# APPLICATION OF QUALITY ENGINEERING IN ASSESSMENT OF MINING TECHNICAL EQUIPMENT FAILURE

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Hard coal mining is characterised by the complexity and specificity of problems related to the use of machines. These problems, which occur at the stage of design, construction and production of machines, build up when the machines are being used. The process of most effective hard coal mining is considerably influenced by reliable mining machines. Every downtime due to a failure translates into the effectiveness of the whole mining process. For this reason the mining industry is searching for new methods and tools which would allow it to improve the production (mining) process in a hard coal mine. The article presents one of the quality management tools used in various industry branches – a Pareto chart, by means of which downtimes in the work of cutter-loaders has been analysed. This tool allowed classifying the causes of particular failures as well as showing which of them are the most significant and which should be removed first.

**KEYWORDS**

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

## 1 INTRODUCTION

In Poland, practically all hard coal mines have an implemented Integrated Quality Management System. In order to evaluate the functioning of this system, management tools are used through the imposed documentation. These tools are applied to assess the process of quality improvement in an enterprise [Habek 2014, Maruszewska 2013, Midor 2012].

Quality management tools are used to collect and process data related to different aspects of quality. The most frequently are used tools for monitoring the whole production cycle, starting with design, construction, manufacture, use and finishing with inspection upon the completion of the whole production process. When talking about the use, we mean the intended use in line with the conditions and instructions of a producer – which is particularly important in the mining industry. Improper use of a machine/device, not suited to the existing geological and mining conditions may result in an increased energy-consumption of the production process, premature wear or prolonged downtimes, which are usually caused by unreliable equipment [Bialy 2012].

The changing economic situation in the world and in Poland, competition as well as increasingly high requirements of mines' recipients (clients) force the management of a mine to look for new ways of improving the production (mining) process [Bialy 2014, Lucki 2005, Skotnicka-Zasadzien 2011]. In the hard coal mining process it is very important to monitor the mining equipment and to analyse downtimes caused by the unreliability of machines/devices taking part in this process.

In this article one of traditional quality management tools – a Pareto chart has been used to evaluate the unreliability of mining machines/devices [Knights 2001, Zasadzien 2014]. A Pareto chart is a tool which enables factors influencing the examined phenomenon to be sorted out. By means of this graphic image, both a relative and absolute distribution of the type of errors, problems and their causes can be presented [Franik 2009].

## 2 MATERIAL AND METHODS

In the mining industry, a Pareto chart can be used to monitor and control mining machines/devices (cutter-loader, scraper conveyor, belt conveyor, crushers as well as power supply and control equipment), which are an important element of the production process in a mine. It is essential to evaluate breaks in the work of these machines/devices, that is, their failure rate and reliability. Moreover, it is also important to show which of the detected causes of downtimes (due to the equipment unreliability) should be eliminated first (Fig. 1) [Bialy 2014, Molenda 2012, Skotnicka-Zasadzien 2011, Wang 2009, Zasadzien 2014].

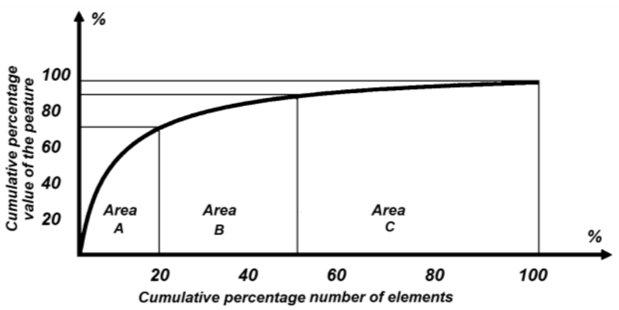


**Figure 1.** Pareto chart

The construction of a Pareto chart for controlling and monitoring the mining process in hard coal mines can be divided into the following stages:

- Collection of information – collection of data on the unreliability of mining machines/devices in particular stages of the mining process,
- Classification of the collected data – assigning particular failures to particular mining machines, such as: a cutter-loader, scraper conveyor, belt conveyor, crusher, mechanised support.
- Calculating the cumulative percentage values – establishing the cumulative percentage values for particular failures,
- Preparing a Pareto chart,
- Interpretation of the Pareto chart.

