Measuring the Efficiency of Rail Freight Transport – A Case Study

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Abstract: Railway transport plays an important role in a country's economic development. Efficiency is one of the most significant performance indicators in the railway sector. Evaluating, monitoring, and improving efficiency is the main goal of every railway company. Different parametric and non-parametric approaches have been used in the literature and in practice to measure and compare the performance of railway companies. DEA (Data Envelopment Analysis) is a non-parametric linear programming technique that is successfully used in evaluating and comparing the efficiency of entities in the service sector. Based on the DEA method, it can be determined whether the DMU units are inefficient compared to the efficient units. Also, it can be concluded how much it is necessary to reduce the input or increase the output for the units to become efficient. Four inputs and two output parameters were used during the measurement of the efficiency of freight rail transport in the Republic of Serbia for the period from 2011 to 2022.

Keywords: Rail transport; efficiency; DEA method

1 Introduction

According to its characteristics, the railway represents a large and very complex business-production, technical-technological, economic, organizational, and information-management system [1]. The railway transport system can transport large quantities-masses of goods and passengers over long distances, and in a relatively short time. At the current level of economic and social development, it is not enough to transport passengers or goods, but more and more the question arises as to how, for what time, with what degree of safety and orderliness, quality, and at what price it will be transported. All this poses numerous and complex qualitatively new tasks for the railway transport system with the requirements that the transport be: fast, reliable, safe, regular, and economical-in a word, rational and efficient.

In today's business, competition in the market is extremely demanding, regardless of the sector or type of services [1] [2]. To survive and make a profit, companies must operate quickly, reliably, and efficiently. Different industries and business systems have different performance criteria [3] [4], but efficiency is one of the basic and most frequently monitored factors.

Railways have adopted modern organizational theory that combines different approaches to improve their operations. This view includes a systems approach to organization, a multidimensional level model, recognition of process dynamism, stochastic models to predict events, and an emphasis on system adaptability [5]. Most routine tasks are performed according to established procedures and hierarchically, with centralized decision–making. Management actively monitors the entire system and makes adjustments based on available data to ensure operational efficiency. If there were an objective method for determining the importance of input and output factors, the analytical calculation of efficiency would be simpler [6] [7].

The MCDM (Multi-Criteria Decision-Making) techniques are commonly employed to assess the management of organizations and evaluate rail traffic performance [8] [9]. DEA can be utilized independently or integrated with MCDM techniques for performance evaluation [10] [11]. The DEA methodology includes various approaches and models used to evaluate the relative efficiency, which helps in making decisions about improvements. Information on efficiency is relative because it depends on the analyzed data. Empirical data often vary due to natural fluctuations and may be subject to influence, either by chance or by design.

After the introductory part, the second chapter of the paper provides an overview of the current literature related to the calculation of efficiency and the application of the DEA method in railway traffic and transport. Then, in the third chapter, the input and output data and DMU units used to establish the DEA model and the analysis of the efficiency of the freight railway traffic of the Republic of Serbia in the time frame from 2011 to 2022, based on the valid statistical data. In the fourth chapter, the results of measuring efficiency based on the CCR (Charnes, Cooper, Rhodes) model of input orientation. Based on the obtained results, units that are fully and partially efficient can be identified. At the end of the paper, it will summarize the key findings and present a comprehensive overview of potential future research directions.

2 Literature Review

The railway represents a large transport system in the field of traffic whose main task is the mass production of transport services, which means the smooth performance of transport services by carrying out the transport of goods and passengers, to satisfy the transport requirements for a wide range of users, starting from the level of state needs that are of interest to the entire social community and individual economic enterprises, institutions, and citizens [12-22]. For these reasons, the activity of railways has features of special social importance and public character of work, and its operations are organized at the level of national companies. To carry out the transportation process, the railway uses its infrastructure – the transport network of railway lines and stations, transport capacities (rolling stock), workforce, and appropriate organization with management, which ensures its functioning in a wide area of its influence [7] [23]. All transport modes, including rail, cause externalities that negatively affect the environment, human health, and the economy. The costs of these effects do not fall directly on those who cause them, but on other road users (such as congestion and accidents) and society (environmental pollution) [24] [25]. This leads to wrong decisions in the transport market, resulting in inefficient use of resources and loss of social benefit [26].

