Mathematical Simulation of Electrotechnology Characteristics of Mining Complexes

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Abstract. The article presents the results of the research and analysis of the efficiency of power consumption at tunneling sections in coal mines. The authors established distribution laws for the shift averages of technological and specific consumption of power. Further, they recommended the criteria and principles for the assessment of the power conservation level, efficiency of mine tunneling and works execution arrangement in terms of power sustainable use by shift teams. The recommendations are provided on defining sustainable levels of the shift average power consumption and rationalizing manufacturing standard indices.

1. Introduction
Aspects of modeling technological processes in the mining industry are of great importance. Many problems are solved by simulating technological processes, machines and installations. These tasks are related to the definition of technical conditions of facilities, operational efficiency, operating modes, reliability parameters, risk management, etc. [1-7].

The efficiency of the mining industry operation is defined by a technical level of the mechanization means and automation of industrial mineral extraction processes. The key requirements set to mining equipment are: increasing operation efficiency and safety, reduction of specific content of metal intensity of mining machines and energy intensity of rock mass destruction, decreasing the environmental damage from mining works.

The concentration of mining practices at prospective mines by means of technical re-equipment of face and tunneling complexes requires significant changes in the process of preparation and mining works. First and foremost it refers to a progressive combine method as the level of combine driving along the leading coal mines varies from 72 to 98% [8-11].

The process of solving the tasks connected to increasing energy efficiency of mining works is conducted in compliance with a regulatory legislative framework defining a set of requirements, conditions and technical regulations for their conduct with the account of the impact on the social and environmental spheres.

The analysis of technical characteristics of series-produced tunneling machines and complexes at the global market showed that key directions related to the increasing energy efficiency of mining works are oriented towards the growth of power-weight ratio and performance of mining equipment. This development is provided by means of transition to the medium- and (35 – 50 t, 100 – 160 kW) and high-duty combines (up to 100 – 150 tons, to 600 – 900 kW) stipulating for mine tunneling with the section up to 40 – 45 m², rock destruction with the uniaxial compressive strength up to 140 – 150 MPa and technical performance up to 26 – 30 m³/h. [12-14].
2. Purpose and objectives of scientific research

Currently, there are several areas of scientific research in the field of energy efficiency improvement of energy-technological complexes of coal mines. Current issues of ensuring the reliability and efficiency of mining operations at modern coal mines are discussed in scientific articles [9, 10, 12, 14]. The results of research in the field of geophysical processes that have a significant impact on the efficiency of mining operations are presented in scientific articles [15-19]. Articles are devoted to the most important direction in the field of creating and improving energy management, developing a strategy for improving the energy efficiency of mining processes [20 – 22]. In the field of modelling energy consumption and creating energy-efficient technologies, it is worth noting the scientific research, the results of which are given in articles [23 – 28].

The analysis of the presented research has shown that when solving the issues of improving the energy efficiency of mining operations in coal mines, a methodological approach is required that allows performing the most objective comprehensive assessment of modern technologies, taking into account organizational and technical and technological factors.

The authors of the presented scientific article carried out research in the field of energy efficiency of mining operations in coal mines, the results of which are given in articles [11-13].

The purpose of scientific research is establishing and justifying the criteria of the assessment of energy efficiency of mining works at coal mines on the basis of the results and analysis of power consumption modes.

To reach the set purpose, the authors set the objective to establish the distribution laws for the indices characterizing the energy efficiency of tunnelling sections on the basis of the data of power and the scope of conducted tunnelling works.

3. Methodology and main methodological principles of scientific research

The methodology for studying the energy efficiency of mining operations is based on the integrated use of methods for collecting, processing and analyzing data from energy technology flows, which allow us to solve this scientific problem.

To create a database on energy technology flows, a Software-analytical complex for energy resources management was used [20]. Modeling of power consumption modes of tunnelling complexes in coal mines was performed in accordance with the methodology developed by the authors [11]. Processing and analysis of the results of the study was carried out in accordance with the methods given in [12, 21, 28]. Microsoft Excel and Statistic Neural Networks were used as licensed software for processing the energy consumption database.

