Prediction of roadheader performance in Serbian underground coal mines

Duško Đukanović, Nemanja Đokić, Rade Tokalić, Luka Crnogorac, Kemal Gutić

PREDICTION OF ROADHEADERS PERFORMANCE IN SERBIAN UNDERGROUND COAL MINES

DOI: 10.25075/BMC.2022.18

Đukanović D.[1], Đokić N.[2], Tokalić R.[3], Crnogorac L.[3], Gutić K.[4]

[1]UNIVERSITY OF BELGRADE, TECHNICAL FACULTY IN BOR
[2]PE UCM RESAVICA, BUREAU OF DESIGN AND DEVELOPMENT, BELGRADE
[3]UNIVERSITY OF BELGRADE, FACULTY OF MINING AND GEOLOGY
SERBIA
luka.crnogorac@rgf.bg.ac.rs
[4]UNIVERSITY OF TUZLA, FACULTY OF MINING, GEOLOGY AND CIVIL ENGINEERING, B&H

Abstract: *Eight underground coal mines in Serbia are gathered into public enterprise for underground coal mining (PE UCM Resavica). Applied mining methods and drifting in these mines have not been changed for last 25 years. Drifting is performed by drilling and blasting. In several mines preparations for introduction of longwall mining is underway. This requires certain dynamics in development operations, so the application of roadheaders is considered. Laboratory testing has been performed to determine mechanical properties of coal and surrounding rock. Preliminary selection of roadheader was performed, based on global experiences and established models, and basic parameters were determineed for selected roadheader: ICR, AV and TCR. Based on these parameters, prediction of financial effects was performed. Obtained results were compared to technical data of the roadheaders. The comparison showed that obtained results are reliable and represent a solid base for efficient utilization of the roadheaders in Serbian underground coal mines.*

Key words: ROADHEADERS, DRIFTING, UNDERGROUND COAL MINE, PERFORMANCE PREDICTION.

INTRODUCTION

Global trends in the last decade, environment restrictions and other market factors, forced mining companies worldwide to improve their operations profitability and competitivity. One of the ways to do it in Serbian coal mines is to replace traditional drilling and blasting techniques of tunneling by mechanical miners.

Since mechanical miners, such as roadheaders, provide continual operations and better advance of the drifts, it is expected that they will increase productivity, reduce costs and improve competitiveness.

In selection of roadheader, the first step is to determine applicability of roadheaders, i.e., to determine whether they can operate in specific conditions with a satisfying performance results. Then it is possible to select the type and determine general properties required from roadheaders, from available machines on the market. Finally, roadheader characteristics should be matched with properties of coal and surrounding rock, to maximize machine performances[1 - 5]. This can be achieved by studying the design parameters and their optimization to suit specific conditions, in our case in Serbian underground coal mines.

Prediction of roadheader performance is usually related to three main parameters: instantaneous cutting rate (ICR), determined as production rate during actual cutting time (tones or m^3 per hour), bit consumption and machine utilization. This paper provides general information about Serbian coal mines, their operations and geotechnical properties, followed by analysis on applicability of roadheaders and methodology for their selection.

COAL MINES IN SERBIA

Serbian underground coal mines are incorporated in Public Enterprise for Underground Coal Mining (PE UCM Resavica). This company is currently in process of restructuring, but it is not known yet when or how this process will end. There are eight coal mines in PE UCM. There is a long tradition of underground mining, because these mines are 80 to 150 years old. Quality of coal varies from subbituminous to bituminous coal and anthracite. Common characteristics for these mines are low productivity, obsolete mining methods, low mechanization, and high utilization of labor. Drilling is performed with hand held electic or pneumatic rock drills. Average annual outputs, as a sum of all mines, reach 500,000 to 600,000 tons of coal. [6]

However, there are some improvements, in progress or in plans. New coal field is going to be open in Strmosten mine, with longwall mining designed. Soko mine is also in phase of opening of new coal field. Štavalj mine has huge reserves of coal and favorable overall mining conditions, which makes it the mine with best perspective in the country. Opening of new coal fields in these three mines includes about 20,000 meters of new drifts. By mine design, new drifts will be 10, 14.8 and 22 m^2 in cross-section areas, with horseshoe shape. Drifts will be supported with yielded steel arches, with 0.8 m spacing between frames when driven in rock and 0.6 m when driven in coal [6]. Figure 1 shows a cross-section of 14.8 m^2 drift, with 12.7 m^2 area after installation of support.