The efficiency of European railway companies in the paper [27] was investigated by the authors using different configurations of input–output parameters in the DEA model. First, the DEA method was used to evaluate efficiency, and then statistical tests and Tobit analysis were conducted to evaluate the impact of various factors on efficiency. Companies from Western Europe showed better performance in passenger and total traffic compared to those from Central and Eastern Europe, while the situation is the opposite when it comes to freight transport. No clear trend of continuous improvement or decrease in efficiency was observed during the observed period. A significant influence of the choice of input-output factors on the results of the analysis was also determined [27].

It follows from the literature, that the efficiency is relative because it refers only to the analyzed data and can only be the same if opposite models are used. In the paper [12], the authors highlight two fundamentally different approaches that can result in the same efficiency: input and output models obtained by DEA analysis methods. Although efficiency information is important, it is not sufficient because it raises the issue of choosing optimal data values or dilemmas between input and output models of DEA analysis. In the example of the railway stations of the Belgrade Passenger Transport Section, it was shown that the inefficient model can be reached either by reducing the number of cashiers and trains in the input model or by increasing the number of passengers and reducing the number of trains in the output model [12].

In today's rapidly changing environment, the performance of railway undertakings is crucial for their survival in the market. To operate efficiently and effectively, maintain competitiveness, and thrive in the transport industry, railway undertakings must seek optimal solutions. The paper [10] aims to identify and assess the factors influencing the efficiency of railway undertakings, thereby enhancing their competitiveness. To address the challenge of criteria selection, the paper experimented with the Fuzzy Analytical Hierarchical Processes (FAHP) method. By employing the DEA approach, the efficiency of railway undertakings was evaluated. The results indicate that this approach effectively consolidates various criteria (including resource, operational, financial, quality, and safety) into a comprehensive assessment of the efficiency of railway undertakings. Furthermore, it provides valuable insights into corrective actions that can be taken to enhance their efficiency [10].

The paper [28] introduces a multi-activity network Data Envelopment Analysis (DEA) model, which integrates production and consumption technologies into a cohesive framework. This model is then employed to assess passenger and freight technical efficiency, service effectiveness, and technical effectiveness concurrently for 20 chosen railways in 2002. The findings indicate notable variations across these metrics. Given that the multi-activity network DEA model accurately reflects the intricacies of railway operations, researchers can extract deeper insights from the obtained results. Consequently, this facilitates the development of strategies to enhance operational performance [28].

The paper [29] delves into the global railway transport sector, investigating 16 countries from 2010 to 2018. Utilizing a three-stage Data Envelopment Analysis (DEA) modeling approach, it aims to empirically assess the sector's efficiencies while mitigating external environmental influences and statistical noise. The paper suggests policy interventions focused on governance strategies geared towards real efficiency enhancement, targeted resource allocation considering environmental influences, and bolstering the competitiveness of railway transport to achieve economies of scale [29].

3 DEA Methodology, Input and Output Data

3.1 DEA Methodology

Multidisciplinary evaluations of efficiency often take different forms in common analyses (cost per unit, profit per unit, satisfaction per unit, etc.). A significant feature of the DEA method is that the inputs and outputs for a specific DMU (Decision-Making Unit) do not have to be related, but these units that are evaluated within one analysis must have the same types of inputs and outputs.

The term decision maker (DMU) is introduced to cover, in a flexible manner, any parameter affecting efficiency, each such parameter being evaluated as part of a whole that uses similar inputs to produce similar results. These evaluations result in a performance score that ranges between zero (minimum value, 0% efficiency) and one (maximum value, 100% efficiency) and is a "degree of efficiency".

