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Multi-criteria optimization of roller selection for mining belt conveyors

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Abstract:

The decision on the selection of rollers is often based on the results of tests conducted in accordance with the requirements of the standard. In order for the sample, the number of which depends on the size of the roller batch, to be compliant with the standard, it must pass all the tests included therein. Whether or not a roller sample meets the standard requirements often determines whether the entire batch is accepted or returned by the ordering party. The paper presents the experience gained during the performance of a series of tests of new roller samples conducted in accordance with the standard requirements. A comparative analysis of the test results with the standard requirements showed that the rejection of a roller sample was often determined by a parameter that slightly exceeded the tolerance and had little practical significance, while at the same time the overall quality of this roller sample was high. On this basis, it was found that the weight of individual parameters is not equal, especially in the aspect of the planned place of use, and consequently the operating conditions of the rollers. The authors proposed the use of the APEKS multi-criteria decision-making method, which allows, with established weights of standard parameters and other parameters determining the suitability of a given idler variant for the expected operating conditions, to select the best variant in the light of the adopted criteria.

Keywords: multi-criteria selection method, belt conveyor, carrying rollers, idlers, underground mining

1. Introduction

The problem of rollers selection is particularly important in the raw materials industry, where belt conveyor systems handle the majority of mined material and are a significant component of production costs. The issues of research and diagnostics as well as the development of new designs and materials of rollers are the subject of interest of many research centers around the world [1-5].

Rollers are one of the most numerous components of the conveyor - there may be more than 3,000 rollers per kilometer of the conveyor length. Despite the simple structure and relatively low unit price, rollers are an important element of belt conveyor operating costs [6-9]. This problem is particularly visible in underground mining, where belt conveyors are an important means of transporting mined material. Mining transportation systems may consist of a large number of belt conveyors and operate under hard environmental conditions. At the same time, high availability and reliability is required. It means that proper selection of rollers for operating conditions can increase durability and reduce costs.

The selection of rollers for a belt conveyor is influenced by a significant number of factors that the designer should take into account. These factors are structural, operational, and others. Structural factors are related to the design of the roller, the semi-finished and the catalog parts used. These factors, combined with the accuracy of machining and assembly, determine the final quality of the roller. The operational factors are mainly dependent on the environmental conditions and some technical and operational parameters of the conveyor. Other factors include those related to price, warranty conditions, and additional features of the roller. Table 1 lists the factors important in the process of selecting idlers for a belt conveyor.

Table 1. Groups of factors that influence the selection of rollers

Structural Factors	Operational Factors	Other Factors
length	belt speed	unit cost
roller diameter	load	lot size
bearing quality	lump size	warranty period
bearing clearance	humidity and water	corrosion protection
type of sealing	dust and dirt	noise emission
radial run-out	operating time	
roller unbalance	human factor	
rotational resistance	temperature	

The roller selection procedure according to the CEMA standard takes into account the following conditions [10]:

- type of material handled,
- idler load,
- effect of load on the predicted bearing L10 life,
- belt speed,
- roller diameter,
- environmental, maintenance, and other special conditions.

It is generally believed that the bearing life is an indicator of roller life. The commonly used and accepted bearing life calculation and rating is the L10 bearing life. L10 for belt conveyors is defined as the basic rated life (number of operating hours at 500 rpm) based on a 90% statistical model which is expressed as the total number of revolutions, 90% of the bearings in an apparently identical group of bearings subjected to identical operating conditions, that will attain or exceed before a defined area of material fatigue occurs on one of its rings or rolling elements. The L10 life is also associated with a 90% reliability for a single bearing under a certain load. However, it must be recognized that the effect of other factors may be more important in determining roller life than bearings [10].

As mentioned above, the service life of the roller is determined by the service life of the bearing. But the bearing service life depends on the design features and operating conditions of the roller, as shown in Table 1. Properly selected roller by the constructor should ensure the assumed L10 lifetime. It will be fulfilled if bearings are well protected against water and dust, raised temperature, overload or impacts [11, 12]. Therefore, the L10 life is determined by the structural and operational factors of the roller (Table 1).