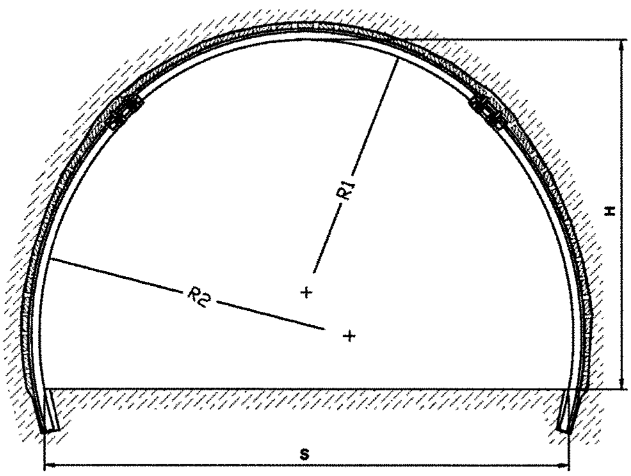

Figure 1. Cross-section and dimensions of development drift supported with yielding steel arches

Design values of cross-section and dimension of development drift (from Figure 1.) are: A = 12.7 m^2, S = 4.75 m, H = 3.23 m, R1 = 2.28 m, R2 = 2.85 m.

Underground drifts in coal mining can be driven through coal or surrounding rocks. Most common surrounding rocks in Serbian coal mines are clay, sandy clay, clayey marl, marl, etc. Density (ρ), Unconfined Compressive Strength (UCS) and Brazilian Tensile Strength (BTS) for rocks occurring in three coal mines are given in Table 1. [6]

Table 1. Rock properties

Rock type	Mine	ρ [t/m^3]	UCS [MPa]	BTS [MPa]
Coal	Rembas Mine, Strmosten	1.33	24.88	3.22
Dark grey, compact, slightly crystalline limestone	Rembas Mine, Strmosten	2.70	39.22	6.92
Red, compact, calcare-ous sandstone	Rembas Mine, Strmosten	2.52	14.60	0.76
Coal	Soko	1.29	21.4	1.71
Grey, compact, calcar-eous, clayey shale	Soko	2.58	28.43	3.12
Coal	Štavalj; West field	1.29	25.6	2.12
Marl	Štavalj; West field	2.01	20.72	2.46

METHODOLOGY OF RESEARCH

Roadheader selection

Roadheaders are most used machines for excavation in soft and medium rocks. In underground mining they are used for drifting (development drifts, haulage drifts, cross-cuts, etc.), while in civil engineering they are used for various types of tunnels. Since roadheaders are adjustable in a sense of excavating area, they can be used for various underground rooms and structures. [1, 7 - 8]

In hard rock, applicability of roadheaders is limited, due to excessive wearing of drag bits. However, the applicability is widening, and nowadays roadheaders successfully work in a hard rock with the values of UCS up to 100 MPa. [9 - 10]

Roadheader properties are referred to major parameters, such as machine type, machine weight, cutterhead type, lacing design, boom type, additional equipment, etc.; and operational parameters, like organization, labor, roof support, supplies, etc. [11]

This diagram can be useful in primary machine selection, indicating the required machine weight, type and cutterhead power based on ground conditions and geometry.

Performance prediction

Numerous performance prediction models were developed in the past. Majority of them is focused on prediction of Instantaneous Cutting Rate (ICR) prediction in relation with variation of parameters like rock compressive strength, machine weight and cutting power.

Various authors analyzed advance rate variations of roadheaders using rock classification system [12 - 13]. Relation between ICR and UCS of the rock for different types of roadheaders was studied by numerous authors [13]. Copur et al. (1997, 1998) added the weight of roadheaders and installed power into prediction model to obtain more realistic performance prediction [5]. Some authors used the data on specific energy consumption to predict the excavation rate [14 - 29].