## 3 DOWNTIMES CAUSED BY FAILURES OF A CUTTER-LOADER SYSTEM

The analysed longwall was equipped with the following machines and devices [The Technical Project of the Coal Face, Operation and Maintenance Manual of a cutter-loader "AE"]:

**mechanised support** - Pioma-Jankowice 19/32,8 –168 pcs, scale 1,5m
**cutter-loader** - „AE"
**face conveyor** – Rybnik 295/842/WB/BP - drop-hole 1x250/85kW P, turning station 1x250/85kW R, chain: 34x126x2
**armoured face conveyor** - Rybnik/Grot E 225/750, power of drives 2x90kW, shaft locks 0,6 m, length 40 m, speed 1,5 m/s, chain 26x92x2
**coal lump crusher -** KKBW-1, power 90kW

The analysis was carried out using the example of one longwall in a mine belonging to Kompania Węglowa S.A., in which a cutter-loader having a working name "AE" was installed. The modular construction (and "AE" cutter-loader has such a construction) of the basic assemblies of a cutter-loader makes it possible to select a system of these assemblies depending on the technological needs of mining (e.g. a one- or two-head or a one- or two-arm cutter loader). Currently, in the world mining industry there is a demand for two-arm cutter-loaders with two cutting heads [Bialy 2014, Krauze 2007].

The time of work of the longwall subjected to analysis from the start to the end of mining was 92 days. All downtimes throughout the whole period of the longwall mining were recorded by the mine controller.

It was assumed that the place of failure was a device (machine) in which a break in work occurred. The places of failures include:

- cutter-loader,
- conveyor (face, armoured face, belt conveyor),
- crusher,
- support,
- other.

All breaks in work (causes of downtimes in the longwall face mining) were classified according to the following algorithm [Bialy 2014]:

- cutter-loader damage,
- damage of conveyors (face, armoured face conveyor as well as belts for mined rock),
- damage of the support and the lack of medium supply,
- mining failures (roof collapse, shock shooting, water pumping, the crushing of lumps, the exceeding of $CH_4$, dinting),
- other causes of downtimes (damaged water hose in the wall, the lack of water, no voltage).

The sum of all downtimes during the work of the cutter-loader has been presented in Table 1 and in a Pareto chart (Fig. 2).

**Table 1.** Total downtime of longwall complex

| Downtime of longwall element | Number of downtime | Total time of downtime [min] | Total downtime [%] | Cumulative time of downtime [%] |
|---|---|---|---|---|
| Cutter-loader | 67 | 6065 | 47 | 47 |
| Transmitter | 70 | 4920 | 39 | 86 |
| Mining | 14 | 725 | 6 | 91 |
| Mechanized housing | 19 | 625 | 5 | 96 |
| Another | 13 | 500 | 4 | 100 |
| **Total:** | **183** | **12835** | **100** | |

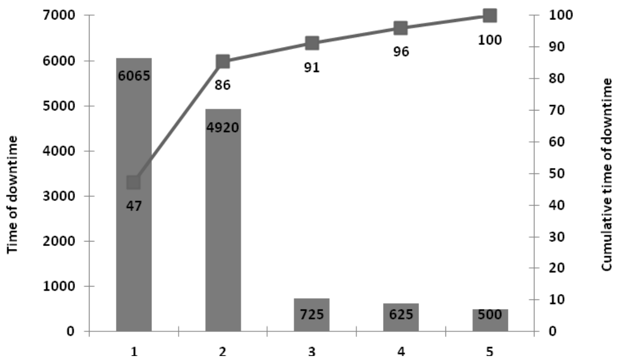


**Figure 2.** Pareto-Lorenz diagram for longwall

Table 1 illustrates the number and the duration of breaks in the work of particular coal face system elements. In terms of the number of breaks, it is visible that the highest failure rate was observed in the case of conveyors, followed closely by the cutter-loader (Fig. 2). If, however, we take into account the total duration of breaks, the total time of downtimes in the coal face system was most influenced by breaks in the work of the cutter-loader, with conveyors in the second place [Books of Reports for The Department of Chief Mechanic, The Daily Reports of Mine's Main Dispatcher].

