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Optimizing Coal Transportation Modes in Jambi Province: Strategic Decision-Making Using Integrated FAHP-Fuzzy TOPSIS

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Abstract:

The process of this research is to integrate the Fuzzy Analytic Hierarchy Process (FAHP) method and the Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS) by creating a strategic decision-making framework to optimize coal transportation modes in Jambi Province, Indonesia. An analysis of the inefficiency of coal transportation in Jambi was conducted due to the failure to achieve production targets, which were only 44-50% of the target set for 2022 and 2023. A thorough analysis has been conducted to determine both the criteria and sub-criteria for evaluating alternative coal transportation modes, starting from trucks using dedicated coal routes, combinations of trucks with dedicated coal trains, combinations of trucks with barges, and combinations of trucks with conveyors and barges. Underpinned by strong methodology controlling evaluation discrepancies and guaranteeing study validity, the approach included expert opinions from 25 stakeholders spanning government, industry, academia, and community sectors. Results reveal that at 43.2%, economic factors are the most significant element; technical factors follow at 18.8%; safety concerns at 15.1%; environmental factors at 13.6%; and social factors at 9.3%. Based on the analysis results, both through criteria weighing and testing against alternatives, it was found that the best mode of transportation is trucks using the special coal road. And it is recommended to consider the level of operational efficiency, reduction of environmental impact, and increasing regional competitiveness compared to other regions by selecting the most effective and strategic mode of transportation.

Keywords: *Coal Transportation, Multi-Criteria Decision Making, Fuzzy AHP, Fuzzy TOPSIS, Jambi Province, Transportation Optimization*

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1. Introduction

As we know, the coal industry plays a significant role in the movement of the economy in Indonesia. That significant role provides massive contributions to the country's revenue and supports the development of the regions around the mining areas. Indonesia is one of the largest coal exporters in the world, but it faces quite complex logistical challenges due to the diverse conditions in the coal-producing regions. As we all know, Jambi Province is one of the significant coal producers in the Sumatra Island area. Operational obstacles faced in the coal sector in Jambi Province include relatively high transportation costs, reaching 30-40% of total operational costs, which are significantly higher than the national average of

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only 20-25%. As a result, this directly reduces the company's profit potential by 12-18%. This makes coal products from Jambi Province difficult to compete with coal products from other provinces that can lower prices more efficiently due to transportation costs. This is one of the reasons why 65 coal companies in Jambi Province out of a total of 159 coal companies (40.9%) remain inactive despite having valid mining permits. (Belanina, 2013; Li et al., 2021).

The province's current transportation infrastructure creates significant bottlenecks. Truck-based transportation is restricted to operating only 11 hours daily (18:00-05:00), resulting in a 54% reduction in potential operational hours. This time constraint directly contributes to Jambi Province achieving only 44.1% (17.5 million metric tons) of its planned coal production (39.7 million metric tons) in 2022 and approximately 50% (18 million metric tons) of its target (36.5 million metric tons) in 2023.

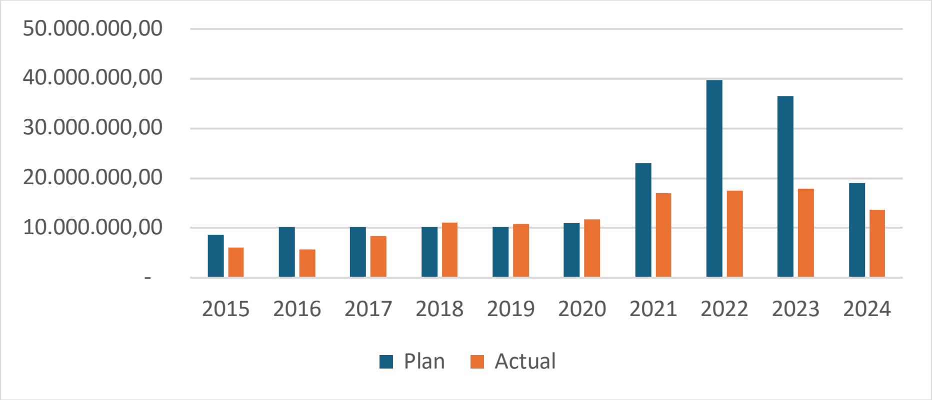

Figure 1. Coal Production of Jambi Province (Ministry of ESDM, 2025)

In 2022, the government implemented an increase in the government royalty rate from a range of 3% to 8%, which could lead to an increase in state revenue from the mining sector. At that time, prices reached an all-time high, prompting many coal mining entrepreneurs to rush to increase their production quantities. At that time, the government should have been able to maximize the benefits from the increase in coal prices. However, due to transportation constraints of coal in Jambi province, the potential and momentum could not be maximized, resulting in the government suffering losses from unmet production targets, which automatically reduced the potential state revenue.

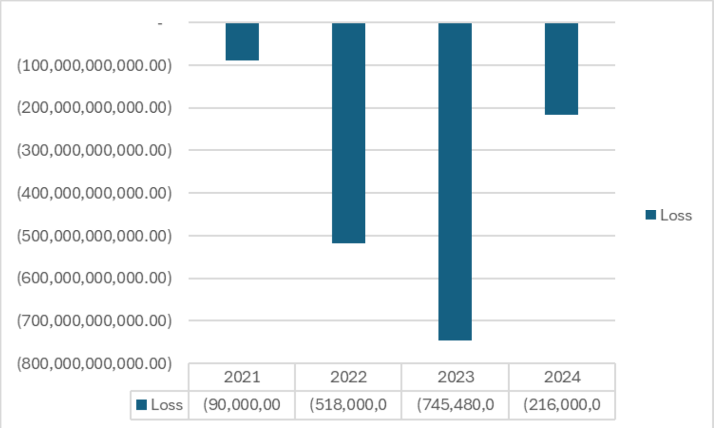

Figure 2. Illustrates the potential loss of state revenue resulting from unmet coal production.

The government incurred losses from the unmet coal production amounting to 90 billion rupiah to 745 billion rupiah. The sole port facility at Talang Duku operates at near capacity (4,500 metric tons per day), creating another significant bottleneck that limits annual throughput to approximately 16 million metric tons, well below the province's production potential. Environmental and social impacts further complicate the transportation system's sustainability. Current truck-based transportation produces approximately 8.8-25.6 kg of CO_2 emissions per ton of coal transported, compared to 2.4-3.8 kg for barge-based systems and 1.2-2.2 kg for rail transport for each 100 km (Klein et al., 2020).

Table 1. CO_2 emissions per ton of coal transported in kilograms (Klein et al., 2020)

Transportation mode	50 km	100 km	200 km	500 km	1000 km
Rail Transport	0.6	1.2	2.4	6	12
Big Barges	1.2	2.4	4.8	12	24
Small Barges	1.9	3.8	7.6	19	38
Big Truck	4.4	8.8	17.6	44	88
Small Truck	12.8	25.6	51.2	128	256

Community surveys indicate that 78% of residents along transportation routes report negative impacts from coal dust pollution, while local government data shows that road maintenance costs have increased by 35% due to damage from overloaded coal trucks.

In complex decision-making situations involving various conflicting criteria, the Multi-Criteria Decision Making (MCDM) approach becomes relevant to apply. The combination of the Fuzzy Analytic Hierarchy Process (FAHP) and Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS) methods is an approach that can overcome uncertainty in decision-making while providing a comprehensive evaluation of various alternatives (Awasthi et al., 2011). FAHP functions to determine the relative importance weight of the evaluation criteria by considering the uncertainty of the assessment, while Fuzzy TOPSIS helps in evaluating and ranking alternatives based on their distance from the positive and negative ideal solutions.

2. Theoretical Background

MCDM Theory and Its Application in Transportation: Multi-Criteria Decision Making (MCDM) has evolved as a methodological approach for solving complex decision problems involving multiple, often conflicting criteria. Transportation mode selection represents a classic MCDM problem due to its inherent complexity and multiple stakeholder considerations. According to Moslem (2023), MCDM has developed into a mature discipline with various methods and variations used in transportation and logistics. Mishra (2021) emphasized that MCDM helps decision makers integrate objective and subjective measures, handle criteria diversity, and improve decision quality through a more transparent and structured process. Kabashkin (2023) further established that MCDM provides a systematic framework for evaluating transportation alternatives based on various criteria simultaneously, which is essential for addressing the bottlenecks in Jambi's transportation system.

Fuzzy Set Theory: Fuzzy set theory addresses the uncertainty and imprecision inherent in human judgment during decision-making processes. In the context of coal transportation in Jambi Province, where expert assessments may vary considerably, fuzzy set theory offers a mathematical framework to capture this ambiguity. Kahraman et al. (2003) demonstrated how fuzzy sets serve as the foundation for fuzzy-based MCDM methods that effectively handle imprecise and subjective information in transportation alternative evaluations. Gül et al. (2018) highlighted recent developments in fuzzy set applications for risk and uncertainty analysis in transportation systems, noting how hybrid models that integrate fuzzy sets with other techniques provide improved prediction accuracy, a critical factor when evaluating coal transportation alternatives in Jambi's diverse topographical conditions.

