Istraživanja i projektovanja za privredu
ISSN 1451-4117
DOI:10.5937/jaes0-68271
www.engineeringscience.rs

Journal of Applied Engineering Science
Original Scientific Paper,
Volume 24, Number 3, Year 2026,
no 1357, pp 604-617

EFFICIENCY EVALUATION OF A PASSENGER RAILWAY OPERATOR USING FAHP AND DEA METHODOLOGY

Mia Poledica

University of Rijeka, Faculty of Tourism and Hospitality Management, Department of Sustainable Development Management, Rijeka, Croatia
*miapoledica71@gmail.com

In accordance with the European regulatory framework and the principles of sustainable mobility, sustainability has become one of the key factors in the evaluation and selection of passenger railway operators by managers, regulatory bodies, and decision-makers within the transport system. In addition to service quality and operational efficiency, railway operators must continuously improve the environmental, social, and technological aspects of their operations in order to contribute to the development of a more sustainable transport system. Effective evaluation of passenger railway operators represents an important basis for improving service quality, increasing user satisfaction, and strengthening the competitiveness of railway transport in the transport market.
Existing studies are mainly focused on a limited number of indicators or specific aspects of railway system performance, while integrated approaches for the evaluation of passenger railway operators remain insufficiently explored. Therefore, this paper proposes an integrated multi-criteria decision-making model that combines the Fuzzy Analytic Hierarchy Process (FAHP) and Data Envelopment Analysis (DEA) methods and includes the key dimensions of passenger railway transport quality that are most commonly used in the evaluation of transport systems. The research is focused on the analysis of four passenger railway operators. The results show that the integration of the FAHP and DEA approaches enables a comprehensive evaluation and ranking of operators and can support managers and decision-makers in improving the service quality and operational performance of railway transport.

Keywords: railway operator efficiency, passenger railway transport, FAHP, DEA, multi-criteria decision-making

HIGHLIGHTS

- An integrated FAHP-DEA model is proposed for passenger railway operator efficiency evaluation.
- The model combines qualitative and quantitative criteria in passenger rail assessment.
- Twenty-one criteria are grouped into five dimensions of railway service performance.
- Results support operator ranking and decision-making in sustainable railway transport.

NOMENCLATURE

AHP - Analytic Hierarchy Process

FAHP - Fuzzy Analytic Hierarchy Process

DEA - Data Envelopment Analysis

MCDM - Multi-Criteria Decision-Making

QMS - Quality Management System

DMU - Decision-Making Unit

CCR - Charnes, Cooper, and Rhodes DEA model

PRM - Persons with Reduced Mobility

CO_2 - Carbon dioxide

A1, A2, A3, A4 - Passenger railway operators considered as alternatives in the model

C1 - C21 - Evaluation criteria used for assessing railway operator performance

K1 - K5 - Main criterion groups in the FAHP model

Wj - Weighting coefficient of criterion j obtained using the FAHP method

I - Aggregated input value used in the DEA model

U - Aggregated output value used in the DEA model

AP/B - Absolutely preferable/better

VP/B - Very preferable/better

SP/B - Strongly preferable/better

PP/B - Pretty preferable/better

QP/B - Quite preferable/better

MP/B - Moderately preferable/better

RP/B - Remotely preferable/better

BP/B - Barely preferable/better

EI/G - Equally important/good

passenger-km - Passenger-kilometre

CO_2/passenger-km - Carbon dioxide emissions per passenger-kilometre

1 Introduction

Passenger railway transport represents one of the key elements of a sustainable transport system due to its energy efficiency, lower level of harmful gas emissions, and high transport capacity [1]. In recent years, the development of the railway sector has been increasingly directed toward improving service quality, increasing safety, advancing digitalization, and strengthening the competitiveness of railway operators in relation to other modes of transport [2]. In line with the European regulatory framework and the principles of sustainable mobility, passenger railway operators are expected to continuously improve their performance through both service quality and operational efficiency.

Improving the quality of passenger railway transport is particularly important because the competitiveness of the railway system depends not only on infrastructure and operational indicators, but also on the experience of passengers. Punctuality, reliability, comfort, safety, accessibility, and the quality of passenger information directly influence user satisfaction and the attractiveness of rail transport [3]. Therefore, a comprehensive evaluation and ranking of passenger railway operators can support managers, regulatory bodies, and decision-makers in identifying performance differences, setting improvement priorities, and strengthening the position of railway transport in the wider transport market [4].

Managers, regulatory bodies, and decision-makers in the railway transport system are faced with the complex problem of evaluating and ranking railway operators, as operator performance depends on several interconnected criteria, such as punctuality, reliability, safety, comfort, service accessibility, digitalization, and the environmental impact of transport. An objective evaluation of these criteria enables the identification of operators' strengths and weaknesses and supports decision-making aimed at improving the quality and competitiveness of the railway system. Indirectly, such an approach can make it easier for users to select a railway operator by allowing operators to be compared on the basis of clear and measurable performance indicators.

Contemporary approaches to the evaluation of railway operators are not based exclusively on operational indicators, such as punctuality, reliability, and capacity utilization, but also include qualitative aspects that influence user perception and overall service quality. Criteria such as travel comfort, service accessibility, safety, digitalization, and the quality of passenger information have a significant influence on user satisfaction and the competitiveness of the railway system in the transport market [3, 5, 6]. Therefore, the evaluation and ranking of railway operators represents a complex problem that requires the consideration of many interconnected criteria of different types.

The literature presents numerous approaches for selecting the best alternative solution to the observed problem. These include simulation models, linear programming models, heuristics, as well as multi-criteria and multi-objective decision-making methods. Since this paper focuses on assessing the efficiency of railway operators, it is appropriate to use the DEA method, which enables the assessment of the relative efficiency of decision-making units based on multiple input and output variables [7]. A review of the literature shows that, in contemporary research, the DEA method is increasingly combined with other multi-criteria decision-making methods to obtain more objective and rational results [8,9]. Since the evaluation of railway operators involves a large number of qualitative criteria, this paper applies the FAHP method, which enables the effective inclusion of linguistic and subjective expert assessments in the decision-making process [10,11].

AHP, FAHP, and integrated multi-criteria approaches have been widely used in transport research, particularly for the selection of alternatives, the assessment of service quality, and the evaluation of system performance. However, much of the existing railway-related literature still focuses on separate aspects of performance, such as punctuality, infrastructure efficiency, station performance, service quality, or passenger satisfaction. As a result, there is still a need for evaluation models that consider passenger railway operators as complex service systems rather than only through isolated indicators.

The research gap addressed in this paper concerns the limited integration of qualitative and quantitative criteria within a single framework for passenger railway operator evaluation. In particular, sustainability, accessibility, digitalization, and passenger-oriented indicators are not always considered together with operational performance and service quality. To address this gap, this paper proposes an integrated FAHP-DEA model. FAHP is used to determine the relative importance of criteria under conditions of uncertainty, while DEA is used to assess the relative efficiency and ranking of the observed operators.

