

A fuzzy AHP-based approach for optimal transport mode selection

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ABSTRACT

The selection of an optimal transport mode in modern logistics systems represents a complex multi-criteria decision-making problem requiring the simultaneous consideration of economic, operational, and environmental factors. This study applies the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) method to determine the weighting coefficients of evaluation criteria and rank alternative freight transport solutions. The analysis focuses on containerized freight flows, considering road, rail, and inland waterway transport as the main alternatives, evaluated according to transportation cost, delivery time, CO₂ emissions, and reliability. A key contribution of the study is reflected in the comparative analysis of three shipment scenarios with different cargo volumes (10, 100, and 500 TEU), enabling a systematic assessment of the influence of shipment size on transport mode selection. The obtained results indicate that increasing cargo volume improves the competitiveness of rail and inland waterway transport due to economies of scale, particularly in terms of cost efficiency and environmental performance, while road transport maintains an advantage primarily in delivery time. The findings confirm the applicability of MCDM approaches in sustainable transport planning and logistics decision-making.

KEYWORDS

Fuzzy AHP, Transport mode selection, MCDM, Container freight, Sustainable logistics

1. INTRODUCTION

The continuous growth of global trade and the increasing complexity of logistics systems have increased the importance of efficient and sustainable freight transport. Containerization has become one of the key elements of modern logistics because it enables standardization, easier cargo handling, and improved integration of different transport modes. Consequently, transport mode selection has become a complex decision-making problem involving multiple conflicting criteria related to economic efficiency, operational performance, and environmental sustainability.

Traditionally, transport mode selection was primarily based on transportation cost and delivery time. However, increasing environmental concerns, stricter emission reduction policies, and the growing importance of sustainable logistics have expanded the decision-making framework to include additional criteria such as CO₂ emissions, energy efficiency, and transport reliability. As a result, decision-makers are required to evaluate transport alternatives while considering uncertainty and subjective expert judgments.

Multi-Criteria Decision-Making (MCDM) methods have been widely applied in transport and logistics research to support complex decision-making processes [1–4]. Among the most frequently applied methods, the Analytic Hierarchy Process (AHP), introduced by Saaty [5], represents an effective approach for determining criterion importance and ranking alternatives. To overcome the limitations of conventional AHP related to uncertainty and vagueness in expert judgments, the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) was developed through the integration of fuzzy set theory with the classical AHP approach [6,7].

Previous studies demonstrated the applicability of hybrid MCDM approaches, including AHP, fuzzy AHP, and fuzzy TOPSIS, in sustainable transport planning and multicriteria logistics evaluation problems [8–10]. In addition, recent studies confirmed the effectiveness of fuzzy MCDM methodologies in transport systems, logistics optimization, transport sustainability assessment, and engineering decision-making problems [11–17].

This paper applies the Fuzzy AHP method to the problem of transport mode selection in containerized freight transport. Three transport alternatives are considered, namely road, rail, and inland waterway transport, while the evaluation is performed according to transportation cost, delivery time, CO₂ emissions, and transport reliability. The analysis is conducted for three shipment scenarios involving 10 TEU, 100 TEU, and 500 TEU in order to investigate the influence of cargo volume on transport mode competitiveness.

The remainder of the paper is organized as follows. Section 2 presents the methodological background of the Fuzzy AHP method. Section 3 describes the case study and decision matrix construction. Section 4 presents the obtained results and discussion, while the final section provides concluding remarks and directions for future research.

2. METHODOLOGY

2.1. Fuzzy AHP Method

The Fuzzy Analytic Hierarchy Process (Fuzzy AHP) method represents an extension of the conventional Analytic Hierarchy Process (AHP) developed by Thomas L. Saaty. The method integrates fuzzy set theory into the pairwise comparison procedure in order to better represent uncertainty and vagueness in expert judgments. Unlike classical AHP, which relies on precise numerical values, Fuzzy AHP enables decision-makers to express preferences using linguistic variables and fuzzy numbers. Similar fuzzy MCDM approaches have been successfully applied in various engineering and transport decision-making problems [9,10].

