	Head of Legal Dept.	Experts C	Holding Company (for Smelter Industry)	Rating Scale (used for TOPSIS)
4	Head of Pyrometallurgy Laboratorium	R1	Technical Consultant in Smelter	Questionnaire - Pairwise Comparison
5	Head of Logistic Dept.	R2	Smelter Company	Questionnaire - Pairwise Comparison
6	Technical Advisor - Smelting	R3	Technical Consultant in Smelter	Questionnaire - Pairwise Comparison
7	Country Director	R4	Technical Consultant in Smelter	Questionnaire - Pairwise Comparison
8	Assistant Manager FAT Dept.: Bank Syndication	R5	Smelter Company	Questionnaire - Pairwise Comparison
9	Manager of FAT	R6	Holding Company (for Smelter Industry)	Questionnaire - Pairwise Comparison
10	Head of Sales Dept	R7	Smelter Company	Questionnaire - Pairwise Comparison
11	Head of HSE Site Services	R8	Smelter Company	Questionnaire - Pairwise Comparison
12	Assistant Manager EXIM Dept. : Import	R9	Smelter Company	Questionnaire - Pairwise Comparison
13	Committee for Acceleration of Priority Infrastructure Delivery (KPPIP) - Economic Analyst	R10	Ministerial	Questionnaire - Pairwise Comparison
14	Head of Export - Import Dept	R11	Smelter Company	Questionnaire - Pairwise Comparison

Data Analysis Method

To address the complexity and uncertainty inherent in project prioritization for capital-intensive smelter development, this research adopts a hybrid multi-criteria decision-making (MCDM) methodology that combines Fuzzy AHP with Hybrid TOPSIS. The selection of this combined approach is based on its proven ability to systematically evaluate both qualitative and quantitative criteria, reduce subjectivity in expert judgment, and generate a reliable ranking of project alternatives under conditions of limited or ambiguous information.

In practice, especially in contexts involving diverse stakeholders or uncertain environments such as smelting industry investment decisions, such assumptions often do not hold. Expert judgments may vary significantly depending on the individual's background, experience, or interpretation of qualitative factors. Within these limitations, this study integrates fuzzy logic into the AHP process, allowing decision-makers to express their preferences using linguistic terms that are then converted into fuzzy triangular numbers. This adjustment accommodates uncertainty and subjective variability in expert assessments, especially in the weighting of qualitative criteria and sub-criteria. Once the weights are derived using Fuzzy AHP, they are applied to the Hybrid TOPSIS model to prioritize the three project alternatives: the Alumina Processing Plant, Pig Iron processing plant, and MHP HPAL project.

The Hybrid TOPSIS method is selected for its ability to rank alternatives based on their relative closeness to the ideal solution, effectively handling both benefit and cost criteria. In this study, the Hybrid TOPSIS model is adapted by integrating fuzzy logic specifically for qualitative criteria. This ensures that the subjective evaluation of alternatives based on expert judgments reflects uncertainty and detail through fuzzy scales. The Pairwise comparison and decision-making judgement were collected using an online questionnaire from experts. Consistency Ratio (CR) for the pairwise comparison process can be obtained from the web-based application. The calculation process, including fuzzy definition, was using Excel tool to calculate Fuzzy AHP and Hybrid TOPSIS method.

This methodology enhances the robustness of the decision-making framework. It reduces the influence of cognitive bias, allows for more realistic modelling of expert uncertainty, and enables integrated analysis of both qualitative and quantitative performance indicators. This methodological configuration represents a marginal yet meaningful contribution, tailoring the standard Fuzzy AHP–Hybrid TOPSIS approach to better reflect the unique requirements of smelter project prioritization under conditions of limited certainty and strategic complexity. The integrated Fuzzy AHP-Hybrid TOPSIS framework leverages the strengths of both methodologies to provide a robust and adaptable solution for complex decision-making problems (Al-Mohamed et al., 2023; Janjua & Hassan, 2020).

FINDINGS AND DISCUSSION

The process of analyzing the best recommendation for Project Prioritization is described in the following section. The MCDM using Fuzzy-AHP and Hybrid TOPSIS method is used to integrate both qualitative and quantitative criteria and give recommendations for the best alternatives based on several factors that influence the project.

Analysis

The analysis of this research is sourced from information through literature review, and quantitative data from smelters. The analysis begins with the criteria and sub-criteria selection, which were determined from the implementation of structured interview with an experienced leader in the smelting industry. The data combines real-world factors that influence project development.

Pairwise comparison judgement from experts will be used for Fuzzy AHP analysis, to get the relative importance of alternatives within the criteria and sub-criteria, and get the weight and evaluate alternatives based on their proximity to an ideal solution and distance from a negative ideal solution.

Alternatives Introduction

The alternatives are based on the potential resources of the commodity to be utilized in Indonesia. The detailed information about the project is needed in the analysis as a consideration of the experts' evaluation. The quantitative smelter information is based on the author analysis through the previous project benchmark with a similar smelter development. The resume of Project Alternatives' key information can be seen in table 3.

Table 3. Summary of Alternative Project Smelter Development

Alternatives	Product & Capacity (tpa)	Investment (Million USD)	Revenue / Net Profit (Million USD)	Market Share
Alumina Processing Plant	Alumina / 2 million	524	755 / 102,7	1,45%
Pig Iron Processing Plant	Pig Iron / 1,6 million	312	479 / 75	0,12%
MHP HPAL Project	MHP / 50,000 Ni	971,6	710,71/157,68	9,03%

Criteria and Sub-Criteria Selection

The criteria and sub-criteria are selected by analyzing the factors that influence the project development through literature review, within a similarity background and cases. Then, an interview with an experienced leader was conducted, to give insight on the selections.

Table 4. Selected Criteria and Sub-Criteria Based on Decision Maker Inputs and Real-World Literature Review

Criteria	Sub-criteria	Remarks	Indicators of Evaluation
Economic	Commodity price stability	The consistency of commodity prices over time.	Stable prices reduce financial risk and help in accurate financial forecasting and planning.
	Investment cost	The total capital required to start and maintain the project, including infrastructure, equipment, and technology.	Lower investment costs are preferable as they reduce financial burden.
	Net Profit	The financial gain after deducting all expenses from revenue.	Higher net profit indicates a more financially successful project.
Technical	Commodity resource utilization	The efficiency with which the raw materials are used to produce the final product.	Higher utilization rates indicate better resource management and cost-efficiency.
	Production Capacity	The maximum output that can be produced under normal operating conditions.	Higher production capacity can meet larger market demands and improve economies of scale.

	Technical Maturity	The level of development and reliability of the technology used in the project.	More mature technologies are typically more efficient and less risky.
Environment	Impact on environment	The extent to which the project affects the natural environment, including emissions, waste, and resource depletion.	Projects with lower environmental impact are more sustainable and likely to face less regulatory and social opposition.
	Supporting Paris Agreement in Climate Change Mitigation	The Product is potentially supporting the climate change initiatives (i.e. material for EV, battery, etc.)	Product that utilized as material for green products and aligned with paris agreement are better for long-term sustainability and compliance with future regulations.
Socio-politic	Political Instability	The risk of political events disrupting project operations.	Lower political instability is favorable as it ensures a more predictable and secure operating environment.
	Social Acceptance	The level of support or opposition from local communities and stakeholders.	High social acceptance reduces the risk of conflicts and facilitates smoother project implementation.
Market	Market share	The proportion of the market controlled by the project.	Higher market share indicates competitive strength and potential for better profitability.
	Product demand	The current and projected demand for the product.	High and growing demand increases revenue potential and project viability.