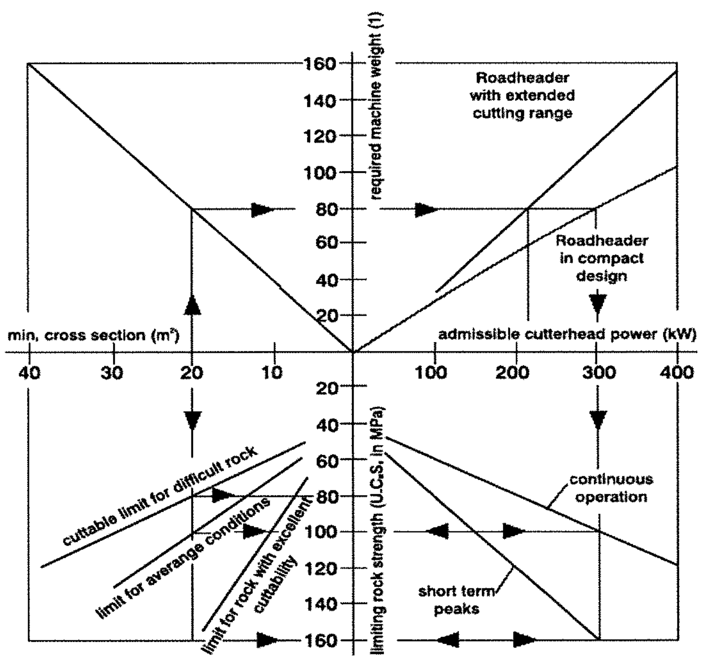

Figure 2. Indicative diagram for roadheader selection [11]

Estimation of the ICR

The instantaneous (net) cutting rate of a cutting machine represents the excavation rate achieved during excavation considering only the active cutting hours without stoppages [4]. Based on previous, the ICR represents effective cutting rate. ICR of roadheader machines can be calculated by the model [5, 30]:

$$ICR=\left(\frac{1{,}739}{UCS^{1.13}}\right)\cdot t_1\ ICR=\left(\frac{1{,}739}{UC\,S^{1.13}}\right)\cdot t_1, \textit{for axial roadheader}\,(230\,kW) \quad (1)$$

$$ICR=\left(\frac{719}{UC\,S^{0.78}}\right)\cdot t_2, \textit{for transverse roadheader}\,(250\,kW) \quad (2)$$

Where:

- t_1 is power correction factor (assuming the effect of power on performance is linear: 200/230 = 0.87) for axial roadheader,
- t_2 is power correction factor (assuming the effect of power on performance is linear: 200/250 = 0.80) for transverse roadheader.

For a transverse roadheader equipped with cutterhead of 132 kW power estimation of the ICR can be calculated with a model given below [5, 26]:

$$ICR = (75.7 - 14.3 \cdot ln(UCS)) \cdot t_3, \quad (3)$$

Where:

- t_3 is the power correction factor (assuming the effect of power on performance is linear: 200/132 = 1.52).

Estimation of Daily Advance Rate

The daily advance rate (AR) can be estimated as follows: [5, 31]

$$AR = \frac{V_{exc}}{A_{face}} [\text{m/day}] \quad (4)$$

Where:

- AR is advance rate per day [m/day];
- Vexc is volume of excavated material per day [m^3/day];
- Aface is area of the cross-section of a roadway [m^2].

The daily excavation volume can be estimated as follows [6]:

$$V_{exc} = ICR \cdot MUT \cdot S_{day} \cdot H_{shift} [m^3/\text{day}] \quad (5)$$

Where:

- ICR is instantaneous cutting rate [m^3/h];
- MUT is machine utilization time [%];
- S_{day} is number of shifts per day [shifts/day];
- H_{shift} is shift time [hours/shift].