As the research object of the paper the authors selected 6 tunnelling sections at the mine “Severnaya”. The mining works at the mine “Severnaya” are conducted by tunnelling combines MB670, JOYR75, 12CM30 and KP-21.

The reference data are shift performance indices and energy efficiency of the tunnelling section in the period from November 2016 to October 2017. The reference data are shift performance indices and energy efficiency of the tunnelling section in the period from November 2018 to October 2019.

4. Theory of building practical models of power consumption at tunnelling sections

The preliminary analysis demonstrated the following. The difference on the compound annual power consumption between the shifts ΔW for each of sections varies from 133 to 5,127 kWh (ΔW% = 0.91 – 4.1). For the sections with a higher power-weight ratio this indicator is higher both in absolute terms and in relative terms (between the shifts in the section territory).

An annual consumption of power for mining works comprise an insignificant part in mine electrical consumption (not more than 10-12%) and does not have any significant impact on aggregate indices of the company’s power consumption. However, at the analysis of the mining works efficiency in view of the efficient use of power by shift teams, the indicator ΔW (ΔW %) related to the average shift power consumption at the section can be one of the assessment criteria of the energy saving level.
The difference on a total rock combined mass extracted from a mine between the shifts ΔQt for each section fluctuates from 87 to 2,301 tons (ΔQt % = 1.1 – 4.41). Absolute and relative indices on the total annual rock mass both for the sections and for the shifts in the sections virtually do not depend on their power-to-weight ratio.

This fact demonstrates that at tunnelling the mines with a constant section the volumes of the extracted rock depend on its geological indices, technical characteristics of tunnelling machines and the quality of drilling and blasting operations. At the assessment of the mining works efficiency in view of the efficient use of power by shift teams, the indicator ΔQ (ΔQ %) related to the running meters passed for a shift can be one of the criteria of mine tunnelling quality.

The difference on the annual indices of the lengths of mine tunnelling between the shifts ΔQt for each section fluctuates from 13.9 to 84.2 tons (ΔQt % = 1.35 – 7.07). Absolute and relative indices of tunnelling both for the sections and for the shifts in the sections virtually do not depend on their power-to-weight ratio. At the re-calculation of annual indices ΔQpm in relation to the value of shift average tunnelling for each section the difference in terms of the taken time between the shift teams is equal to 4 - 35 shifts (24-210 hours per year).

This fact shows that at mine tunnelling the tunnelling quality index Qpm depends not only on mining, geological and technological factors but also on a correct arrangement of the team work during the shift. At the assessment of the mining works efficiency in view of the efficient (economical) use of power by shift teams, the indicator ΔQpm (ΔQpm %) related to the average shift performance at the section can be one of the efficiency criteria of mine tunnelling. In compliance with the method of analytical research the authors conducted the analysis of performance and power consumption modes at tunnelling sections of the mine «Severnaya» [13,15].

At the first step the authors define shift average (see Table 1) performance indices for the sections in terms of the extracted rock mass Q1 (tons), passed mine running meters Q2 (rm) as well as on the shift consumption of power W (kWh) and its specific consumption ω1 (kW∙h/tons) and ω2 (kW∙h/rm).

| Indicator | Dimensions | No.1. | No.5. | No.6. | No.8. | No.9 | No.10. |
|-----------|------------|------|------|------|------|------|-------|
| Q1        | tons       | 45.94| 76.24| 19.57| 87.31| 173.28| 45.02 |
| Q2        | running meter | 1.99 | 3.45 | 2.02 | 3.53 | 8.47 | 2.03 |
| W         | kWh        | 109.6| 182.1| 49.35| 207.6| 415.4| 107.6 |
| ω1        | kWh/tons   | 2.41 | 2.47 | 2.57 | 2.49 | 2.5  | 2.47  |
| ω2        | kWh/rm     | 59.95| 56.5 | 26.8 | 62.6 | 51.92| 57.87 |

Similar indices were also defined for tunnelling sections in compliance with work shifts. The range of change of the specific power consumption in relation to rock mass at the sections is equal to ω1 = 2.4 – 2.57 kW∙h/tons (Δε = 6.6%) , in relation to tunnelling ω2 = 51.9 – 65.8 kW∙h/tons (Δε = 21%). Such spread of values can be explained by the fact the direct extraction of rock mass within the industrial process is conditioned by its volume, rock density, degree of shattering and the bucket or feeding table of the mucking machine packing.