The DEA method measures the relative efficiency of units by constructing an empirical efficiency frontier or production possibilities frontier based on data on used inputs and realized outputs of all units. It consists of a series of optimizations – linear programming tasks (one for each unit included in the analysis). For each unit, the maximum measure of performance is calculated concerning all other units in the observed population that must satisfy the condition that they "lie" on or below the extreme limit, which is called the efficiency limit or envelope. The effective envelope can be lower or upper depending on the number of input/output variables, but also the orientation of the model [30] [31].

The primary concept of measuring the effectiveness of the decision maker (DMU) is formalized in the form of a mathematical model of linear programming that can be expressed by the following mathematical expression (Eq. 1-3):

$$Max\ h_0 = \sum_{j=1}^{n} u_j y_{jk0} \tag{1}$$

$$\sum_{i=1}^{m} v_i x_{ik0} = 1 \tag{2}$$

$$\sum_{j=1}^{n} u_j y_{jk0} \leq \sum_{i=1}^{m} v_i x_{ik0} \tag{3}$$

where: ***k*** is the number of decision-making units, ***m*** is the number of inputs, ***n*** is the number of inputs, ***u*** is the output weight coefficient and ***v*** is the input weight coefficient.

The basic models commonly used in efficiency research are CCR (Charnes, Cooper, Rhodes) and BCC (Banker, Charnes, Cooper). The main difference between these two models is the assumed transformation of inputs into outputs. The CCR model is the most famous DEA model that is based on the assumption of constant returns, which means that each feasibility of activity (x_y) entails the feasibility of activity (x_t, y_t) for each positive number t.

After determining the input and output, the weight coefficient is determined using linear programming to maximize the ratio of virtual input to output.

The optimal weighting coefficient varies from one DMU to another DMU. Thus, the "weighting coefficients" in DEA analysis are derived from the data, rather than being predetermined. It is necessary to find non-negative weighting coefficients, using linear programming, to maximize the virtual output/virtual input ratio, with the restriction that their ratio cannot be greater than one, for each observed DMU (Eq. 4-6).

$$Max\, h_k = \sum_{j=1}^{n} u_j y_{jk} / \sum_{i=1}^{m} v_i x_{ik} \tag{4}$$

provided that:

$$\sum_{j=1}^{n} u_j y_{jk} \leq \sum_{i=1}^{m} v_i x_{ik} \tag{5}$$

i.e.:

$$\sum_{j=1}^{n} u_j y_{jk} / \sum_{i=1}^{m} v_i x_{ik} \leq 1 \tag{6}$$

whereby:

$u_j \geq 0,\ j = 1,2,\ldots n;\ and\ u_j \geq \varepsilon$

$v_i = 0, i = 1,2,\ldots n;\ and\ v_i \geq \varepsilon$

where: $\boldsymbol{h_k}$ relative efficiency of k-th DMU, ***k*** number of decision units, ***m*** number of inputs (x), ***n*** number of outputs (y), ***v*** weight coefficients of inputs (x), ***u*** weight coefficients of outputs (y), ***ε*** a small positive value (most often $=10^{-6}$).

Maximization of efficiency is sought for the k-th DMU with the condition that the weighted sum of the outputs is less than the weighted sum of the inputs, which follows from $0 < h_k \leq 1$. If the function $h_k=1$, then the k–th DMU is relatively efficient, and if h_k is less < than 1, then the k-th DMU is relatively inefficient, and the h_k value itself shows how much it is necessary to relatively rationalize the consumption of resources or increase the results for the k–th DMU to become efficient. In the case of increasing or decreasing returns, when a proportional change in the input variable results in a more or less proportional increase in the output, the BCC model of DEA analysis is used.

3.2 Input and Output Data

In developing a DEA analysis model, the number of DMU decision units, more precisely variant solutions, is first determined. There are certain recommendations in the literature about the relationship between the number of DMUs and the number of input and output sizes. It is suggested that the number of DMUs is at least twice the sum of input and output sizes. Given that a model with a total of six variables (four inputs and two outputs (Figure 1)) is proposed, the efficiency of twelve years (DMU1 – DMU12) was considered.