A triangular fuzzy number (TFN), represented as $\tilde{A} = (l, m, u)$, is characterized by a membership function where parameter "m" represents the most favorable value, while "l" and "u" correspond to the minimum and maximum possible values, respectively. This mathematical framework provides the foundation for handling uncertainty in expert judgments throughout the evaluation process.

The concept of fuzzy set theory emerged to address uncertainties stemming from imprecision or vagueness. A fuzzy set $A^{\sim} = \{(x, \mu A^{\sim}(x)) | x \in X\}$ comprises ordered pairs, with X being a subset of the real numbers R, where $\mu A^{\sim}(x)$ denotes the membership function assigning a membership grade between zero and one to each object x. Since its inception, fuzzy set theory has found extensive application in resolving real-world challenges involving the analysis and manipulation of uncertain information by decision-makers. A convex normalized fuzzy set exhibits a particular instance referred to as a fuzzy number. Various contexts necessitate the utilization of diverse fuzzy numbers. Triangular and trapezoidal fuzzy numbers commonly address the inherent ambiguity in assessments concerning the performance levels of alternative options across each criterion. A triangular fuzzy number (TFN) arises when the two primary values of a trapezoidal fuzzy number coincide, thus constituting a specific subtype of trapezoidal fuzzy numbers. Owing to its simplicity and computational efficiency, the TFN emerges as the preferred membership function across numerous applications. TFNs are frequently deployed to quantify the ambiguity inherent in decision criteria. Depicted through boundaries rather than precise values, TFNs effectively capture the indeterminacy characterizing decision-makers' judgments when formulating pairwise comparison matrices. A triangular fuzzy number, represented as $A^{\sim} = (l, m, u)$, is characterized by the membership function as in Equation (1).

$$u_{\tilde{F}}(x) = \begin{cases} 0 & (x < l) \\ \left(\frac{x-l}{m-l}\right) & (l \leqslant x \leqslant m) \\ \left(\frac{u-x}{u-m}\right) & (m \leqslant x \leqslant u) \\ 0 & (x > u) \end{cases} \tag{1}$$

Figure II.1 shows a triangular fuzzy number A˜. Where the parameter “m” represents the most favorable value, while “l” and “u” correspond to the minimum and maximum possible values, respectively, delimiting the range of potential evaluations. When l = m = u, the triangular fuzzy number simplifies to a crisp number. The (l, m, u) is used to describe a fuzzy event.

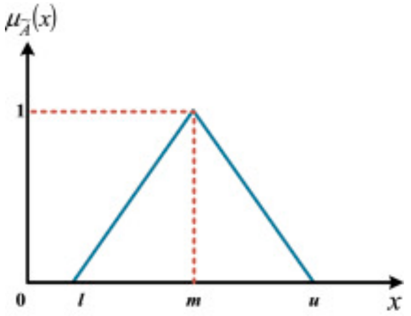

Figure 3. A triangular fuzzy number, A˜ = (l, m, u).

Consider two TFNs, represented as A1˜ and A2˜, where A1˜=(l1,m1,u1) and A2˜=(l2,m2,u2). Equations (2), (3), (4), and (5) allow for the calculation of the addition, multiplication, division, and reciprocal of two TFNs, respectively.

$$\tilde{A}_1 \oplus \tilde{A}_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{2}$$

$$\tilde{A}_1 \otimes \tilde{A}_2 \approx (l_1 l_2, m_1 m_2, u_1 u_2) \text{for} l_i > 0, m_i > 0, u_i > 0, i = 1,2 \tag{3}$$

$$\frac{\tilde{A}_1}{\tilde{A}_2} = \left(\frac{l_1}{u_2}, \frac{m_1}{m_2}, \frac{u_1}{l_2}\right) \text{for } l_i > 0, m_i > 0, u_i > 0, i = 1,2 \tag{4}$$

$$\tilde{A}_1^{-1} \approx \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}\right) \text{for } l_1 > 0, m_1 > 0, u_1 > 0 \tag{5}$$

Transportation Mode Selection Theory: Transportation optimization aims to minimize total logistics costs while meeting capacity constraints, delivery schedules, and carbon emission targets. Liu et al. (2023) developed a bulk commodity transportation optimization model by integrating genetic algorithms and Monte Carlo simulations to handle uncertainties in demand and transportation costs, resulting in significant cost savings while maintaining system reliability when applied to a coal transportation network in China. Ma et al. (2018) explained that optimization in intermodal transportation not only considers economic efficiency but also energy efficiency, operational costs, and environmental impacts simultaneously, which is highly relevant to the selection of sustainable coal transportation modes.

Sustainability Concepts in Coal Transportation: The concept of sustainability in transportation encompasses three main dimensions: economic, environmental, and social. Wang et al. (2024) stated that coal transportation needs to undergo a transformation to meet global sustainability goals, given its significant impacts on the environment and society. In their comprehensive study of coal supply chains in Asia, they found that sustainable approaches involve minimizing greenhouse gas emissions, reducing energy consumption, electrifying modes of transportation, and mitigating negative social impacts. Li et al. (2021) developed a sustainability evaluation framework for coal supply chains that includes economic (costs), environmental (CO2 emissions, land use), and social (health impacts, safety) indicators, demonstrating how it can be used to compare alternative coal transportation modes based on sustainability performance.

Coal Transportation Modes: Coal transportation modes include road (truck), rail, river, and sea, with each having different characteristics, advantages, and limitations. According to Sherwood et al. (2020), coal transportation modes include road (truck), rail, river, and sea, with each having different characteristics, advantages, and limitations that significantly impact cost efficiency, distribution speed, and environmental impact.

Coal transportation modes are based on economic distance, carrying capacity, energy efficiency, and operational flexibility, finding that for short distances (<50 km), trucks are often the optimal choice, while for medium distances (50-500 km), rail or water transportation (barges) are more economical, and for long distances (>500 km), a combination of rail and large ships is usually more efficient (Li et al., 2021). They also highlighted the importance of considering topography and available infrastructure in the selection of transportation modes.

Conducting a specific study on coal transportation in Indonesia, analyzing the challenges and opportunities in the context of an archipelagic geography (Belanina, 2013). They found that multimodal transportation integrating trucks, conveyors, and water transportation (barges) is often the optimal solution for Indonesia's geographic conditions, although it requires complex coordination and significant infrastructure investment.

Fuzzy Analytic Hierarchy Process (FAHP) FAHP is a decision-making method that combines the principles of fuzzy logic and Analytic Hierarchy Process (AHP). FAHP helps in determining the weight of criteria more accurately through a pairwise comparison process involving uncertainty aspects (Kusumawardani, 2015).

A comparative study of various variations of the FAHP method concluded that the fuzzy extent analysis approach and the fuzzy geometric mean method showed good performance in transportation and logistics applications, including the selection of transportation modes for bulk commodities such as coal (Kaewfak et al., 2019).

Applying FAHP to sustainable transportation evaluation and planning, showing that this method can handle inconsistencies and uncertainties in expert assessments when comparing transportation criteria such as cost, time, safety, and environmental impact (Ghorbanzadeh et al., 2018). Their study successfully integrated qualitative and quantitative assessments into a comprehensive analysis framework.

Developing an enhanced FAHP model for the selection of transportation modes for bulk commodities, with an emphasis on sustainability aspects (Kaewfak et al., 2019). They introduced interval-based triangular fuzzy numbers to better capture the uncertainty in expert judgments and proposed a more robust defuzzification procedure to obtain crisp weights. This model has been successfully applied in the case of coal transportation in several Southeast Asian countries, including Indonesia.

Within this subsection, we aim to provide an exposition on the fuzzy AHP methodology. A matrix $A^{\sim}$ is constructed using fuzzy pairwise comparisons, as described in Equation

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \dots & \tilde{a}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & 1 \end{bmatrix} \tag{6}$$

where $a^{\sim}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ represents the fuzzy comparison value between criterion i and criterion j Subsequently, the fuzzy weights for each criterion are calculated as depicted in Equations

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \dots \otimes \tilde{a}_{in})^{1/n} \text{for } i = 1,2,\dots,n \tag{7}$$

$$\widetilde{w}_i = \frac{\tilde{r}_i}{\tilde{r}_1 \oplus \tilde{r}_2 \oplus \dots \oplus \tilde{r}_n} \text{for } i = 1,2,\dots,n \tag{8}$$

where $\tilde{r}_i$ represents the geometric mean of the fuzzy comparison values between criterion i and each criterion, while $\widetilde{w}_i$ signifies the fuzzy weight assigned to the i th criterion. The construction of the fuzzy weight vector, denoted as $\widetilde{W}$, proceeds as in the equation.

$$\widetilde{W} = (\widetilde{w}_1, \widetilde{w}_2, \dots, \widetilde{w}_n)^T \tag{9}$$

The framework for formulating the evaluation index system encompasses the following sequential procedures:

Step 1

Constructing a hierarchical framework for the index system

The construction of the index system involves the incorporation of all pertinent factors and sub-factors pertaining to the research inquiry. The hierarchical arrangement of the evaluation index system derives from the delineated factors and sub-factors. At the primary tier of the system lies the overarching goal, with subsequent tiers comprising factors and sub-factors. Furthermore, this stage entails the segmentation of the problem into constituent components based on shared attributes. The majority of decision-makers find it challenging to manage more than seven to nine elements simultaneously when making a decision.