The Pareto chart (Fig. 2) shows that breaks in the work of the cutter-loader and conveyors cause the longest downtimes in the work of the coal face system – their total sum reaches 86%. The sum of breaks in the group: mining, mechanised support and "other", which were not caused by man and are not connected with the wear of particular elements of the coal face system, accounts for merely 14%.

The most unreliable element of the coal face system turned out to be the cutter-loader (47%) – that is why a detailed analysis of the failure rate with a division into main systems has been conducted.

The failures of particular cutter-loader systems have been divided as follows [Bialy 2014, Skotnicka-Zasadzien 2011]:

- mechanical system – all kinds of mechanical failures of the cutter-loader and its equipment (e.g. upper covers, filling up with oil in mechanised systems),
- electrical system – all kinds of failures connected with the control, the lack of voltage on the cutter-loader (e.g. related to the ground fault on the cutter-loader line in the longwall, as each time after such a failure occurred the cutter-loader's computer was damaged, the computer or electric motors had to be exchanged),
- hydraulic system – any failures connected with the functions performed by the cutter-loader's hydraulic systems (e.g. wires leakage, exchange of a pump or a servo-motor, filling up with oil in the hydraulic tank),
- other – including: no water flow in the cutter-loader, an exchange of worn knives on the cutting heads, the cutter-loader's going off the BP route.

The sum of failures of particular cutter-loader's systems have been contained in Tab. 2, which presents the influence of particular cutter-loader's systems on the number of failures, the total duration of a failure as well as the duration of all failures (expressed in %).

**Table 2.** Total failures of the harvester systems

| Place of failure | Failure number | Total failures time [min] | Total failures time [%] | Cumulative failures time [%] |
|---|---|---|---|---|
| Electrical system | 39 | 3955 | 63 | 63 |
| Mechanical system | 18 | 1980 | 31 | 94 |
| Another | 7 | 300 | 5 | 99 |
| Hydraulic system | 3 | 105 | 1 | 100 |
| **Total** | **67** | **6340** | **100** | |

The Pareto chart (Fig. 3) presents the failure rate of the cutter-loader, taking into consideration its particular systems. It suggests that the unreliability of the cutter-loader's electrical system had the biggest percentage share (63%) in downtimes in the total work time, followed by mechanical failures (31%).

The highest unreliability is observed in the case of the electrical system, which was influenced chiefly by electric motors (poor condition of the insulation, moistness, ground faults) and their replacements, damage to the computer as well as damage to the cutter-loader's cable in the longwall. Mechanical failures were most frequently related to the breaking of the overload clutch in the advancing haulage. Other failures most often include the recurring lack of water flow through the electric motors, which have been working in the cutter-loader since the very beginning, and a limited flow of water due to depositing scale.

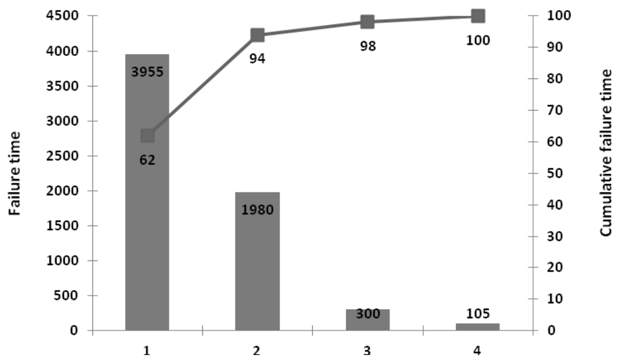


**Figure 3.** Pareto-Lorenz diagram for cutter-loader

The total sum of the cutter-loader's failures according to the place of their occurrence has been presented in Table 3 and in the Pareto chart (Fig. 4), showing the number of these failures, the total time and the duration of all failures.