Estimation of Cutter (tool) consumption rate (TCR)

Beside excavation rates and stoppages, performance of roadheader is determined by tool consumption rate and costs. To precisely evaluate the cuttability of rock mass, it is necessary to predict TCRs. [5, 31]

Based on Copur et al. [7, 14]studies, a model for prediction of TCR was defined in case of excavation in a rock with UCS value < 60 MPa, with a machine (roadheader) that has transverse cutting head equipped with conic tools [5]:

$$TCR = 897 \cdot RCI^2 + 6.18 \cdot RCI [\text{tools/m}^3]$$

$$RCI = \frac{UCS}{P_{inst} \cdot W \cdot CHD} [\frac{\text{MPa}}{\text{kW} \cdot \text{t} \cdot \text{m}}] \quad (6)$$

Where:

- TCR is tool consumption rate for excavation of unit volume of rock [tools/m^3];
- RCI is roadheader tool consumption index [MPa/kW·t·m];
- UCS is uniaxial compressive strength of the rock [MPa];
- Pinst is installed cutterhead power [kW];
- CHD is cutterhead diameter [m].

RESULTS AND DISCUSSION

Roadheader selection

Analysis of conditions for drifting in Serbian underground coal mines shows that the selected machine must be applicable in following conditions:

- cross-section areas from 10 to 22 m^2 and up to 18° inclination;
- rock strength (UCS) up to 60 MPa;
- machine's pressure to the ground up to 0.15 MPa.

Preliminary machine selection was performed using diagram in Figure 2. For a minimal cross-section area of 10 m^2 and maximal UCS of 60 MPa, according to diagram, cutterhead power should be between 105 and 132 kW, while machine weight should be between 26 and 40 t. For further calculations, selected machine will have 132 kW of cutterhead power and weight of 26 tons.

Performance prediction

According to performance prediction model, calculations were carried out for horseshoe shaped drift with 14.8 m2 cross-section, supported by steel arches with 0.8 m spacing in coal and 0.6 m spacing in footwall. Calculation results are shown in Table 2. Daily rates are defined for ICR by Thuro and Plinninger [26].

Table 2. Results of calculations of roadheader performance

No.	Coal Mine	UCS [MPa]	BTS [MPa]	Calculated instantaneous cutting rate [m^3/h]*	Calculated instantaneous cutting rate [m^3/h]**	Daily rate [m/day]	Pick (bit) consumption rate [pick/ m^3]
1.	**Rembas Mine, Strmosten (Coal)**	24.88	3.22	30.94	29.74	12.06	0.150
2.	**Rembas Mine, Strmosten (Grey limestone)**	39.22	6.92	21.69	23.23	9.41	0.317

3.	**Rembas Mine, Strmosten (Red limestone)**	14.60	0.76	46.89	37.36	15.14	0.066
4.	**Soko Mine (Coal)**	21.4	1.71	32.43	31.89	12.93	0.118
5.	**Soko Mine (Shale)**	28.43	3.12	27.89	27.83	11.28	0.186
6.	**Štavalj Mine, West field (Coal)**	25.6	2.12	30.26	29.33	11.89	0.157
7.	**Štavalj Mine, West field (Marl)**	20.72	2.46	35.69	32.35	13.11	0.112

*Gehring [30];**Thuro and Plinninger [26]

Estimation of the ICR (Instantaneous (net) cutting rate)

Roadheader in Serbian underground coal mines would need to excavate various rock mass with UCS range from 14.60 to 39.22 and BTS from 0.76 to 6.92 a chart was made for each ICR prediction model. The variation of ICR, estimated by using the model developed by Gehring [30] is shown in Figure 3, while a chart at Figure 4 shows a prediction developed by Thuro and Plinninger [26]. Charts are showing the variation of the ICR in different geological conditions that are present in Rembas, Soko and Štavalj underground mines in Serbia and can be used by mining engineers.