The conveyor supplier equips it with rollers, which it purchases or, in some cases, manufactures. Currently, there are many rollers manufacturers on the market that offer countless types and designs of rollers. Regardless of the source of the roller, to check its quality, it must be tested. There are standards such as PN-M-46606 and DIN 22112, which specify what tests a roller sample of a batch of a specified number must undergo in order to be considered compliant [13, 14, 15]. This guarantees that such rollers are likely to achieve the assumed L10 durability. The user of a belt conveyor usually purchases rollers from a manufacturer whose product passes standard tests. At the same time, the user expects the lowest possible price, which is contrary to the high quality of the roller and compliance with standard requirements. The authors' experience in rollers standard testing indicates that one of crucial tests is water tightness of the labyrinth seal, which is the most common cause of rejecting rollers batch. It should be noted that even if a roller fails the standard test due to sealing only, it can still be considered a high-quality product capable of providing L10 durability, but without being exposed to water. This can be achieved by installing the roller under dry conditions or, in other words, by matching the roller characteristics with the operating conditions.

Similar results were obtained by the author in article [9], where the tested roller equipped with a typical labyrinth seal did not meet the requirements of the standard [13] regarding water tightness. Moreover, one of the results of mentioned work was that even at the stage of laboratory tests the suitability of a particular idler to certain operational conditions is possible to determine. The selection of rollers for belt conveyors based on laboratory tests carried out under operating load conditions may also provide benefits in the form of reduced energy consumption of belt transport. The authors in [16, 17] demonstrated that the conditions and methods of roller rotation resistance tests appropriately selected allow the selection of an energy-efficient solution.

2. Roller's selection criteria in terms of operational conditions

The multi-criteria decision-making method requires defining variants and evaluation criteria. In the case of belt conveyor rollers, the selection criteria may be technical and operational parameters defined by standards [13, 14] and others, for example, economic parameters specified by the customer. A roller variant is understood as various manufacturers, design varieties, components used, etc. The essence of the roller selection method for a mining belt conveyor proposed by the authors is to select the best variant for specific operating conditions in light of the adopted criteria. Therefore, it is crucial to correctly define the operating conditions of the rollers.

Belt conveyors in underground mines play a key role in output transport systems. They are used at every stage of extraction, from faces, through branch and main transport, and ramps to processing plants

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on the surface. This means that mining conveyors operate under extremely different operating and ambient conditions. The ambient conditions have a very large impact on the operation of machines and devices, including rollers. For the purposes of this publication, the operating conditions of the belt conveyors were determined for three different locations within a mine.

Location No. 1 in the area of the main or collective haulage, characterized by high efficiency, good conveyor route setting, and continuous operation. Rollers for location No. 1 should be characterized primarily by low rotation resistance (low energy consumption), good balance, and low radial run-out. However, parameters such as the mass of the roller or its water tightness will be negligible at this location. An example views of location 1 is shown in Figure 1.

Location No. 2 is located within the department haulage, which includes preparatory works, characterized by low efficiency, large amounts of water, periodic work, considerable distance from the shaft, and large amounts of stone in the mined material. An example view of location 2 is shown in Figure 2.

Fig. 1. Location 1 example view – main haulage [18]

Fig. 2. Location 2 example view – department haulage [19]

Location No. 3 includes a processing plant where the conveyor is built in the hall, the environment is dry, there is a lot of dust, the conveyor is short but high capacity, and there is a need to reduce noise. An example views of location 3 is shown in Figure 3.

Fig. 3. Location 3 example view – processing plant [19]

The working conditions in the locations cited correspond to the actual conditions that can be found in many underground mines, e.g. hard coal mines. The authors are aware that they do not fully describe the actual conditions but are based on the most common features of individual locations. Each mining plant is characterized by its own specific working conditions, which are most often similar to those cited above.

As mentioned in the introduction to this article, acceptance of a roller for operation involves the need to meet all the requirements contained in the standards [13, 14]. As a result of this approach, a roller intended for operation in a place not exposed to, for example, moisture must meet the condition of water tightness. On the one hand, there is nothing wrong with the roller meeting all standard requirements, but it should be known that this can significantly increase production costs. When considering the operating characteristics of the roller, it should be realized that, for example, introducing a very effective seal or excessively limiting the axial clearance can negatively affect an important parameter, i.e., the dynamic resistance to rotation of the roller. Precise machining of the roller hubs will have a positive effect on low radial run-out or balance, but will negatively affect the price of the product.