However, one should note that the power consumption has its characteristic dynamics for various time intervals (days, weeks, months). The characteristic graph of power consumption by the example of the tunnelling section No. 6 is presented in Figure 1.

In the process of conducting the power consumption analysis at tunnelling sections the authors established distribution laws to which average shift performance indices of tunnelling sections are subject, their stable levels and ranges of permitted deviations are defined. This allowed rationalized performance standards for tunnelling sections and assess the potential of increasing the mining works efficiency.
For the research 4 tunnelling sections were selected. At these sections the tunnelling was conducted for the mines with various sections equipped with various tunnelling complexes.

As a result of statistical analysis the key indices for tunnelling sections were defined: М – average value (mathematical expectation), σ – standard deviation, Me – median line and others. To check for the compliance with a normal distribution law the following values were defined: А – asymmetry, Е – excess, kR – oscillation ratio, kD – relative linear deviation ratio, ν – variation ratio.

**Figure 1.** Combined graph of the technological W(t) and specific ω(t) consumption of power at the tunnelling section No. 6.

5. Discussion of results
The results of the analysis can be formalized in the following conclusions:

- for the presented indices quite a vast variation range is characterized in relation to the average value. Its characterizing oscillation ratio changes within the range $k_R = 30\%–170\%$. The greatest variation range in relation to the mean square value is characteristic for the indices of the specific power indices $\omega_1$ (kWh/tons), $\omega_2$ (kWh/rm) and performance $Q_2$ (rm).
- The difference between average and median values of performance indices virtually coincides: relative error $\Delta \varepsilon = +0.01\%$, for the technological power consumption $\Delta \varepsilon = +2.6\%$. However, for the specific power consumption the relative error is $\Delta \varepsilon = -9\%$. The latter demonstrates the necessity to establish the reasons of such inconsistency.
- ratios of skewness, excess and variation point to the compliance with performance indices and technological consumption of power to the normal law distribution by means of the symmetry of average values and homogeneity of total values. At this a low excess ratio can characterize such distributions as homogeneous.
- The indices of specific power consumption are characterized by a positive skewness and small excess which, with the account of the sampling, is characteristic for the exponential distribution law. Establishing the distribution laws of shift averages was conducted for 4 tunnelling sections. Characteristic histograms and the functions density $f(\omega)$ and $f(W)$ are provided in Figures 2. The
statistical analysis demonstrated that the nature of changes of specific power consumption are subject to a normal distribution law.

The hypothesis on the normal function of \( f(\omega) \) and \( f(W) \) distribution is confirmed in compliance with the Pearson and Kolmogorov fitting criteria.

The distribution of frequencies \( f(W) \) is characterized by a symmetry in relation to \( \bar{W} \), i.e., its average value \( M \) virtually coincides with a medial \( M_e \). With the account of the mean square deviation the power consumption level of the tunnelling section is defined in the range \( W \pm \sigma \).

Establishing the distribution laws of shift averages was conducted for 4 tunnelling sections.

![Figure 2. a - Histogram of density function \( f(W) = 0.045e^{-(W-26.8)^2/156.6} \); b - Histogram of density function \( f(W) = 0.06e^{-(W-49.35)^2/86.85} \).](image)

Therefore, a sustainable power consumption level (main trend) can be set by the value \( \bar{W} \). The distribution of frequencies \( f(W) \) is characterized by a symmetry in relation to \( \bar{\omega} \), i.e., its average value \( M \) does not coincide with a medial \( M_e \). At this the median line in relation to the average value is directed towards lower values. Therefore, a sustainable level of the specific power consumption (main trend) can be set by the value \( M_e \).