Step 2

Constituting a collective of decision-makers

A panel comprising decision-makers is convened, consisting of proficient individuals possessing expertise relevant to the research problem. It is incumbent upon these decision-makers to ascertain the relative weights of each factor and sub-factor.

Step 3

Identifying the linguistic variables and establishing the fuzzy conversion scale

Decision-makers compare the importance or preference of each pair of factors systematically. Utilizing questionnaires and employing linguistic variables, factors are juxtaposed against one another. A linguistic variable is characterized by values represented as words or sentences in a language, natural or artificial, facilitating comparison between factors (Zadeh, 1975). In this study, subjective pairwise comparisons made by decision-makers are expressed using terms such as “equally important,” “weakly important,” “fairly important,” “strongly important,” and “absolutely important.” These linguistic values are transformed into fuzzy scales employing triangular fuzzy conversion scales and linguistic scales proposed by Kahraman et al. (2003), as illustrated in Figure II.2 and Table II.1.

Step 4

Constructing comparison matrices

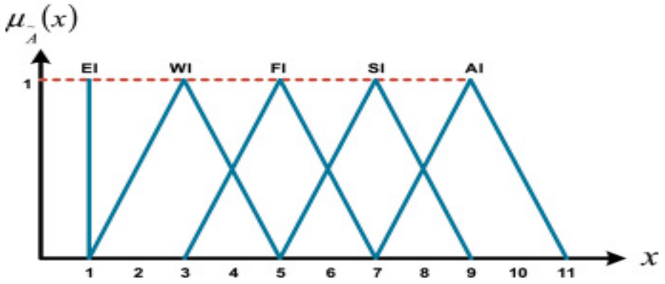

Figure 4 Scale of linguistic expressions denoting relative importance

Table 2: Linguistic scales and fuzzy scales for importance.

Linguistic scale for importance	**Simple Fuzzy Number (SFN)**	**Triangular Fuzzy Number (TFN)**	**Reciprocal Triangular Fuzzy Number (TFN)**
Equally important (EI)	1	(1, 1, 1)	(1,1,1)
Weakly important (WI)	3	(1, 3, 5)	(1/5, 1/3, 1)
Fairly important (FI)	5	(3, 5, 7)	(1/7, 1/5, 1/3)
Strongly important (SI)	7	(5, 7, 9)	(1/9, 1/7, 1/5)
Absolutely important (AI)	9	(7, 9, 11)	(1/11,1/9, 1/7)

Suppose there exists a single-level issue encompassing n factors where the relative weights of factors i and j are expressed as triangular fuzzy numbers $\widetilde{a_{ij}} = (l_{ij}, m_{ij}, u_{ij})$. For instance, if a decision-maker perceives factor i to be more important than factor j, they might set $a_{ij} = (5,7,9)$. Conversely, if factor j is deemed significantly more important than factor i, $a_{ij} = (1/9,1/7,1/5)$ it could represent the pairwise comparison between the two factors. Analogous to the conventional AHP, the comparison matrix $\tilde{A} = \{\widetilde{a_{ij}}\}$ can be derived, which can be inferred as shown in Equation (10).

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \dots & \tilde{a}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & 1 & \dots & \tilde{a}_{2n} \\ \dots & \dots & \dots & \dots \\ 1/\tilde{a}_{1n} & 1/\tilde{a}_{2n} & \dots & 1 \end{bmatrix} \quad (10)$$

Step 5

Determining the consistency index and consistency ratio of the comparison matrix.

Assessing the consistency of an evaluation is essential to ensure a certain standard of decision quality. (Saaty, 2002) introduced a consistency index to quantify consistency, which can be employed to evaluate the consistency of pairwise comparison matrices. To evaluate consistency, it is necessary to convert fuzzy comparison matrices into crisp matrices. Various defuzzification techniques exist to derive a precise value from a triangular fuzzy number. In this study, we choose to defuzzify the fuzzy numbers using the approach Chang (1996) suggested. This approach effectively illustrates the fuzziness of perception. Decision-makers can grasp the uncertainties inherent in different scenarios by considering their preferences (α) and their tolerance for risk (λ).

As depicted in Equation (11), the following steps can be used to defuzzify the triangular fuzzy number $\widetilde{a_{ij}} = (l_{ij}, m_{ij}, u_{ij})$ and obtain a crisp number.

$$\left(a_{ij}^{\alpha}\right)^{\lambda} = \left[\lambda . l_{ij}^{\alpha} + (1-\lambda) u_{ij}^{\alpha}\right], 0 \le \lambda \le 1, 0 \le \alpha \le 1 \qquad (11)$$

where $l_{ij}^{\alpha} = (m_{ij} - l_{ij}) . \alpha + l_{ij}$ presents the left-end value of α-cut for $u_{ij}^{\alpha} = u_{ij} - (u_{ij} - m_{ij}) . \alpha$. represents a_{ij} the right-end value for the α-cut operation. Notably, α is any integer between 0 and 1 and may be seen as either a steady or fluctuating situation. Through increasing α, the environment for making decisions becomes more stable. When $\alpha = 0$, there is the most uncertainty. Moreover, the range, which measures the optimism of a decision-maker, is from 0 to 1. When λ equals 0, the decision-maker tends to be more optimistic, whereas a value of 1 indicates a pessimistic outlook. After converting all triangular fuzzy numbers in each element to crisp numbers, the comparison matrix is now defined as shown in Equation (12).

$$\left[(A^{\alpha})^{\lambda}\right] = \left[\left(a_{ij}\right)^{\lambda}\right] = \begin{bmatrix} 1 & (a_{12}^{\alpha})^{\lambda} & \dots & (a_{1n}^{\alpha})^{\lambda} \\ (a_{21}^{\alpha})^{\lambda} & 1 & \dots & (a_{2n}^{\alpha})^{\lambda} \\ \dots & \dots & \dots & \dots \\ (a_{n1}^{\alpha})^{\lambda} & (a_{n2}^{\alpha})^{\lambda} & \dots & 1 \end{bmatrix}$$

Utilizing Equation (13), it is possible to compute the consistency index (CI) for a given comparison matrix.

$$CI = \frac{\lambda_{\max} - n}{n-1} \qquad (13)$$

where, $\lambda_{\max}$ represents the highest eigenvalue of the comparison matrix, while n denotes the matrix's dimension.

The consistency ratio, as described in Equation (14), signifies the extent of consistency present within a particular evaluation matrix in comparison to the consistency observed in a randomly generated matrix.

$$CR = \frac{CI}{RI(n)} \qquad (14)$$

Where, $RI(n)$ is a random index influenced by the dimensionality n, as illustrated in Table 3.

Step 6

Constructing the comprehensive matrix comprising all decision-makers

Table 3 Random index (RI) of random matrices

n	**3**	**4**	**5**	**6**	**7**	**8**	**9**
RI(n)	0.58	0.9	1.12	1.24	1.32	1.41	1.45

An admissible comparison matrix has a consistency ratio (CR) of equal to or less than 0.1. If the consistency ratio (CR) is deemed unsatisfactory, the decision-maker is recommended to carry out further pairwise comparisons.

Aggregating individual judgments becomes necessary to reach a consensus among decision-makers, as everyone's judgment matrix reflects their unique perspective. Two primary methods employed in traditional AHP for combining individual preferences into a collective preference are the Aggregation of Individual Judgments (AIJ) and the Aggregation of Individual Priorities (AIP). The fuzzy AHP can leverage the principles and methods employed in traditional AHP. The group judgment matrix is formulated through the AIJ approach, wherein the priorities for a "new individual" are established based on a collective solution, treating the group judgment matrix as that of the "new individual." Conversely, the AIP approach allows each group member to operate independently. Specifically, individual priorities are derived from individual judgment matrices, and group priorities are subsequently determined from these. The decision to use AIJ or AIP depends on the complexity of the required fuzzy arithmetic operations. In this research, we employ the AIJ technique to aggregate group decisions.

Consider a cohort comprising K decision-makers involved in the research endeavor, wherein they engage in pairwise comparisons of n criteria. Following the pairwise comparisons, a collection of K matrices $\tilde{A}_k = \{\tilde{a}_{ijk}\}$, where $\tilde{a}_{ijk} = (l_{ijk}, m_{ijk}, u_{ijk})$ is obtained, signifying the relative importance of criterion i to j, as evaluated by expert k. Equation (15) can be utilized to determine the triangular fuzzy numbers present within the group judgment matrix.

$$l_{ij} = \min_{k=1,2,\ldots,K} (l_{ijk})$$

$$m_{ij} = \sqrt[K]{\prod_{k=1}^{K} m_{ijk}\, m_{ijk}} \qquad (15)$$

$$u_{ij} = \max_{k=1,2,\ldots,K} (u_{ijk})$$

Step 7

Determining the weights of criteria and sub-criteria.

