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IMPACT OF DOWNTIME PATTERN ON MINING MACHINERY EFFICIENCY

UTICAJ UZORKA ZASTOJA NA EFIKASNOST RUDARSKIH MAŠINA

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Ključne reči
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Abstract

In this paper, problem of mining machinery efficiency is considered through impact of different types of downtimes. New methodology is suggested based on comparison impact of mechanical and technological mining machinery time in fault (M_t, T_t) and mechanical and technological mining machinery downtime frequencies (M_f, T_f) on machine work done (W). Benchmarking analysis is conducted by pairing variables M_t-W, T_t-W, M_f-W and T_f-W, and determining relationships between observed variables. By comparing the increment of the cumulative downtime curve with the cumulative curve of the machine's operating volume, it can be assessed whether the observed downtime develops a concave or convex character of the operating volume cumulative curve, in respect to significant losses. Results indicate that the relationship between cumulative downtime curve and cumulative work done curve can successfully serve as a parameter for evaluating the impact of specific downtime on the efficiency of the machine. A multi-criteria analysis, namely, an analysis of the criteria - frequency and time spent in downtime for each of the observed causes of downtime, clearly determines the critical pattern of downtime on the efficiency of the observed machine.

Izvod

U radu je razmatran problem efikasnosti rudarskih mašina preko uticaja različitih vrsta zastoja (mašinskih, mehaničkih zastoja usled kvara, loma, i sl.). Predložena je nova metodologija koja se bazira na poređenju uticaja mašinskih i tehnoloških vremena u zastoju (M_t, T_t) i mašinskih i tehnoloških frekvencija zastoja (M_f, T_f) na izvršeni rad mašine (W). Benčmarking analiza je sprovedena uparivanjem varijabli M_t-W, T_t-W, M_f-W i T_f-W, kao i utvrđivanjem zavisnosti između posmatranih varijabli. Poređenjem prirasta kumulativne krive zastoja sa prirastom kumulativne krive izvršenog rada, može da se utvrdi da li posmatrani zastoji utiču na konkavan ili konveksan oblik kumulativne krive izvršenog rada, odnosno, kada imamo značajne gubitke. Rezultati istraživanja ukazuju da zavisnost između kumulativne krive zastoja i kumulativne krive izvršenog rada može da se koristi kao parametar za ocenu uticaja specifičnog zastoja na efikasnost posmatrane mašine. Višekriterijumskom analizom, tj. analizom kriterijuma frekvencija pojave i dužine trajanja zastoja za svaki od uočenih uzroka zastoja, jasno se određuje kritični uzorak zastoja na efikasnost rada posmatrane mašine.

INTRODUCTION

Contemporary engineering systems performance has significantly increased due to better design practices and testing possibilities, but traditional time in use and maintenance time have not changed much. According to ISO 10303-226, a fault is defined as an abnormal condition or defect at the component, equipment, or sub-system level which may lead to a failure, /1/. We are witnessing today that faults still frequently occur, although both scientific and professional community aims to prevent it.

Li et al. /2/ carried out experiment in order to examine fault diagnosis of rotating machinery. Main focus was on vibration signals to detect the faults of machine components and to reduce downtime of machinery. Brodny and Tutak /3/ say that the major problem in mining industry is the ineffective use of mining machinery. Authors in /3-5/ suggest the overall equipment effectiveness (OEE) model to analyse availability and performance of the equipment, and calculated performance of individual machines is determined based on the estimated values of the amount of extraction in particular shifts, ant this value is the indicator.

Brodny at al. /4/ suggest integration of TPM (Total Productive Maintenance) and OEE (Overall Equipment Effectiveness) as strategy for improvement effectiveness of mining machinery. The authors analysed work of 4 mining machine in period of 64 work shifts. They calculated average, maximum and minimum daily values of availability indicator of these machines. Also, they analysed the structure of brakes during work. General conclusion is that the methodology for determining the indicator of effectiveness of the mining machines is an important source of knowledge for assessing the state of machine work. The results of studies indicate on reserves in availability area of examined mining machines, while studies on machines' breakdown structure indices on reserves in availability in the cases of eliminating some of detected faults.

Kumar and Srivastava /6/ developed an expert system for optimal maintainability of mine excavators and its components such as engine, hydraulic and transmission system, brake system, electrical and safety system, suspension, and track in order to reduce the unit production cost in mining. They designed databases to store historical maintenance data and data continuously and periodically monitored. CBM (Condition based maintenance) technique is applied to incorporate knowledge in form of rules and generate interference engine in expert system.

Kumar and Srivastava /6/ present the framework for a new optimal maintenance methodology for mine excavator component failure detection and system related failures and accordingly databases are formed by the FMEA, FMECA and CBM (condition based maintenance) models which predict fault or deterioration in excavator components.