The article presents a new approach to the selection of idlers based on the developed and applied APEKS method. The APEKS method can be used as a tool to support decisions in very different areas, from the selection of a passenger car through the evaluation of design solutions [20] to the selection of technological dump trucks intended for work in open-cast mines [21]. Wherever there is a significant number of available variants and evaluation criteria, the use of this method can greatly facilitate making the best, optimal decision.

Table 2 below presents a number of criteria that influence investment costs.

Users of belt conveyors may have developed an approach to the selection of rollers based on their own experience. In such a case, it may happen that the person responsible for the selection of the rollers will base it on one dominant criterion, e.g. the price of the product. Selection will depend on a limited number of criteria based on the subjective feeling of the decision maker. Such an approach will not always be associated with the best solution for the company because rollers have many features that should be taken into account in detail during their selection.

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Table 2. List of criteria

Criterion No.	Criterion name	Unit
K1	Price	EUR
K2	Dimensions	Number of compliant
K3	Radial runout	Number of compliant
K4	Static rotational resistance	Nm
K5	Dynamic rotational resistance	N
K6	Balance	Number of compliant
K7	Water tightness	Number of compliant
K8	Dust tightness	Number of compliant
K9	Corrosion protection	Rating 1 to 3
K10	Bearing quality	Rating 1 to 3
K11	Mass	kg
K12	Noise level	dBA

Selecting the cheapest product in the long term of operation may involve the need for several replacements, which will result in multiplying the costs. However, the selection of the most expensive roller for an unreliable conveyor is also not economically justified. Therefore, in order to take into account a larger number of criteria, a decision support method, e.g. APEKS, should be used. Taking into account the experience of experts, information from publications, and knowledge of the tender realities regarding the purchase of rollers, a number of the most important criteria were selected that should be included in the roller selection process.

The criteria in Table 2 are numbered 1 to 12. As can be seen, these are criteria characterized by different units. Different units cause problems in comparing criteria with each other. Therefore, in the rest of the article, the APEKS method is used, which reduces the adopted criteria to percentage values, determines their weights, and provides the best variant.

3. Methodology

A roller as a technical object has quality defined as a set of features and properties that characterize it under the conditions of actual use. All the features and properties of a roller determine its ability to work at a given time and under specific operating conditions. In this approach, we consider features that are unchangeable during use (roller identification data, brand, type, etc.) and properties whose values change during use, such as rotation resistance (this is determined by wear processes). Both features and properties can be qualitative (then their assessment is subjective) and quantitative (they are measurable, i.e., objective). Therefore, a roller variant is a combination of its features and properties. These features and properties are criteria (Table 2) that are used in the process of making decisions about the selection of a variant.

As mentioned above, the selection of a roller for a mining belt conveyor can be supported by the APEKS multicriteria decision-making method. A significant advantage of this method is the ability to compare the values of the criterion assessments with different units, and the result obtained is dimensionless and can be a percentage assessment of each of the variants analyzed. The roller variant with the highest assessment is selected.

The APEKS method can be divided into eight steps [22, 23]. Following the procedure, an evaluation result is obtained, which is reduced to percentage values characterizing the level of quality in relation to the ideal, fictitious APEKS variant. Table 3 shows the sequence of performing the APEKS procedure.

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Table 3. Steps of APEKS method [22]

Step number	Description of the procedure
1	List of variant W_i summary
2	List of criteria K_i summary
3	List of mixed evaluation criteria K_j
4	Determination of criteria weighting indicators w_j by forced decision method
5	Estimating the value of quantitative and qualitative assessments a_{ij}
6	Calculating relative percentage estimates C_{ij}
7	Calculation of relative percentage critical values K_{kri} for each of the variants
8	Selecting the variant with the highest relative critical value K_{kri}

In step no. 1, a list of Wi variants should be compiled. The batches of rollers tested by the authors of the publication, marked W1 to W4, were adopted as variants. These are four batches of rollers that differ in terms of manufacturer, manufacturing technology, price, and technological features and properties. Each batch consisted of six rollers.