The extended analysis fuzzy AHP method is utilized to ascertain the weights of both the criterion and sub-criteria.

Fuzzy TOPSIS: Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS) is a method used to evaluate and rank various alternatives based on their proximity to positive and negative ideal solutions under conditions of uncertainty (Awasthi et al., 2011). This method is suitable for complex situations such as transportation mode selection that has many evaluation criteria.

Fuzzy TOPSIS for cargo transportation selection by considering economic, technical, environmental, and social criteria, showing that this method produces robust and reliable alternative rankings (Hadadi et al., 2021). Their study includes a comparison of various transportation modes for bulk commodities, including coal, with a special focus on sustainability aspects.

The Fuzzy TOPSIS model integrated with Geographic Information Systems (GIS) for bulk commodity transportation route selection by considering geographical factors, disaster risks, and environmental impacts (Nguyen et al., 2020). This model has been successfully applied in coal transportation planning in several provinces in Indonesia with complex topography.

A comparative study between various variations of Fuzzy TOPSIS methods, including interval-valued fuzzy and intuitionistic fuzzy TOPSIS models, in the context of transportation mode selection (Baric & Zeljko, 2021). They concluded that interval-valued fuzzy TOPSIS provides more stable results under conditions of highly uncertain information, while intuitionistic fuzzy TOPSIS is more suitable for situations with diverse and potentially conflicting expert judgments.

According to the TOPSIS technique, an alternative is deemed optimal when it is nearest to the positive ideal solution and farthest from the negative ideal solution. The fuzzy TOPSIS method has been detailed in various studies. The fuzzy TOPSIS method encompasses the subsequent steps:

- Step 1: The identification of alternatives and criteria is undertaken.
- Step 2: The determination of criteria weight is conducted utilizing the fuzzy AHP method employed in this study.
- Step 3: Subsequently, the decision matrix is defined as shown in Equation (16).

$$\widetilde{D} = \begin{array}{cc} & \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ \cdots \\ A_m \end{array} & \begin{bmatrix} \widetilde{x_{11}} & \widetilde{x_{12}} & \cdots & \widetilde{x_{1n}} \\ \widetilde{x_{21}} & \widetilde{x_{22}} & \cdots & \widetilde{x_{2n}} \\ \cdots & \vdots & \ddots & \vdots \\ \widetilde{x_{m1}} & \widetilde{x_{m1}} & \cdots & \widetilde{x_{mn}} \end{bmatrix} \end{array} \tag{16}$$

$i = 1,2,\dots,m; j = 1,2,\dots,n$

$$\tilde{x}_{ij} = \frac{1}{K}(\tilde{x}_{ij}^{-1} \oplus \dots \oplus \tilde{x}_{ij}^{-k} \dots \oplus \tilde{x}_{ij}^{-K})$$

Here, $\tilde{x}_{ij}^{-k}$ represents the assessment provided by the k-th expert regarding alternative A_i concerning criterion C_j, denoted as $\tilde{x}_{ij}^{-k} = \left(l_{ij}^{k}, m_{ij}^{k}, u_{ij}^{k}\right)$

- Step 4: The decision matrix is subjected to normalization procedures.

The normalized fuzzy decision matrix is denoted by $\tilde{R}$ and is represented as outlined in Equation (17).

$$\tilde{R} = \left[\widetilde{r_{ij}}\right]_{m\times n}, i = 1,2,\dots,m; j = 1,2,\dots n \tag{17}$$

Normalization can be achieved using Equation (18).

$$\widetilde{r_{ij}} = (\frac{l_{ij}}{u_j^+}, \frac{m_{ij}}{u_j^+}, \frac{u_{ij}}{u_j^+}), u_j^+ = max\{u_{ij} | i = 1,2,\dots,n\} \tag{18}$$

The desired optimal level u_j^+ can be defined where $j = 1,2,\dots,n$ equals one; otherwise, it is set to zero. The weight of the normalized fuzzy decision matrix $\tilde{V}$ can be determined as in Equation (19).

$$\tilde{V} = [\widetilde{v_{ij}}_{n\times n}], i = 1,2,\dots,m; j = 1,2,\dots,n. \tag{19}$$

Where $\tilde{v}_{ij} = \tilde{r}_{ij} \otimes \tilde{w}_j$

- Step 5: Identifying the fuzzy positive-ideal solution (FPIS) and the fuzzy negative-ideal solution (FNIS).

The positive triangular fuzzy numbers (PTFNs) are normalized into the range of closed interval [0,1]. The FPIS (aspirational levels) A+ and FNIS A− can be obtained using Equation (20) and (21).

$$A^+ = (\tilde{v}_1^+, \dots, \tilde{v}_j^+, \dots, \tilde{v}_n^+) \tag{20}$$

$$A^- = (\tilde{v}_1^-, \dots, \tilde{v}_j^-, \dots, \tilde{v}_n^-) \tag{21}$$

Where $\tilde{v}_j^* = (1,1,1) \otimes \widetilde{w_j} = (lw_j, mw_j, uw_j)$

- Step 6: Determining the distance of each alternative from the FPIS and FNIS.

The distances ($\widetilde{d_i^+}$ and $\widetilde{d_i^-}$) of each alternative from A^+ and A^- can be computed using the area compensation method, as outlined in Equations (22) and (23).

$$\tilde{d}_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij,}\tilde{v}_j^*)\,, i = 1,2,\dots,m; j = 1,2,\dots,n \tag{22}$$

$$\tilde{d}_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij,}\tilde{v}_j^-)\,, i = 1,2,\dots,m; j = 1,2,\dots,n \tag{23}$$

Here, d represents the distance between two fuzzy numbers.

- Step 7: Calculating the closeness coefficients

The closeness coefficients are determined using Equation (24).

$$CC_i = \frac{\tilde{d}_i^-}{\tilde{d}_i^+ + \tilde{d}_i^-} \quad (24)$$

- Step 8: Establishing the order of preference ranking

The alternatives are arranged in a descending order based on the CC_i index.

3. Methodology

This study employed a quantitative approach with the Multi-Criteria Decision Making (MCDM) method, specifically integrating Fuzzy Analytic Hierarchy Process (FAHP) and Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS). This approach was selected to ensure objectivity in decision-making while effectively handling the uncertainty and complexity inherent in coal transportation mode selection in Jambi Province.

Expert Sampling Strategy and Selection: The research employed a purposive expert sampling strategy to ensure comprehensive representation of all stakeholder perspectives relevant to coal transportation in Jambi Province. The expert panel consisted of 16 respondents distributed across five key stakeholder categories:

1. Government Officials (5 experts)
    - Mining and Energy Department (2)
    - Transportation Department (1)
    - Environmental Department (2)
2. Coal Mining Industry Representatives (5 experts)
    - Large-scale mining companies (2)
    - Medium-scale mining companies (2)
    - Mining contractors (1)
3. Transportation Service Providers (3 experts)
    - Road transportation companies (2)
    - River transportation operators (1)
4. Academic and Research Experts (3 experts)
    - Mining engineering (2)
    - Environmental science (1)

Experts were selected based on specific qualification criteria, including professional experience (minimum 5 years of direct professional experience), educational background (minimum bachelor's degree in relevant fields), knowledge depth, geographical representation, and impartiality.

Criteria and Sub-criteria Definition

Economic Criteria: Economic considerations form the foundation of transportation decision-making in resource industries. As emphasized by Yucekaya (2015), transportation costs typically constitute 30-40% of total coal logistics expenses, directly affecting operational viability and competitiveness. For Jambi Province, where transportation costs have constrained production to 44-50% of targets (Department of Energy and Mineral Resources of Jambi Province, 2024), economic efficiency represents a critical priority.

Initial Investment Cost (CAPEX) represents the total capital expenditure required for infrastructure development and equipment acquisition before operationalization. Wang Chen et al. (2016) established this as a critical economic factor in transportation mode selection, particularly for resource-intensive industries. In Jambi's context, this includes costs for constructing dedicated roads (estimated at Rp 15-20 billion per kilometer) or rail infrastructure (estimated at Rp 15-18 trillion for a 120-150 km network).

Operating Expenses (OPEX) encompasses all recurring costs associated with day-to-day operation and maintenance. Yucekaya (2015) demonstrated that these costs typically constitute 30-40% of total coal logistics expenses in developing regions. For Jambi, with its high proportion of small and medium-sized operators (78% of mining entities), operational cost efficiency is particularly critical to business sustainability.

Additional Economic Value represents broader economic benefits beyond direct transportation services. As noted by Belanina (2013), transportation infrastructure in Indonesia can serve as a catalyst for regional economic development through multi-purpose utilization and stimulation of supporting industries.