Kirmani and Ercelebi /7/ developed an expert system for hydraulic excavator and truck selection in surface mining. For selecting of hydraulic excavators, trucks, and equipment they apply 6 criteria: digibility, reduction criteria, mine parameters, geological and geotechnical factors, equipment criteria, unit production cost. For expert system development, authors used KappaPCcs expert system shell and IF-THEN form of production rules.

Karim at al. /8/ proposed a concept for knowledge discovery in maintenance with focus on big data and analytics. This concept consists of 4 interdependent phases:

– the Maintenance Descriptive Analytics phase - access to data related to system operation, system condition, and expected condition. Relation of events and states could be determined in this phase;
– the Maintenance Diagnostic Analytics phase - to identify causes of failures. Focus on this phase is detection, isolation and identification of each failure;
– the Maintenance Predictive Analytics phase - to predict upcoming failure and fault there is a need to provide business data such as planned operation and planned maintenance to this phase;
– the Maintenance Prescriptive Analytics - to predict upcoming failure and fault there is a need to provide resource planning data and business data.

Sivarao et al. /9/ also recognize the importance of faults which appear and propose innovative system which alerts employees responsible for device management via wireless technology when electrical malfunctions or mechanical damage is detected. Other research, described in /10-13/ emphasizes the importance of methodology for capacity utilization, which is crucial for the observation of machine downtime and maintenance diagnostics. Incorporating the theory of capacity utilization in knowledge for assessing of the state of machine work could be one of the upcoming challenges in research and knowledge acquisition.

RESEARCH METHODOLOGY

In this research we observed influence of faults on mining machine efficiency. The survey methodology is based on monitoring the downtime of the mining machine for 200 working days. All downtime is classified into groups, and then the effects of each downtime group on the efficiency of machine operation is observed. Technology-related downtime and mechanical downtime has accounted for more than 80% of the total downtime, as well as the total downtime of the machine under study. Therefore, only these two downtime groups are monitored further.

Methodological steps in the research are as follows:

1. Rank the frequency of technological downtime by day, so that the first-ranked day is the day with the highest number of downtime caused by the technological nature.
2. Calculation of the percentage share of daily frequencies of technological downtime.
3. Calculation of cumulative daily frequencies of technological downtime.
4. For the obtained ranking of daily frequencies of technological downtime, calculate the daily machine work done.
5. For the obtained rank of daily frequencies of technological downtime, calculate the percentage share of the daily machine work done.
6. For the obtained rank of daily frequencies of technological downtime, calculate the cumulative daily machine work done.
7. For the obtained rank of daily frequencies of technological downtime and cumulative daily machine work done, generate histograms, Fig. 1.
8. Observe the surface that represents the difference between cumulative frequencies of daily technological downtime and the cumulative daily machine work done.

Let T_f be technological fault frequency; M_f - mechanical fault frequency; T_t - technological downtime; M_t - mechanical downtime. Notation for quantity of machine work done is W_d measured in kilograms of goods produced.

Let data set $(a_0, a_1, \ldots, a_{n-1})$ be the input set, then after sorting in declining order, the output set will be $(a_0', a_1', \ldots, a'_{n-1})$, where $a_0' \leq a_1' \leq \ldots \leq a'_{n-1}$.

By adopted notation, one gets:

$(T'_{f0}, T'_{f1}, \ldots, T'_{fn-1})$, where $T'_{f0} \leq T'_{f1} \leq \ldots \leq T'_{fn-1}$

$(M'_{f0}, M'_{f1}, \ldots, M'_{fn-1})$, where $M'_{f0} \leq M'_{f1} \leq \ldots \leq M'_{fn-1}$

$(T'_{t0}, T'_{t1}, \ldots, T'_{tn-1})$, where $T'_{t0} \leq T'_{t1} \leq \ldots \leq T'_{tn-1}$

$(M'_{t0}, M'_{t1}, \ldots, M'_{tn-1})$, where $M'_{t0} \leq M'_{t1} \leq \ldots \leq M'_{tn-1}$

and $i = 0, 1, \ldots, n-1$, where i-number of days of monitoring.