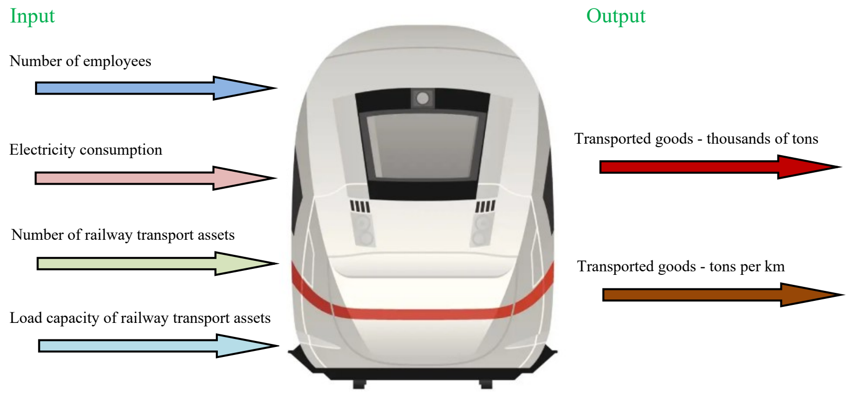

Figure 1
Input and output variables of the DEA model

Table 1
Input - output parameters and DMU units for the DEA model

DMUs		**Input parameters**				**Output parameters**	
No.	Year	Number of employees	Electricity consumption	Railway transport assets of the freight car fleet		Transported goods	
		number	MWh, thousand	number	load capacity, thousand	tons, thousand	tons per kilometer
DMU1	2011	18557	170	8447	430	12620	3611
DMU2	2012	18356	143	8449	431	9451	2769
DMU3	2013	18047	148	8452	431	10463	3022
DMU4	2014	17078	139	8486	432	10826	2988
DMU5	2015	16622	136	8486	432	11887	3249
DMU6	2016	13641	120	7277	411	11896	3087
DMU7	2017	10229	116	6781	342	12352	3288
DMU8	2018	10226	115	6843	346	13449	3932
DMU9	2019	10703	104	5661	258	11475	2861
DMU10	2020	10587	91	5660	295	10118	2612
DMU11	2021	10497	94	4304	223	10783	2925
DMU12	2022	10346	102	4194	226	10155	2780

Once the number of input–output parameters is determined, the next step is to determine the parameters themselves. After the DMU units, the number and sizes of the input-output parameters are determined, and the DEA model is set up.

The following parameters of the DEA model were used as input parameters: the number of employees in traffic and transport, electricity consumption in traffic – in thousands of MWh, the number of railway transport assets of the freight car fleet, and the load capacity of railway transport assets expressed in thousands (Table 1). The following parameters were used as output parameters: transported goods expressed in thousands of tons and transported goods in tons per kilometer (Table 1). In the conducted analysis, available data collected by statistical reports of the transport company "Serbia Cargo" DOO were used [32].

4 The Approach and Results Discussion for Case Study: The Serbian Railway

This part of the paper presents an example of the application of the DEA method for measuring the efficiency of rail freight transport in the Republic of Serbia for the period from 2011 to 2022. Efficiency measurement was performed based on the input-oriented CCR model. If an output-oriented DEA model had been used, the differences in the obtained results would have been directed towards the maximization of performance, i.e., an increase in output, i.e., transported tons of cargo for a given level of input (personnel, energy, number of rolling stock). In this approach, the priority is to maximize production and services instead of optimizing resources. Such a model would reveal which units are not using their maximum potential in relation to existing resources, and efficiency would be measured by how successful units are in achieving maximum results for the same inputs.

The calculation was created and implemented within the MS Excel program based on equations (1-6). The model consists of DMU units, which represent specific years, 4 inputs, and 2 output parameters. The analysis results of the rail freight transport efficiency in the Republic of Serbia are shown in Table 2.

Based on the results shown, it can be easily seen that the units (DMU 7, DMU 8, DMU 10, DMU 11, and DMU 12) have an efficiency of 1, that is, the mentioned units form an efficient envelope. The mentioned units can be considered completely efficient, given that they do not have "surpluses" in the input variables or "deficiencies" in the output variables. Other units cannot be considered efficient.

