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APPLICATION OF QUALITY MANAGEMENT TOOLS FOR EVALUATING THE FAILURE FREQUENCY OF CUTTER-LOADER AND PLOUGH MINING SYSTEMS

WYKORZYSTANIE NARZĘDZI ZARZĄDZANIA JAKOŚCIĄ DO OCENY AWARYJNOŚCI KOMBAJNOWYCH I STRUGOWYCH KOMPLEKSÓW ŚCIANOWYCH

Failure frequency in the mining process, with a focus on the mining machine, has been presented and illustrated by the example of two coal-mines. Two mining systems have been subjected to analysis: a cutter-loader and a plough system.

In order to reduce costs generated by failures, maintenance teams should regularly make sure that the machines are used and operated in a rational and effective way. Such activities will allow downtimes to be reduced, and, in consequence, will increase the effectiveness of a mining plant. The evaluation of mining machines' failure frequency contained in this study has been based on one of the traditional quality management tools – the Pareto chart.

Keywords: failure frequency, quality management tools,, mining machine, Pareto chart

Awaryjność maszyn i urządzeń jest istotnym problemem w każdym przedsiębiorstwie. Awarie powodują przestoje w procesie produkcyjnym, a tym samym mogą przyczynić się do zmniejszenia wolumenu produkcji oraz strat finansowych i niedotrzymywania planów produkcyjnych.

Większość organizacji stara się coraz skuteczniej minimalizować przestoje spowodowane uszkodzeniami maszyn i urządzeń poprzez zmniejszenie ich awaryjności. Ważniejszym od awaryjności wskaźnikiem mającym wpływ na prawidłowe funkcjonowanie całego procesu produkcyjnego oraz biorących w nim udział maszyn i urządzeń jest dostępność środków technicznych.

W polskim górnictwie węglowym eksploatacja pokładów węglowych odbywa się systemami ścianowymi za pomocą maszyn urabiających pracujących na zasadzie skrawania. Dlatego też, jednym z istotnych obszarów działalności Kopalń jest eksploatacja maszyn/urządzeń. Działanie to powinno polegać na między innymi na kontroli racjonalnego oraz efektywnego użytkowania i obsługiwania maszyn i urządzeń w procesie eksploatacji.

Śledząc ciąg urabiania możemy stwierdzić, że jest to system szeregowy. Awaria jednego z wymienionych ogniw powoduje „wyłączenie" pozostałych elementów tego ciągu Aby obniżyć koszty generowane przez awarie, służby utrzymania ruchu powinny na bieżąco prowadzić kontrolę racjonalnego

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oraz efektywnego użytkowania i obsługiwania maszyn. Konsekwencją tych działań będzie zmniejszenie przerw w pracy, a tym samym obniżenie kosztów produkcji, czyli zwiększenie efektywności działania zakładu górniczego.

W niniejszym artykule do oceny awaryjności maszyn/urządzeń górniczych wykorzystano jedno z tradycyjnych narzędzi zarządzania jakością – diagram Pareto-Lorenza.

Diagram Pareto-Lorenza skonstruowany jest według następujących zasad:

- zbieranie danych związanych z rodzajem awarii maszyn/urządzeń górniczych,
- przyporządkowanie poszczególnych awarii do konkretnych maszyn/urządzeń górniczych,
- obliczenie skumulowanych wartości procentowych (ustalenie skumulowanych wartości procentowych dla poszczególnych wyróżnionych awarii). Dokonano tego wykorzystując następujące wzory:

$$PIE_j = \frac{100}{IE} \tag{1}$$

$$SPIE_j = PIE_j + PIE_{j-1} \tag{2}$$

$$PIA_j = \frac{100 \cdot IA_j}{\sum_{i=1}^{IE} IA_j} \tag{3}$$

$$SPIA_j = PIA_j + PIA_{j-1} \tag{4}$$

gdzie:

PIE_j – procentowa ilość elementów,
$SPIE_j$ – skumulowana procentowa ilość elementów,
IE – liczba elementów,
PIA_j – procentowa ilość awarii,
$SPIA_j$ – skumulowana procentowa ilość awarii,
IA – liczba awarii.

Diagram Pareto-Lorenza wykorzystuje się do uporządkowania i przeanalizowania wcześniej zebranych danych. Znajduje zastosowanie gdy naszym celem jest przeciwdziałanie:

1. zjawiskom negatywnym o największej częstotliwości występowania,
2. zjawiskom przysparzającym największych kosztów.