In step no. 2, the K_i criteria were established, which are presented in Table 2. In this step, other criteria can also be established depending on their nature and importance, remembering the condition of uniqueness and unambiguity.

In step no. 3, the collected criteria should be set in the appropriate order depending on their importance in the adopted location (Table 4). At this stage, the subjective expert assessment that affects the selection of the roller ends. Table 4 presents a list of mixed criteria according to the weight for each location.

Table 4. List of mixed evaluation criteria K_j for each location

No.	Order of criteria		
	Location 1	Location 2	Location 3
1	K5	K1	K1
2	K6	K7	K10
3	K3	K8	K8
4	K1	K9	K12
5	K10	K11	K3
6	K12	K5	K5
7	K9	K2	K6
8	K4	K3	K2
9	K8	K4	K4
10	K2	K6	K9
11	K7	K12	K11
12	K11	K10	K7

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In step no. 4, the weighting factors w_j are determined for each specific location using the forced decision method. At this stage, the criteria should be assessed by comparing each of them. The more important criterion takes the value 1, the less important value 0.

For a better understanding of this stage of the method, 5 criteria are written below, the importance of which is organized, for example, in the order K2, K3, K5, K1, K4. Table 5 shows a comparison of the criteria with each other using the forced decision method. For example, let us consider criterion K3 (Table 5). We can see that criterion K3 is more important (value 1) than criterion K1, K4, K5 and less important (value 0) than criterion K2.

Table 5. Criteria weighting indicators w_j

Criteria	Forced decisions N=10					Sum of values d_j	Criteria weight value w_j
	K1	K2	K3	K4	K5		
K1		0	0	1	0	1	0,1
K2	1		1	1	1	4	0,4
K3	1	0		1	1	3	0,3
K4	0	0	0		0	0	0
K5	1	0	0	1		2	0,2

The explanation of this stage of the APEKS analysis is shown in Table 6, which shows three variants and five selected criteria from which the fictitious variant a_{Aj} was selected.

Table 6. Quantitative and qualitative assessments a_{ij}

Criteria	a_{ij}			a_{Aj}
	Variant 1	Variant 2	Variant 3	
K1	35 EUR	68 EUR	52 EUR	35 EUR
K2	1,61 N	2,59 N	3,32 N	1,61 N
K3	43	60	50	60
K4	1	3	1	3
K5	58 dBA	50 dBA	63 dBA	50 dBA

On this basis, the sum of forced decisions d_j was determined and the values of dimensionless weight indices w_j were determined:

$$w_j = \frac{d_j}{N} \tag{1}$$

$$N = \frac{n(n-1)}{2} \tag{2}$$

where:

d_j – sum of the "1" obtained by the j-th criterion in all comparisons,

N – the number of all forced decisions defined by formula (2),

n – number of criteria.

In step no. 5, the values of the quantitative and qualitative assessments a_{ij} should be estimated. Expert knowledge, technical, economic, and other data are used for this purpose. Referring to Table 2, an analysis should be performed in which the best variant a_{Aj} is selected from each adopted criterion based on its maximization or minimization (the highest or lowest value).

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Then, in step no. 6, based on the estimated values of variants a_{ij} and a_{Aj}, the relative percentage values on C_{ij} estimates for the criteria and the analysed variants are determined [23]:

$$C_{ij} = \left[\left(\frac{a_{ij}}{a_{Aj}} \right)^{\pm 1} \cdot 100 \right]^{w_{ij}} \tag{3}$$

where:

a_{ij} – evaluation value for the i-th variant according to the j-th evaluation criterion,

a_{Aj} – evaluation value for the APEKS variant according to the j-th evaluation criterion.

The exponent in equation (3) (marked ±1) is +1 for the criteria that are maximized (higher rating value is better), while the exponent is -1 for the criteria that are minimized (lower rating value is better). In the considered example (Table 2), criteria K2, K3, K6, K7, K8, K9 and K10 are maximized while criteria K1, K4, K5, K11 and K12 are minimized.