To achieve efficiency for the year 2011 (DMU 1), it is necessary to either reduce the first input parameter (number of employees) by 44.89%, the second input parameter (energy consumption) by 32.35%, the third input parameter (number of means of railway freight transport of the vehicle fleet) by 18.99%, and the fourth input parameter (tons of capacity of railway transport assets) by 19.53% (Table 3).

Or it is necessary to increase both output parameters (transported goods t and transported goods tkm) by 6.57% and 8.89%, respectively. Corrective actions of other inefficient units can be defined similarly.

Table 2
Results of the calculation of the efficiency of rail freight transport in the Republic of Serbia

DMU/Year		**Efficiency**	
DMU 1	2011	0.938	
DMU 2	2012	0.704	
DMU 3	2013	0.778	
DMU 4	2014	0.805	
DMU 5	2015	0.884	
DMU 6	2016	0.885	
DMU 7	2017	1	✓
DMU 8	2018	1	✓
DMU 9	2019	0.994	
DMU 10	2020	1	✓
DMU 11	2021	1	✓
DMU 12	2022	1	✓

Table 3
Results of the calculation of the efficiency of rail freight transport in the Republic of Serbia

	Inputs				**Outputs**	
	Number of employees [%]	Electricity consumption [%]	Railway transport assets of the freight car fleet		Transported goods	
			number [%]	load capacity [%]	tons [%]	tons per kilometer [%]
DMU1	–44.89	–32.35	–18.99	–19.53	6.57	8.89
DMU2	–44.29	–19.58	–19.01	–19.72	42.30	42.00
DMU3	–43.34	–22.30	–19.04	–19.72	28.54	30.11
DMU4	–40.12	–17.27	–19.36	–19.91	24.23	31.59
DMU5	–38.48	–15.44	–19.36	–19.91	13.14	21.02
DMU6	–25.03	–4.17	–5.96	–15.82	13.05	27.37
DMU7	0	0	0	0	0	0
DMU8	0	0	0	0	0	0
DMU9	–2.65	–3.87	–11.21	0	0.58	12.25
DMU10	0	0	0	0	0	0
DMU11	0	0	0	0	0	0
DMU12	0	0	0	0	0	0

As can be seen from Table 3, additions and differences to the target inputs and outputs are the size of the changes required for the efficient operation of Serbian Railways, which is shown graphically in Figure 2.

The changes are in the domain of the number of employees, electricity energy consumption, number, and tonnage capacity of the means of railway transport of the freight car park. In the case of such a dilemma when the changes have already been quantified, it is necessary to further measure the weight and possibility of implementing measures to improve efficiency and make a decision accordingly.

From the results, it can be seen that the reorganization of the railway was successfully implemented in terms of increasing efficiency, and the new organization includes a reduction in the number of employees, electricity consumption, and the railway transport assets of the freight car fleet (number and load capacity). On the other hand, the increase of transported goods in thousands of tons and ton kilometers presupposes the improvement of the transport service, i.e., more effective service, and it is a measure that is more difficult to implement.

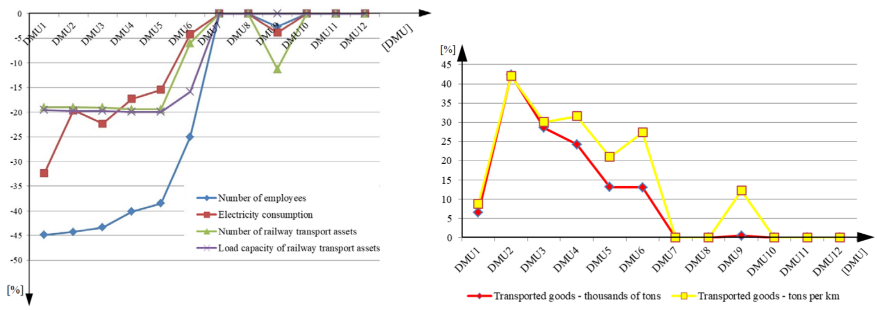

Figure 2

The necessary changes in the input and output variables of DEA models

Conclusions

In this paper, an assessment of the efficiency of the railway operation in the Republic of Serbia was carried out, using the input-oriented CCR model, based on data collected for the period from 2011 to 2022. Each DMU unit represents a certain year, that is, 4 input parameters and 2 output parameters, based on which, the calculation model was created.