Construction of Hierarchy

The hierarchy will help us visualize the relationship of criterion, sub-criterion, and alternatives to achieve decision-making goals, which includes the selection of the smelting project. Decompose a complex decision problem into manageable, structured levels, facilitating analysis and comparison of criteria and alternatives.

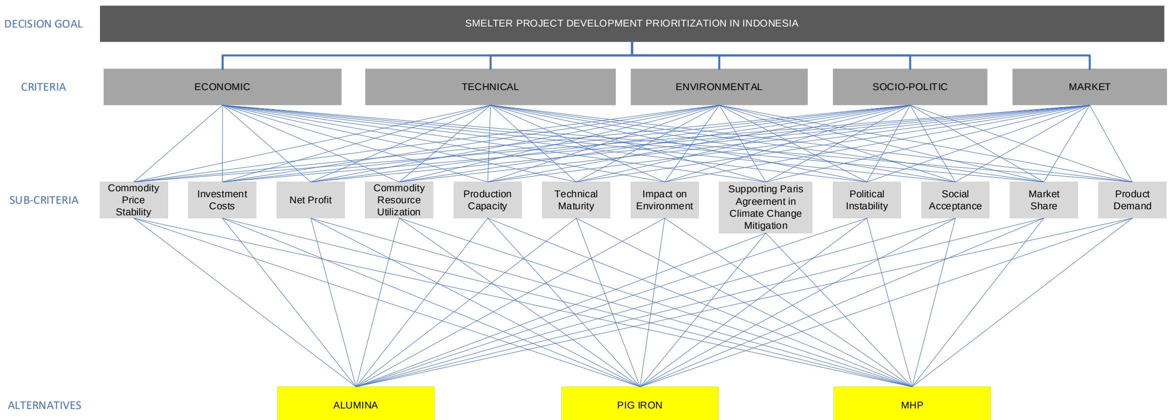

Figure 4. Hierarchy of Criteria, Sub-criteria, and Alternatives of the Project

Construction Pairwise comparison matrices

Pairwise comparison matrices are made after collecting the results from questionnaire. The questionnaire from experts also calculated the Consistency Ratio to provide the minimum standard CR<0.1 analysis and check the judgement consistency from respondents. This research utilizes a web-based application developed by Klaus D. Goepel (https://bpmsg.com/) and applies the relative scale of importance proposed by Saaty (1980), as presented in Table 5

Table 4. AHP definition of Relative Importance

Definition	**Intensity of importance**
Equal Importance	1
Moderate Importance	3
Strong Importance	4
Very Strong Importance	7
Extreme Importance	9
values in-between	2,4,6,8

Table 5. Summary of Pairwise Comparison matrices of selected Criteria

Pairwise Comparison			**Respondent**										
Criteria Comparison			**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**R10**	**R11**
Market	<--->	Economy	4	5	2	2	7	3	3	8	2	4	4
Market	<--->	Technical	3	4	1	2	2	3	6	6	2	6	7
Market	<--->	Socio-Politic	2	7	3	5	3	6	6	4	6	6	5
Market	<--->	Environment	4	7	2	2	9	5	9	6	7	4	6
Economy	<--->	Technical	4	8	2	2	7	3	3	6	2	8	7
Economy	<--->	Socio-Politic	1	7	2	5	2	1	6	7	5	3	6
Economy	<--->	Environment	2	7	2	1	3	3	6	3	4	8	3
Technical	<--->	Socio-Politic	2	6	2	3	7	1	4	3	1	9	2
Technical	<--->	Environment	2	7	2	1	9	1	7	3	6	3	9
Socio-Politic	<--->	Environment	2	8	2	2	9	3	3	7	4	8	8

Note: The numbers indicate the relative importance values of the criteria provided by experts. Green and blue highlight the criteria to which the values correspond.

Table 6. Summary of Pairwise Comparison matrices of selected Sub-Criteria

Pairwise Comparison			**Respondent**										
Sub-Criteria Comparison			**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**R10**	**R11**
Under Market Critera													
M1	<----->	M2	1	5	1	3	9	6	7	7	7	7	8
Under Economy Criteria													
EC1	<----->	EC2	3	2	2	2	4	1	6	8	4	4	5
EC1	<----->	EC3	1	4	1	6	4	1	3	4	5	7	4
EC2	<----->	EC3	4	2	2	7	9	1	8	5	8	4	8
Under Technical Critera													
T1	<----->	T2	1	1	2	5	2	4	4	7	6	4	5
T1	<----->	T3	1	5	1	3	8	1	3	3	8	5	3
T2	<----->	T3	2	5	2	5	4	4	6	5	3	9	7
Under Socio-Politic Criteria													
SP1	<----->	SP2	3	3	2	3	8	4	4	5	7	9	6
Under Environment Criteria													
EN1	<----->	EN2	4	5	2	3	9	4	3	7	7	7	8

Note: The number represent relative importance value of criteria from experts, and green & blue color represent relative to what criteria.

M1 : Market Share
M2 : Product Demand
EC1 : Commodity Price Stability
EC2 : Investment Cost
EC3 : Net Profit
T1 : Commodity Resources Utilization
T2 : Production Capacity
T3 : Technology Maturity
SP1 : Political Instability
SP2 : Social Acceptance
EN1 : Impact on Environment
EN2 : Supporting Paris Agreement on Climate Change

The results of the pairwise comparison questionnaires varied across experts, reflecting their respective backgrounds; these responses were then aggregated across criteria and sub-criteria to determine global priorities, with the Consistency Ratio calculated using the web-based application (https://bpmsg.com/) to assess the reliability of the comparisons.

Table 7. Consistency Ratio of The Project

	Criteria	Market	Economy	Technical	Socio-politic	Environment
R1	8.9%	0%	1%	5.6%	0%	0%
R2	4.3%	0%	0%	0%	0%	0%
R3	6.3%	0%	0%	0%	0%	0%
R4	2.3%	0%	14.1%	0%	0%	0%
R5	7.5%	0%	3.9%	0%	0%	0%
R6	11%	0%	0%	0%	0%	0%
R7	9.2%	0%	7.7%	5.6%	0%	0%
R8	10%	0%	9.8%	6.8%	0%	0%
R9	7.8%	0%	7.7%	9.8%	0%	0%
R10	9.2%	0%	8%	7.4%	0%	0%
R11	0.2%	0%	9.8%	6.8%	0%	0%

Fuzzified Matrices

Experts provide their judgments on the relative importance of each criterion and sub-criterion using linguistic variables (e.g., equally important, moderately more important). These are translated into fuzzy triangular numbers to account for subjectivity and ambiguity in expert input. The fuzzy matrices are calculated using excel calculation based on the definition of relative importance as shown in Table 9.