W praktyce diagram Pareto-Lorenza stosuje się do grupowania poszczególnych problemów i ich przyczyn, aby w pierwszej kolejności rozwiązać te problemy, które dla danego przedsiębiorstwa są najistotniejsze. Diagram ten, wykorzystuje prosty aparat matematyczny i statystykę matematyczną.

Na przykładzie dwu Kopalń Węgla Kamiennego, przedstawiona została awaryjność w procesie wydobywczym, ze szczególnym uwzględnieniem maszyny urabiającej. Analizie poddane zostały dwa kompleksy wydobywcze: kombajnowy oraz strugowy.

Słowa kluczowe: awaryjność, narzędzia zarządzania jakością, maszyna urabiająca, diagram Pareto-Lorenza

1. Introduction

The effectiveness of hard coal-mines depends among others on failure-free production work in the technological system of a mining plant. To achieve the goal, i.e. the mining plant's effectiveness, it is necessary to define specific rules leading to a reduction of its cost (Kandananond, 2010; Maruszewska, 2012; Kołodziej & Maruszewska, 2015). Technological development in the mining industry, the increasing complexity, efficiency and power of the applied mining machines and equipment impose enhanced requirements regarding the culture of their use. The equipment must fulfil the conditions of energy efficiency, reliability, high durability and industrial safety (Krauze & Kotwica, 2007).

Mining machines and equipment are complex technical objects which should be characterised by an adequately high level of durability and reliability over a relatively long operational time.

These features are greatly influenced by the process of designing, constructing and installation, but they are also (and perhaps mainly) dependant on failure prevention by maintaining their good technical condition.

In Polish mining industry, coal seams are exploited by means of mining cutting machines. For this reason, one of the crucial areas of a mine's activity is the operation of machines/devices (Jonak, 2002). This activity should among others involve control over the rational and effective use and operation of machines/devices (Peter, 2001; Zasadzień, 2014).

Technical systems of hard coal mines are characterised by:

- considerable scattering,
- complexity,
- limitation of the working area by the size of underground excavations.

The main task of maintenance service teams is to ensure the continuity of work of the machines/devices used (at a given moment). Such activity results in a reduction of maintenance costs, and, in consequence, reduction of production costs, i.e. the costs of the mining plant's activity. Any disturbances in this process lead to huge losses.

The main element in the coal mining process is the sequence of mining, which includes the following stages (Biały & Bobkowski, 2004a, 2004b):

- the process of mining,
- horizontal transport,
- vertical transport.

The mining line is a serial system. A failure of one of the above mentioned links „switches off" the remaining elements of the line.

2. Maintenance of the mining line

Tasks related to the maintenance of mining machines/equipment are carried out by the service teams of the mine and external companies. The external companies are usually the producers of a particular machine/device.

Each machine in a mine which is subject to maintenance and repair can be classified according to its location in the structure of repairs (Fig. 1):

– repairs/maintenance of mechanical elements,
– repairs/maintenance of electrical elements,
– repairs/maintenance of hydraulic (pneumatic) elements.

Until present, Polish hard coal mines have not developed a uniform system of mining machines maintenance, either in the process of operation or repairs. Such a system should take into account (Biały & Bobkowski, 2004b):

- observation, recording and analysis of particular activities,
- scheduling of activities,
- manner of collecting information on the machines and devices,
- procedure for establishing the scope of service works between the user and the manufacturer,
- shaping the adequate competences of employees who perform maintenance works,
- collection and processing of information on maintenance works.

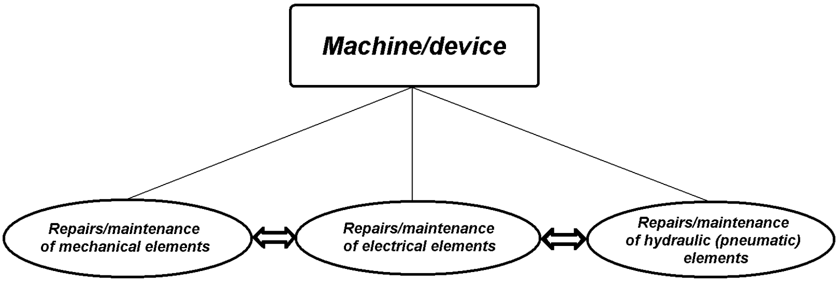

Fig. 1. Repair structure flow chart

3. Problem analysis

In the mining industry the Pareto chart can be applied to monitor and control mining machinery (mining machine, scraper conveyor, belt conveyor, crushers as well as power and control devices), which is a crucial element of the mining process. It is important to evaluate the machines' failure frequency and reliability and to establish which of the detected causes of failures should be the first to eliminate (Wolniak & Skotnicka, 2011; Zasadzień, 2014).