Due to the conducted analysis and obtained results, it can be concluded that:

- Units DMU 7, DMU 8, DMU 10, DMU 11, and DMU 12 (i.e., years 2017, 2018, 2020, 2021, and 2022, respectively) are fully efficient, with an efficiency score of 1, and these units form the efficient frontier, serving as benchmarks for optimal performance.
- Inefficient units DMU 1, DMU 2, DMU 3, DMU 4, DMU 5, DMU 6, and DMU 9 (i.e., years 2011, 2012, 2013, 2014, 2015, 2016, and 2019, respectively) have been identified, requiring targeted corrective actions adopted in inputs and outputs presented in tabular form to improve efficiency.
- The analysis provides a clear framework for performance improvement in the Serbian Railways.

It is necessary to either reduce the input parameters (number of employees, energy consumption, number of means of railway freight transport of the vehicle fleet, and tons of capacity of railway transport assets). Input parameters should be improved through increasing the capacity and quality of infrastructure (modernization of tracks and signaling and maintenance), technical equipment and rolling stock (renewal of trains and improvement of cargo handling equipment), human resources (training and development of employees), and energy efficiency (reducing energy consumption). Or, on the other side, it is necessary to increase both output parameters transported goods in tons and transported goods tkm (increasing the volume of cargo transportation through improvement of logistics capacities and optimization of routes, increase in service quality through reduction of delays, increase in schedule accuracy, maximization of income through improvement of tariff policies, diversification of services and expansion of the market, optimization of operating costs, introduction of new technologies for monitoring and informing users about cargo status). Improving the adopted input and output parameters in accordance with the mentioned recommendations can help to overcome inefficiencies and improve the overall performance of railway freight transport in Serbia.

Considering the fluctuating efficiency results during different years, there are external socio-economic or infrastructural factors (variables) that influence these variations and they can be: economic factors (changes in national or regional economic growth, inflation, and energy prices can affect railroad operations), demographic changes (population migration), political and regulatory environments (changes in legislation, or regulations can positively or negatively affect railroad performance), infrastructural investments (the modernization of railway infrastructure), technological progress (new technologies), and climatic and seasonal factors (extreme weather conditions, seasonal variations or natural disasters).

The question is how to include these variables in future efficiency studies using the DEA methodology. This could be achieved as follows: adding external variables (demographic trends and political factors), geographically specific analyses (i.e., regions with different infrastructure or demographic characteristics), and scenario simulations (the model could include scenario simulations, analyzing how changes in key external factors (such as increased investment or reduced subsidies) affect railway efficiency). This would provide a more comprehensive insight into the performance of rail freight transport and enable more informed and effective strategic decisions.

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References

[1] Youssef, M. I., & Hausawi, Y. M., Utilizing the Enterprise Architecture Model to Develop the Structure of Public Sector Entities in Saudi Arabia. J. Eng. Manag. Syst. Eng., 3(3), 2024, pp. 164-174, https://doi.org/10.56578/jemse030304

[2] Subotić, T., & Bošković, B., Research on the resilience concept and its applications in the railway transport market, Železnice, 2, 2022, pp. 89-101, https://www.casopis-zeleznice.rs/index.php/zeleznice/article/view/110

[3] Hussain, A., & Ullah, K., An Intelligent Decision Support System for Spherical Fuzzy Sugeno-Weber Aggregation Operators and Real-Life Applications, Spectrum of Mechanical Engineering and Operational Research, 1(1), 2024, pp. 177-188, https://doi.org/10.31181/smeor11202415

[4] Barać, M., Vitković, N., Stanković, Z., Rajić, M., & Turudija, R., Description and Utilization of an Educational Platform for Clean Production in Mechanical Engineering, Spectrum of Mechanical Engineering and Operational Research, 1(1), 2024, pp. 145-158, https://doi.org/10.31181/smeor11202413