Technical Criteria: Technical aspects determine the operational feasibility and performance capabilities of transportation systems. Li et al. (2021) established that technical parameters such as capacity, speed, and operational complexity significantly impact transportation system effectiveness. Given Jambi's geographical diversity and infrastructure limitations, technical considerations are essential for ensuring practical implementation.

Maximum Load Capacity measures the maximum volume or weight that can be transported in a single shipment or defined time period. Li et al. (2021) identified carrying capacity as a key parameter in their evaluation framework for bulk commodity transportation. The production data analysis of Jambi Province shows that current transportation constraints have limited actual production to only 44-50% of targets in 2022-2023.

Transport Speed evaluates the velocity at which coal can be moved from source to destination. Sherwood et al. (2020) emphasized distribution speed as a critical factor in coal logistics optimization, particularly for meeting delivery schedules. Time series analysis shows a significant correlation ($r=0.78$, $p<0.01$) between transportation cycle time and monthly production volume in Jambi.

Ease of Operation considers the complexity, technical sophistication, and adaptability of transportation systems. Parmar et al. (2024) established operational complexity as a significant factor in transportation mode selection, particularly relevant given Jambi's diverse topography ranging from lowlands to hills with slopes of 15-25%.

Environmental Criteria: The inclusion of environmental criteria reflects the growing emphasis on sustainability in transportation planning. Wang et al. (2024) highlighted that transportation systems must increasingly balance operational requirements with environmental responsibility. For Jambi Province, where 78% of residents along transportation routes report negative impacts from coal dust pollution, environmental considerations carry significant weight.

Carbon Emissions quantifies greenhouse gas emissions associated with each transportation mode. Wang et al. (2024) highlighted decarbonization as a global imperative in transportation systems. Environmental impact assessments in Jambi show that current truck-based transportation produces approximately 85-95 kg of CO_2 emissions per ton, compared to 45-55 kg for barge-based systems and 25-35 kg for conveyor-rail combinations.

Energy Consumption measures the amount of energy required for transportation operations. Ma et al. (2018) established energy efficiency as a key environmental criterion in transportation optimization frameworks, demonstrating its correlation with both environmental impact and operational costs.

Ecosystem Impact considers broader environmental effects beyond emissions, including impacts on biodiversity, water quality, and natural habitats. Li et al. (2021) integrated ecosystem impacts in their comprehensive sustainability evaluation framework for coal supply chains, providing a structured approach to assessment.

Safety Criteria: Safety represents a critical dimension in transportation system evaluation that impacts both human welfare and operational continuity. Nguyen et al. (2020) emphasized that risk assessment should be integral to transportation planning. Analysis of coal transportation accidents in Jambi (2018-2023) shows an increasing trend, highlighting the relevance of safety considerations.

Accident Risk assesses the probability and potential severity of accidents during transportation operations. Nguyen et al. (2020) emphasized risk assessment in transportation route planning, developing a framework that integrates geographical hazards with operational risks. Analysis of coal transportation accident data in Jambi (2018-2023) shows an increasing trend, with 68% of incidents involving truck transportation on public roads.

Load Security evaluates the protection and integrity of cargo during transit. Haddad et al. (2021) included cargo security in their criteria for transportation mode evaluation, noting its importance for both economic and environmental reasons. Field observations in Jambi documented significant coal spillage along current transportation routes.

Lane Safety considers the safety aspects of the transportation route itself. Štilić & Puška (2023) integrated infrastructure safety in their sustainable engineering framework, providing a methodology for evaluating route-specific risks. Topographical analysis of Jambi Province shows that 43% of mining areas are in hilly regions, creating specific safety challenges.

Social Criteria: Transportation infrastructure significantly impacts surrounding communities, making social acceptance crucial for long-term viability. Setiowati et al. (2017) demonstrated that community perspectives are essential for sustainable transportation planning in Indonesia. In Jambi, where transportation corridors intersect with multiple communities, social considerations are vital for implementation success.

Community Acceptance measures the degree to which local communities receive and support transportation activities. Setiowati et al. (2017) incorporated community perspectives in their evaluation of transportation preferences in Indonesia.

Community surveys indicate that 78% of residents along current transportation routes report negative impacts from coal dust pollution.

Risk of Social Conflict assesses potential for disputes arising from transportation activities. Kabashkin (2023) developed a framework for evaluating social conflict risks in transportation infrastructure projects. Stakeholder mapping identified 14 potential conflict hotspots related to land acquisition for new transportation corridors.

Potential for Labor Absorption evaluates employment opportunities created throughout the transportation lifecycle. (Roozbeh Nia et al., 2024) incorporated job creation in their extended framework for evaluating supply chain alternatives. Regional economic simulations indicate that implementation of dedicated coal roads could create 12,000-15,000 new jobs within the coal transportation ecosystem in Jambi Province.

Managing Expert Judgment Inconsistencies: To minimize inconsistencies in expert judgments, several preventive measures were implemented, including expert calibration workshops, structured evaluation protocols, and cognitive bias reduction techniques. For detection and correction of inconsistencies, the approach included consistency ratio (CR) monitoring, automated inconsistency identification, and iterative revision processes. The final aggregation of expert judgments employed a weighted geometric mean method with expertise weighting mechanisms, fuzzy aggregation procedures, and consensus measurement and management.

Data Collection and Analysis: Data was collected through questionnaires, interviews, field observations, and documentation studies. The FAHP analysis was conducted using the fuzzy extent analysis approach (Kusumawardani, 2015). Fuzzy TOPSIS analysis was conducted using the methodology that was applied in their research (Chisale & Lee, 2023).

Research Validation: Validation of the study was conducted through method triangulation, expert validation, and robustness testing. The triangulation method used three different analysis methods to evaluate alternative coal transportation modes. Expert validation was conducted through Focus Group Discussion (FGD) with transportation, mining, and economic experts.

4. Empirical Findings/Result

Criteria Weight Analysis Results (FAHP)

The FAHP analysis revealed the relative importance of the main criteria for coal transportation mode selection. The results showed that economics was the most important criterion, with a weight of 43.2%, followed by technical (18.8%), safety (15.1%), environment (13,6%), and social (9.3%).

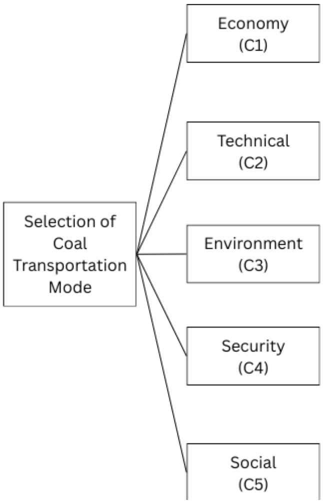

Figure 5. Selection of Coal Transportation Mode Criteria

Table 4. Comparation between criteria

Criteria	C1			C2			C3			C4			C5		
	L	**M**	**U**	**L**	**M**	**U**	**L**	**M**	**U**	**L**	**M**	**U**	**L**	**M**	**U**
C1	1	1	1	2.80	3.20	3.60	2.60	3.60	4.60	1.80	3.00	4.20	2.20	3.20	4.20
C2	0.28	0.31	0.36	1	1	1	0.91	1.72	2.53	1.03	1.64	2.27	1.35	1.98	2.72
C3	0.22	0.28	0.38	0.39	0.58	1.09	1	1	1	0.91	0.92	0.93	1.07	1.90	2.85
C4	0.24	0.33	0.56	0.44	0.61	0.97	1.07	1.09	1.09	1	1	1	1.28	2.13	3.20
C5	0.24	0.31	0.45	0.37	0.50	0.74	0.35	0.53	0.94	0.31	0.47	0.78	1	1	1

Table 5. Normalization of All Criteria

Criteria	C1	C2	C3	C4	C5
C1	1	3.20	3.60	3.00	3.20
C2	0.32	1	1.72	1.65	2.02
C3	0.29	0.69	1	0.92	1.94
C4	0.38	0.67	1.08	1	2.20
C5	0.34	0.54	0.61	0.52	1
Normalization	2.32	6.10	8.01	7.09	10.36

Table 6. Coal Transportation Mode Criteria

Criteria	C1	C2	C3	C4	C5	Priority Vector
C1	0.43	0.52	0.45	0.42	0.31	0.43
C2	0.14	0.16	0.22	0.23	0.19	0.19
C3	0.13	0.11	0.12	0.13	0.19	0.14
C4	0.16	0.11	0.14	0.14	0.21	0.15
C5	0.14	0.09	0.08	0.07	0.10	0.10

Table 7. Result of Defuzzified Weight Criteria

Criteria	Defuzzified Weight
C1	0.43
C2	0.19
C3	0.14
C4	0.15
C5	0.10

Table 8. Checking Data of Criteria

λ Max	5.28
CI	0.07
CR	0.06

The consistency ratio for all pairwise comparison matrices was below 0.10, indicating acceptable consistency in expert judgments.