The Fuzzy AHP procedure applied in this study consists of the following steps:

- Definition of alternatives and evaluation criteria;
- Construction of the fuzzy pairwise comparison matrix;
- Calculation of fuzzy synthetic values;
- Determination of fuzzy criterion weights;
- Defuzzification and normalization of weights;
- Ranking of transport alternatives.

The obtained weighting coefficients are subsequently used for evaluating the considered transport alternatives within different shipment scenarios.

2.2. Triangular Fuzzy Numbers

In this study, triangular fuzzy numbers (TFNs) are used to represent pairwise comparisons between evaluation criteria. A triangular fuzzy number is defined as:

$$\tilde{A} = (l, m, u) \quad (1)$$

where:

- l denotes the lower bound,
- m denotes the most probable value,
- u denotes the upper bound.

The linguistic importance scale applied in the analysis is presented in Table 1.

Table 1: Linguistic importance scale and triangular fuzzy numbers

Linguistic importance	Triangular fuzzy number
Equal importance	(1, 1, 1)
Moderate importance	(2, 3, 4)
Strong importance	(4, 5, 6)
Very strong importance	(6, 7, 8)
Extreme importance	(8, 9, 10)

The application of triangular fuzzy numbers enables more flexible modeling of subjective expert evaluations and reduces the limitations associated with precise numerical judgments.

2.3. Determination of Criterion Weights

The fuzzy pairwise comparison matrix is constructed based on expert evaluations regarding the relative importance of the considered criteria. The geometric mean method is then applied to calculate the fuzzy weights of criteria.

The fuzzy geometric mean value for criterion i is calculated as:

$$\tilde{r}_i = \left(\prod_{j=1}^n \tilde{a}_{ij} \right)^{1/n} \quad (2)$$

where:

- $\tilde{a}_{ij}$ represents the fuzzy comparison value between criteria i and j ,
- n denotes the total number of criteria.

The fuzzy weights are obtained using:

$$\tilde{w}_i = \tilde{r}_i \otimes (\sum_{i=1}^n \tilde{r}_i)^{-1} \quad (3)$$

After determining fuzzy weights, the defuzzification procedure is performed in order to transform fuzzy values into crisp weighting coefficients. In this study, the center of area (COA) method is applied:

$$w_i = \frac{(l_i + m_i + u_i)}{3} \quad (4)$$

Finally, the obtained weights are normalized and used for the evaluation and ranking of transport alternatives for different shipment scenarios (10 TEU, 100 TEU, and 500 TEU). The proposed Fuzzy AHP framework was applied to the transport corridor between Pančevo and Novi Sad in order to evaluate the competitiveness of road, rail, and inland waterway transport under different shipment scenarios. The obtained criterion weights were combined with the normalized performance values of transport alternatives to determine the final evaluation scores and rankings.

3. CASE STUDY

The case study focuses on the transport corridor between Pančevo and Novi Sad, Serbia, which represents an important regional freight transport route with developed road, rail, and inland waterway infrastructure. The corridor was selected due to its significant intermodal transport potential and the possibility of analyzing different transport alternatives under varying shipment volumes. The considered logistics scenario enables the comparative evaluation of economic, operational, and environmental performance of the analyzed transport modes.

The proposed Fuzzy AHP methodology is applied to the problem of transport mode selection in containerized freight transport. The analysis considers three commonly used transport alternatives, namely road transport, rail transport, and inland waterway transport. The objective of the study is to evaluate the competitiveness of these transport modes under different shipment volumes while simultaneously considering economic, operational, and environmental criteria.

3.1. Transport Alternatives

The following transport alternatives are included in the analysis:

- A₁ – Road transport, characterized by high flexibility and short delivery time, but associated with higher transportation costs and CO₂ emissions for large shipment volumes;
- A₂ – Rail transport, characterized by favorable transportation costs and reduced environmental impact, particularly for medium and large shipment sizes;
- A₃ – Inland waterway transport, characterized by high transport capacity and low environmental impact, but generally associated with longer delivery times.