In order to address the identified gap, this paper proposes an integrated FAHP-DEA model for the evaluation of passenger railway operators. The proposed model enables the simultaneous inclusion of quantitative and qualitative criteria, as well as linguistic expert assessments, in the decision-making process. The model uses 21 criteria grouped into five categories: service quality, safety and sustainability, operational performance, accessibility and inclusiveness, and digitalization and passenger information. The formation of these groups of criteria enabled a systematic consideration of the key aspects of railway operator performance and the integration of operational, qualitative, and sustainability-related dimensions into a unified evaluation framework. In the first phase of the methodology, the FAHP method is applied to determine the relative weights of the criteria, while in the second phase, the DEA method is used to assess the efficiency and rank the observed operators.

Based on the assumption that quality management in passenger railway transport can contribute to increasing user satisfaction, strengthening the competitiveness of railways, and developing sustainable travel patterns, the following research questions are defined in this paper:

- RQ1: How can an integrated FAHP-DEA model be applied to the evaluation and ranking of passenger railway operators?
- RQ2: In what way does the integration of qualitative and quantitative indicators enable a more comprehensive assessment of passenger railway operator performance?
- RQ3: How can a QMS-oriented approach based on measurable criteria support decision-making aimed at improving the quality of passenger railway transport?

The main objectives of the paper are reflected in:

- the development of an integrated FAHP and DEA model for the evaluation of passenger railway operators;
- the integration of qualitative and quantitative indicators into a unified decision-making framework; and
- the establishment of a QMS-oriented approach to support decision-making and improve the quality of passenger railway transport.

The contribution of this paper is reflected in the development of a structured FAHP-DEA framework for evaluating passenger railway operators. Unlike approaches that focus mainly on a smaller number of operational indicators, the proposed model includes 21 criteria grouped into five dimensions of railway service performance. In this way, the model connects service quality, safety and sustainability, operational performance, accessibility and inclusiveness, and digitalization and passenger information within one evaluation process. The paper also contributes by linking the evaluation framework with a QMS-oriented perspective, which supports more systematic performance monitoring and decision-making in passenger railway transport.

The proposed model can represent a useful decision-support tool for managers, regulatory bodies, and decision-makers in the process of evaluating railway operator performance, identifying improvement priorities, and increasing the competitiveness and sustainability of the railway transport system. The integration of qualitative and quantitative criteria enables a more detailed assessment of operator performance and supports the selection, ranking, and improvement of railway operators in accordance with the principles of sustainable mobility and service quality improvement.

The paper is organized as follows. After the introduction, the second section provides a review of the relevant literature on FAHP, DEA, and integrated FAHP and DEA approaches in railway transport. The third section presents the proposed research methodology and the steps involved in applying the FAHP and DEA model. The fourth section defines the alternatives and evaluation criteria, followed by the results of the model application and the ranking of railway operators. Finally, the paper presents a discussion of the results, research limitations, and directions for future research.

1.1 Literature review

The literature review aims to analyze previous research in the field of multi-criteria decision-making and efficiency assessment in the railway and transport sectors, with a particular focus on the application of the FAHP and DEA methods. The literature review focuses on the analysis of dominant methodological approaches, the most commonly used evaluation criteria, and the limitations of existing studies, which provide the basis for defining the research framework of this paper.

Owing to its ability to incorporate both quantitative and qualitative criteria, the FAHP method is widely used in transport and logistics research for performance evaluation, alternative selection, and the prioritization of decision-making criteria [12]. In the field of railway transport, the FAHP and AHP methods have been used to determine the importance of service quality criteria, evaluate railway stations, and assess user satisfaction with railway transport [13-15].

Hajipoor et al. [16] applied an integrated AHP and DEA approach to the evaluation and selection of software architecture, where AHP was used to determine the weights of quality criteria, and DEA was applied to assess the efficiency of alternatives. Prevolšek et al. [17] used a DEA-AHP model to assess the efficiency of tourist farms based on six input and four output variables. Tavana et al. [9] analysed different integrated AHP and DEA models for solving multi-criteria decision-making problems, where AHP and other MADM methods were used to determine criterion weights, while DEA was applied to assess the efficiency of alternatives. Similarly, Ammirato et al. [18] used an integrated AHP and DEA approach to evaluate the efficiency of production processes, while Yilmaz et al. [19] applied a spherical fuzzy AHP and DEA model to assess the operational efficiency of airports.

In addition to the above-mentioned studies, integrated AHP and DEA, as well as FAHP and DEA models, have also been applied in the field of railway transport. Mohajeri et al. [20] used a combined AHP and DEA approach to select the best alternatives in railway systems, while Čabrić et al. [21] and Petrović et al. [22] applied multi-criteria approaches to evaluate organizational models and the performance of railway systems. However, most existing studies focus on a limited number of criteria or on individual aspects of performance, such as operational efficiency or technical system indicators.

Contemporary research increasingly applies integrated FAHP, AHP, and DEA approaches to solve complex selection problems. The integration of these methods enables the combination of subjective expert assessments and objective efficiency assessment of alternatives, thereby providing a multidimensional evaluation of the system. The advantage of this approach lies in the possibility of incorporating the relative importance of criteria into DEA analysis, while its main limitation is the greater complexity of the model and the dependence of the results on expert assessments.

Based on the analysed literature, it can be concluded that existing studies mainly consider partial aspects of the performance of transport and railway systems, with operational and quantitative performance indicators being dominant. Qualitative criteria related to user perception, service quality, accessibility, digitalization, and sustainability are less frequently integrated into existing evaluation models. Most studies are based on the integration of classical AHP and DEA methods, while the application of fuzzy approaches is significantly less represented. However, in the evaluation of passenger railway operators, a large number of criteria are qualitative in nature and are based on subjective and linguistic assessments provided by experts and users. For this reason, this paper applies the FAHP method, which enables the modelling of uncertainty and imprecision when determining the relative importance of the criteria.

2 Materials and methods

This paper applies a hybrid methodology for determining the efficiency of railway operators. The hybrid model represents a combination of the FAHP method [10] and the DEA method [7]. In the first part of the methodology, FAHP is applied to determine the relative weights of the criteria. After that, DEA is used to rank the alternatives according to their efficiency. Microsoft Excel Solver was used to determine the weighting coefficients using the FAHP method, while the efficiency of the alternatives was evaluated using the DEA method in MaxDEA software. Methods developed in a fuzzy environment are suitable for describing insufficiently precise data, interval assessments, and similar types of uncertainty.