Constructing a Pareto chart for controlling and monitoring the mining equipment is divided into the following stages:

- collecting information (collecting data on the failure frequency of mining equipment at particular stages of the mining process),
- putting the collected data in order (assigning particular failures to particular mining machines, such as: mining machine, scraper conveyor, belt conveyor, crusher, powered support),
- computing the cumulative percentage values (establishing the cumulative percentage values for particular failures),
- preparing a Pareto chart,
- interpretation of the prepared Pareto chart.

3.1. Characteristics of the failure frequency of mining machines and devices

Depending on their location, failures occurring in hard coal mines can be divided into the following categories:

- mining failures – where the main causes include: rock mass shocks, roof collapse, water pumping, lump breaking, exceeding the level of CH_4 etc. Generally, it can be said that these failures are not caused by man,
- technical failures – occur when the machines/devices working in the production process break down – such machines include: cutter-loaders/coal ploughs, conveyors, powered supports and crushers,
- organisational failures – independent from the mining conditions and machine operation. Such failures include e.g.: lack of water supply, lack of power supply.

In terms of the type of failure, the following can be distinguished:

- mechanical,

- electrical,
- hydraulic.

For the purposes of a more thorough analysis of a failure in a particular mining machine/device, failures can be additionally divided according to the place of their occurrence, e.g.: cutter-loader's frame, arms, mining parts, traction systems, hydraulic systems, wiring (Biały & Czerwiński, 2011).

In the process of hard coal mining the mining line is a basic element influencing the volume of output, therefore, its failure frequency has been subjected to analysis. The analysis regarded the failure frequency of two mining systems applied in Polish (and global) coal mining:

1. cutter-loader system,
2. plough system.

The location of failure occurrence has been assumed to be the machine/device which ceased to work. Failure locations include:

- cutter-loader/coal plough,
- conveyor (longwall conveyor, beam stage conveyor, belt conveyor),
- crusher,
- support,
- other.

Any interruptions in work (the causes of downtime) have been systemized according to the following algorithm (Biały & Czerwiński, 2011):

- damage to the cutter-loader/plough,
- damage to the conveyors (longwall conveyor, beam stage conveyor and mined rock conveyors),
- damage to the support and lack of medium supply,
- mining failures (roof collapse, shock blasting, water pumping, lump crushing, exceeding the level of CH_4, dinting),
- other causes of downtime (damaged water hose in the longwall, lack of water, lack of voltage).

For each of the systems (cutter-loader/plough) one longwall (throughout the period of its exploitation), characterised by a similar time of work as well as similar geological and mining conditions has been analysed.

The analysis allowed distinguishing approximately 400 types of failures. Table 1 presents examples of failures which occurred in the mining machines/devices of the analysed cutter-loader system.

4. Using the Pareto chart for evaluating the failure frequency of mining machinery

The analysis of mining machinery's failure frequency has been based on the Pareto chart. The construction of the Pareto chart has been based on the following stages:

- Data regarding the type of mining machines/devices, such as: mining machine (cutter-loader/plough), conveyors (scraper conveyor, belt conveyor), powered supports has been collected,