**Table 3.** Total failures of the harvester by place of their uprising

| Place of failure | Failure number | Total failures time [min] | Total failures time [%] | Cumulative failures time [%] |
|---|---|---|---|---|
| Arm and bodies mining | 16 | 1970 | 34 | 34 |
| Tractors, traction systems | 18 | 1640 | 28 | 62 |
| Electrical system | 23 | 1390 | 24 | 86 |
| Hydraulic system | 6 | 720 | 12 | 98 |
| Frame (body) | 4 | 165 | 2 | 100 |
| **Total** | **67** | **5885** | **100** | |

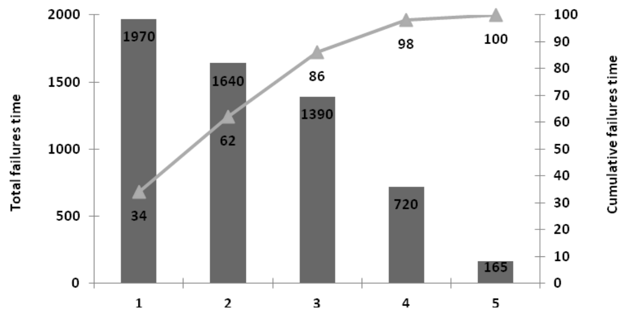


**Figure 4.** Pareto-Lorenz diagram for harvester failures

In this division (Table 3), the cutter-loader's subassemblies have been divided according to the place of failure occurrence [Bialy 2014, Skotnicka-Zasadzien 2011]:

- arm and cutting heads – the lack of water flow, replacement of arms' electric motors, damage of loading machines, filling up with oil in the arm, failures of the ranging arm, replacement of hydraulic motors in loaders, replacement of knives on the cutting head, the screwing in of the cover on a cutting head, replacement of load rollers, replacement of the lifting servo-motor,
- haulage and traction systems – failures of mechanical haulage transmission gears, replacements of stars and cage rests, replacements of DC electric drive motors, replacements of haulage load rollers, the lack of water flow through electric motors, ground faults and damage to the brush-holder of electric motors, damage to the brake,
- hydraulic system – failures related to electrovalves, damage of the electric wire and plugs which control electrovalves, damage of the hydraulic pumps and their mechanical transmission gears and electric motor, filling up with oil in the hydraulic tank, removal of leakage in the system, replacement of hoses, replacement of filters,
- frame – replacement of sidewall runners, damage of the upper covers, damage of the cable holder,
- electrical system – the lack of voltage supply to the cutter-loader, e.g. damage of the cable in the wall, damage of a cable in the cutter-loader, no control on the cutter-loader, damage to the computer, replacement of the radio aerial, shortening of the cutter-loader's cable, damage to the radio chamber, burnt fuses, replacement of control cards, damage to the water apparatus, the blowing of fuses due to overloads.

The conducted analysis suggests that the most unreliable places in a cutter-loader are its arms, haulage and electrical system (Fig. 4).

## 4 THE SHARE OF BREAKS IN THE AVAILABLE TIME

During the longwall mining there were 183 downtimes (recorded by the mine controller), the total duration of which reached 12835 minutes (Table 1). The total available time of the work of the coal face system was 102120 minutes [Books of Reports for The Department of Chief Mechanic, The Daily Reports of Mine's Main Dispatcher].

Tab. 4 (Fig. 5) shows the duration of breaks and their participation in the available time, with a division into particular elements of the coal face system.

**Table 4.** Downtime share in longwall harvester complex (total and dispositional time)

| Downtime of longwall element | Number of downtime | Total time of downtime [min] | Downtime share in the dispositional time [%] |
|---|---|---|---|
| Cutter-loader | 67 | 6065 | 5.94 |
| Transmitter | 70 | 4920 | 4.82 |
| Mining | 14 | 725 | 0.71 |
| Mechanized housing | 19 | 625 | 0.61 |
| Another | 13 | 500 | 0.49 |
| **Total** | **183** | **12835** | **12.57** |

Table 5 and Figure 6 present failures of particular cutter-loader's systems, specifying:

- the place of failure occurrence,
- the number of failures,
- the total time of failures duration (expressed in minutes and in percentage),
- the participation of failures in the total available time.