- The model uses 21 criteria grouped into five categories: service quality, safety and sustainability, operational performance, accessibility and inclusiveness, and digitalization and passenger information. These groups of criteria are the result of an analysis of the relevant literature, the European regulatory framework, expert interviews, and a passenger survey. The criteria provide the basis for forming the hierarchical structure of the FAHP model and subsequently for defining the aggregated input and output variables in the DEA analysis.
- In contemporary research in the fields of transport and multi-criteria decision-making, FAHP and DEA methods are widely applied. FAHP represents a fuzzy extension of the AHP method and is used under conditions of uncertainty and subjective expert assessment. The method is used to determine the relative importance of criteria through pairwise comparisons, while the fuzzy approach enables the modelling of imprecision and uncertainty in the decision-making process [10,11]. DEA is a non-parametric method based on linear programming that is used to assess the relative efficiency of homogeneous decision-making units based on multiple input and output variables [7]. Its application in the railway sector is particularly evident in analyses of the efficiency of railway operators, infrastructure, and railway stations [23-25].
- Although the combination of FAHP and DEA methods enables the integration of subjective expert assessments and objective efficiency assessments, their application to evaluating passenger railway operators with an extended set of criteria and a QMS-oriented approach remains insufficiently explored. For this reason, this paper proposes an integrated FAHP and DEA model to provide a more comprehensive assessment of performance by combining qualitative and quantitative criteria within a unified decision-making framework.
- Although the proposed model provides a basis for the systematic evaluation of railway operators, the research also has certain limitations that should be considered when interpreting the results. The limitations of the paper concern the number of alternatives analysed, the dependence of the results on the expert assessments used in the FAHP method, and the availability of homogeneous data on railway operators' performance. In addition, some of the criteria rely on qualitative and subjective assessments of service quality, which may introduce additional uncertainty in the evaluation process. The methodology is described step by step below.

2.1 Step 1 – Defining the problem structure

At the beginning, in accordance with the AHP method, the problem must also be hierarchically structured when applying FAHP. The structure includes the definition of the goal, criteria, subcriteria, and alternatives.

2.2 Step 2 – Pairwise comparison

The Saaty scale (1–9) is used for pairwise comparisons in the AHP method. In accordance with FAHP, fuzzy sets must be defined using the same scale. Pairwise comparisons should be performed for all subcriteria and criteria with respect to the higher level of the hierarchy. Table 1 presents the linguistic assessments and the corresponding triangular fuzzy numbers used in the evaluation process. The same fuzzy scale is applied both for pairwise comparison of criteria and subcriteria and for evaluation of alternatives. In this notation, “P” refers to “preferable” when criteria and subcriteria are compared, while “B” refers to “better” when alternatives are evaluated. Therefore, the same abbreviations are used consistently throughout the manuscript.

Table 1. Linguistic evaluations for the comparison of criteria/alternatives

Linguistic evaluations	Fuzzy set
Absolutely preferable/better (AP/B)	(8,9,10)
Very preferable/better (VP/B)	(7,8,9)
Strongly preferable/better (SP/B)	(6,7,8)
Pretty preferable/better (PP/B)	(5,6,7)
Quite preferable/better (QP/B)	(4,5,6)
Moderately preferable/better (MP/B)	(3,4,5)
Remotely preferable/better (RP/B)	(2,3,4)
Barely preferable/better (BP/B)	(1,2,3)
Equally important/good (EI/G)	(1,1,2)

2.3 Step 3 – Defining the fuzzy matrix $\tilde{\in}$

In this step, the fuzzy matrix used for pairwise comparisons in the FAHP method is defined. A separate matrix is constructed for each set of criteria or subcriteria that are compared with one another.

$$\tilde{\in}=\begin{bmatrix}\tilde{a}_{11} & \cdots & \tilde{a}_{in}\\ \vdots & \ddots & \vdots\\ \tilde{a}_{n1} & \cdots & \tilde{a}_{nn}\end{bmatrix} \tag{1}$$

2.4 Step 4 – Determining the relative weights of the criteria

For each pairwise comparison, it is necessary to calculate the priority vector (W), where $W=(w_1,\dots,w_n)>0,\sum_{j=1}^{n} w_j=1$. In the FAHP method, the priority vector (W) can be calculated using various techniques and methods. For this study, the Logarithmic Fuzzy Preference Programming (LFPP) method was selected [26]. Each triangular fuzzy number is defined as follows: $\tilde{a}_{ij}=(l_{ij},m_{ij},u_{ij})$. The LFPP method is based on calculating the logarithmic form of a fuzzy number as follows:

$$\ln\tilde{a}_{ij}\approx(\ln l_{ij},\ln m_{ij},\ln u_{ij})\,;i,j=1,\dots,n \tag{2}$$

$$Min\,J=(1-\lambda)^2+M\times\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}(\delta_{ij}^2+\eta_{ij}^2) \tag{3}$$

$$.t.\begin{cases} x_i-x_j-\lambda\ln(m_{ij}/l_{ij})+\delta_{ij}\geq\ln l_{ij}, i=1,\dots,n-1; j=i+1,\dots,n\\ -x_i+x_j-\lambda\ln(u_{ij}/m_{ij})+\eta_{ij}\geq-\ln u_{ij}, i=1,\dots,n-1; j=i+1,\dots,n\\ \lambda,x_i\geq 0, i=1,\dots,n\\ \delta_{ij},\eta_{ij}\geq 0, i=1,\dots,n-1; j=i+1,\dots,n\end{cases} \tag{4}$$

Where is:

$x_i^*(i=1,\dots,n)$ – optimal solution

$M=10^3$ – very large constant

In order to avoid that the membership degree λ takes a negative value, non-negative variables are introduced δ_{ij} and η_{ij} for $i=1,\dots,n-1\,;j=i+1,\dots,n$ so they satisfy the following inequalities:

$$\ln w_i-\ln w_j-\lambda\ln\left(\frac{m_{ij}}{l_{ij}}\right)+\delta_{ij}\geq\ln l_{ij}, i=1,\dots,n-1; j=i+1,\dots,n \tag{5}$$

$$-\ln w_i+\ln w_j-\lambda\ln(m_{ij}/l_{ij})+\eta_{ij}\geq-\ln u_{ij}, i=1,\dots,n-1; j=i+1,\dots,n \tag{6}$$

The normalized criteria weights of the matrix $\tilde{A}=(\tilde{a}_{ij})_{n\times m}$ are calculated as follows:

$$W_i^*=\frac{exp(x_i^*)}{\sum_{j=1}^{n}exp(x_j^*)}, i=1,\dots n \tag{7}$$

where is:

$$exp(x_i^*)=e^{x_i^*} \tag{8}$$

In order to ensure that the criteria are evaluated correctly, a consistency check (CR) is performed for each matrix [27], as follows:

$$CR=\frac{CI}{RI} \tag{9}$$

Where the consistency index (CI) is calculated as follows:

$$CI = \frac{Z_{max} - 0}{0 - 1} \quad (10)$$

The Random Index (RI) depends on the size of the matrix and is given in Saati (1996). Z_{max} in equation (9) represents the eigenvalue of the matrix $\tilde{\in}$. CR values must be less than 0.10 for all comparisons to achieve consistency.