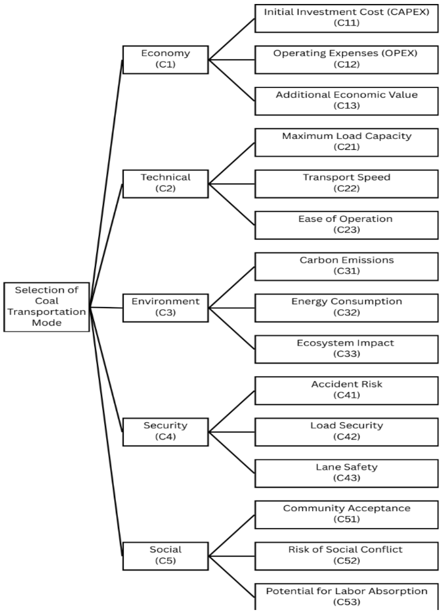

Figure 6. Selection of Coal Transportation Mode Sub-Criteria

Table 9. Comparasion between Sub-Criteria

Sub-Criteria	C11			C12			C13		
	L	**M**	**U**	**L**	**M**	**U**	**L**	**M**	**U**
C11	1	1	1	2.12	2.53	3.00	2.20	2.60	3.00
C12	0.33	0.39	0.47	1	1	1	1.40	2.00	2.60
C13	0.33	0.38	0.45	0.38	0.50	0.71	1	1	1

Sub-Criteria	C21			C22			C23		
	L	M	U	L	M	U	L	M	U
C21	1	1	1	1.92	3.33	4.80	2.72	3.33	4.00
C22	0.21	0.30	0.52	1	1	1	1.55	2.58	3.72
C23	0.25	0.30	0.37	0.27	0.39	0.64	1	1	1
Sub-Criteria	**C31**			**C32**			**C33**		
	L	**M**	**U**	**L**	**M**	**U**	**L**	**M**	**U**
C31	1	1	1	1.60	2.80	4.00	1.60	2.40	3.20
C32	0.25	0.36	0.63	1	1	1	0.92	1.53	2.20
C33	0.31	0.42	0.63	0.45	0.65	1.09	1	1	1
Sub-Criteria	**C41**			**C42**			**C43**		
	L	**M**	**U**	**L**	**M**	**U**	**L**	**M**	**U**
C41	1	1	1	2.60	3.60	4.60	2.40	3.40	4.40
C42	0.22	0.28	0.38	1	1	1	0.91	1.52	2.13
C43	0.23	0.29	0.42	0.47	0.66	1.09	1	1	1
Sub-Criteria	**C51**			**C52**			**C53**		
	L	**M**	**U**	**L**	**M**	**U**	**L**	**M**	**U**
C51	1	1	1	1.60	2.60	3.60	2.52	3.73	5.00
C52	0.28	0.38	0.63	1	1	1	1.80	3.20	4.60
C53	0.20	0.27	0.40	0.22	0.31	0.56	1	1	1

Table 10. Coal Transportation Mode Sub-Criteria

Sub-Criteria	C11	C12	C13	Priority Vector
C11	0.56	0.64	0.46	0.56
C12	0.22	0.25	0.36	0.28
C13	0.22	0.10	0.18	0.17
Sub-Criteria	**C21**	**C22**	**C23**	**Priority Vector**
C21	0.61	0.72	0.48	0.60
C22	0.21	0.21	0.38	0.27
C23	0.19	0.07	0.14	0.13
Sub-Criteria	**C31**	**C32**	**C33**	**Priority Vector**
C31	0.54	0.65	0.48	0.56
C32	0.22	0.23	0.31	0.26
C33	0.24	0.12	0.20	0.19
Sub-Criteria	**C41**	**C42**	**C43**	**Priority Vector**
C41	0.62	0.72	0.57	0.64
C42	0.18	0.20	0.26	0.21
C43	0.19	0.08	0.17	0.15
Sub-Criteria	**C51**	**C52**	**C53**	**Priority Vector**
C51	0.58	0.67	0.47	0.57
C52	0.25	0.26	0.40	0.30
C53	0.17	0.08	0.13	0.12

Table 11. Table of Weighted Coal Transportation Mode Sub-Criteria

Subcriteria	Weight per Sub-Criteria
Initial Investment Cost (CAPEX) - C11	0.55
Operating Expenses (OPEX) - C12	0.27
Additional Economic Value - C13	0.17
Maximum Load Capacity - C21	0.61
Transport Speed - C22	0.26
Ease of Operation - C23	0.14
Carbon Emissions - C31	0.55
Energy Consumption - C32	0.25
Ecosystem Impact - C33	0.20
Accident Risk - C41	0.63
Load Security - C42	0.21
Lane Safety - C43	0.17
Community Acceptance - C51	0.58
Risk of Social Conflict - C52	0.30
Potential for Labor Absorption - C53	0.13

Further analysis of sub-criteria under each main criterion revealed:

1. Under Economic: Initial Investment Cost (55.4%), Operating Expenses (27.2%), Additional Economic Value (17.4%)
2. Under Technical: Maximum Load Capacity (60.5%), Transport Speed (25.6%), Ease of Operation (13.8%)
3. Under Environmental Impact: Carbon Emissions (55.0%), Energy Consumptions (24.9%), Ecosystem Impact (20.2%)
4. Under Safety: Accident Risk (62.8%), Load Security (20.6%), Lane Safety (16.5%)
5. Under Social: Community Acceptance (57.7%), Risk of Social Conflict (29.7%), Potential of Labor Absorption (12.6%)

Table 12. Checking Data of Sub-Criteria

Economic Sub Cirteria		Technical Sub Cirteria		Environment Sub Cirteria		Safety Sub Cirteria		Social Sub Cirteria	
λ Max	3.01	λ Max	3.10	λ Max	3.05	λ Max	2.95	λ Max	3.12
CI	0.01	CI	0.05	CI	0.02	CI	0.03	CI	0.06
CR	0.01	CR	0.09	CR	0.04	CR	0.05	CR	0.10

The consistency ratio for all pairwise comparison matrices was below 0.10, indicating acceptable consistency in expert judgments.

Alternative Evaluation and Ranking Results (Fuzzy TOPSIS)

Based on the weights derived from FAHP, the four transportation alternatives were evaluated using Fuzzy TOPSIS. The analysis involved constructing fuzzy decision matrices, normalizing values, determining fuzzy positive and negative ideal solutions, calculating distances, and computing closeness coefficients.

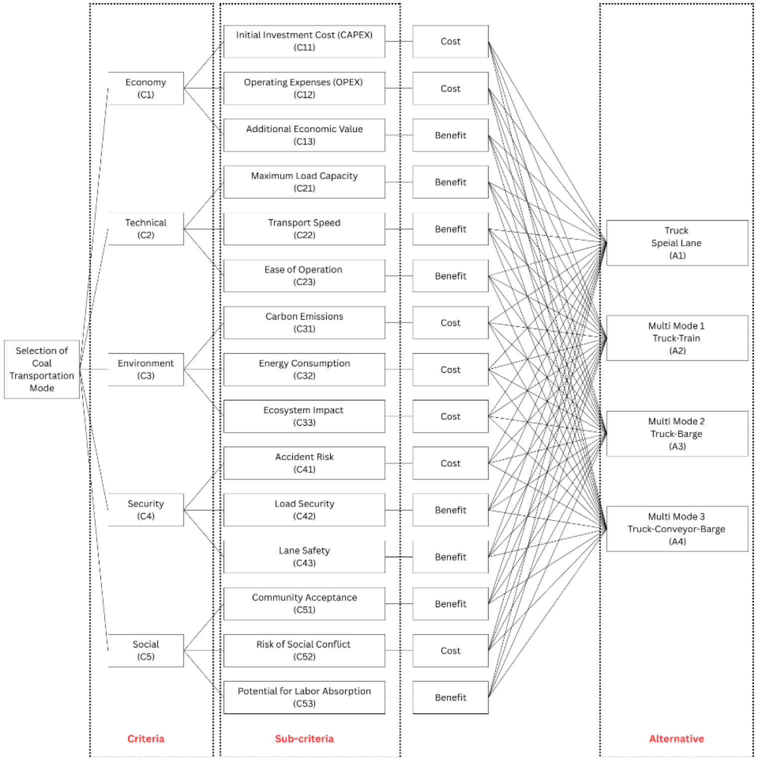

Figure 7. Hierarchical Structure for Selection of Coal Transportation Mode

Table 13. The type of each sub-criteria

Criteria	Sub-Criteria	Type
Economy	Initial Investment Cost (CAPEX)	Cost
	Operating Expenses (OPEX)	Cost
	Additional Economic Value	Benefit
Technical	Maximum Load Capacity	Benefit
	Transport Speed	Benefit
	Ease of Operation	Benefit
Environment	Carbon Emissions	Cost
	Energy Consumption	Cost
	Ecosystem Impact	Cost
Security	Accident Risk	Cost
	Load Security	Benefit
	Lane Safety	Benefit
Social	Community Acceptance	Benefit
	Risk of Social Conflict	Cost
	Potential for Labor Absorption	Benefit