Table 8. AHP Definition of Relative Importance and Fuzzy Scale of Relative Importance

Definition	Intensity of importance	Fuzzy Scale of Relative Importance	Reciprocal Fuzzy Scale
Equal	1	(1,1,1)	
Moderate	3	(2,3,4)	$(1/4, 1/3, 1/2)$
Strong	4	(4,5,6)	$(1/6, 1/5, 1/4)$
Very Strong	7	(6,7,8)	$(1/8, 1/7, 1/6)$
Extremely Strong	9	(9,9,9)	$(1/9, 1/9, 1/9)$

Definition	Intensity of importance	Fuzzy Scale of Relative Importance	Reciprocal Fuzzy Scale
values in-between	2	(1,2,3)	$(1/3, 1/2, 1)$
	4	(3,4,5)	$(1/5, 1/4, 1/3)$
	6	(5,6,7)	$(1/7, 1/6, 1/5)$
	8	(7,8,9)	$(1/9, 1/8, 1/7)$

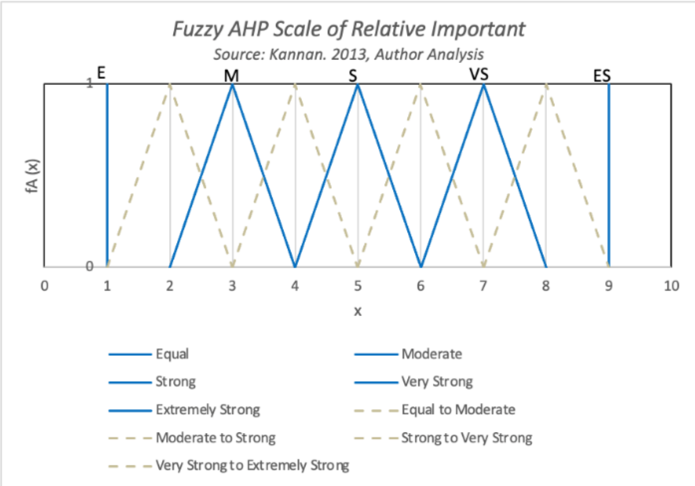

Figure 5. Fuzzy Scale of Relative Importance (Kannan et al., 2013)

Table 9. Sample of fuzzified Pairwise Comparison Matrix of Criteria (From Respondent 1)

Pairwise Comparison Matrix

	M	**EC**	**T**	**SP**	**EN**
M	1	$\frac{1}{4}$	3	$\frac{1}{2}$	$\frac{1}{4}$
EC	4	1	4	1	$\frac{1}{2}$
T	$\frac{1}{3}$	$\frac{1}{4}$	1	$\frac{1}{2}$	$\frac{1}{2}$
SP	2	1	2	1	$\frac{1}{2}$
EN	4	2	2	2	1

===>

Fuzzified Pairwise Comparison Matrix

	M			**EC**			**T**			**SP**			**EN**		
M	1	1	1	$\frac{1}{5}$	$\frac{1}{4}$	$\frac{1}{3}$	2	3	4	$\frac{1}{3}$	$\frac{1}{2}$	1	$\frac{1}{5}$	$\frac{1}{4}$	$\frac{1}{3}$
EC	3	4	5	1	1	1	3	4	5	1	1	1	$\frac{1}{3}$	$\frac{1}{2}$	1
T	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{5}$	$\frac{1}{4}$	$\frac{1}{3}$	1	1	1	$\frac{1}{3}$	$\frac{1}{2}$	1	$\frac{1}{3}$	$\frac{1}{2}$	1
SP	1	2	3	1	1	1	1	2	3	1	1	1	$\frac{1}{3}$	$\frac{1}{2}$	1
EN	3	4	5	1	2	3	1	2	3	1	2	3	1	1	1

Table 10. Sample of fuzzified Pairwise Comparison Matrix of Sub-Criteria (From Respondent 1)

Market

	M1	M2
M1	1	1
M2	1	1

===>

Market

	M1			M2		
M1	1	1	1	1	1	1
M2	1	1	1	1	1	1

Economy

	EC1	EC2	EC 3

Economy

	EC1			EC2			EC3		

Market					Market									
EC1	1	3	1		EC1	1	1	1	2	3	4	1	1	1
EC2	$\frac{1}{3}$	1	$\frac{1}{4}$	===>	EC2	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{2}$	1	1	1	$\frac{1}{5}$	$\frac{1}{4}$	$\frac{1}{3}$
EC3	1	4	1		EC3	1	1	1	3	4	5	1	1	1

Technical					Technical									
	T1	T2	T3				T1			T2			T3	
T1	1	1	1		T1	1	1	1	4	5	6	3	4	5
T2	1	1	$\frac{1}{2}$	===>	T2	$\frac{1}{8}$	$\frac{1}{7}$	$\frac{1}{6}$	1	1	1	7	8	9
T3	1	2	1		T3	$\frac{1}{5}$	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{9}$	$\frac{1}{8}$	$\frac{1}{7}$	1	1	1

Socio-Politic				Socio-Politic						
	SP1	SP2				SP1			SP2	
SP1	1	$\frac{1}{3}$	===>	SP1	1	1	1	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{2}$
SP2	3	1		SP2	2	3	4	1	1	1

Environment				Environment						
	EN1	EN2				EN1			EN2	
EN1	1	$\frac{1}{4}$	===>	EN1	1	1	1	$\frac{1}{5}$	$\frac{1}{4}$	$\frac{1}{3}$
EN2	4	1		EN2	3	4	5	1	1	1

Aggregate Expert Judgement

The aggregation of expert judgements facilitates the calculation of fuzzy matrices as a form of group-based judgement, thereby reducing potential bias from individual perspectives and reflecting a consensus that represents the collective opinion of the expert group. The calculation used in this research is the arithmetic mean, for lower, middle, and upper values in fuzzy form. However, other approaches, such as the geometric mean, are also widely used in literature because the approach of calculation is to capture the multiplicative nature of judgments and mitigate extreme values. By utilizing the overall fuzzy matrices of the criteria, the aggregate expert judgment is calculated, with the results presented in Table 12.

Table 11. Aggregate Fuzzy Pairwise Comparison Matrix of Criteria

		M			EC			T			SP			EN	
M	1,00	1,00	1,00	1,27	1,84	2,45	2,03	2,76	3,49	3,34	4,10	4,89	1,93	2,24	2,58
EC	1,95	2,46	3,05	1,00	1,00	1,00	2,94	3,77	4,60	3,27	4,09	4,91	1,37	1,86	2,39
T	1,18	1,43	1,79	1,00	1,24	1,59	1,00	1,00	1,00	1,81	2,21	2,67	2,07	2,55	3,07
SP	0,66	0,96	1,27	0,35	0,40	0,52	1,47	1,87	2,31	1,00	1,00	1,00	0,78	1,10	1,52
EN	2,98	3,54	4,14	1,84	2,33	2,87	2,18	2,39	2,64	3,61	4,27	4,94	1,00	1,00	1,00

Table 12. Aggregate Fuzzy Pairwise Comparison Matrix of Sub-Criteria

		M1			**M2**	
M1	1,00	1,00	1,00	1,45	1,65	1,86
M2	3,93	4,48	5,03	1,00	1,00	1,00

		EC1			EC2			EC3	

EC1	1,00	1,00	1,00	2,86	3,51	4,20	0,94	1,05	1,19
EC2	0,96	1,19	1,46	1,00	1,00	1,00	1,46	1,76	2,10
EC3	2,65	3,29	3,93	3,77	4,33	4,89	1,00	1,00	1,00
		T1			T2			T3	
T1	1,00	1,00	1,00	4,00	5,00	6,00	3,00	4,00	5,00
T2	0,13	0,14	0,17	1,00	1,00	1,00	7,00	8,00	9,00
T3	0,20	0,25	0,33	0,11	0,13	0,14	1,00	1,00	1,00
		SP1			SP2				
SP1	1,00	1,00	1,00	3,14	3,79	4,45			
SP2	1,32	1,63	1,99	1,00	1,00	1,00			
		EN1			EN2				
EN1	1,00	1,00	1,00	3,78	4,43	5,09			
EN2	1,13	1,43	1,78	1,00	1,00	1,00			

Fuzzy Geometric Mean Value

The fuzzy geometric mean value is used to aggregate the fuzzy pairwise comparison judgements made to obtain the fuzzy priority vector. Initiated by Buckley (1985), this method will synthesize fuzzy preferences to produce fuzzy weights that reflect the relative importance of each criterion and sub-criterion. For the overall analysis, the fuzzy geometric mean value will be calculated using the previous calculation data.