In the second part of the methodology, the DEA method is used to assess the relative efficiency of the alternatives, namely railway operators, based on the defined inputs and outputs. DEA is a non-parametric method based on linear programming that enables the comparison of multiple decision-making units (DMUs) in terms of their ability to generate the highest possible outputs using the available inputs. In this study, railway operators are considered decision-making units, while the efficiency of each alternative is evaluated based on the relationship between the output and input variables. In accordance with the defined research objective, a conventional output-oriented DEA approach is applied to examine the extent to which outputs can be maximized at a given level of inputs.

2.5 Step 5 – Defining the decision-making units, inputs, and outputs

After determining the relative weights of the criteria using the FAHP method, the criteria were classified according to the nature of their impact on the efficiency of railway operators. Criteria for which lower values are preferable were grouped into the input variable, whereas criteria for which higher values are preferable were grouped into the output variables. To simplify the DEA model and ensure a clearer evaluation of the alternatives, the individual criteria were aggregated into composite values using the weights obtained through the FAHP analysis, resulting in one input variable and one output variable.

This approach ensures a direct methodological link between the FAHP and DEA methods, since the results of the FAHP method provide the basis for structuring the DEA model. The aggregated variables defined in this manner enable the efficiency of railway operators to be assessed in the second stage of the analysis through the relationship between one input and two outputs, while preserving the relative importance of all previously evaluated criteria.

2.6 Step 6 – Formulating the DEA model

To assess the relative efficiency of the alternatives, the conventional CCR DEA model, which assumes constant returns to scale, is applied in this study. Since the analysis adopts an output-oriented approach, the objective of the model is to maximize outputs at predetermined input levels. In other words, the model examines the extent to which a railway operator can improve its output performance without increasing the level of input resources used.

The basic form of the DEA model for the decision-making unit under evaluation, DMU_0, can be expressed as the ratio of the weighted sum of outputs to the weighted sum of inputs:

$$max h_0 = \frac{\sum_{r=1}^{s} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{r0}} \quad (11)$$

with restrictions:

$$\frac{\sum_{r=1}^{s} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{r0}} \leq 1, j = 1, \dots, n \quad (12)$$

$$u_r \geq 1, 1, \dots, s \quad (13)$$

$$v_i \geq 1, 1, \dots, m \quad (14)$$

where is:

$y_{r,j}$ – value of the r-th output for the j-th decision-making unit

$x_{i,j}$ – value of the i-th input for the j-th decision-making unit

u_r – weight assigned to the r-th output

v_i – weight assigned to the i-th input

n – number of decision-making units

s – number of outputs

m – number of inputs

Since the above model is expressed in fractional form, it is transformed into an equivalent linear form to facilitate its solution. The linearization is performed by normalizing the denominator, that is, by setting the weighted sum of inputs for the decision-making unit under evaluation equal to 1. The model then takes the following form:

$$max \sum_{r=1}^{s} u_r y_{r0} \quad (15)$$

on condition:

$$\sum_{i=1}^{m} v_i x_{i0} = 1 \quad (16)$$

$$\sum_{r=1}^{s} u_r y_{r0} - \sum_{i=1}^{m} v_i x_{i0} \leq 0, j = 1, \dots, n \quad (17)$$

$$u_r \geq 0, 1, \dots, s \quad (18)$$

$$v_i \geq 0, 1, \dots, m \tag{19}$$

Based on the model defined above, the optimal input and output weights are determined for each decision-making unit. Each alternative is allowed to select the most favorable set of weights, subject to the condition that the efficiency score of no other alternative may exceed 1. In this way, DEA enables an objective comparison of the alternatives against the best practices observed within the analyzed set.

2.7 Step 7 – Calculating the efficiency of the alternatives

By applying the DEA model, a relative efficiency score is obtained for each alternative. Decision-making units located on the efficiency frontier are considered efficient, whereas scores below the efficiency frontier indicate relative inefficiency compared with the other alternatives. The obtained results enable the identification of reference units and provide insight into potential performance improvements for inefficient alternatives.

2.8 Step 8 – Ranking the alternatives

The alternatives, namely the railway operators, are ranked based on the calculated efficiency scores. Alternatives with higher efficiency scores occupy better positions in the final ranking, thereby providing a clear basis for comparison and selection of the most efficient alternative. The results of the DEA analysis therefore represent an important basis for final decision-making.

The defined methodological procedure provides the basis for testing the proposed theoretical model. The following section presents the application of the integrated FAHP-DEA model through the determination of criteria weights, the formation of input and output variables, the assessment of relative efficiency, and the ranking of the observed passenger railway operators.

3 Results and discussion

3.1 Testing of the theoretical framework

In order to analyse the performance of passenger railway transport, this paper considers four passenger railway operators operating within Europe. The operators are labelled A1, A2, A3 and A4 in order to preserve anonymity and ensure a more objective comparison of performance without directly focusing on individual companies. The selection of operators was based on their market presence, traffic volume, level of railway network development, and the availability of relevant data for performance analysis. The selected operators were considered suitable for comparative evaluation because they represent different levels of development in passenger railway transport. They differ in terms of infrastructure quality, degree of digitalization, traffic organization, service reliability, and accessibility conditions. This diversity enables the proposed model to be tested on operators with different performance characteristics, while anonymization allows the analysis to focus on the methodological application and comparative performance patterns rather than on the public identification of individual railway companies. Although the operators are anonymized, they are based on real passenger railway systems from countries in the Balkan region, while the labels A1, A2, A3, and A4 are used to protect the identity of individual operators and avoid direct public comparison.

The data sources used in the research include official annual reports of railway operators, statistical data from regulatory bodies and international organizations, as well as data available in reports of the European Union Agency for Railways [28]. In addition, some qualitative indicators are based on analyses of user satisfaction and expert assessments, which enable the inclusion of subjective aspects of service quality in the evaluation process.

Operator A1 is characterized by a high level of operational organization and developed railway infrastructure, with a significant degree of network modernization and electrification. The operator profile corresponds to a system with modernized main corridors, relatively higher operating speeds, and modern or partly modernized rolling stock. The system achieves a high level of punctuality and reliability, with relatively minor deviations from the planned timetable. The operator has developed digital services, including online ticket sales, mobile applications, and real-time passenger information systems. Particular attention is given to service accessibility and support for persons with reduced mobility through adapted infrastructure and assistance services. The observed system demonstrates a balanced level of development across the operational, technological, and qualitative aspects of passenger railway transport.

Operator A2 operates within a developed railway network with a large volume of passenger traffic and a significant number of transported passengers. The system includes important electrified sections, developed intermodal nodes, and partly modernized infrastructure and rolling stock. Its operational performance is characterized by a stable level of punctuality and reliability, with occasional deviations caused by infrastructure limitations and traffic intensity. Digital sales channels and passenger information systems are well developed, while continuous investments in infrastructure and rolling stock represent an important part of the strategy for improving service quality. Compared with A1, this operator shows a slightly lower level of operational stability and digital integration, but still maintains a relatively strong level of service frequency and intermodal connectivity.