3.2. Evaluation Criteria

The transport alternatives are evaluated according to four criteria frequently used in transport and logistics planning:

- C₁ – Transportation cost (€). Represents the total transportation cost for a given shipment volume. Lower values are preferred (min).
- C₂ – Delivery time (h). Represents the total transport duration from origin to destination. Lower values are preferred (min).
- C₃ – CO₂ emissions (kg). Represents the environmental impact generated during transportation. Lower values indicate better environmental performance (min).
- C₄ – Reliability (%). Represents the consistency and dependability of transport operations. Higher values are preferred (max).

3.3. Shipment Scenarios

In order to analyze the influence of cargo volume on transport mode competitiveness, three shipment scenarios are considered:

- Scenario 1 (S₁): 10 TEU
- Scenario 2 (S₂): 100 TEU
- Scenario 3 (S₃): 500 TEU

The considered scenarios enable a comparative analysis of economies of scale effects and provide insight into the sustainability and operational performance of different transport modes under varying transport demand conditions.

3.4. Decision Matrix

The decision matrix used in the analysis is presented in Table 2.

Table 2: Decision matrix for analyzed shipment scenarios

Scenario	Alternative	Cost (€)	Time (h)	CO ₂ (kg)	Reliability (%)
S1 – 10 TEU	Road transport	600	2.0	1320	90

Scenario	Alternative	Cost (€)	Time (h)	CO ₂ (kg)	Reliability (%)
S2 – 100 TEU	Rail transport	480	3.3	216	80
	Inland waterway transport	360	8.3	360	85
	Road transport	5200	2.5	13200	88
S3 – 500 TEU	Rail transport	3200	4.0	2160	84
	Inland waterway transport	2500	10.0	3600	82
	Road transport	25500	3.5	66000	85
S3 – 500 TEU	Rail transport	13500	5.0	10800	86
	Inland waterway transport	9800	12.0	18000	83

The presented values are used as the basis for the application of the Fuzzy AHP method and the comparative evaluation of transport alternatives under different shipment volumes.

4. RESULTS AND DISCUSSION

Based on expert evaluations and the application of the Fuzzy AHP method, the weighting coefficients of the considered criteria were determined (Table 3). The consistency of expert judgments was verified through the calculated consistency ratio (CR = 0.08), indicating acceptable consistency.

Table 3: Fuzzy pairwise comparison matrix of evaluation criteria

Criteria	C ₁ Cost	C ₂ Time	C ₃ CO ₂	C ₄ Reliability
C ₁ Cost	(1,1,1)	(2,3,4)	(1,2,3)	(4,5,6)
C ₂ Time	(1/4,1/3,1/2)	(1,1,1)	(1/5,1/4,1/3)	(2,3,4)
C ₃ CO ₂	(1/3,1/2,1)	(3,4,5)	(1,1,1)	(4,5,6)
C ₄ Reliability	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1/6,1/5,1/4)	(1,1,1)

The fuzzy pairwise comparison matrix was constructed according to the relative importance of the evaluation criteria. Transportation cost (C₁) and CO₂ emissions (C₃) were assigned higher importance because they directly reflect the economic and environmental efficiency of freight transport. The obtained normalized criterion weights are presented in Table 4.

Table 4: Normalized criterion weights obtained by Fuzzy AHP

Criterion	Description	Weight
C ₁	Transportation cost	0.37
C ₂	Delivery time	0.18
C ₃	CO ₂ emissions	0.32
C ₄	Reliability	0.13

The results indicate that transportation cost and CO₂ emissions represent the most influential criteria in the transport mode selection process, confirming the increasing importance of sustainable and cost-efficient logistics systems.

After determining criterion weights, the transport alternatives were evaluated across the analyzed shipment scenarios. The obtained results are presented in Table 5.