The fuzzy geometric mean is obtained by taking the fuzzy product of all fuzzy judgements in a row and then taking the fuzzy nth root (where n is the number of criteria). By applying the fuzzified pairwise comparison matrix in Table 12, the calculation is obtained using Equation (1)

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \ldots \otimes \tilde{a}_{in})^{1/n} \ldots (1)$$

Where,
$\tilde{r}_i$: Fuzzy geometric mean for row i;
$\tilde{a}_{ij}$: Fuzzy triangular number representing the judgement for criterion i compared to j;
$\otimes$: Fuzzy multiplication operator.
n : Number of criteria.

The overall results are calculated and subsequently applied to the criteria and sub-criteria matrices for all fuzzy pairwise comparison matrices.

Table 13. Result of Geometric Mean Value Calculation of Fuzzy Pairwise Comparison Matrices of Criteria and Sub-Criteria

	Fuzzy Geometric Mean Value		
M	**1,75**	**2,16**	**2,55**
EC	1,92	2,34	2,78
T	1,35	1,59	1,88
SP	0,76	0,95	1,18
EN	2,12	2,43	2,74
Market	**Fuzzy Geometric Mean Value**		
M1	1,21	1,29	1,36
M2	1,98	2,12	2,24
Economy	Fuzzy Geometric Mean Value		
EC1	1,39	1,55	1,71
EC2	1,12	1,28	1,45
EC3	3,16	3,77	4,38

Market	Fuzzy Geometric Mean Value		
Technical		Fuzzy Geometric Mean Value	
T1	2,29	2,71	3,11
T2	0,96	1,05	1,15
T3	0,15	0,18	0,22
Socio-Politic		Fuzzy Geometric Mean Value	
SP1	1,77	1,95	2,11
SP2	1,15	1,28	1,41
Environment		Fuzzy Geometric Mean Value	
EN1	1,94	2,10	2,26
EN2	1,06	1,20	1,33

Fuzzy Weight of Criteria and Sub-Criteria

Fuzzy weight represents the relative importance of each criterion and sub-criterion in the decision-making process. The calculation is done by normalizing the fuzzy geometric mean. This step ensures the total weight of all criteria will be equal to 1, in a fuzzy sense, and preserves the uncertainty captured in the fuzzy pairwise judgement. Fuzzy weights will be calculated by multiplying the fuzzy geometric mean value by the sum of reciprocals of the geometric mean value. Using the geometric mean value presented in Table 13 as an example, the fuzzy weight is calculated based on the formula provided in Equation (2).

$$\widetilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \ldots \oplus \tilde{r}_n)^{-1} \ldots (2)$$

The overall results are presented with the fuzzy weight calculation subsequently applied to the remaining criteria and sub-criteria as outlined in Table 15

Table 14. Result of Fuzzy Weight Calculation of Criteria and Sub-Criteria

	Fuzzy Local Weight of Criteria
M	(0,16, 0,23, 0,32)
EC	(0,17, 0,25, 0,35)
T	(0,12, 0,17, 0,24)
SP	(0,07, 0,1, 0,15)
EN	(0,19, 0,26, 0,35)
Market	Fuzzy Local Weight of Sub-Criteria
M1	(0,33, 0,38, 0,43)
M2	(0,55, 0,62, 0,7)
Economy	Fuzzy Local Weight of Sub-Criteria
EC1	(0,18, 0,23, 0,3)
EC2	(0,15, 0,19, 0,26)
EC3	(0,42, 0,57, 0,77)
Technical	Fuzzy Local Weight of Sub-Criteria
T1	(0,51, 0,69, 0,92)
T2	(0,21, 0,27, 0,34)
T3	(0,03, 0,04, 0,06)
Socio-Politic	Fuzzy Local Weight of Sub-Criteria
SP1	(0,5, 0,6, 0,72)

Fuzzy Local Weight of Criteria	
SP2	(0,33, 0,4, 0,48)

Environment	Fuzzy Local Weight of Sub-Criteria
EN1	(0,54, 0,64, 0,75)
EN2	(0,3, 0,36, 0,44)

To get the Fuzzy Global Weight, the multiplication of the parent criteria Fuzzy Local Weight and the Fuzzy Local Weight of Sub-criteria is calculated.

Table 15. Fuzzy Global Weight Calculation Result

Fuzzy Local Weight of Criteria				**Fuzzy Local Weight of Sub-Criteria**				**Fuzzy Global Weight**	
M	0,16	0,23	0,32	M1	0,33	0,38	0,43	WM1	(0,053, 0,087, 0,138)
				M2	0,55	0,62	0,70	WM2	(0,088, 0,143, 0,224)
EC	0,17	0,25	0,35	EC1	0,18	0,23	0,30	WEC1	(0,031, 0,058, 0,105)
				EC2	0,15	0,19	0,26	WEC2	(0,026, 0,048, 0,091)
				EC3	0,42	0,57	0,77	WEC3	(0,071, 0,143, 0,27)
T	0,12	0,17	0,24	T1	0,51	0,69	0,92	WT1	(0,061, 0,12, 0,221)
				T2	0,21	0,27	0,34	WT2	(0,025, 0,05, 0,082)
				T3	0,03	0,04	0,06	WT3	(0,004, 0,007, 0,014)
SP	0,07	0,10	0,15	SP1	0,50	0,60	0,72	WSP1	(0,035, 0,06, 0,108)
				SP2	0,33	0,40	0,48	WSP2	(0,023, 0,04, 0,072)
EN	0,19	0,26	0,35	EN1	0,54	0,64	0,75	WEN1	(0,103, 0,166, 0,263)
				EN2	0,30	0,36	0,44	WEN2	(0,057, 0,094, 0,154)

Hybrid TOPSIS Analysis

The hybrid TOPSIS method is a comprehensive decision-making tool that integrates both qualitative and quantitative data to rank alternatives based on their proximity to an ideal solution. In this approach, qualitative sub-criteria are evaluated using fuzzy values that reflect expert judgments on relative importance, while quantitative sub-criteria rely on crisp data gathered from smelter project information and literature review. For this study, the utilization of this method will effectively address benefit criteria (where higher values are preferable, like production capacity and market share) and cost criteria (where lower values are better, such as investment costs). By combining these two data types, hybrid TOPSIS provides an objective and balanced analysis, reducing biases and supporting strategic decision-making.

Decision Maker Ratings

Expert ratings play a crucial role in evaluating the relative importance of sub-criteria among the available alternatives. The questionnaire serves as a tool to identify the relationships between sub-criteria and alternatives using linguistic ratings. As presented in Table 17, data were collected from three experts through the questionnaire.

Table 16. Questionnaire Result on Relative Importance of Sub-Criteria and Alternatives.