TABLE 1

Examples of the types of failures and their causes

Type of failure	Machine	Examples of damage
Mechanical failures	Cutter-loader	Damaged cutter-loader cable
		Damaged cable layer
		Protection system exchange
		Damaged cooler of the cutter-loader lower arm
		Damaged water cable
Electrical failures	Cutter-loader	No control
		Electrical damage of the cutter-loader cable
		Burnt fuse of the hydraulic pump
Hydraulic failures	Cutter-loader	Damaged cutter-loader water hose
		Damaged sealing of the cutter-loader upper head
		Water hose exchange
Organisational failures	Cutter-loader	No water for the cutter-loader
		No power supply on the face
		No pressure on the face
Mechanical failures	Chain conveyor	No control
		Damaged coupling insert
		Seized bearing of the right gear
Electrical failures	Chain conveyor	Damaged set of chokes on the upper drive contactor
		Damaged control panel
		No control – damaged fuse
Organisational failures	Chain conveyor	No water
		No power supply
Mechanical failures	Belt conveyor	Damaged coupling
		Gear exchange
Electrical failures	Belt conveyor	No control
		Fuse exchange
		No brake control
Organisational failures	Belt conveyor	No power supply on transport equipemnt
		No power supply
Mechanical failures	Crushers	Flux exchange
		Broken ram
Electrical failures	Crushers	No control
		No power supply
Mechanical failures	Support	Exchange of hose in pressure conduit
		Damaged hose
Electrical failures	Support	No pump control
Organisational failures	Support	Pipeline sealing

- Specific failures have been assigned to particular mining machines/devices,
- Cumulative percentage values have been computed (establishing the cumulative percentage values for particular failures).

The following formulas have been used to construct the Pareto chart:

$$PIE_j = \frac{100}{IE} \tag{1}$$

$$SPIE_j = PIE_j + PIE_{j-1} \tag{2}$$

$$PIA_j = \frac{100 \cdot IA_j}{\sum_{i=1}^{IE} IA_j} \tag{3}$$

$$SPIA_j = PIA_j + PIA_{j-1} \tag{4}$$

where:

PIE_j — percentage number of elements,
$SPIE_j$ — cumulative percentage number of elements,
IE — number of elements,
PIA_j — percentage number of failures,
$SPIA_j$ — cumulative percentage number of failures,
IA_j — number (time) of failures,
j — subsequent element,
$j - 1$ — preceding element.

The Pareto chart is a tool which allows the elements influencing the examined phenomenon to be put in order. This graphic picture allows presenting both the relative and absolute distribution of errors, problems and their causes (Wolniak & Skotnicka, 2011). In practice, the Pareto chart is applied for grouping particular problems and their causes so that the major problems related to a failure can be solved in the first place.

4.1. Cutter-loader longwall system

The analysis was conducted for the longwall in which a cutter-loader was installed (the cutter-loader's working name was „AE") in one of the mines belonging to Kompania Węglowa S.A. Table 2 presents the locations where failures occurred, their number and percentage share, whereas Fig. 2 shows the Pareto chart presenting the failure frequency of the analysed cutter-loader system in a graphic form (Raporty, 2009, 2010).

TABLE 2

Mining machinery failures

Type of equipment	Cumulative percentage number of elements	Number of failures	Percentage number of failures	Cumulative percentage number of failures
	SPIE	IA	PIA	SPIA
Cutter-loader	20	6065	47	47
Conveyor	40	4920	39	86
Mining	60	725	6	91
Powered support	80	625	5	96
Other	100	500	4	100

The total number of downtimes in the work of the cutter-loader longwall system has been presented in Table 2 and in the Pareto chart (Fig. 2).

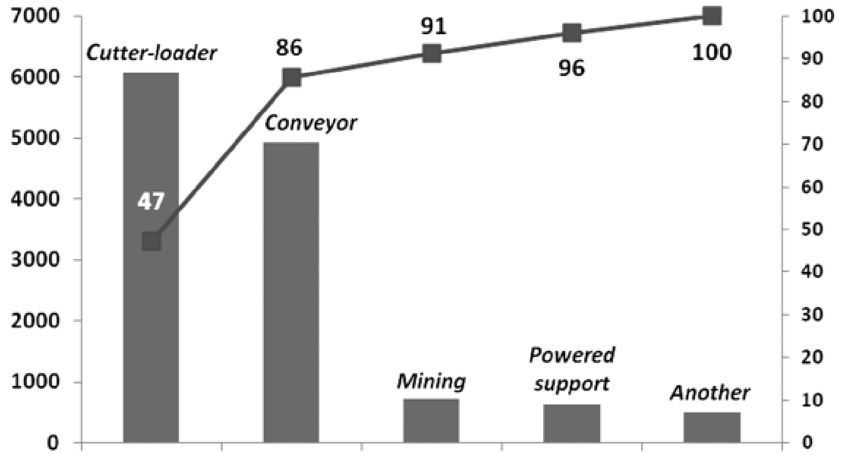

Fig. 2. Pareto chart for the longwall

From the point of view of downtime duration, the most significant were interruptions in the operation of the cutter-loader, followed by the conveyors.