Operator A3 is characterized by a large operational traffic volume, but also by significant challenges in terms of system reliability and stability. The operator's infrastructure includes a combination of modernized and outdated network segments, which affects achieved speeds, punctuality, and traffic continuity. The rolling stock is partly modernized, while some parts of the system still require additional technical and organizational improvement. Digital services and customer support systems are available to passengers, but with a lower level of functionality and integration compared with more developed systems. Although safety indicators are aligned with European standards, the system is exposed to infrastructure and organizational constraints that affect operational efficiency and service quality.

Operator A4 operates within a railway system with a limited traffic volume and significant infrastructure constraints. Its operational profile corresponds to a system with lower operating speeds on certain sections, older or only partly modernized rolling stock, and a lower level of technical modernization compared with the other observed operators. The infrastructure and rolling stock have been partially modernized, but the system still largely depends on older technical solutions and limited investment capacity. Digital services, including online ticket sales and basic customer support systems, are available to passengers, but the possibilities for real-time passenger information during travel and the integration of digital services remain limited. These characteristics indicate weaker reliability, lower accessibility performance, and the need for additional investment in infrastructure, traffic organization, and service quality improvement.

3.2 Evaluation criteria

Based on the analysis of the relevant literature, the European regulatory framework, and the practices of railway operators, a set of criteria for the evaluation of passenger railway operators was defined. The criteria were selected based on their representation in the literature, their importance for assessing service quality, and their applicability in the process of evaluating railway system performance. In order to provide a more systematic assessment of operator performance, the criteria were grouped into five main categories (Table 2): Service Quality, Safety and Sustainability, Operational Performance, Accessibility and Inclusiveness, and Digitalization and Passenger Information. The definition of the criteria is based on the principles of sustainable mobility, the QMS approach, and the requirements of the European regulatory framework for railway transport [27, 28].

Table 2. Defined criteria by group

Criterion group	Criterion group	Criterion group
Service Quality [3, 5, 6, 31].	Reliability (C1)	Stability and continuity of service provision
	Punctuality (C2)	Alignment between the realized and planned timetable
	Staff professionalism (C3)	Professionalism and the attitude of staff toward passengers
	Travel comfort (C4)	Comfort and quality of travel conditions during the journey
	Cleanliness (C5)	Hygiene conditions in trains and stations
	On-board services (C6)	Availability of additional services during the journey
Safety & Sustainability [28,29]	Safety incidents (C7)	Number of safety incidents per passenger-kilometre
	Perceived safety (C8)	Subjective perception of safety during the journey
	CO_2 emissions (C9)	CO_2 emissions per passenger-kilometre
Operational Performance [28, 29]	Service frequency (C10)	Frequency of departures and availability of the service
	Intermodality (C11)	Integration with other modes of transport
	Speed performance (C12)	Achieved speeds and operational traffic efficiency
	Rolling stock turnaround time (C13)	Efficiency of rolling stock utilization
	Capacity utilization (C14)	Utilization of available capacity
Accessibility & Inclusiveness [32,33]	Accessibility for PRM (C15)	Accessibility for persons with reduced mobility
	Infrastructure accessibility (C16)	Physical accessibility of stations and infrastructure
	Ticket affordability (C17)	Economic affordability of the service
	Passenger orientation and signage clarity (C18)	Clarity of signage and availability of information within the system
Digitalization & Passenger Information [6, 30]	Real-time passenger information (C19)	Availability of real-time information
	Digital ticketing (C20)	Functionality of digital sales channels
	Digital customer support (C21)	Availability of digital customer support

3.3 Model testing and results

In accordance with the hierarchical structure of the FAHP method defined in Section 3, the problem was formulated accordingly. The objective, that is, the problem being solved, was defined in the Introduction of the paper as the evaluation of railway operators for passenger transport. The alternative solutions to be evaluated were defined in Section 3.1, and the criteria used for the evaluation were defined in Section 3.2. The following section presents the solution to the problem of evaluating and ranking railway operators using the model defined in Section 3.

During the pairwise comparison process within the FAHP method, the linguistic evaluations presented in Table 1 were used. This resulted in the formation of matrix (1). A triangular fuzzy number was defined for each criterion (2). The following section presents the assigned linguistic evaluations used in pairwise comparisons within all criterion groups, as well as between the criteria themselves (Tables 3, 4, 5, 6, 7, and 8). The evaluation was conducted by experts in railway transport, service quality, and transport planning, with experience in analysing railway system performance and applying multi-criteria decision-making methods. The expert panel included 13 professionals with experience in passenger railway transport, transport planning, service quality assessment, and multi-criteria decision-making. The experts were selected because of their professional knowledge of railway system performance and their ability to assess both operational and qualitative aspects of railway services. Their expertise covered areas such as railway operations, accessibility, sustainability-related indicators, passenger service quality, and digital service development. This profile was considered appropriate because the proposed model includes both measurable operational indicators and criteria that require professional judgment, such as passenger orientation, perceived safety, comfort, and digital service quality. Their assessments were used to compare the criteria and subcriteria within the FAHP method.

Table 3. Pairwise comparison of subcriteria within the Service Quality group

	C1	C2	C3	C4	C5	C6
C1	/	*BP*	*RP*	*QP*	*PP*	*VP*
C2		/	*RP*	*MP*	*PP*	*SP*
C3			/	*RP*	*MP*	*PP*
C4				/	*RP*	*QP*
C5					/	*MP*
C6						/

Table 4. Pairwise comparison of subcriteria within the Safety and Sustainability group

	C7	C8	C9
C7	/	*RP*	*VP*
C8		/	*MP*
C9			/

Table 5. Pairwise comparison of subcriteria within the Operational Performance group

	C10	C11	C12	C13
C10	/	*BP*	*QP*	*VP*
C11		/	*MP*	*PP*
C12			/	*QP*
C13				/

Table 6. Pairwise comparison of subcriteria within the Accessibility and Inclusiveness group

	C14	C15	C16	C17
C14	/	BP	MP	PP
C15		/	BP	MP
C16			/	RP
C17				/

Table 7. Pairwise comparison of subcriteria within the Digitalization and Passenger Information group

	C18	C19	C20	C21
C18	/	*RP*	*QP*	*SP*
C19		/	*MP*	*PP*
C20			/	*RP*
C21				/

Table 8. Pairwise comparison of criteria

	K1	K2	K3	K4	K5
K1	/	*RP*	*MP*	*PP*	*SP*
K2		/	*RP*	*MP*	*QP*
K3			/	*RP*	*MP*
K4				/	*MP*
K5					/

After applying the FAHP method using the input data presented in the previous tables, the criteria weights were obtained using Equation (7). The defuzzified criteria weights are presented in Table 9.