Table 14. Normalization Sub-criteria – Alternative

Sub-Criteria	Types of Criteria	Alternative	NL	NM	NU
Initial Investment Cost (CAPEX)	Cost	Truck (Special Lane)	0.61	0.71	0.84
Initial Investment Cost (CAPEX)	Cost	Multi-Mode 1 (Truck - Train)	0.61	0.71	0.84
Initial Investment Cost (CAPEX)	Cost	Multi-Mode 2 (Truck - Barge)	0.64	0.77	0.96
Initial Investment Cost (CAPEX)	Cost	Multi-Mode 3 (Truck - Conveyor - Barge)	0.66	0.79	1.00
Operating Expenses (OPEX)	Cost	Truck (Special Lane)	0.51	0.59	0.70
Operating Expenses (OPEX)	Cost	Multi-Mode 1 (Truck - Train)	0.56	0.68	0.85
Operating Expenses (OPEX)	Cost	Multi-Mode 2 (Truck - Barge)	0.61	0.74	0.96
Operating Expenses (OPEX)	Cost	Multi-Mode 3 (Truck - Conveyor - Barge)	0.53	0.70	1.00
Additional Economic Value	Benefits	Truck (Special Lane)	0.77	0.89	1.00
Additional Economic Value	Benefits	Multi-Mode 1 (Truck - Train)	0.68	0.84	1.00
Additional Economic Value	Benefits	Multi-Mode 2 (Truck - Barge)	0.55	0.73	0.91

Additional Economic Value	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.59	0.77	0.95
Maximum Load Capacity	Benefits	Truck (Special Lane)	0.60	0.77	0.93
Maximum Load Capacity	Benefits	Multi-Mode 1 (Truck - Train)	0.72	0.86	1.00
Maximum Load Capacity	Benefits	Multi-Mode 2 (Truck - Barge)	0.63	0.79	0.95
Maximum Load Capacity	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.77	0.88	1.00
Transport Speed	Benefits	Truck (Special Lane)	0.69	0.83	0.98
Transport Speed	Benefits	Multi-Mode 1 (Truck - Train)	0.62	0.81	1.00
Transport Speed	Benefits	Multi-Mode 2 (Truck - Barge)	0.52	0.74	0.95
Transport Speed	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.60	0.79	0.98
Ease of Operation	Benefits	Truck (Special Lane)	0.69	0.83	0.98
Ease of Operation	Benefits	Multi-Mode 1 (Truck - Train)	0.64	0.81	0.98
Ease of Operation	Benefits	Multi-Mode 2 (Truck - Barge)	0.57	0.76	0.95
Ease of Operation	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.57	0.79	1.00
Carbon Emissions	Cost	Truck (Special Lane)	0.59	0.73	0.96
Carbon Emissions	Cost	Multi-Mode 1 (Truck - Train)	0.69	0.81	1.00
Carbon Emissions	Cost	Multi-Mode 2 (Truck - Barge)	0.58	0.71	0.92
Carbon Emissions	Cost	Multi-Mode 3 (Truck - Conveyor - Barge)	0.59	0.73	0.96
Energy Consumption	Cost	Truck (Special Lane)	0.54	0.70	1.00
Energy Consumption	Cost	Multi-Mode 1 (Truck - Train)	0.50	0.63	0.86
Energy Consumption	Cost	Multi-Mode 2 (Truck - Barge)	0.53	0.68	0.95
Energy Consumption	Cost	Multi-Mode 3 (Truck - Conveyor - Barge)	0.49	0.59	0.76
Ecosystem Impact	Cost	Truck (Special Lane)	0.56	0.71	0.96
Ecosystem Impact	Cost	Multi-Mode 1 (Truck - Train)	0.54	0.65	0.81
Ecosystem Impact	Cost	Multi-Mode 2 (Truck - Barge)	0.59	0.73	0.96
Ecosystem Impact	Cost	Multi-Mode 3 (Truck - Conveyor - Barge)	0.58	0.73	1.00
Accident Risk	Cost	Truck (Special Lane)	0.58	0.73	1.00
Accident Risk	Cost	Multi-Mode 1 (Truck - Train)	0.54	0.69	0.96
Accident Risk	Cost	Multi-Mode 2 (Truck - Barge)	0.54	0.69	0.96
Accident Risk	Cost	Multi-Mode 3 (Truck - Conveyor - Barge)	0.52	0.65	0.85
Load Security	Benefits	Truck (Special Lane)	0.57	0.75	0.93

Load Security	Benefits	Multi-Mode 1 (Truck - Train)	0.64	0.82	1.00
Load Security	Benefits	Multi-Mode 2 (Truck - Barge)	0.59	0.77	0.95
Load Security	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.55	0.75	0.95
Lane Safety	Benefits	Truck (Special Lane)	0.58	0.79	1.00
Lane Safety	Benefits	Multi-Mode 1 (Truck - Train)	0.58	0.79	1.00
Lane Safety	Benefits	Multi-Mode 2 (Truck - Barge)	0.58	0.79	1.00
Lane Safety	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.58	0.79	1.00
Community Acceptance	Benefits	Truck (Special Lane)	0.67	0.83	1.00
Community Acceptance	Benefits	Multi-Mode 1 (Truck - Train)	0.60	0.79	0.98
Community Acceptance	Benefits	Multi-Mode 2 (Truck - Barge)	0.50	0.69	0.88
Community Acceptance	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.60	0.79	0.98
Risk of Social Conflict	Cost	Truck (Special Lane)	0.60	0.75	1.00
Risk of Social Conflict	Cost	Multi-Mode 1 (Truck - Train)	0.55	0.67	0.86
Risk of Social Conflict	Cost	Multi-Mode 2 (Truck - Barge)	0.60	0.75	1.00
Risk of Social Conflict	Cost	Multi-Mode 3 (Truck - Conveyor - Barge)	0.57	0.69	0.86
Potential for Labor Absorption	Benefits	Truck (Special Lane)	0.73	0.87	1.00
Potential for Labor Absorption	Benefits	Multi-Mode 1 (Truck - Train)	0.27	0.49	0.71
Potential for Labor Absorption	Benefits	Multi-Mode 2 (Truck - Barge)	0.42	0.62	0.82
Potential for Labor Absorption	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.44	0.64	0.84

Table 15. Result of FPIS, FNIS, D-FPIS & D-FNIS

Sub-Criteria	**Types of Criteria**	**Alternative**	**FPIS**	**FNIS**	**D FPIS**	**D FNIS**
Initial Investment Cost (CAPEX)	Cost	Truck (Special Lane)	0.34	0.55	0.080	0.162
Initial Investment Cost (CAPEX)	Cost	Multi-Mode 1 (Truck - Train)	0.34	0.55	0.080	0.162
Initial Investment Cost (CAPEX)	Cost	Multi-Mode 2 (Truck - Barge)	0.34	0.55	0.123	0.136

Initial Investment Cost (CAPEX)	Cost	Multi-Mode 3 (Truck - Conveyor - Barge)	0.34	0.55	0.137	0.128
Operating Expenses (OPEX)	Cost	Truck (Special Lane)	0.28	0.55	0.065	0.226
Operating Expenses (OPEX)	Cost	Multi-Mode 1 (Truck - Train)	0.28	0.55	0.122	0.181
Operating Expenses (OPEX)	Cost	Multi-Mode 2 (Truck - Barge)	0.28	0.55	0.164	0.152
Operating Expenses (OPEX)	Cost	Multi-Mode 3 (Truck - Conveyor - Barge)	0.28	0.55	0.168	0.178
Additional Economic Value	Benefits	Truck (Special Lane)	0.55	0.30	0.081	0.196
Additional Economic Value	Benefits	Multi-Mode 1 (Truck - Train)	0.55	0.30	0.114	0.179
Additional Economic Value	Benefits	Multi-Mode 2 (Truck - Barge)	0.55	0.30	0.172	0.130
Additional Economic Value	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.55	0.30	0.151	0.151
Maximum Load Capacity	Benefits	Truck (Special Lane)	0.55	0.34	0.149	0.117
Maximum Load Capacity	Benefits	Multi-Mode 1 (Truck - Train)	0.55	0.34	0.100	0.155
Maximum Load Capacity	Benefits	Multi-Mode 2 (Truck - Barge)	0.55	0.34	0.137	0.127
Maximum Load Capacity	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.55	0.34	0.083	0.163
Transport Speed	Benefits	Truck (Special Lane)	0.55	0.29	0.113	0.183
Transport Speed	Benefits	Multi-Mode 1 (Truck - Train)	0.55	0.29	0.136	0.180
Transport Speed	Benefits	Multi-Mode 2 (Truck - Barge)	0.55	0.29	0.175	0.153
Transport Speed	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.55	0.29	0.147	0.169
Ease of Operation	Benefits	Truck (Special Lane)	0.55	0.32	0.113	0.159
Ease of Operation	Benefits	Multi-Mode 1 (Truck - Train)	0.55	0.32	0.130	0.152
Ease of Operation	Benefits	Multi-Mode 2 (Truck - Barge)	0.55	0.32	0.158	0.136