Experts A								
Project	*Questionnaire Result*							
	EC1	*T1*	*T3*	*EN1*	*EN2*	*SP1*	*SP2*	*M2*
Alumina	M	H	L	L	H	M	M	L
Pig Iron	M	M	H	M	H	M	L	H
MHP	VL	VH	L	L	H	VH	M	L

Experts B

Project	Questionnaire Result							
	EC1	T1	T3	EN1	EN2	SP1	SP2	M2
Alumina	H	M	M	M	L	M	M	M
Pig Iron	M	H	M	M	L	M	M	H
MHP	L	M	H	VH	H	H	M	L

Expert C

Project	Questionnaire Result							
	EC1	T1	T3	EN1	EN2	SP1	SP2	M2
Alumina	H	M	H	M	L	L	H	H
Pig Iron	M	L	H	M	L	M	M	M
MHP	L	H	M	H	H	H	L	M

Table 17 – Fuzzy Number based on linguistic value

Linguistic Value	Label	Fuzzy Number		
Very Low	VL	1	1	3
Low	L	1	3	5
Medium	M	3	5	7
High	H	5	7	9
Very High	VH	7	9	9

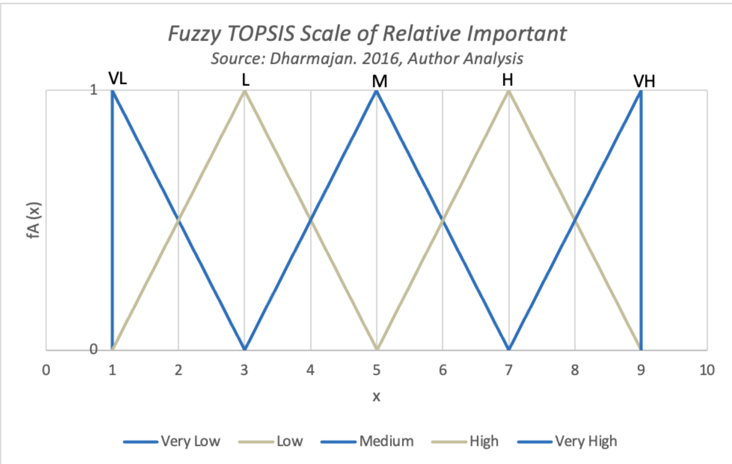

Figure 6. Fuzzy TOPSIS of Relative Importance.

Table 18. Fuzzified decision matrices of Experts.

Experts A

Project	EC1			T1			T3			EN1			EN2			SP1			SP2			M2		
Alumina	3	5	7	5	7	9	1	3	5	1	3	5	5	7	9	3	5	7	3	5	7	1	3	5
Pig Iron	3	5	7	3	5	7	5	7	9	3	5	7	5	7	9	3	5	7	1	3	5	5	7	9
MHP	1	1	3	7	9	9	1	3	5	1	3	5	5	7	9	7	9	9	3	5	7	1	3	5

Experts B

Project	EC1			T1			T3			EN1			EN2			SP1			SP2			M2		
Alumina	5	7	9	3	5	7	3	5	7	3	5	7	1	3	5	3	5	7	3	5	7	3	5	7
Pig Iron	3	5	7	5	7	9	3	5	7	3	5	7	1	3	5	3	5	7	3	5	7	5	7	9
MHP	1	3	5	3	5	7	5	7	9	7	9	9	5	7	9	5	7	9	3	5	7	1	3	5

Experts C

Project	EC1			T1			T3			EN1			EN2			SP1			SP2			M2		
Alumina	5	7	9	3	5	7	5	7	9	3	5	7	1	3	5	1	3	5	5	7	9	5	7	9
Pig Iron	3	5	7	1	3	5	5	7	9	3	5	7	1	3	5	3	5	7	3	5	7	3	5	7
MHP	1	3	5	5	7	9	3	5	7	5	7	9	5	7	9	5	7	9	1	3	5	3	5	7

The process continues to calculate the aggregating Fuzzy Decision Matrix. The combined matrix derived from the three datasets is estimated using the geometric mean.

Table 19. Aggregate Decision Matrix from Experts

Project		**EC1**			**T1**			**T3**			**EN1**	
Alumina	4,2	6,3	8,3	3,6	5,6	7,6	2,5	4,7	6,8	2,1	4,2	6,3
Pig Iron	3,0	5,0	7,0	2,5	4,7	6,8	4,2	6,3	8,3	3,0	5,0	7,0
MHP	1,0	2,1	4,2	4,7	6,8	8,3	2,5	4,7	6,8	3,3	5,7	7,4
Project		EN2			SP1			SP2			M2	
Alumina	1,7	4,0	6,1	2,1	4,2	6,3	3,6	5,6	7,6	2,5	4,7	6,8
Pig Iron	1,7	4,0	6,1	3,0	5,0	7,0	2,1	4,2	6,3	4,2	6,3	8,3
MHP	5,0	7,0	9,0	5,6	7,6	9,0	2,1	4,2	6,3	1,4	3,6	5,6

Compute Normalized Decision Matrix

The normalization step is crucial for converting the fuzzy decision data into a common scale across diverse criteria. This ensures that each criterion, regardless of its original measurement unit or range, contributes equitably and consistently to the analysis. For benefit-oriented criteria, the fuzzy normalization typically involves dividing each fuzzy number by the maximum upper bound across all alternatives. Conversely, for cost-based criteria, the normalization process divides the minimum lower bound by the fuzzy numbers of each alternative. This standardization aligns all fuzzy data between 0 and 1, preserving the triangular fuzzy shape and enabling accurate distance calculations to the fuzzy positive and negative ideal solutions in the subsequent stages.

- Fuzzy benefit:

$$\tilde{r}_{ij} = \left(\frac{l_{ij}}{u_j^*}, \frac{m_{ij}}{m_j^*}, \frac{u_{ij}}{l_j^*}\right) \quad \dots (3)$$

Where,

$\tilde{r}_{ij}$: Normalized fuzzy number for alternative i under criterion j;
u_j^* : Maximum upper bound among all alternatives for criterion j;
m_j^* : Maximum middle value among all alternatives for criterion j;
l_j^* : Maximum lower bound among all alternatives for criterion j.

- Fuzzy cost:

$$\tilde{r}_{ij} = \left(\frac{l_j^-}{u_{ij}}, \frac{m_j^-}{m_{ij}}, \frac{u_j^-}{l_{ij}}\right) \quad \dots (4)$$

Where,

l_j^-, m_j^-, u_j^- : Minimum lower, middle, and upper bounds respectively, among all alternatives for the criterion j

Table 20. Normalized Fuzzy Decision Matrix

Type of Criteria		**beneficial criteria**			**beneficial criteria**			**beneficial criteria**			**cost criteria**	
Project		EC1			T1			T3			EN1	
Alumina	0,51	0,76	1,00	0,43	0,68	0,92	0,30	0,57	0,82	0,33	0,49	1,00
Pig Iron	0,36	0,60	0,85	0,30	0,57	0,82	0,51	0,76	1,00	0,30	0,42	0,69

MHP	0,12	0,25	0,51	0,57	0,82	1,00	0,30	0,57	0,82	0,28	0,36	0,64

Type of Criteria	beneficial criteria			cost criteria			beneficial criteria			beneficial criteria		
Project	EN2			SP1			SP2			M2		
Alumina	0,19	0,44	0,68	0,33	0,49	1,00	0,47	0,73	1,00	0,30	0,57	0,82
Pig Iron	0,19	0,44	0,68	0,30	0,42	0,69	0,27	0,55	0,82	0,51	0,76	1,00
MHP	0,56	0,78	1,00	0,23	0,27	0,37	0,27	0,55	0,82	0,17	0,43	0,68

Weighted Normalized Fuzzy Decision Matrix

This step reflects the relative importance of each criterion, as determined through the fuzzy AHP analysis. The normalized fuzzy numbers are multiplied by the corresponding fuzzy weights from the fuzzy AHP process. This incorporates the subjective importance of each criterion, as expressed by the decision makers. By combining these weights with the normalized matrix, the weighted normalized fuzzy decision matrix is constructed, enabling a comprehensive comparison of all alternatives in the subsequent calculations. The application of fuzzy weights, which incorporate the uncertainty and vagueness of human judgment, makes this approach particularly effective for real-world decision-making where crisp values alone may not capture the complexity of the situation.