[5] Potter, A, Soroka, A, & Naim, M., Regional resilience for rail freight transport, Journal of Transport Geography, 104 (103448), 2022, https://doi.org/10.1016/j.jtrangeo.2022.103448

[6] Foroutan, L. F. S., Bamdad, S., Efficiency measurement of railway passenger stations through network data envelopment analysis, Research in Transportation Business & Management, 46, 2023, 100767, https://doi.org/10.1016/j.rtbm.2021.100767

[7] Fischer, S., & Szürke, S. K., Detection process of energy loss in electric railway vehicles, Facta Universitatis-Series Mechanical Engineering, 21(1), 2023, pp. 81-99, https://doi.org/10.22190/FUME221104046F

[8] Rakić, M., Žižović, M., Miljković, B., Njeguš, A., Žižović, R. M., & Đorđević, I., Multi-criteria selection of standards for system analyst activities in organizations, Facta Universitatis-Series Mechanical Engineering, 21(3), Special Issue, 2023, pp. 433-451, https://doi.org/10.22190/FUME230521023R

[9] Božanić, D., Epler, I., Puška, A., Biswas, S., Marinković, D., & Koprivica, S., Application of the DIBR II – rough MABAC decision-making model for ranking methods and techniques of lean organization systems management in the process of technical maintenance, Facta Universitatis-Series Mechanical Engineering, 22(1), 2024, pp. 101-123, https://doi.org/10.22190/FUME230614026B

[10] Blagojević, A., Vesković, S., Kasalica, S., Gojić, A., & Allamani, A., The application of the fuzzy AHP and DEA for measuring the efficiency of freight transport railway undertakings, Operational Research in Engineering

Sciences: Theory and Applications, 3(2), 2020, pp. 1-23, https://doi.org/10.31181/oresta2003001b

[11] Li, R., A TOPSIS and DEA Based Approach to Evaluate the Operational Efficiency of Sponge City, Tehnički vjesnik, 30(1), 2023, pp. 8-16, https://doi.org/10.17559/TV-20221020010813

[12] Vuković, D. R., Railway stations as efficiency decision-making units – input and output DEA model, Tehnika – Saobraćaj, 63(3), 2016, pp. 441-448, https://doi.org/10.5937/tehnika1603441V

[13] Petrović, N., Mihajlović, J., Jovanović, V., Ćirić, D., & Živojinović, T., Evaluating Annual Operation Performance of Serbian Railway System by using Multiple Criteria Decision-Making Technique, Acta Polytechnica Hungarica, 20(1), 2023, https://doi.org/10.12700/APH.20.1.2023.20.11

[14] Aydin, N., A fuzzy-based multi-dimensional and multi-period service quality evaluation outline for rail transit systems, Transport Policy, 55, 2017, pp. 87-98, https://doi.org/10.1016/j.tranpol.2017.02.001

[15] Ézsiás, L., Tompa, R., & Fischer, S., Investigation of the possible correlations between specific characteristics of crushed stone aggregates, Spectrum of Mechanical Engineering and Operational Research, 1(1), 2024, pp. 10-26, https://doi.org/10.31181/smeor1120242

[16] Németh, A., & Fischer, S., Investigation of the glued insulated rail joints applied to CWR tracks, Facta Universitatis-Series Mechanical Engineering, 19(4), 2021, pp. 681-704, https://doi.org/10.22190/FUME210331040N

[17] Fischer, S., Harangozó, D., Németh, D., Kocsis, B., Sysyn, M., Kurhan, D., & Brautigam, A., Investigation of heat-affected zones of thermite rail welding, Facta Universitatis-Series Mechanical Engineering, 2023, https://doi.org/10.22190/FUME221217008F

[18] Brautigam, A., Szalai, S., Légmán, N., & Fischer, S., Laboratory investigation on seams between rails and hardened fine-grained as well as Hadfield steel plates prepared by manual arc welding, Acta Polytechnica Hungarica, Paper 6645, 2024, accepted manuscript