Table 9. Criteria weights

Ci	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21
Wj	0.180	0.140	0.078	0.044	0.025	0.012	0.171	0.067	0.019	0.072	0.047	0.017	0.006	0.040	0.023	0.013	0.005	0.022	0.012	0.004	0.003

For the purpose of applying DEA, the weighted criteria were transformed into aggregated input and output variables. In this research, inputs refer to the weighted service and operational conditions that describe the level of resources, effort, and system characteristics involved in providing passenger railway services. Outputs refer to the achieved performance effects of operator activity, particularly in terms of safety, sustainability, and intermodal performance. This classification made it possible to adapt the multidimensional FAHP results to the DEA structure and to calculate the relative efficiency of the observed operators. The final classification of criteria into inputs and outputs is presented in Table 10.

Table 10. Inputs and Outputs

Inputs	Outputs
C1, C2, C3, C4, C5, C6, C10, C12, C13, C14, C15, C16, C17, C18, C19, C20, C21	C7, C8, C9, C11

Table 1 presents the linguistic evaluations of alternatives according to the criteria. The evaluations used within the DEA method were defined using the same fuzzy sets as those applied in the FAHP method. Based on this, the evaluation matrix of alternatives according to the criteria was formed (Table 11).

Table 11. Evaluation of alternatives according to the criteria

	A1	A2	A3	A4
C1	VP/B	PP/B	QP/B	BP/B
C2	AP/B	SP/B	QP/B	EP/G
C3	SP/B	SP/B	PP/B	PP/B
C4	PP/B	PP/B	QP/B	MP/B
C5	SP/B	PP/B	QP/B	QP/B
C6	VP/B	VP/B	VP/B	PP/B
C7	AP/B	VP/B	SP/B	MP/B
C8	AP/B	VP/B	PP/B	PP/B
C9	AP/B	SP/B	SP/B	QP/B
C10	VP/B	AP/B	VP/B	PP/B
C11	VP/B	AP/B	SP/B	QP/B
C12	VP/B	VP/B	PP/B	RP/B
C13	VP/B	SP/B	PP/B	RP/B
C14	VP/B	VP/B	SP/B	SP/B
C15	VP/B	PP/B	PP/B	MP/B
C16	VP/B	PP/B	QP/B	RP/B
C17	SP/B	SP/B	QP/B	RP/B
C18	SP/B	SP/B	QP/B	BP/B
C19	SP/B	VP/B	PP/B	RP/B
C20	AP/B	AP/B	VP/B	VP/B
C21	AP/B	AP/B	VP/B	VP/B

The values of the criteria weighting coefficients obtained by applying the FAHP method, presented in Table 9, were combined with the evaluations of alternatives presented in Table 11. The FAHP and DEA methods were connected through the weighted evaluation of alternatives. FAHP was first used to determine the relative importance of each criterion based on expert pairwise comparisons. The four operators were then evaluated against all criteria using the predefined linguistic scale. These evaluations were transformed into numerical values and combined with the corresponding FAHP weights. The resulting weighted values were aggregated according to the input and output structure presented in Table 10 and then used in the DEA model to calculate the relative efficiency of each operator. In this way, the input data for applying the DEA method were formed. The criteria previously classified as inputs were aggregated into a single input value, while the same procedure was applied to the criteria classified as outputs.

After forming the input and output data, the DEA method was applied to assess the relative efficiency of the observed alternatives. The final ranking of alternatives obtained by applying the DEA method is presented in Table 12. The obtained results indicate that alternative A1 is the best-ranked alternative, which means that it achieves the most favourable relationship between the engaged inputs and achieved outputs compared with the other analysed alternatives. The ranking results show that A1 achieved the highest efficiency score because it demonstrates a balanced relationship between service conditions and achieved performance effects. This operator is characterized by a higher level of operational organization, reliable service provision, developed digital services, and better accessibility performance. A2 also achieved a high efficiency score, which indicates stable performance, although with certain limitations compared with A1. The lower efficiency scores of A3 and A4 suggest that infrastructure constraints, weaker digital integration, lower service reliability, and limited accessibility can reduce the overall efficiency of passenger railway operators. In practical terms, these results indicate that the proposed model can help decision-makers identify not only the best-performing operator, but also the areas in which lower-ranked operators require improvement.

Table 12. Model results

Alternative	U	I	Efficiency
A1	0.209	0.795	1.000
A2	0.196	0.694	0.930
A3	0.187	0.570	0.802
A4	0.185	0.330	0.468

3.4 Discussion

Passenger railway transport plays an important role in the development of sustainable transport systems due to its energy efficiency, high transport capacity, and lower negative environmental impact compared with other modes of transport. The contemporary development of the railway sector is directed toward improving service quality, increasing operational efficiency, advancing digitalization, and strengthening the competitiveness of railway operators in accordance with the principles of sustainable mobility and European regulatory requirements. Under such conditions, the evaluation of railway operators represents a complex decision-making problem that requires the simultaneous consideration of a large number of quantitative and qualitative criteria, including operational performance, service quality, sustainability, accessibility, and system digitalization.

The research results confirm that the integration of FAHP and DEA methods represents a suitable approach for the evaluation and ranking of passenger railway operators [9,18]. The proposed model enables the simultaneous consideration of qualitative and quantitative criteria, thereby providing a more comprehensive assessment of operator performance compared with approaches based on a limited number of indicators. The application of the FAHP method enabled the determination of the relative importance of criteria under conditions of uncertainty and linguistic expert assessments, while the DEA method was used to assess the relative efficiency of operators based on defined input and output variables [10,11].The results of the FAHP analysis indicate the importance of criteria related to service reliability, safety, and the quality of railway traffic organization, confirming that operational stability and safety represent key factors of quality in passenger railway transport [5,6]. At the same time, criteria related to digitalization, accessibility, and the quality of passenger information are becoming increasingly important in the operator evaluation process due to the development of modern transport systems and the growing expectations of users [33,34]. The obtained results confirm that the quality of railway service no longer depends exclusively on operational indicators, but also on the ability of operators to ensure a high level of user experience and service accessibility. The DEA analysis indicated differences in the level of efficiency among the observed operators [7]. Operator A1 achieved the highest efficiency value, indicating the most favourable relationship between input and output performance within the observed set of alternatives. The high efficiency level of this operator can be associated with developed infrastructure, a high level of traffic reliability, well-developed digital services, and a higher level of service accessibility. On the other hand, operators with lower efficiency values showed more pronounced infrastructure constraints, a lower level of digitalization, and weaker operational performance, indicating the need for additional investments and improvements in the organization of the railway system.

From a transport policy and railway technology perspective, the obtained efficiency scores show that operator performance is strongly influenced by infrastructure quality, rolling stock modernization, electrification, operating speed, and digital service development. Operator A1 achieved the highest efficiency score because it represents a more modernized passenger railway system, with a higher level of electrification, more reliable rolling stock, better service organization, and more developed digital passenger services. These characteristics support punctuality, reliability, lower environmental burden, and better passenger information. The lower efficiency score of operator A4 can be explained by stronger infrastructure constraints, lower operating speeds on certain sections, older or only partly modernized rolling stock, and weaker digital integration. These limitations reduce service reliability and make it more difficult to achieve stable operational performance. In practical terms, the results indicate that the efficiency of weaker operators can be improved through infrastructure modernization, rolling stock renewal, electrification, improved traffic organization, and the development of real-time passenger information systems. The obtained results are consistent with previous studies emphasizing the importance of reliability, safety, passenger information quality, and digitalization in the evaluation of railway and transport systems [3,6,32]. The research results confirm that integrated FAHP and DEA approaches facilitate a more detailed and objective assessment of operator performance compared with models based exclusively on operational or quantitative indicators.