Table 21. Weighted Normalized Fuzzy Decision Matrix

Type of Criteria	beneficial criteria			beneficial criteria			beneficial criteria			cost criteria		
Weightage	0,031	0,058	0,105	0,061	0,12	0,221	0,004	0,007	0,014	0,103	0,166	0,263
Project	**EC1**			**T1**			**T3**			**EN1**		
Alumina	0,016	0,044	0,105	0,026	0,081	0,203	0,001	0,004	0,012	0,034	0,082	0,263
Pig Iron	0,011	0,035	0,089	0,018	0,068	0,182	0,002	0,005	0,014	0,031	0,069	0,182
MHP	0,004	0,015	0,053	0,035	0,099	0,221	0,001	0,004	0,012	0,029	0,060	0,167
A*	0,016	0,044	0,105	0,035	0,099	0,221	0,002	0,005	0,014	0,034	0,082	0,263
A-	0,004	0,015	0,053	0,018	0,068	0,182	0,001	0,004	0,012	0,029	0,060	0,167
Type of Criteria	**beneficial criteria**			**cost criteria**			**beneficial criteria**			**beneficial criteria**		
Weightage	*0,057*	*0,094*	*0,154*	*0,035*	*0,06*	*0,108*	*0,023*	*0,04*	*0,072*	*0,088*	*0,143*	*0,224*
Project	**EN2**			**SP1**			**SP2**			**M2**		
Alumina	0,01	0,04	0,10	0,01	0,03	0,11	0,01	0,03	0,07	0,03	0,08	0,18
Pig Iron	0,01	0,04	0,10	0,01	0,02	0,07	0,01	0,02	0,06	0,04	0,11	0,22
MHP	0,03	0,07	0,15	0,01	0,02	0,04	0,01	0,02	0,06	0,02	0,06	0,15
A*	0,03	0,07	0,15	0,01	0,03	0,11	0,01	0,03	0,07	0,04	0,11	0,22
A-	0,01	0,04	0,10	0,01	0,02	0,04	0,01	0,02	0,06	0,02	0,06	0,15

Calculate Distance from Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS)

A triangular fuzzy number from the previous calculation will be used to find the best performance for each criterion across alternatives, and it depends on the nature of sub-criteria. Criteria Type is divided into 2, which are benefit criteria and cost criteria. To get the best ideal solution, the type will calculate differently to get ideal in the middle of uncertainty.

Table 23. Definitions of FPIS and FNIS and Ideal Solutions for Benefit and Cost Criteria

Type	Benefit Criteria	Cost Criteria

FPIS	Max (l, m, u)	Min (l,m,u)
FNIS	Min (l,m,u)	Max (l, m, u)

After obtaining the FPIS and FNIS value, the next step is to calculate the distance for each sub-criterion. By calculating distance, we can explore the similarity of each alternative to the best and the worst, also determine the similarity. By calculating the distance of the weighted normalized fuzzy decision matrix value with positive ideal solution (A*) and negative ideal solution (A-), we can estimate the distance from FPIS and FNIS and later can quantify the relationship between both using (CC) measurement. Referring to Table X, the distances from the Fuzzy Positive Ideal Solution (Di^{+}) and the Fuzzy Negative Ideal Solution (Di^{-}) are calculated using the vertex method.

Using vertex method, then calculate distance to FPIS and FNIS

$$d_{ij}^{\pm} = \sqrt{\frac{1}{3}\left[\left(l_i - Al_j^{\pm}\right)^2 + \left(m_i - Am_j^{\pm}\right)^2 + \left(u_i - Au_j^{\pm}\right)^2\right]} \quad \ldots (5)$$

Where,

$d_{ij}^{\pm}$: Distance of alternative i under criterion j to the FPIS (+) or FNIS (−) for fuzzy numbers.

l_i, m_i, u_i : lower, middle, and upper values of the fuzzy number for the alternative i

$Al_j^{\pm}, A\,m_j^{\pm}, Au_j^{\pm}$: lower, middle, and upper values of the ideal solution (FPIS or FNIS) for criterion j

Table 22. Calculation of Distance to FPIS and FNIS

Distance from FPIS	Fuzzy di⁺	EC1	T1	T3	EN1	EN2	SP1	SP2	M2
Alumina	**0,08**	0,000	0,015	0,002	0,000	**0,036**	0,000	0,000	0,030
Pig Iron	**0,15**	0,011	0,030	0,000	0,047	0,036	0,019	0,009	0,000
MHP	**0,19**	0,035	0,000	0,002	0,057	0,000	0,040	0,009	0,053

Distance from FNIS	Fuzzy di⁻	EC1	T1	T3	EN1	EN2	SP1	SP2	M2
Alumina	**0,18**	0,035	0,015	0,000	0,057	**0,000**	0,040	0,009	0,023
Pig Iron	**0,11**	0,024	0,000	0,002	0,010	0,000	0,021	0,000	0,053
MHP	**0,07**	0,000	0,030	0,000	0,000	0,036	0,000	0,000	0,000

Quantitative Decision Matrix

Quantitative information on the alternatives was incorporated into the calculation to provide additional comparative values. Unlike fuzzy numbers, crisp data are treated separately and subsequently integrated in the distance and closeness coefficient calculations. The data for the alternatives are presented in Table 3.

Table 23. Quantitative Data on Specified Categories

Project	Investment Costs (Million USD)	Net Profit (Million USD)	Capacity (product ton per annum)	Market Share

Alumina	524,00	102,70	2.000.000	1,45%
Pig Iron	312,00	75,00	1.600.000	0,12%
MHP	971,60	157,68	50.000	9,03%

To get a similar scale with other matrices, the quantitative value of sub-criteria is then defined by using additional information related to the factors. The defining processes are:

1. Investment Cost

According to many sources, the total investment value can show the scale of the industry. The quantitative valuation is used to convert different units (USD) to a scale of 0–1. Please refer to Table 24 for the normalized scale of the quantitative classification sub-criterion, Total Investment.

Table 24. Quantitative Classification of Total Investment.

Quantitative Rating	Category of Investment	Indicative Capex	Typical Use Cases	Reference Sources
0,2	Micro-scale	< $10 million	Startups, pilot facilities, R&D demonstration plants, very small-scale ventures	IFC SME Finance Forum (2021); UNIDO (2020)
0,4	Small-scale	$10 million – $100 million	SME-scale factories, local energy systems, agro-processing, basic infrastructure	IFC Enterprise Size Classification (2021); UNIDO Industrial Project Manual
0,6	Medium-scale	$100 million – $500 million	Regional power plants, medium-sized smelters, water treatment plants, basic refineries	OECD Infrastructure Governance Indicators (2023); World Bank PAD examples
0,8	Large-scale	$500 million – $1 billion	National infrastructure, large processing plants, rail segments, strategic industrial parks	McKinsey Global Institute (2016); World Bank PPP Knowledge Lab
1	Mega-scale	> $1 billion	National priority or flagship projects: airports, oil refineries, HPAL nickel plants, metros	OECD "Unlocking Infrastructure Investment" (2021); IFC project portfolio

2. Net Profit

Since the alternatives has a different nature of economic value, especially in the business industry and trade, it is difficult to compare only based on net profit. Given the potential differences in project scale, the economic ratio of Net Profit Margin is employed in the calculation to allow for comparison on a standardized scale ranging from 0 to 1, with the revenue and net profit data presented in Table 3.