[19] Barna, V., Brautigam, A., Kocsis, B., Harangozó, D., & Fischer, S., Investigation of the effects of Thermit welding on the mechanical properties of the rails, Acta Polytechnica Hungarica, 19(3), 2022, pp. 37-49, https://doi.org/10.12700/APH.19.3.2022.3.4

[20] Macura, D., Laketić, M., Pamučar, D., & Marinković, D., Risk Analysis Model with Interval Type-2 Fuzzy FMEA – Case Study of Railway Infrastructure Projects in the Republic of Serbia, Acta Polytechnica Hungarica, 19(3), 2022, pp. 103-118, https://doi.org/10.12700/APH.19.3.2022.3.9

[21] Marković, D., Stanković, A., Marinković, D., & Pamučar, D., Metaheuristic Algorithms for the Optimization of Integrated Production Scheduling and

Vehicle Routing Problems in Supply Chains, Tehnički vjesnik, 31(3), 2024, pp. 800-807, https://doi.org/10.17559/TV-20240207001318

[22] Campisi, T., Tesoriere, G., Russo, A., & Rashid, A. A. M., Spatial distribution and characterization of consumers of E-grocery services in sicily: Insights for sustainable urban logistics, Engineering Review, 43(3), 2023, pp. 54-67, https://doi.org/10.30765/er.2177

[23] Bešinović, N., Resilience in railway transport systems: a literature review and research agenda, Transport Reviews, 40(4), 2020, pp. 457-478, https://doi.org/10.1080/01441647.2020.1728419

[24] Petrović, N., Jovanović, V., Nikolić, B., Pavlović, J., & Mihajlović, J., A comparative analysis of road and rail freight transport through the Republic of Serbia from the aspect of external costs, Acta Technica Jaurinensis, 15(3), 2022, pp. 130-137, https://doi.org/10.14513/actatechjaur.00655

[25] Petrović, N., Bojović, N., Marinković, D., Jovanović, V. & Milanović, S., A Two-Phase Model for the Evaluation of Urbanization Impacts on Carbon Dioxide Emissions from Transport in the European Union, Tehnički vjesnik, 30(2), 2023, pp. 514-520, https://doi.org/10.17559/TV-20221018103946

[26] Sarfraz, M., & Božanić, D., Optimization of Market Risk via Maclaurin Symmetric Mean Aggregation Operators: An Application of Interval-Valued Intuitionistic Fuzzy Sets in Multi-Attribute Group Decision-Making, J. Eng. Manag. Syst. Eng., 3(2), 2024, pp. 100-115, https://doi.org/10.56578/jemse030205

[27] Kapetanović, M., Milenković, M., Bojović, N., & Avramović, Z., Evaluation of European Railway Companies Efficiency: Application of a TwoStage Analysis, Tehnika – Saobraćaj, 64(3), 2017, pp. 403-410, https://doi.org/10.5937/tehnika1703403K

[28] Yu, M. M., & Lin, E. T. J., Efficiency and effectiveness in railway performance using a multi-activity network DEA model, Omega, Elsevier, 36(6), 2008, pp. 1005-1017, https://doi.org/10.1016/j.omega.2007.06.003

[29] Niu, Y., Li, X., Zhang, J., Deng, X., & Chang, Y., Efficiency of railway transport: A comparative analysis for 16 countries, Transport Policy, 141, 2023, pp. 42-53, https://doi.org/10.1016/j.tranpol.2023.07.007

[30] Banker, R. D., Charnes, A., & Cooper, W. W., Models for estimating technical and returns to-scale efficiencies in DEA, Management Science, 30, 1984, pp. 1078-1092

[31] Boussofiane, A., Dyson, R. G., & Thanassoulis, E., Applied data envelopment analysis, European Journal of Operational Research, 52, 1991, pp. 1-15

[32] Statistical Office of the Republic of Serbia, Statistical Yearbook of the Republic of Serbia, 2020, Available at: https://www.stat.gov.rs/enus/publikacije/publication/?p=12694