The practical implication of this research relates to the possibility of applying the proposed FAHP and DEA framework as a decision-support tool in the evaluation of passenger railway operators. The defined model can assist managers, regulatory bodies, and decision-makers in identifying the strengths and weaknesses of operators, determining improvement priorities, and managing service quality more effectively. In addition, the model enables a more transparent comparison of operators based on a larger number of criteria, which may contribute to improving competitiveness and increasing user satisfaction in railway transport. The theoretical implication lies in the establishment of an integrated methodological framework for the evaluation of passenger railway operators that includes 21 criteria grouped into five categories: service quality, safety and sustainability, operational performance, accessibility and inclusiveness, and digitalization and passenger information. Unlike existing studies, which mainly focus on a smaller number of criteria or partial aspects of system performance [17,18], the proposed approach provides a more detailed and systematic evaluation of operators through the integration of qualitative and quantitative indicators into a unified decision-making framework. A particular contribution of the paper refers to the inclusion of criteria defined in accordance with the principles of sustainable mobility and the QMS approach, which enables a more detailed assessment of railway operator performance.

4 Conclusions

This paper proposed an integrated FAHP-DEA model for the evaluation of passenger railway operators. The model combines qualitative and quantitative criteria and enables the ranking of operators according to their relative efficiency. The application of the model showed that operator A1 achieved the highest efficiency score, while operator A4 achieved the lowest score. These results indicate that differences in infrastructure quality, rolling stock modernization, electrification, service reliability, accessibility, digitalization, and traffic organization can strongly influence the efficiency of passenger railway operators. The scientific contribution of this paper is reflected in the development of an integrated QMS-oriented FAHP-DEA framework that enables the evaluation of passenger railway operators using a multidimensional set of qualitative and quantitative criteria. The proposed framework can support managers, regulatory bodies, and decision-makers in identifying performance gaps, setting improvement priorities, and improving the quality and sustainability of passenger railway transport. Although the proposed model provides significant opportunities for operator evaluation, the research also has certain limitations that should be considered when interpreting the results. The first limitation refers to the number of analysed alternatives, since the research was conducted on a limited sample of railway operators. Including a larger number of operators could contribute to a more detailed assessment of performance differences and greater generalization of the results. The second limitation refers to the dependence of the results on the expert assessments used in the FAHP method. Although the fuzzy approach is used to model the uncertainty and subjectivity of expert evaluations, the final values of criteria weights and ranking results still depend on the experience and preferences of the experts involved in the evaluation process. In addition, some of the criteria used in the research are based on qualitative assessments and subjective perceptions of service quality, which may represent an additional source of uncertainty in the decision-making process. Another limitation of the research relates to the availability and homogeneity of data on railway operator performance. Future research should be directed toward expanding the set of alternatives, including additional criteria, and applying other multi-criteria, fuzzy, or grey approaches in order to improve the robustness of the model and compare the results of different methodological approaches. In addition, future research could include the application of dynamic DEA models, sensitivity analysis of the results, and the use of real operational data from a larger number of railway operators in order to improve the accuracy and practical applicability of the model.

5 Acknowledgement

This paper was supported by the University of Rijeka Foundation through the Prometej Fund for PhD Students (Grant No. N-PROM 2/2025).

6 References

[1] Ezsias, L., Brautigam, A., Kocsis Szurke, S., Szalai, S., & Fischer, S. (2023). Sustainability in railways: A review. *Chemical Engineering Transactions, 107*, 7–12. https://doi.org/10.3303/CET23107002

[2] Liu, L., & Lin, C. (2025). An empirical investigation of service quality of intercity rail transit in the Pearl River Delta using AHP-fuzzy comprehensive evaluation. *Asia Pacific Journal of Marketing and Logistics, 37*(10), 3024–3041. https://doi.org/10.1108/APJML-08-2024-1043

[3] Ibrahim, S., Zhang, Y., & Ahmad, A. (2025). Rail-based public transportation service quality and customer satisfaction: A decade of insights and advances. *Public Transport, 17*(1), 45–69. https://doi.org/10.1007/s12469-024-00382-7

[4] Liu, S., & Putro, U. S. (2024). Passenger service satisfaction evaluation of Jakarta–Bandung high-speed railway. *European Journal of Business and Management Research, 9*(4), 115–126. https://doi.org/10.24018/ejbmr.2024.9.4.2432

[5] Bakti, I. G. M. Y., & Sumaedi, S. (2015). P-TRANSQUAL: A service quality model of public land transport services. *International Journal of Quality & Reliability Management, 32*(6), 534–558. https://doi.org/10.1108/IJQRM-06-2013-0094

[6] Romero, C., Zamorano, C., & Monzón, A. (2023). Exploring the role of public transport information sources on perceived service quality in suburban rail. *Travel Behaviour and Society, 33*, Article 100642. https://doi.org/10.1016/j.tbs.2023.100642

[7] Emrouznejad, A., & Yang, G. L. (2018). A survey and analysis of the first 40 years of scholarly literature in DEA: 1978–2016. *Socio-Economic Planning Sciences, 61*, 4–8. https://doi.org/10.1016/j.seps.2017.01.008

[8] Pascoe, S., Cannard, T., Dowling, N. A., Dichmont, C. M., Asche, F., & Little, L. R. (2023). Use of data envelopment analysis (DEA) to assess management alternatives in the presence of multiple objectives. *Marine Policy, 148*, Article 105444. https://doi.org/10.1016/j.marpol.2022.105444

[9] Tavana, M., Soltanifar, M., Santos-Arteaga, F. J., & Sharafi, H. (2023). Analytic hierarchy process and data envelopment analysis: A match made in heaven. *Expert Systems with Applications, 223*, Article 119902. https://doi.org/10.1016/j.eswa.2023.119902

[10] Tadić, S., Krstić, M., Dabić-Miletić, S., & Božić, M. (2023). Smart material handling solutions for city logistics systems. *Sustainability, 15*(8), Article 6693. https://doi.org/10.3390/su15086693

[11] Gompf, K., Traverso, M., & Hetterich, J. (2021). Using analytic hierarchy process (AHP) to introduce weights to social life cycle assessment of mobility services. *Sustainability, 13*(3), Article 1258. https://doi.org/10.3390/su13031258

[12] Rostampoor, M. (2023). Definition of analytic hierarchy process and its effect on environmental decisions in engineering for landfill siting. In F. De Felice & A. Petrillo (Eds.), *Analytic hierarchy process: Models, methods, concepts, and applications*. IntechOpen. https://doi.org/10.5772/intechopen.1001080