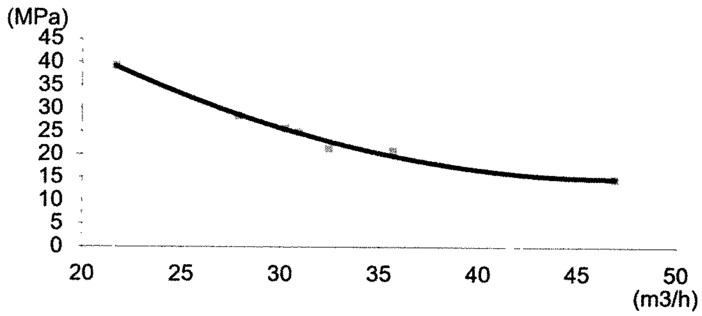

Figure 3. Relation between UCS and ICR by Gehring (1989) calculation

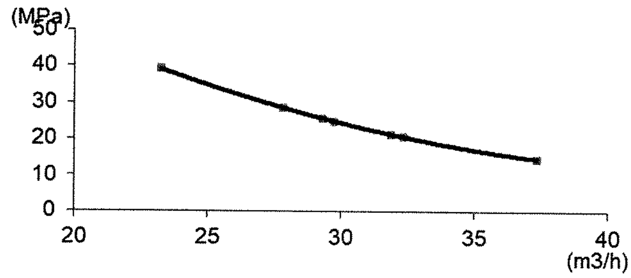

Figure 4. Relation between UCS and ICR by Thuro and Plinninger (1999) calculation

Estimation of Daily Advance Rate

Daily Advance Rate was calculated for three shifts per day and 25% of machine utilization. Results are given in Figure 5 and Table 2.

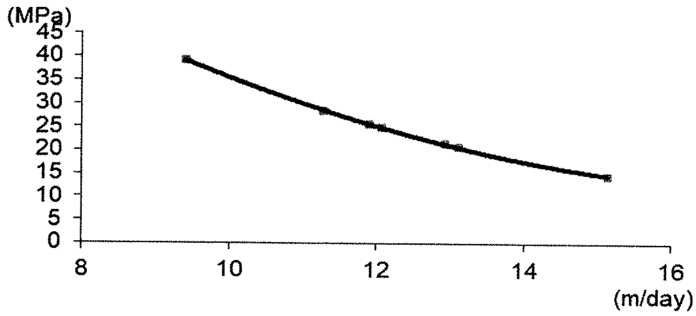

Figure 5. Relation between UCS and Daily Advance Rate

Estimation of Cutter (Tool) Cosumption Rate (TCR)

A chart in Figure 6, showing Tool Consumption Rate, is made based on data presented in Table 2.

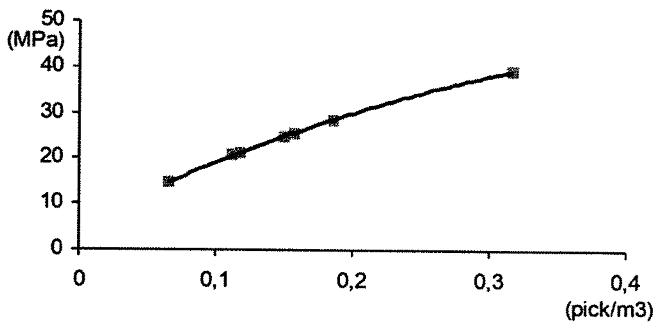

Figure 6. Relation between UCS and TCR

It is a fact that tool consumption rate in many cases is an indicator that shows applicability of mechanized excavation method [5]. In table 3. the financial effect of tool consumption rate on project and actions required are presented.

Table 3. Tool consumption rate financial effect on the project and actions required

TCR (tool/m³)	**Financial effect**	**Aplicability**
TCR>0.5	Very negative financial effect on excavation price caused by high tool consumption (tool breakages and tool wear).	Mehanized excavation usually not applicable; Other methods of excavation are preferred.
0.2< TCR>0.5	Costs of project are critical. This much TCR can be compromised.	Costs should be reviewed; Comparative cost analysis is key to determine the applicability of excavation method over other methods.
TCR>0.2	Mostly positive financial effect on excavation price.	Mechanized excavation is applicable in most cases, with no problems in excavation.

For Serbian coal mines, TCR exceeds 0.2 tools/m³ in only one occasion (Table 2), which means that, considering TCR, there would be no problem in application.

Comparison of gained results with the data provided by the manufacturers, based on experiences in coal mines, shows that gained results are within the scope of referent values [32].

Cost studies

To define financial effects of transition from drilling and blasting technology to roadheaders, their costs were compared. The analysis was performed with following input parameters: 1,000 m excavation length, 8 h shift, 3 shifts per day, 25 working days per month, 12 working months per year.