4.2. Plough longwall system

The analysis of failure frequency conducted for a plough longwall system in one of the mines belonging to Jastrzębska Spółka Węglowa S.A. covered the whole period of its exploitation. The plough longwall was exploited from August 2009 to March 2010 (Raporty, 2009, 2010).

Table 3 presents data on the causes of failures, the cumulative percentage number of particular machines/devices, the duration of failures which occurred in particular elements of the mining system, the percentage number of failures and cumulative percentage number of failures (Wolniak & Skotnicka, 2011).

TABLE 3

Mining machinery failures

Type of machinery	Cumulative percentage number of elements	Number of failures	Percentage number of failures	Cumulative percentage number of failures
	SPIE	IA	PIA	SPIA
Conveyor	33.33	13204	57	57
Coal plough	66.66	8215	35	92
Powered support	100	1822	8	100

Fig. 3 presents the Pareto chart showing the failure frequency of the plough longwall subjected to analysis.

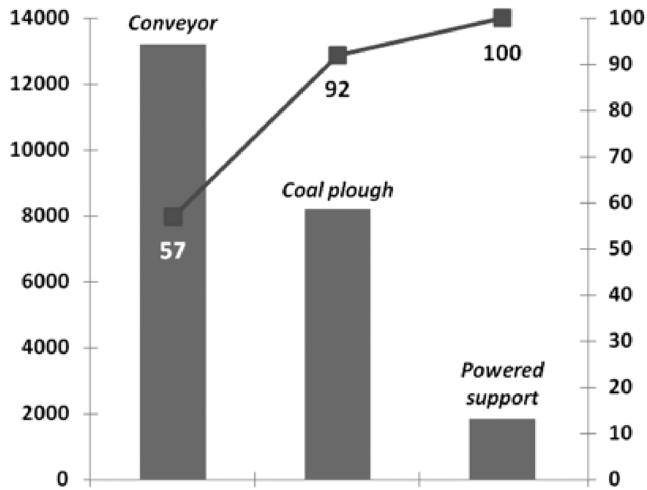

Fig. 3. Pareto chart for coal plough

5. Summary

The analysis of the cutter-loader system elements (Tab. 2, Fig, 2) indicates that the cutter-loader has proved to be the element most frequently affected by failures (47%).

On the other hand, in the case of the plough system (Tab. 3, Fig. 3) the conveyors turned out to be the most unreliable elements from the point of view of total downtime (57%).

Failures of particular elements in the mining system, especially cutter-loaders in cutter-loader systems and conveyors in plough systems, generate economic losses for mining plants; therefore, it seems advisable to undertake activities which could reduce the number of potential breakdowns of these mining machines/devices.

These two elements of the mining systems should therefore be subjected to a detailed analysis. The analysis should reveal the major causes of a failure and indicate what steps and preventive measures should be undertaken to reduce the failure frequency in the mining systems.

People monitoring and controlling the work of machines/devices should take particular care of the technical condition of these machines/devices and try to prevent failures. Moreover, the management of a mine should verify the principles regarding the selection of people for crucial posts, in line with generally accepted principles of human resources management (Kołodziej, 2004). The principles of selecting people for particular positions at work may translate into a decreased (or increased) failure frequency.

To prevent frequent downtimes, workers operating these machines/devices should be regularly trained within the scope of operation and maintenance, especially in such areas as:

- intended use, construction as well as the principle of operation and application of the control and diagnostic system,
- principles of system sensors' operation and installation,
- structure, construction and the principle of operation of components and subassemblies,
- methods of installation, starting-up and operation,
- diagnostics and analysis of the causes of failures and their removal,

- maintenance instructions,
- OSH requirements,
- streamlining the maintenance process by introducing worksheets,
- scheduling of employees' work time, which enables better planning of mining machines' maintenance periods,
- creating a database of mining machines' failures, which allows a better analysis of the causes and effects of particular breakdowns.

In this group of failures man is not a direct cause, but can effectively prevent the occurrence of some of these failures. The duration of failure removal can be reduced by frequently training the staff within the scope of failure removal. It is also necessary to conduct training courses regarding proper maintenance of machines/devices, which will extend the time of the machinery's failure-free work.

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