[13] Sivilevičius, H., & Maskeliūnaitė, L. (2010). The criteria for identifying the quality of passengers' transportation by railway and their ranking using the AHP method. *Transport, 25*(4), 368–381. https://doi.org/10.3846/transport.2010.46

[14] Humić, R., & Abramović, B. (2020). Modeling criteria for services of general interest organized by train operators. *EMC Review: Economy and Market Communication Review, 10*(2), 542–558. https://doi.org/10.7251/EMC2002542H

[15] Šperka, A., Čamaj, J., Dedík, M., & Bulková, Z. (2023). Evaluation methodology of railway stations using the AHP method in transport hubs from the freight transport point of view. *Infrastructures, 8*(12), Article 177. https://doi.org/10.3390/infrastructures8120177

[16] Hajipoor, M., Motameni, H., & Ebrahimnejad, A. (2025). A hybrid AHP–DEA approach for software architecture evaluation and selection. *Turkish Journal of Electrical Engineering and Computer Sciences, 33*(3), 224–247. https://doi.org/10.55730/1300-0632.4124

[17] Prevolšek, B., Borlinič Gačnik, M., & Rozman, Č. (2023). Applying integrated data envelopment analysis and analytic hierarchy process to measuring the efficiency of tourist farms: The case of Slovenia. *Sustainability, 15*(5), Article 4314. https://doi.org/10.3390/su15054314

[18] Ammirato, S., Fattoruso, G., & Violi, A. (2022). Parsimonious AHP–DEA integrated approach for efficiency evaluation of production processes. *Journal of Risk and Financial Management, 15*(7), Article 293. https://doi.org/10.3390/jrfm15070293

[19] Yılmaz, M. K., Kuşakcı, A. O., Aksoy, M., & Hacıoğlu, Ü. (2022). The evaluation of operational efficiencies of Turkish airports: An integrated spherical fuzzy AHP/DEA approach. *Applied Soft Computing, 119*, Article 108620. https://doi.org/10.1016/j.asoc.2022.108620

[20] Mohajeri, N., Amin, G. R., & Emrouznejad, A. (2010). Railway station site selection using analytic hierarchy process and data envelopment analysis. *Computers & Industrial Engineering, 59*(1), 107–114. https://doi.org/10.1016/j.cie.2010.03.006

[21] Čabrić, N., Branković, N., & Kalem, A. (2023). The selection of a possible organizational structure of railway companies by application of the fuzzy ARAS method. *Science, Engineering and Technology, 3*(1), 20–27. https://doi.org/10.54327/set2023/v3.i1.42

[22] Petrović, N., Jovanović, V., Marinković, D., Marković, S., & Nikolić, B. (2025). Measuring the efficiency of rail freight transport: A case study. *Acta Polytechnica Hungarica, 22*(4), 123–136. https://doi.org/10.12700/APH.22.4.2025.4.8

[23] Blagojević, A., Vesković, S., & Stojić, G. (2019). DEA model za ocjenu efikasnosti i efektivnosti željezničkih putničkih operatera. *Železnice, 64*(2), 81–94.

[24] Tong, H., Hou, Q., Dong, X., Duan, Y., Gao, W., & Lei, K. (2025). Assessing the spatial efficiency of Xi'an rail transit station areas using a data envelopment analysis (DEA) model. *Applied Sciences, 15*(1), Article 384. https://doi.org/10.3390/app15010384

[25] Victorino, T., & Bertussi, G. (2023). The efficiency of railway concessions and the regulation of service quality. *Journal of Applied Research and Technology, 21*(6), 921–934. https://doi.org/10.22201/icat.24486736e.2023.21.6.2014

[26] Wang, Y. M., & Chin, K. S. (2011). Fuzzy analytic hierarchy process: A logarithmic fuzzy preference programming methodology. *International Journal of Approximate Reasoning, 52*(4), 541–553. https://doi.org/10.1016/j.ijar.2010.12.004

[27] Lamant, L., Meggetto, F., Al Saati, T., Brugières, L., de Paillerets, B. B., Dastugue, N., Bernheim, A., Rubie, H., Terrier-Lacombe, M. J., Robert, A., Rigal, F., Schlaifer, D., Shiuta, M., Mori, S., & Delsol, G. (1996). High incidence of the t(2;5)(p23;q35) translocation in anaplastic large cell lymphoma and its lack of detection in Hodgkin's disease: Comparison of cytogenetic analysis, reverse transcriptase-polymerase chain reaction, and p80 immunostaining. *Blood, 87*(1), 284–291.

[28] European Environment Agency. (2022). *Transport and environment report 2022: Digitalisation in the mobility system: Challenges and opportunities*. Publications Office of the European Union. https://www.eea.europa.eu/en/analysis/publications/transport-and-environment-report-2022

[29] European Commission. (2019). *The European Green Deal* (COM(2019) 640 final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640

[30] European Union. (2021). *Regulation (EU) 2021/782 of the European Parliament and of the Council of 29 April 2021 on rail passengers' rights and obligations (recast)*. *Official Journal of the European Union, L 172*, 1–52. https://eur-lex.europa.eu/eli/reg/2021/782/oj/eng

[31] Wisutwattanasak, P., Champahom, T., Jomnonkwao, S., Aryuyo, F., Se, C., & Ratanavaraha, V. (2023). Examining the impact of service quality on passengers' intentions to utilize rail transport in the post-pandemic era: An integrated approach of SERVQUAL and health belief model. *Behavioral Sciences, 13*(10), Article 789. https://doi.org/10.3390/bs13100789

[32] European Union. (2014). *Commission Regulation (EU) No 1300/2014 of 18 November 2014 on the technical specifications for interoperability relating to accessibility of the Union's rail system for persons with disabilities and persons with reduced mobility*. *Official Journal of the European Union, L 356*, 110–178. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32014R1300

[33] Olsson, L. E., Friman, M., & Lättman, K. (2021). Accessibility barriers and perceived accessibility: Implications for public transport. *Urban Science, 5*(3), Article 63. https://doi.org/10.3390/urbansci5030063

[34] Xu, X., Cong, J., & Xia, T. (2024). A study of the impact of the use of real-time crowding information on the perceived service quality of high-speed rail by passengers with unfixed-seat tickets. *Applied Sciences, 14*(2), Article 535. https://doi.org/10.3390/app14020535

7 Conflict of interest statement

The author declares no conflict of interest.

8 Author contributions

Mia Poledica: conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing, original draft preparation, writing, review and editing, visualization, supervision, project administration.

9 Data availability statement

The data used in this study are based on publicly available reports, regulatory documents, literature sources, and expert assessments. The processed data supporting the findings of this study are not publicly shared due to the anonymized presentation of the railway operators analysed.

10 Supplementary materials

There are no supplementary materials to include.

Paper submitted: 15.04.2026.
Paper accepted: 05.08.2026.