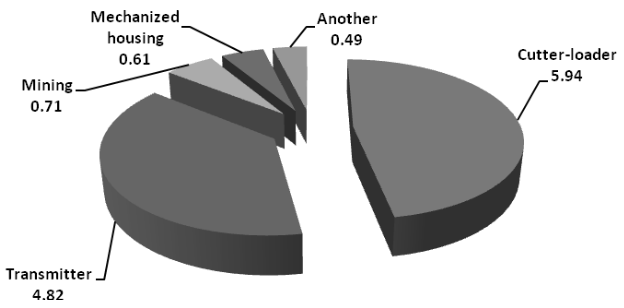


**Figure 5.** Total time of downtime of the longwall complex

***Table 5:*** *Failures of the harvester in dispositional time (total and dispositional time)*

| Place of failure | Failure number | Total failures time [min] | Failures share in the dispositional time [%] |
|---|---|---|---|
| Electrical system | 39 | 3955 | 3.87 |
| Mechanical system | 18 | 1980 | 1.94 |
| Another | 7 | 300 | 0.29 |
| Hydraulic system | 3 | 105 | 0.10 |
| **Total** | **67** | **6340** | **6.20** |

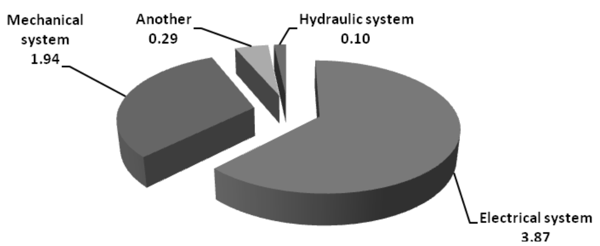


**Figure 6.** Failures share in the dispositional time

The cutter-loader's failures according to the place of their occurrence have been presented in Table 6 and, graphically, in Figure 7. The conducted analysis shows that the least unreliable element of the cutter-loader is its arm (frame) and the hydraulic system. The remaining elements cause 85% failures (Table 6).

**Table 6.** Harvester failures by place of their uprising (total and dispositional time)

| Place of failure | Failure number | Total failures time [min] | Failures share in the dispositional time [%] |
|---|---|---|---|
| Arm and bodies mining | 16 | 1970 | 1.93 |
| Tractors, traction systems | 18 | 1640 | 1.61 |
| Electrical system | 23 | 1390 | 1.36 |
| Hydraulic system | 6 | 720 | 0.71 |
| Frame (body) | 4 | 165 | 0.16 |
| **Total** | **67** | **5885** | **5.77** |

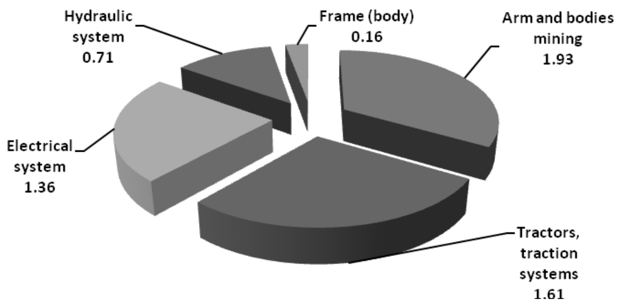


**Figure 7.** Failures share by place of their uprising

## 5 PRODUCTION RESULTS FOR THE ANALYSED LONGWALL

Work on the longwall was organised in a four-shift system, in a downstream mode, with a cyclic mining downstream [The Technical Project of the Coal Face]. Shifts 1, 2 and 3 were mining-production shifts, while shift 4 was a maintenance-repair shift.

Natural threats in the mined longwall were as follows:

methane threat - III category,

water threat - I degree,

rock bump threat - absent,

endogenic fire threat - III group of auto-flammability,

faults and throws threat - 0,3m to 2,7m

A list of working days in the analysed longwall [Books of Reports for The Department of Chief Mechanic, The Daily Reports of Mine's Main Dispatcher]:

- May – 7,
- June – 20,
- July – 23,
- August – 21,
- September – 21.

The total number of working days in the analysed longwall was 92 – the low number of working days in May (7) resulted from the longwall start-up.

An analysis of the longwall production results in the analysed period of time, with a division into daily and monthly production has been presented in Table 7 and in the charts (Fig. 8).