3. Production Capacity

The alternatives have different scale of project, includes nature of product and demand on the market. Huge amount of the production capacity not always benefit to the industry, if its already saturated by other competitors, or there are smelting industry with more bigger production capacity.

Therefore, on this calculation we use benchmark to the existing facilities that already produce the same products, so we can compare how competitive the project based on the same Industry and products. For the reference of industrial benchmark.

Table 25. Industrial Benchmark for Production Capacity Leader In Similar Industries

Product	Prod. Capacity (tpa)	Owner of Project & Location
Alumina	6.300.000	Norsk Hydro's Alunorte alumina refinery, Brazil
Pig Iron	650.000	NZ Steel, New Zealand
MHP	120.000	Vale JV, Indonesia

4. Market Share

Market share data are obtained from the project feasibility study, representing a comparison between total global production and the projected contribution of each alternative. The corresponding values are presented in Table 3. As the data are already expressed on a ratio scale (0–1), no further calculation is required, allowing them to be directly utilized as quantitative input and ensuring comparability with other sub-criteria in the final aggregation.

Table 26. Value Definition for Quantitative Sub-Criteria

Type of Criteria	**cost criteria**	**beneficial criteria**	**beneficial criteria**	**beneficial criteria**
Project	**Investment Costs**	**Net Profit Margin**	**Capacity**	**Market Share**
Alumina	0,80	0,136	0,3175	0,0145
Pig Iron	0,60	0,157	1,0000	0,0012
MHP	0,80	0,222	0,4167	0,0903

Weighting Quantitative Sub-criteria

The objectives of weighting for quantitative sub-criteria are similar to the common practice calculation on Hybrid TOPSIS, to know the relative importance of each sub-criterion in the Hybrid TOPSIS calculation, where the weight is obtained from previous Fuzzy AHP calculation. Since the value is a fuzzy number, there will be an additional de-fuzzifier calculation to accommodate from the triangular number into crisp data, so can later be used to calculate weightage. The de-fuzzifier process is carried out using the standard arithmetic mean method.

Table 27. De-Fuzzifier Calculation to Obtain The Crisp Value of Weight.

Sub-Criteria	***l***	***m***	***u***	**De-fuzzifier**
Investment Costs	0,03	0,05	0,09	***0,06***
Net Profit Margin	0,07	0,14	0,27	***0,16***
Capacity	0,03	0,05	0,08	***0,05***
Market Share	0,05	0,09	0,14	***0,09***

The weighted quantitative sub-criteria were obtained by multiplying the quantitative sub-criteria weights derived from the de-fuzzified Fuzzy AHP, using the value definitions shown in Table 27. At the same time, the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) were determined. These represent hypothetical alternatives with the most desirable and least desirable performance on each criterion, respectively. In Beneficial Criteria, PIS is obtained by looking maximum value, and in contrast, in Cost Criteria, they are looking for the minimum value for a better option.

Table 28. Weighted Quantitative Decision Matrix

Type of Criteria	**Cost Criteria**	**Beneficial Criteria**	**Beneficial Criteria**	**Beneficial Criteria**
Defuzzified Weightage	***0,06***	***0,16***	***0,05***	***0,09***
Project	Investment Costs	Net Profit Margin	Capacity	Market Share
Alumina	0,04400	0,02195	0,01661	0,0013
Pig Iron	0,03300	0,02526	0,05233	0,0001
MHP	0,04400	0,03579	0,02181	0,0084
A*	0,0330	0,03579	0,05233	0,0084
A-	0,04400	0,02195	0,01661	0,0001

Calculate Distance from PIS & NIS

To calculate the istance from PIS and NIS, the Euclidean equation is employed as follows:

$$d_{ij}^{\pm} = \sqrt{\sum (v_{ij} - A_j^{\pm})^2} \quad \text{... (6)}$$

Where:

$d_{ij}^{\pm}$: Distance from weighted crisp value to the ideal solution for criterion j;
v_{ij} : Weighted normalized crisp value of alternative i for criterion j;
$A_j^{\pm}$: Ideal solution (PIS or NIS) crisp value for criterion j.

Using the data from Table 31, the distances from the PIS and NIS are calculated, with the results presented in the same table.

Table 31. Result of Calculation Distance from PIS and NIS

Type of Criteria	**Cost Criteria**	**Beneficial Criteria**	**Beneficial Criteria**	**Beneficial Criteria**	**Di+**	**Di-**
Project	Investment Costs	Net Profit Margin	Capacity	Market Share		
Alumina	0,04400	0,02195	0,01661	0,0013	0.0405	0.0012
Pig Iron	0,03300	0,02526	0,05233	0,0001	0,0134	0,037
MHP	0,04400	0,03579	0,02181	0,0084	0,0324	0,0169
A*	0,0330	0,03579	0,05233	0,0084		
A-	0,04400	0,02195	0,01661	0,0001		

Integration of Distance From Both Quantitative and Qualitative Calculation

Hybrid TOPSIS integrates the use of both fuzzy calculations and crisp numbers, applying the concept of measuring the distance from an ideal solution to identify the most beneficial alternatives. The Weighted Decision Matrix derived from both approaches is analyzed in relation to the Positive Ideal Solution and the Negative Ideal Solution, with the correlation coefficient subsequently calculated based on the distance data.

Table 32. Distances Di+Di+ and Di−Di− from FPIS and FNIS, Showing the Combination of Distances from Fuzzy Calculations and Crisp Quantitative Values

Project	**Di+ Total**	**Di- Total**	**Di+ Fuzzy**	**Di- Fuzzy**	**Di+ Crisp**	**Di- Crisp**
Alumina	0,1205	0,1812	0,08	0,18	0,0405	0,0012
Pig Iron	0,1634	0,147	0,15	0,11	0,0134	0,037
MHP	0,222	0,0869	0,19	0,07	0,0324	0,0169

Closeness Coefficient (CC)

CC in the Hybrid TOPSIS method is a numerical measure that represents how close each alternative is to the ideal solution (best scenario) while simultaneously being farthest from the negative ideal solution (worst scenario). It is calculated as the ratio of the distance to the negative ideal solution to the sum of the distances to both the positive and negative ideal solutions. A higher CC value (close to 1) indicates that the alternative is more desirable, being closer to the optimal conditions defined by the decision criteria. This measure effectively integrates multiple evaluation factors, making it a reliable indicator for prioritizing or ranking alternatives in decision-making processes.

... (7)

$$CC_i = \frac{D_i^-}{D_i^- + D_i^+}$$

Table 33. Result of Closeness Coefficient

Project	CC	Di+ Total	Di- Total
Alumina	**0,6**	0,1205	0,1812
Pig Iron	**0,47**	0,1634	0,147
MHP	**0,28**	0,222	0,869

Summary of the Key Result

This research analyzes and interprets the findings obtained from the hybrid Fuzzy AHP–Hybrid TOPSIS methodology research. The analysis incorporated both expert judgments and quantitative data to evaluate the prioritization of three smelter projects under the Alumina Processing Plant, Pig Iron Processing Plant, and MHP HPAL Project. The final calculation resulted in closeness coefficient (CC) values as follows: 0.6 for the Alumina Processing Plant, 0.47 for the Pig Iron Processing Plant, and 0.28 for the MHP HPAL Project, demonstrating relative desirability of each project. Table 15 presents the fuzzy global weights of the five main criteria, with the results indicating a sequential ranking of Environment, Economy, Market, Technical, and Socio-Political factors. The sub-criteria global weights reveal that Net Profit, Resource Utilization, Impact on Environment, and Product Demand are the most decisive factors.