6. Conclusion
1. At the analysis of the mining works efficiency in view of the efficient use of power by shift teams, the indicator \( \Delta W (\Delta W \%) \) related to the average shift power consumption at the section \( \bar{W}_{cm} \) can be one of the assessment criteria of the energy saving level.
2. At the assessment of the mining works efficiency in view of the efficient (economical) use of power by shift teams, the indicator \( \Delta Q_{pm} (\Delta Q_{pm} \%) \) related to the average shift performance at the section \( \bar{Q}_{pm} \) can be one of the efficiency criteria of mine tunnelling.
3. At the assessment of the mining works efficiency in view of the efficient use of power by shift teams, the indicator \( \Delta Q_t (\Delta Q, \%) \) related to the running meters passed for a shift \( \bar{Q}_{tm} \) can be one of the criteria of mine tunnelling quality.
4. General energy efficiency assessment should be defined by the level of actual energy capacity comparing with the target indices.
5. The developed models have been tested on real mining facilities. The methodological support was successfully used in the educational programs for the training of mining engineers of electrical engineering specialization [29-30].
References

[1] Sturgul J R 2001 Modeling and Simulation in Mining - Its Time Has Finally Arrived *Simulation* **76** (5) pp 286-288 doi: 10.1177/003754970107600509

[2] Goncharenko S N, Duong L B, Petrov M V and Stoyanova I A 2014 Modeling of parameters of innovation water-protection measures on the basis of industrial-technological indices of coal mining at Vietnam enterprises *Gornyi Zhurnal* **9** pp 143-146

[3] Kulikova E Y 2018 Estimation of factors of aggressive influence and corrosion wear of underground structures *Materials Science Forum* vol. **931** MSF pp 385-390 doi: 10.4028/www.scientific.net/MSF.931.385

[4] Busygin A M 2020 Cabled Feeder for Underground Drilling Machines *Lecture Notes in technical Engineering* pp 231-237 doi: 10.1007/978-3-030-22041-9_27

[5] Busygin A M 2018 The force analysis of the caterpillar excavator stick arrangement mechanism with three degrees of freedom 2018 *Mining Informational and Analytical Bulletin*, 2018 **1** pp 133-142 doi: 10.25018/0236-1493-2018-1-0-133-142

[6] Kulikova E Y 2019 Assessment of operating environment of concrete lining of sewage collector tunnels *IOP Conference Series: Materials Science and Engineering* **687** (4) doi: 10.1088/1757-899X/687/4/044035

[7] Kulikova E Y Shornikov I I 2020 Method of Estimation of Pressure Forces from Power Plant in Microtunneling *Lecture Notes in Mechanical Engineering* pp 783-789 doi: 10.1007/978-3-030-22041-9_84

[8] Shkрабets F 2017 Electric supply of underground consumers of deep energy-intensive mines *Gornye nauki i tekhnomologii = Mining Science and Technology* **3** pp 25-42 https://doi.org/10.17073/2500-0632-2017-3-25-42

[9] Shpiganovich A N, Shpiganovich A A, Zatsepina V and Zatsepin E 2017 State of the issue of the power supply system's reliability *Gornye nauki i tehnologii = Mining Science and Technology* **3** https://doi.org/10.17073/2500-0632-2017-3-47-73

[10] Petrov V, Sadridinov A and Pichuev A 2020 Analysis and Modeling of Power Consumption Modes of Tunnelling Complexes in Coal Mines *EES Web of Conferences* **174** doi: 10.1051/e3sconf/202017401006

[11] Pichuev A 2017 Saarbrücken, Germany. Energy efficiency of mining works *LAP LAMBERT Academic Publishing* 115 p

[12] Sadridinov A and Pichuyev A 2013 Energy characteristics of tunneling combines with executive bodies of selective action. *Mining information and analytical bulletin (scientific and technical journal)* **N** **9** pp 348 – 350.