In step no. 7, the critical relative percentage values K_{kri} are determined for each of the variants [23] using the formula (4):

$$K_{kri} = \prod_{j=1}^{j=m} C_{ij} \tag{4}$$

The last step in the standard APEKS method is to select the best of the compared variants, i.e. the one with the highest value of the critical relative percentage value K_{kri}. The obtained K_{kri} value determines how a given variant reflects the best variant, which is APEKS. The closer the obtained value is to 100, the closer the given variant is to the APEKS variant. On this basis, it is also possible to conclude which criteria should be improved in a given variant to make it better.

4. Results

The result of the APEKS method is the selection of the best variant taking into account all available criteria. As shown in Table 4, depending on the adopted location, the order of criteria is different. As a result, the selection of the best variant will also be different. The tables below show the selection of the best roller for location no. 1, the features of which are described in point 2.

Based on the adopted order of criteria (Table 3), they were compared using the forced decision method. The number of forced decisions in the case under consideration is N = 66. As a result of the comparison of criteria, a matrix was created (Table 7), based on which the values of the weight indices w_j were calculated according to formula 1.

Table 7. Determining the weighting of criteria by the method of "forced decisions" for location no. 1

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12	w_j
K1		1	0	1	0	0	1	1	1	1	1	1	**0,1212**
K2	0		0	0	0	0	1	0	0	0	1	0	**0,0303**
K3	1	1		1	0	0	1	1	1	1	1	1	**0,1364**
K4	0	1	0		0	0	1	1	0	0	1	0	**0,0606**
K5	1	1	1	1		1	1	1	1	1	1	1	**0,1667**
K6	1	1	1	1	0		1	1	1	1	1	1	**0,1515**
K7	0	0	0	0	0	0		0	0	0	1	0	**0,0152**
K8	0	1	0	0	0	0	1		0	0	1	0	**0,0455**
K9	0	1	0	1	0	0	1	1		0	1	0	**0,0758**
K10	0	1	0	1	0	0	1	1	1		1	1	**0,1061**
K11	0	0	0	0	0	0	0	0	0	0		0	**0,0000**
K12	0	1	0	1	0	0	1	1	1	0	1		**0,0909**

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As is known from the APEKS method described above, the next step is to estimate the value of the quantitative and qualitative evaluations of the adopted criteria for each variant.

Table 8. Quantitative and qualitative assessment values

Variant	Estimating the value of quantitative and qualitative assessments a_{ij}											
	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12
W1	38	43	12	0,07	1,61	6	1	4	1	2	7	58
W2	48	60	17	0,15	2,59	6	4	4	3	3	9	50
W3	42	55	13	0,03	2,12	6	1	4	1	3	10	48
W4	53	60	18	0,13	2,72	6	1	4	2	3	12	45
Variant APEKS a_{Aj}												
a_{Aj}	38	60	18	0,03	1,61	6	4	4	3	3	7	45

Table 8 presents the actual values of the quantitative and qualitative assessments a_{ij} of all the adopted criteria for the considered variants. Data come from laboratory tests conducted by the authors and from the reconnaissance of the roller market and information obtained from users. The last row of the table presents the best idealized features of the idler a_{Aj}, the so-called APEKS variant.

Using formula 3, the percentage values of the C_{ij} estimates of all criteria were calculated for each variant considered. The values of the C_{ij} estimates are presented in Table 9.

Table 9. Relative percentage values C_{ij} and critical percentage values K_{kri} for location no. 1

Variant	Relative percentage estimates C_{ij}												K_{kri}
	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12	
W1	1,748	1,138	1,773	1,256	2,154	2,009	1,050	1,233	1,304	1,561	1,000	1,485	**75,0**
W2	1,701	1,150	1,859	1,199	1,990	2,009	1,072	1,233	1,417	1,630	1,000	1,505	**80,2**
W3	1,724	1,147	1,792	1,322	2,058	2,009	1,050	1,233	1,304	1,630	1,000	1,511	**80,5**
W4	1,678	1,150	1,874	1,210	1,974	2,009	1,050	1,233	1,375	1,630	1,000	1,520	**76,5**
APEKS	1,748	1,150	1,874	1,322	2,154	2,009	1,072	1,233	1,417	1,630	1,000	1,520	**100,0**

Based on the percentage values of the estimates, the relative percentage critical values K_{kri} were determined for location 1. The last row of Table 9 shows the idealized APEKS variant, i.e., a set of all the best features of the rollers from all available variants. Note that such a variant does not exist, but thanks to it, it is possible to see what can be improved in the product to achieve the best solution.