Ease of Operation	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.55	0.32	0.153	0.153
Carbon Emissions	Cost	Truck (Special Lane)	0.32	0.55	0.131	0.156
Carbon Emissions	Cost	Multi-Mode 1 (Truck - Train)	0.32	0.55	0.158	0.116
Carbon Emissions	Cost	Multi-Mode 2 (Truck - Barge)	0.32	0.55	0.116	0.166
Carbon Emissions	Cost	Multi-Mode 3 (Truck - Conveyor - Barge)	0.32	0.55	0.131	0.156
Energy Consumption	Cost	Truck (Special Lane)	0.27	0.55	0.179	0.174
Energy Consumption	Cost	Multi-Mode 1 (Truck - Train)	0.27	0.55	0.129	0.203
Energy Consumption	Cost	Multi-Mode 2 (Truck - Barge)	0.27	0.55	0.161	0.184
Energy Consumption	Cost	Multi-Mode 3 (Truck - Conveyor - Barge)	0.27	0.55	0.094	0.223
Ecosystem Impact	Cost	Truck (Special Lane)	0.30	0.55	0.146	0.168
Ecosystem Impact	Cost	Multi-Mode 1 (Truck - Train)	0.30	0.55	0.096	0.196
Ecosystem Impact	Cost	Multi-Mode 2 (Truck - Barge)	0.30	0.55	0.150	0.156
Ecosystem Impact	Cost	Multi-Mode 3 (Truck - Conveyor - Barge)	0.30	0.55	0.162	0.160
Accident Risk	Cost	Truck (Special Lane)	0.29	0.55	0.167	0.160
Accident Risk	Cost	Multi-Mode 1 (Truck - Train)	0.29	0.55	0.148	0.179
Accident Risk	Cost	Multi-Mode 2 (Truck - Barge)	0.29	0.55	0.148	0.179
Accident Risk	Cost	Multi-Mode 3 (Truck - Conveyor - Barge)	0.29	0.55	0.110	0.196
Load Security	Benefits	Truck (Special Lane)	0.55	0.30	0.161	0.140
Load Security	Benefits	Multi-Mode 1 (Truck - Train)	0.55	0.30	0.130	0.172
Load Security	Benefits	Multi-Mode 2 (Truck - Barge)	0.55	0.30	0.151	0.151
Load Security	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.55	0.30	0.167	0.146
Lane Safety	Benefits	Truck (Special Lane)	0.55	0.32	0.150	0.150

Lane Safety	Benefits	Multi-Mode 1 (Truck - Train)	0.55	0.32	0.150	0.150
Lane Safety	Benefits	Multi-Mode 2 (Truck - Barge)	0.55	0.32	0.150	0.150
Lane Safety	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.55	0.32	0.150	0.150
Community Acceptance	Benefits	Truck (Special Lane)	0.55	0.28	0.119	0.200
Community Acceptance	Benefits	Multi-Mode 1 (Truck - Train)	0.55	0.28	0.147	0.180
Community Acceptance	Benefits	Multi-Mode 2 (Truck - Barge)	0.55	0.28	0.192	0.136
Community Acceptance	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.55	0.28	0.147	0.180
Risk of Social Conflict	Cost	Truck (Special Lane)	0.30	0.55	0.161	0.151
Risk of Social Conflict	Cost	Multi-Mode 1 (Truck - Train)	0.30	0.55	0.107	0.186
Risk of Social Conflict	Cost	Multi-Mode 2 (Truck - Barge)	0.30	0.55	0.161	0.151
Risk of Social Conflict	Cost	Multi-Mode 3 (Truck - Conveyor - Barge)	0.30	0.55	0.110	0.176
Potential for Labor Absorption	Benefits	Truck (Special Lane)	0.55	0.15	0.095	0.338
Potential for Labor Absorption	Benefits	Multi-Mode 1 (Truck - Train)	0.55	0.15	0.301	0.159
Potential for Labor Absorption	Benefits	Multi-Mode 2 (Truck - Barge)	0.55	0.15	0.228	0.217
Potential for Labor Absorption	Benefits	Multi-Mode 3 (Truck - Conveyor - Barge)	0.55	0.15	0.217	0.228

Table 16. Result of Sigma D-FPIS, Sigma D-FNIS & CC

Alternative	**∑ DFPIS**	**∑ DFNIS**	**CC**
Truck (Special Lane)	1.91	2.68	0.584
Multi-Mode 1 (Truck - Train)	2.05	2.55	0.555
Multi-Mode 2 (Truck - Barge)	2.39	2.32	0.494
Multi-Mode 3 (Truck - Conveyor - Barge)	2.13	2.56	0.546

The final ranking of alternatives based on closeness coefficients was:

1. Truck (Special Lane) (0.584)

2. Truck-Train (0.555)
3. Truck-Conveyor-Barge (0.546)
4. Truck-Barge (0.494)

The Truck-Conveyor-Barge alternative emerged as the optimal solution, performing particularly well on the environmental impact and cost criteria, which had the highest weights. This alternative showed a balanced performance across all criteria, with performance in operational cost efficiency, minimal environmental impact, and a good safety record.

5. Discussion

The results of this study reveal several important implications for coal transportation in Jambi Province. The integrated FAHP-Fuzzy TOPSIS methodology provided a systematic framework for evaluating transportation alternatives considering multiple criteria with diverse levels of importance.

The dominance of economic factors (43.2% weight) in the decision-making process aligns with industry priorities in developing regions, where cost efficiency often drives operational decisions, as noted by Yucekaya (2015) in their study of coal supply chains. However, the substantial weight assigned to environmental impact (13.6%) reflects growing recognition of sustainability concerns, suggesting a shift toward more balanced decision-making that incorporates both economic and ecological considerations. The Truck (Special Lane) alternative emerged as the optimal solution with several advantages:

Economic Advantages: Using special routes for coal transport trucks will make the coal production achievement level relatively more measurable by ensuring that all coal special road areas are safe to traverse without considering other aspects such as river water conditions, unlike modes that use barges as one of their transport methods. With this improvement, it will increase regional income and stimulate the economy in the Jambi area through collaborations between the government, the managers of the special coal roads, and the surrounding communities, ensuring that no party is left behind in every process. This is effective in reducing the unemployment rate in the areas around the special road that is traversed by empowering the local people. The use of this special coal road can also maximize truck loads by utilizing trucks with large capacities, thereby improving fuel efficiency in relation to the amount of cargo transported. With the use of larger equipment, the number of machines in circulation will decrease, thereby reducing maintenance costs and lowering the potential accident rate due to the reduced number of machines, which in turn minimizes the company's losses from accidents. This is primarily achieved through reduced fuel consumption, lower maintenance costs, and improved operational efficiency through continuous material flow. The higher throughput capacity can potentially increase provincial coal production realization from the current 44-50% to 70-80% of planned capacity.

Environmental Benefits: This alternative significantly reduces carbon footprint by replacing long-distance truck transportation with more energy-efficient conveyor and barge systems. Emissions modelling indicates potential reductions of 35-40% in CO_2 emissions compared to truck-only options. Additionally, the enclosed conveyor systems minimize coal dust dispersal, addressing a major community concern.

Operational Improvements: The multimodal system overcomes the current 11-hour operational restriction on public roads by enabling 24-hour operation of conveyor systems and river transportation, effectively increasing daily throughput capacity. System reliability analysis suggests potential improvement in delivery predictability by 25-30%, critical for meeting contractual obligations.

Infrastructure Development Requirements: Implementation would require coordinated development of:

1. Strategic loading terminals at mine-conveyor interfaces
2. Approximately 120-150 km of enclosed conveyor systems connecting major mining clusters
3. River depth maintenance and navigational improvements for the Batanghari River
4. Expanded port facilities to handle increased throughput

These findings align with Belanina (2013) observations that multimodal solutions represent optimal approaches for Indonesia's geographical conditions, though they require significant coordination and infrastructure investment. The proposed solution addresses the specific challenges identified in Jambi's transportation system while providing a balanced approach to economic, environmental, and social considerations.

6. Conclusions

This research has successfully developed and applied an integrated FAHP-Fuzzy TOPSIS framework to optimize coal transportation mode selection in Jambi Province, demonstrating the effectiveness of this approach in addressing complex multi-criteria decision problems under uncertainty.

The study determined that cost and environmental impact represent the dominant decision criteria, collectively accounting for approximately 66% of the decision weight. This finding reflects the dual imperatives facing the industry: maintaining economic competitiveness while addressing growing environmental concerns. The identification of the Truck-Conveyor-Barge alternative as the optimal transportation mode demonstrates the potential for multimodal systems to balance these competing priorities more effectively than single-mode solutions.

The research empirically confirmed that coal transportation represents a critical bottleneck in Jambi's production capacity, with current inefficiencies resulting in substantial opportunity costs estimated at 35-45% of potential provincial coal revenue. The recommended multimodal solution addresses these inefficiencies while simultaneously reducing environmental impact, particularly in terms of emissions and community disturbance.

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