[13] Lu S 2012 Coal mining industrial robots the institutions of the modeling and simulation *Advanced Materials Research* **482-484** pp 1490-94 DOI: 10.4028/www.scientific.net/AMR.482-484.149

[14] Borisenko V F, Zemlyansky A I, Sidorov V A and Sidorova E V Diagnostics of Thermal Condition of Electromechanical Machinery *Gornye nauki i tehnologii = Mining Science and Technology (Russia)* 2019 **4** (3) pp 188-201 https://doi.org/10.17073/2500-0632-2019-3-188-201

[15] Dias D and Kastner R 2013 Movements caused by the excavation of tunnels using face pressurized shields *Analysis of monitoring and numerical modeling results Engineering Geology* **152** (1) pp 17-25 doi: 10.1016/j.enggeo.2012.10.002

[16] Zhang T, Neil Taylor R, Zheng G, Sun J, Fan Q, Diao Y and Zhou H 2018 Modelling ground movements near a pressurised tunnel heading in drained granular soil *Computers and Geotechnics* **104** pp 152-166 doi: 10.1016/j.compgeo.2018.08.015

[17] Antsiferov N S Ways to Reduce Power Losses in Mining Power Supply Lines *Gornye nauki i tehnologii = Mining Science and Technology* 2019 **4** (2) pp 150-156 https://doi.org/10.17073/2500-0632-2019-2-150-156

[18] Beglyakov V, Aksenov V, Kostinets I and Khoreshok A 2017 Determining the forces of
interaction of main geokhods systems with geo-environment and with each other Gornye nauki i tehnologii = Mining Science and Technology(Russia) (3) pp 3-10
https://doi.org/10.17073/2500-0632-2017-3-3-8
[19] Lyakhomskiy A,Perfilieva E, Kychkin A and Genrikh N 2015 A software-hardware system of remote monitoring and analysis of the energy data Russian Electrical Engineering V 86 № 6 pp 314-319.
[20] Lyakhomskiy A,Perfilieva E, Petrochenkov A and Bochkarev 2015 Conceptual design and engineering strategies to increase energy efficiency at enterprises research, technologies and personnel. Forum Strategic Partnership of Universities and Enterprises of Hi-Tech Branches (Science. Education. Innovation 2015 4th) pp 44-47
[21] Fashilenko V and Reshetnyak S 2015 Improving the energy performance of industrial enterprises. Miner's week – 2015. Reports of the XXIII international scientific pp 570-573
[22] Verl A, Abele E, Heisel U, Dietmair A, Eberspächer P, Rahäuser R, Schrems S and Braun S 2011 Modular modeling of energy consumption for monitoring and control Glocalized Solutions for Sustainability in Manufacturing Proceedings of the 18th CIRP International Conference on Life Cycle Engineering pp 341-342 doi: 10.1007/978-3-642-19692-8-59
[23] Draganescu F, Gheorghe M and Doicin C 2003 Models of machine tool efficiency and specific consumed energy Journal of Materials Processing Technology 141 (1) pp 9-15 doi: 10.1016/S0924-0136(02)00930-5
[24] Zakharova A 2017 Bottom-up approach to modeling power use in a coal mine. Gornyi Zhurnal 2 pp 79-82 doi: 10.17580/gzh.2017.02.15
[25] Kuznetsov N and Morozov I 2016 Modeling of power consumption of ball mill. Gornye nauki i tehnologii = Mining science and technology https://doi.org/10.17073/2500-0632-2016-4-50-58
[26] Bevilacqua M, Ciarapica F, Diamantini C and Potena D 2017 Big data analytics methodologies applied at energy management in industrial sector: A case study International Journal of RF Technologies: Research and Applications 8 (3) pp 105-122 doi: 10.3233/RFT-171671
[27] Babokin G, Shprekher D and Kolesnikov E 2017 Parameter control and forecast for electric drive parameters of cutter-loader International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM) IEEE Conference Publications doi: 10.1109/ICIEAM.2017.8076303 pp 1-4
[28] Shprekher D M, Babokin G I and Zelenkov A V 2020 Development of adaptive load regulator for shearer electric drive, providing maximum response time of control system Journal of Theoretical and Applied Information Technology 98 (17) pp 3544-3554
[29] Petrov V L 2016 Federal training and guideline association on applied geology, mining, oil and gas production and geodesy-A new stage of government, academic community and industry cooperation Gornyi Zhurnal 9 pp 115-119 DOI: 10.17580/gzh.2016.09.23
[30] Petrov V L Training of mineral dressing engineers at Russian Universities 2017 Tsvetnye Metally 7 pp 14-19 doi: 10.17580/tsm.2017.07.02