*Table 7: Daily and monthly minerals and clean coal mining*

| Month | Mining Mg/day | | Mining Mg/month | |
|---|---|---|---|---|
| | Total mining | Clean coal | Total mining | Clean coal |
| May | 3131 | 2205 | 21919 | 15417 |
| June | 4280 | 3060 | 85580 | 61209 |
| July | 4326 | 3120 | 99957 | 71701 |
| August | 4838 | 3717 | 101604 | 70552 |
| September | 4485 | 3537 | 94184 | 74268 |
| **Average** | **4212** | **3128** | **80649** | **58629** |

Source: [Books of Reports for The Department of Chief Mechanic, The Daily Reports of Mine's Main Dispatcher]

Table 7 and the chart (Fig. 8) present the average total output of the extracted ore and coal in particular months – when divided into particular months, the results were different. The chart (Fig. 8) shows that the longwall considerably exceeded the assumed production result (3000 Mg/24h). In May the average daily output was significantly different from the remaining months, which resulted from the longwall start-up. On the other hand, the highest daily output was reached in August and September. The obtained monthly results were considerably influenced by the cutter-loader's failures. Also the participation of coal in particular mining months was differentiated. In this case the dependence was strongly related to the geological and mining conditions.

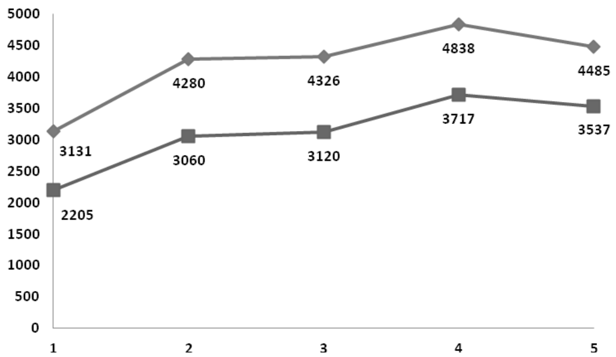


*Figure 8: Daily minerals and clean coal mining*

The rate of advance (daily, monthly) and the number of cycles (daily, monthly) in the analysed period of time, with a division into particular months has been presented in Table 8 and in the charts (Fig. 9, 10).

*Table 8: Daily and monthly progresses and cycles*

| Month | Daily progress [m] | Monthly progress [m] | Daily number of cycles | Monthly number of cycles |
|---|---|---|---|---|
| May | 2.8 | 19.8 | 4.0 | 28.3 |
| June | 4.2 | 83.0 | 6.0 | 119.0 |
| July | 4.0 | 91.0 | 5.7 | 130.0 |
| August | 4.5 | 94.3 | 6.4 | 135.0 |
| September | 4.3 | 90.5 | 6.2 | 129.0 |
| **Average** | **4.0** | **75.7** | **5.7** | **108.3** |

Source: [Books of Reports for The Department of Chief Mechanic, The Daily Reports of Mine's Main Dispatcher]

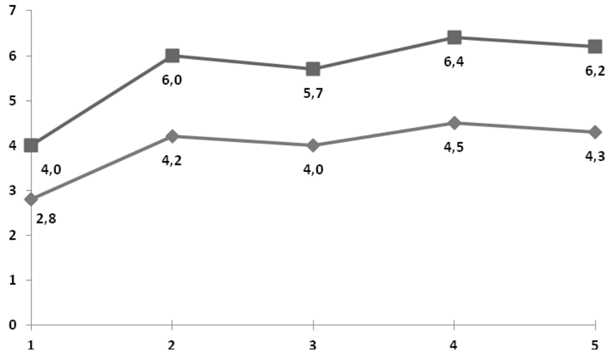


*Figure 9: Daily average progress and daily number of cycles*

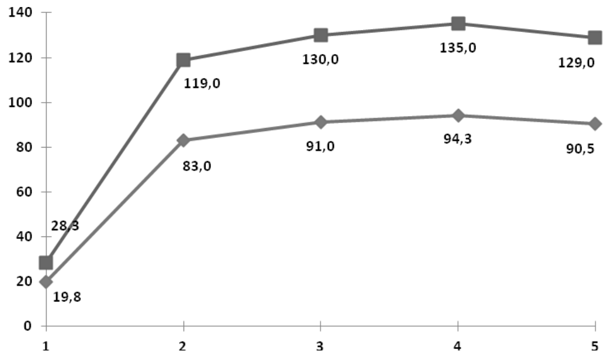


*Figure 10: Monthly average progress and monthly number of cycles*

The presented charts show that in the analysed period of time the average daily number of cycles and daily face advance (Fig. 9) in particular months (except May) did not differ much. The face advance and the number of cycles in particular months was dependant on the number of working days in a given month and on the breaks in the work of the coal face system (Fig. 10). It also depended on geological and mining conditions.