Number of workers on the coal face in case of drilling and blasting is four in a shift, with occasional engagement of foreman. In case of roadheader, seven workers in a shift are needed (foreman, excavation machine operator, three support installation staff, loco and crane operator).

Coal haulage is identical in both cases, with chain conveyors and belt conveyors. So, calculation of costs included only labor, material and energy. Costs of haulage and supplies were excluded because they are identical in both cases. Results of analysis are shown in table 4 (for drilling and blasting technology) and table 5 (for roadheaders) [33].

Table 4. Cost analysis for drilling and blasting technology

	Rembas Mine, Strmosten (C)	Rembas Mine, Strmosten (GL)	Rembas Mine, Strmosten (RL)	Soko Mine (C)	Soko Mine (S)	Štavalj Mine West field (C)	Štavalj Mine West field (M)
UCS [MPa]	24.88	39.22	14.6	21.4	28.43	25.6	20.72
Labor costs [€]	208,200	275,583	275,583	208,200	275,583	208,200	275,583
Material [€]	687,000	864,000	862,000	685,900	863,000	686,800	862,550
Equipment [€]	2,735	2,735	2,735	2,735	2,735	2,735	2,735
Energy [€]	9,000	9,800	9,700	8,900	9,750	8,950	8,920
Total [€]	906,935	1,152,118	1,150,018	905,735	1,151,068	906,685	1,149,788
Time of excavation (months)	16.7	22.2	22.2	16.7	22.2	16.7	22.2

Table 5. Cost analysis for roadheaders

	Rembas Mine, Strmosten (C)	Rembas Mine, Strmosten (GL)	Rembas Mine, Strmosten (RL)	Soko Mine (C)	Soko Mine (S)	Štavalj Mine West field (C)	Štavalj Mine West field (M)
***UCS* [MPa]**	24.88	39.22	14.6	21.4	28.43	25.6	20.72
Labor costs [€]	62,826	80,519	50,045	58,600	67,170	63,725	57,795
Material [€]	647,000	844,000	798,000	645,800	829,100	647,250	810,700
Equipment [€]	41,791	53,560	33,290	38,980	44,680	42,390	38,450
Energy [€]	15,200	16,300	14,250	14,970	15,930	15,450	14,850
Total [€]	766,817	994,379	895,585	758,350	956,880	768,815	921,795
Time of excavation (months)	3.3	4.3	2.7	3.1	3.6	3.4	3.1

Comparison between data in these two tables shows that not only excavation time is significantly shorter, but excavation costs are also lower in case of roadheader application. Material costs hold the largest share in structure of costs, which indicates that support system should be reconsidered. Low equipment costs in drilling and blasting indicate that level of mechanization is very low, causing exceeded utilization of manpower, and consequently exceeded labor costs.

As stated above, material cost indicated that current support system in Serbian underground coal mines (steel frame support) should be reconsidered. As an alternative option, a rock bolt support system should be considered. Implementation of machines such as continuous bolter miners, can achieve both better advance rates in terms of excavation speed with parallel installation of previously designed adequate rock bolt support system, saving time in excavation process and fulfilling the stability conditions of roadways [34]. Further research should analyze the effectiveness of rock bolt support system and justify its incorporation in roadway construction process in Serbian mines.

Researchers also focus on finding the way to develop appropriate automatic control system for different type of rock excavation by roadheaders [35]. Automated excavation process would give even better excavation rates.

CONCLUSIONS

Serbian underground coal mines are struggling to provide acceptable outputs and positive financial results. To improve, technological improvements are necessary in each segment of mining. Therefore, the tunneling also needs to be improved, and one of possible ways is transition from traditional drilling and blasting technology to roadheaders.

Application of roadheaders requires careful selection of machine type and performance. That is why performance prediction is an important factor for successful roadheader application.

The prediction of instantaneous cutting rate, machine utilization time and advance rates is a very important part of tunneling technology design, as well as the economy of entire tunneling project.

After the preliminary selection, basic parameters of selected roadheader are defined based on models by Gehring and Thuro and Plinninger. Comparison of gained results with data provided by the manufacturers shows that gained results are reliable and they represent a solid base for introduction of roadheaders into Serbian underground coal mines.