Table 5: Final scores and ranking of transport alternatives

Scenario	Alternative	Score	Rank
S1 – 10 TEU	Rail transport	0.412	1
	Inland waterway transport	0.356	2
	Road transport	0.232	3
Scenario	Alternative	Score	Rank
S2 – 100 TEU	Rail transport	0.438	1
	Inland waterway transport	0.371	2
	Road transport	0.191	3
S3 – 500 TEU	Inland waterway transport	0.446	1
	Rail transport	0.421	2
	Road transport	0.133	3

The obtained scores indicate that rail transport achieves the best balance between economic, operational, and environmental performance for small and medium shipment volumes. However, inland waterway transport becomes the most competitive alternative for large shipment sizes due to economies of scale and lower environmental impacts. In contrast, the competitiveness of road transport decreases with increasing cargo volume because of higher transportation costs and CO₂ emissions. Figure 1 presents a graphical comparison of transport alternative scores for different shipment scenarios.

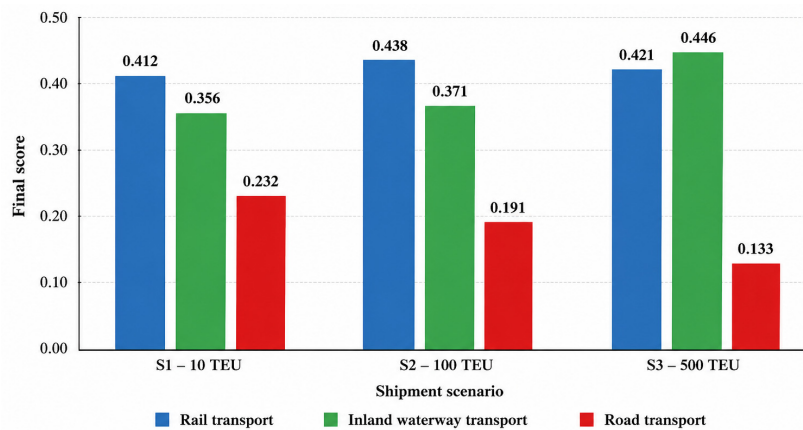


Figure 1: Comparative evaluation of transport alternatives under different shipment volumes

The graphical analysis confirms the strong influence of cargo volume on transport mode selection. Smaller shipment volumes favor road transport due to operational flexibility and shorter delivery times, while larger shipment volumes favor rail and inland waterway transport because of their superior sustainability and cost-efficiency characteristics. Similar applications of fuzzy MCDM approaches in transport and logistics systems were reported in recent studies [16,17].

The obtained findings confirm the applicability of the Fuzzy AHP method in complex transport planning problems involving uncertainty and multiple conflicting criteria.

5. CONCLUSION

This paper presented the application of the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) method for transport mode selection in containerized freight transport. The proposed approach enabled the evaluation of three transport alternatives, namely road, rail, and inland waterway transport, based on multiple economic, operational, and environmental criteria including transportation cost, delivery time, CO₂ emissions, and reliability.

The analysis was conducted for three shipment scenarios involving 10 TEU, 100 TEU, and 500 TEU in order to investigate the influence of cargo volume on transport mode competitiveness. The obtained results indicated that transportation cost and CO₂ emissions represent the most influential criteria in the decision-making process. Furthermore, the results demonstrated that increasing shipment volume significantly improves the competitiveness of rail and inland waterway transport due to economies of scale and better environmental performance.

Rail transport achieved the best overall balance between economic efficiency and sustainability for small and medium shipment volumes, while inland waterway transport became the most favorable solution for large shipment sizes. In contrast, road transport-maintained advantages primarily in terms of delivery time, but showed lower competitiveness for larger cargo volumes due to higher transportation costs and CO₂ emissions.

The findings confirm that the Fuzzy AHP method represents an effective decision-support tool for sustainable transport planning under uncertainty. The proposed framework may assist logistics planners and decision-makers in selecting appropriate transport solutions while simultaneously considering operational efficiency and environmental sustainability. Future research may include additional criteria, larger transport networks, and the integration of other MCDM methods for comparative analysis.

The study is limited by the use of estimated operational data and a limited number of evaluation criteria.

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