In reality a much better production result could have been achieved, but failures of the coal face system (chiefly the cutter loader – 47.30% of all the failures) as well as difficulties related to geological and mining conditions lowered the production results.

## 6 SUMMARY

In the process of the longwall mining (92 days) the failures recorded by the mine controller caused 183 breaks in the work of the coal face, the total duration of which reached 12835 minutes.

The operation time of work during one shift reached 330 minutes, i.e. 5.5 hours – the longwall worked in a 4-shift system. In terms of shifts, the analysed face output was "prolonged" due to failures by 39 shifts (12835 : 330 = 38.9 shifts).

The conducted analysis implies that downtimes were caused mainly by the cutter-loader's failures, which accounted for 47.30% of failures.

The distribution of failures in the cutter-loader's systems was as follows:

- Electrical system – the failures accounted for 62.40% (3955 min). The number of failures was 39, which caused the prolonged work of the system by the total of 65.90 hours – 12 shifts were needed to remove these failures.

- Mechanical system – 31.20% of the total duration of downtimes – 1980 minutes – 6 mining shifts were needed to remove these failures.
- Other failures and hydraulic system failures reached respectively: 4.70% and 1.70% of all downtimes resulting from failures. It may be said that these failures did not influence the prolonging of the coal face system work.

An analysis of the cutter-loader's failures (Table 8) shows that there are three main places where failures occur, namely:

1. The arm and cutting heads – 33.50% of the total duration of failures,
2. Haulage, traction systems – 27.90% of the duration of failures,
3. Electrical system – 23.60% of the total duration of failures.

The remaining failures (the hydraulic system and the frame) account for a total of 15% of all failures' duration. This means that the failures (items 1-3) caused in total a 5000-minute-downtime (85%), which contributed to the "prolonging" of the longwall work by 9 mining shifts.

The analysis of the coal face system elements (Table 1) shows that the most unreliable machine in terms of downtime duration turned out to be the cutter-loader (47.30%) – despite a lower number of breaks in work (67) in relation to the conveyors (70).

The sum of the cutter-loader's downtimes in the total duration of downtimes reached over 11 mining shifts (6065 : 330 = 11 shifts), which was most influenced by replacements of electric motors and the long delivery of replaced parts (the lack of motors supply). This is related to the hardest working conditions in which this element of the coal face system works.

Failures of particular mining machines, in particular cutter-loaders cause big losses for a mine. For this reason it seems reasonable to propose measures which would help limit the number of potential failures of these mining machines.

Therefore, to prevent frequent downtimes (67), the employees whose work is related with the cutter-loader's operation, should be frequently trained within the scope of the operation and use of this equipment, in particular in such areas as:

- the intended use, the construction and the principle of operation as well as the application of the control system and diagnostics,
- the principle of system sensors' operation and installation,
- the structure, the construction and the principle of operation of components and subassemblies,
- the methods of installation, start-up and operation,
- diagnostics and analysis of the causes of failures and their removal,
- maintenance directives,
- OSH requirements.

In this group of failures man is not a direct cause, but he can effectively prevent some of these failures. It is possible to reduce the time of failure removal by frequently training the staff on how to remove the effects of failures. It is also necessary to provide training courses connected with proper maintenance of machines, which will contribute to their prolonged failure-free work [Kolodziej 2004].

The analysis of production results confirms the achievement of the assumed production goals. The presented Tab. (4, 5) and charts (Fig. 5, 6, 7) show that the longwall (despite a big slope of the bed [The Technical Project of the Coal Face]) had an average output of 3268Mg/24h, i.e. it carried out the production plan of 3000Mg/24h.

Despite the fact that the cutter-loader mined the fourteenth longwall in the mine (production year 1992 [Operation and Maintenance Manual of a cutter-loader "AE"]), in the presented analysis it received a favourable evaluation, achieving the planned daily output.

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