Comparison of costs calculated for application of drilling and blasting and application of roadheaders, shows that roadheaders provide significantly shorter excavation times along with lower total costs. Also, cost analysis shows that support system with steel arches causes exceeded costs and some other support type should be considered.

However, application of roadheaders requires well organized and precise logistics. It means that supply of support and all the necessary material, maintenance, transport, all of that must be well organized and work properly.

Conflict of Interest: The authors declare that they have no conflict of interest.

REFERENCES

1. Andrejiová M., Grinčová A., Marasová D. and Grendel P.: Multicriterial assessment of the raw material transport Acta Montanistica Slovaca Volume 20 (2015), number 1, 2015, pp. 26-32.
2. Avunduk E., Tumac D. and Atalay AK.:Prediction of roadheader performance by artificial neural network. Tunn Undergr Space Technol, 2014, 44:3–9.
3. Bilgin N., Yazıcı S., Eskikaya S.: A model to predict the performance of roadheaders and impact hammers in tunnel drivages. In: Proceedings, Eurock '96, Balkema, 1996, pp. 715–720.
4. Bilgin N., Tuncdemir, H., Balci C., Copur H., Eskikaya S.:A model to predict the performance of tunneling machines under stressed conditions. In: Proceedings of the AITES-ITA 2000 World Tunnel Congress, Durban, Published by The South African Institute of Mining and Metallurgy, Johannesburg, Republic of South Africa, May 13–18, 2000, pp. 47–53.
5. Bilgin N., Copur H., Balci C.: Mechanical Excavation in Mining and Civil Industries by CRC Press Reference - 180 B/W Illustrations ISBN 9781466584747, 2013, 388 p.
6. Đukanović D.: Fisibility study of mechanized drifting in coal mines of JP PEU (in Serbian) Ugaljprojekt-Design Bureau, Belgrade, 2010.
7. Copur H., Ozdemir L., Rostami J.: Roadheader applications in mining and tunneling. Mining Engineering 50 (3), 1998, pp.38–42.
8. Konečný P., Lednická M., Souček K., Staš L:, Kubina L. and Gribovszki K.: Determination of dynamic Young's modulus of vulnerable speleothems, Acta Montanistica Slovaca Volume 20 (2015), number 2, 2015, pp. 156-163.
9. Kasap Y-, Beyhan S. and Karataş U:E:The effects of breakdown and delay times on TBM progress efficiency Acta Montanistica Slovaca Ročník 18 (2013), číslo 4, 2013, pp. 207-216.
10. Mahdevari S., Torabi S.R., Monjezi M.:Application of artificial intelligence algorithms in predicting tunnel convergence to avoid TBM jamming phenomenon International Journal of Rock Mechanics and Mining Sciences, 55 (2012), 2012, pp. 33-44.
11. Sandbak L.A. Roadheader drift excavation and geomechanical rock classification at San Manuel, Arizona, Proceedings of the Rapid Excavation and Tunnelling Conference. New York, 1985, pp. 902-916.
12. Copur, H., Rostami, J., Ozdemir, L., Bilgin, N.: Studies on performance prediction of roadheaders. In: Proceedings of the 4th International Symposium on Mine Mechanization and Automation, Brisbane, Qld., Australia, 1997, pp. A4-1–A4-7.
13. Ebrahimabadi A., Azimipour M., Bahreini A.: Prediction of roadheaders' performance using artificial neural network approaches (MLP and KOSFM), Journal of Rock Mechanics and Geotechnical Engineering, Volume 7, Issue 5, 2015, pp. 573-583, ISSN 1674-7755, https://doi.org/10.1016/j.jrmge.2015.06.008.
14. Comakli R., Kahraman S, Balci C.2014: Performance prediction of roadheaders in metallic ore excavation. Tunn Undergr Sp Tech, 2014, pp. 40:38–45.

15. Ebrahimabadi A., Goshtasbi K., Shahriar K., M. Cherghi Seifabad: A model to predict the performance of roadheaders based on rock mass brittleness index, Journal of the South African Institute of Mining and Metallurgy, 111 (5), 2011, pp. 355-364.