The differences in K_{kri} values for location 1 are small, but they indicate that variants 2 and 3 are a better choice, while variants 1 and 4 are slightly worse.

5. Discussion and Conclusions

The method indicates which variant of idlers is the most advantageous for a given place of operation. Of course, the final decision always belongs to the ordering party, and the result of the analysis is a sorting out of a significant number of adopted criteria.

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As shown in the previous chapter, for location 1 the APEKS analysis indicated the best variants W2 and W3 for location no. 1. For the other locations considered, the order of criteria was different (Table 3). In Figure 4 the relative percentage critical values K_{kri} for all three locations are shown.

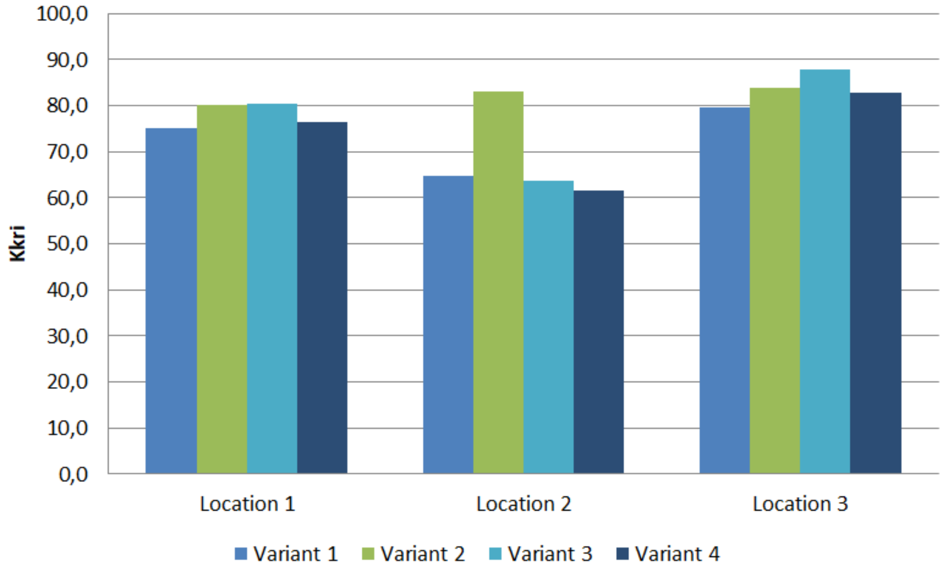

Fig. 4. Relative percentage critical values K_{kri}

Analyzing location 2, one can notice a clear dominance of variant W2. Variant W2 is characterized by a relatively high price but has very good sealing ensuring water tightness, which is crucial for location 2. For location 3, the best choice is variant W3, where the dominant features when choosing a variant are price, bearing quality, dust sealing, and noise emission level.

Due to the use of the APEKS method, the selection of rollers is no longer based on the subjective opinion of the ordering person. All available criteria are used; there may be more or less of them, depending on the knowledge and experience of the roller's users.

The results obtained show that operating conditions have a significant impact on which variant is better for a given location. Selecting rollers for a specific location can reduce investment and operating costs while increasing the durability of the rollers.

The selection of a specific roller based on the guidelines specified in the design stage of the belt conveyor should be preceded by a comparative analysis of the solutions offered on the market and the selection of the variant most suitable for the operating conditions. Using the proposed method, one can depart from the only dominant criterion (price), thanks to which one obtains a product that is adapted to real conditions. As a result, the rollers can be cheaper and better adapted to the prevailing operating conditions.

The multi-criteria method of idler selection proposed by the authors in combination with various methods of diagnosing the technical condition of rollers [24-26] may constitute an element of sustainable operation of conveyor systems in mining.

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