Based on the analysis, Environment and Economy emerge as the most critical criteria. The Environmental criterion is heavily weighted due to pressure to reduce emissions and environmental risks. The Alumina Project shows strong alignment here, as alumina refining has a lower environmental impact than HPAL's chemical-intensive processing or iron sand's carbon-intensive production. The Economic criterion, particularly net profit and investment cost, also plays a decisive role. Although the HPAL Project has the highest net profit, its capital intensity and complex technology reduce its attractiveness. The Bauxite Project's moderate investment and high return ensure a balanced financial profile. Technical feasibility and production capacity are critical considerations in project evaluation. The Alumina Project demonstrates the highest production capacity, surpassing both the Pig Iron and MHP HPAL projects. While the Pig Iron Project benefits from simpler RKEF technology, it lacks strong market synergy, whereas the complexity of HPAL technology introduces significant execution risks. From a market perspective, the Alumina Project also secures the top ranking, supported by sustained global demand for alumina given aluminum's strategic role in renewable energy and infrastructure development. In contrast, the pig iron market is already mature, and the HPAL project faces substantial technical and regulatory challenges within the electric vehicle sector.

Showing the good performance in economic rate, high value in environmental impact, the highest production capacity among others, and demand that is currently robust in global markets, showing the excellence of the bauxite project. Conversely, while the iron sand project performs well in aspects such as lower investment requirements and higher production capacity, it falls short in environmental considerations when compared to the alumina project. The HPAL project is showing strong net profit per annum and a high market share due to the new development industry, but the investment cost is very high, and since the technology is relatively new, it has led to technical challenges, contributing to lower CC results. Several factors that make the Alumina project become the project with a high score are:

a. Alignment with most influential Criteria and Sub-Criteria
   Alumina projects perform strongly in the top-weighted criteria: Environmental Impact, Net Profit, Market Demand, and Technical Capacity. Environmental impact plays a significant role, as Indonesia's downstreaming policies prioritize green and sustainable projects. From

an economic perspective, while bauxite may not provide the highest profit contribution within the portfolio, it offers strong profitability with relatively lower investment risks. Although the current demand for construction materials is declining, aluminum remains highly promising for future automotive development due to its adaptability in forming processes, lighter weight, abundant availability, and its potential to complement the substantial growth of the nickel sector in recent years.

b. Lower Risk Profile
   Bauxite development is associated with relatively lower environmental impacts when contrasted with the complex waste management challenges of HPAL projects and the high carbon emissions of iron sand projects. Other than that, development in Indonesia is showing a positive to investors, due outlook to lower political and regulatory hurdles, enhancing the feasibility of developing projects.
c. Balanced Financial and Technical Profile
   The Bauxite Project has a moderate investment amount and high production capacity, offering a strong ROI. Higher result on finance factors makes the Alumina project promising and still very potential.

CONCLUSIONS

The method is proven to evaluate project and to be analyzed for prioritizing the project. Combined with the result and analysis, it can be a strategic excellence for preparing company movement. Since the project not only affected by the factors internally, but also global conditions, knowing the conditions might be the wise solution for initial of business transformation. The recommendation should cover all alternatives analysis, and make a recommendation based on the analysis of findings.

The factors influencing the prioritization of smelting project development can be analyzed using the global weights obtained from the Fuzzy AHP. By identifying the key factors that affect smelting project development, we can focus on addressing inhibiting factors and enhancing the project's potential in order to determine the best solution for each alternative.

The ranking of alternatives is determined by the Closeness Coefficient, which reflects the proximity of each alternative to the ideal solution. The results are influenced by the global weights derived from experts' assessments and the decision maker's judgment of relative importance. Integrating quantitative data with fuzzy logic in the calculation helps reduce bias and increases the reliability of the results.

This research successfully identifies the most feasible smelter project in Indonesia through a robust evaluation framework combining fuzzy logic and hybrid decision-making methodologies. The study confirms that the most influential criteria driving project prioritization are environmental impact and economic viability, supported by technical, market, and socio-political considerations. Among these, environmental sustainability and net profit emerge as the most decisive sub-criteria, aligning with Indonesia's industrial policy and global sustainability goals.

The final analysis positions the Alumina Processing Plant as the most strategic and feasible project for immediate development, offering a balanced environmental footprint, strong profitability, and supportive political and resource conditions. The Pig Iron Processing Plant, although technically mature and supported by abundant resources, faces challenges related to environmental concerns and a more saturated market landscape, leading to its position as the second priority. The MHP HPAL Project, despite its relevance to the growing electric vehicle market, ranks third due to its high capital intensity, complex environmental management needs, and market volatility.

Table 34. Resume of Project Prioritization correlation with top influencing factors

Factor	*Alumina*	*Pig Iron*	*MHP HPAL*
Prioritization	*1st*	*2nd*	*3rd*
Environmental Impact	Moderate (red mud management)	High (coastal degradation)	High (tailings, energy use)
Product Demand	High (domestic aluminum needs)	Moderate (infrastructure projects)	High (EV battery demand)
Resource Utilization	Abundant bauxite reserves	Abundant iron sand reserves	Limited nickel reserves
Climate Change Contribution	Potentially positive (with renewables)	Negative (coal reliance)	Mixed (EV benefits vs. emissions)
Market Conditions	Competitive (global surplus)	Stable (domestic demand)	Volatile (price fluctuations)
Political Conditions	Supportive but cautious	Encouraging with scrutiny	Challenging (community opposition)
Technology Maturity	Established (Bayer process)	Mature (RKEF)	Developing (HPAL)

The hybrid approach used in this study not only validates the project rankings by integrating both expert insights and quantitative data but also provides a clear, actionable path to pursue sustainable and profitable industrial growth in alignment with national downstreaming policies. In complex decision-making, especially in multiple factors like a capital-intensive industry, Fuzzy AHP and Hybrid TOPSIS contribute to balancing the analysis from both expert's insight and quantitative information, increasing the reliability of the results. This method can be considered to be used by stakeholder (governmental sectors, institutional, policy maker) in industry to comparing which industry should be focused and prioritized to get maximum benefit and used by company to make a strategic development to enhance profitability, by adding scenario planning to give a picture on how potential future can happened from various potential impacts.

LIMITATION & FURTHER RESEARCH

The limitations of this study are closely related to methodological constraints, including challenges in data collection, a scarcity of prior research on similar topics, and the methods used to collect and analyze the data. Additional limitations for the researcher include restricted access to data, time constraints, and potential bias in respondents' feedback. These limitations may affect the reliability and generalizability of the findings, potentially leading to inaccurate conclusions.

For future research, it is recommended to involve a larger number of respondents in the AHP pairwise comparisons to minimize individual judgement bias and strengthen the group consensus. In addition, employing alternative methods within the multi-criteria decision-making framework is suggested to assess the consistency of the prioritization results. Furthermore, conducting a sensitivity analysis would provide valuable insights into the stability of the rankings when parameters are varied.

By addressing these limitations, it is hoped that future studies and findings will continue to improve and contribute to supporting the sustainable development of the smelting industry. Exploring different methods will make the decision-making process more robust and applicable to real-world case studies. Additionally, incorporating scenario planning into future research could help address potential dynamic changes, particularly in policies related to capital-intensive industries.

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