16. Ebrahimabadi A., Goshtasbi K., Shahriar K., M. Cherghi Seifabad: A universal model to predict roadheaders' cutting performance, Archives of Mining Sciences, 57 (4), 2012, pp. 1015-1026

17. Enayatollahi I, Bazzazi AA, Asadil A.:Comparison between neural networks and multiple regression analysis to predict rock fragmentation in open-pit mines. Rock Mech Rock Eng 47(2), 2013, pp.799–807

18. Kržanović D, Kolonja B. and Stevanović D.: Maximizing the net present value by applying an optimal cut-off grade for long-term planning of the copper open pits Acta Montanistica Slovaca Volume 20 (2015), number 1, 2015, pp.49-61.

19. Grima M.A., Babuska R.:Fuzzy model for the prediction of unconfined compressive strength of rock samples. International Journal of Rock Mechanics and Mining Sciences, 36 (3), 1999, pp. 339-349.

20. Kahraman E. Kahraman S.:The performance prediction of roadheaders from easy testing methods, Bulletin of Engineering Geology and the Environmental, 75 (4), 2016, pp. 1585-1596

21. Ocak I, Bilgin N.:Comparative studies on the performance of a roadheader, impact hammer and drilling and blasting method in the excavation of metro station tunnels in Istanbul. Tunn Undergr Sp Tech 25, 2010, pp.181–187.

22. Ocak I, Seker SE.:Calculation of surface settlements caused by EPBM tunneling using artificial neural network, SVM, and Gaussian processes. Environ Earth Sci 70(3), 2013, pp. 1263–1276.

23. Salsani A., Daneshian J., Shariati S., Yazdani-Chamzini A., Taheri M.: Predicting roadheader performance by using artificial neural network, Neural Computing and Applications, 24 (7–8), 2014, pp. 1823-1831.

24. Sonmez H, Gokceoglu C, Kayabas A, Nefeslioglu HA.: Estimation of rock modulus: for intact rocks with an artificial neural network and for rock masses with a new empirical equation. Int J Rock Mech Min Sci 43(2), 2006, 224–235.

25. Straka M., Bindzár P. and Kaduková A.: Utilization of the multicriteria decision-making methods for the needs of mining industry, Acta Montanistica Slovaca Ročník 19, číslo 4, 2014, 199-206.

26. Thuro, K., and Plinninger, R.J.:Predicting roadheader advance rates. Tunnels and Tunnelling.31,1999.

27. B. Tiryaki B.,Application of artificial neural networks for predicting the cuttability of rocks by drag tools, Tunnelling and Underground Space Technology, 23 (3), 2008, pp. 273-280

28. Tiryaki B., Dikmen AC.: Effects of rock properties on specific cutting energy in linear cutting of sandstones by picks. Rock Mech Rock Eng 39(2), 2006, 89–120.

29. Xu J., Xu Y.: Grey correlation-hierarchical analysis for metro-caused settlement. Environ Earth Sci 64(5), 2011, 1246–1256
30. Gehring K.H.: A cutting comparison. Tunnels and Tunnelling (November), 1989, pp.27-30.
31. Fowell, R.J., Speight, N.E.: The influences of operational parameters of roadheader productivity and efficiency with particular reference to cutting pick wear, Mech E,C 357,1984.
32. Restner U.: Sandvik Mining and Construction G.m.b.H.,Geotechnical Consulting& Engineering, 2007.
33. Đukanović D., Denić M., Dragojević D.: Effect of the form of an underground opening and types of support machine utilization for construction of underground spaces in the coal mines, Underground Mining Engineering 18, RGF, 2011, Beograd.
34. Xie Z., Zhang N., Qian, D., Han, C.,An, Y.,Wang Y.:Rapid Excavation and Stability Control of Deep Roadways for an Underground Coal Mine with High Production in Inner Mongolia. *Sustainability* 2018, 10, 1160. https://doi.org/10.3390/su10041160
35. Cheluszka P. Optimization of the Cutting Process Parameters to Ensure High Efficiency of Drilling Tunnels and Use the Technical Potential of the Boom-Type Roadheader. (2020) Energies 2020, 13, 6597. https://doi.org/10.3390/en13246597