Total technological fault frequencies for all days of monitoring is:

$$\sum_{i}^{n-1} T'_{fi} \,, \tag{1}$$

and also corresponding other sums for technological and mechanical downtimes are:

$$\sum_{i}^{n-1} T'_{ti} \,,\; \sum_{i}^{n-1} M'_{ti} \,,\; \sum_{i}^{n-1} M'_{fi} \,. \tag{2}$$

In percentage share, corresponding parameters will be described as follows:

$$\frac{T'_{fi}}{\sum_{i}^{n-1} T'_{fi}}, \frac{T'_{ti}}{\sum_{i}^{n-1} T'_{ti}}, \frac{M'_{fi}}{\sum_{i}^{n-1} M'_{fi}}, \frac{M'_{ti}}{\sum_{i}^{n-1} M'_{ti}}, \quad (3)$$

and finally, cumulative values will be:

$$T'_{cfi} = T'_{f0} + \frac{T'_{fi}}{\sum_{i}^{n-1} T'_{fi}} \quad \text{technological frequencies downtime,} \quad (4)$$

$$T'_{cti} = T'_{t0} + \frac{T'_{ti}}{\sum_{i}^{n-1} T'_{ti}} \quad \text{technological time in downtime,} \quad (5)$$

$$M'_{cfi} = M'_{f0} + \frac{M'_{fi}}{\sum_{i}^{n-1} T'_{fi}} \quad \text{mechanical frequencies downtime,} \quad (6)$$

$$M'_{cti} = M'_{t0} + \frac{M'_{ti}}{\sum_{i}^{n-1} T'_{ti}} \quad \text{mechanical time in downtime.} \quad (7)$$

Same methodology is applied for display corresponding machine work done by ranking observed parameters of downtimes. For cumulative technological frequencies downtime:

$$T'_{cfi} = T'_{f0} + \frac{T'_{fi}}{\sum_{i}^{n-1} T'_{fi}}, \quad (8)$$

corresponding cumulative machine work done will be

$$W_{cT'_f i} = W_{T'_f 0} + \frac{W_{T'_f i}}{\sum_{i}^{n-1} W_{T'_f i}}. \quad (9)$$

For cumulative technological time in downtime:

$$T'_{cti} = T'_{t0} + \frac{T'_{ti}}{\sum_{i}^{n-1} T'_{ti}}, \quad (10)$$

corresponding cumulative machine work done will be

$$W_{cT'_t i} = W_{T'_t 0} + \frac{W_{T'_t i}}{\sum_{i}^{n-1} W_{T'_t i}}. \quad (11)$$

For

$$M'_{cfi} = M'_{f0} + \frac{M'_{fi}}{\sum_{i}^{n-1} M'_{fi}}, \quad (12)$$

corresponding cumulative machine work done will be

$$W_{cM'_f i} = W_{M'_f 0} + \frac{W_{M'_f i}}{\sum_{i}^{n-1} W_{M'_f i}}. \quad (13)$$

For

$$M'_{cti} = M'_{t0} + \frac{M'_{ti}}{\sum_{i}^{n-1} M'_{ti}}, \quad (14)$$

corresponding cumulative machine work done will be

$$W_{cM'_t i} = W_{M'_t 0} + \frac{W_{M'_t i}}{\sum_{i}^{n-1} W_{M'_t i}}. \quad (15)$$

Technological faults

The presented metrological steps are applied for technological frequencies downtime used for generating histograms of cumulative technological frequencies downtime and corresponding cumulative machine work done. For 220 monitoring days, the formulas will be:

$$T'_{cfi} = T'_{f0} + \frac{T'_{fi}}{\sum_{0}^{220} T'_{fi}} = 1.01 + \frac{T'_{fi}}{2976}, \quad (16)$$

$$W_{cT'_f i} = W_{T'_f 0} + \frac{W_{T'_f i}}{\sum_{0}^{220} W_{T'_f i}} = 0.45 + \frac{W_{T'_f i}}{5821829}. \quad (17)$$

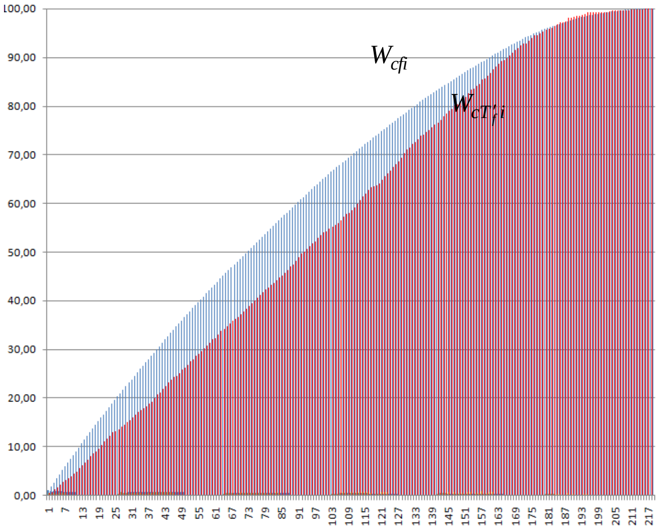

Figure 1. Cumulative curve of technological faults frequency and machine work done.

Methodological steps for examination of the time spent in technological downtime and machine performed work done are:

1. Ranking technological downtime by day, so that the first-ranked day is the day with the longest downtime caused by the technological nature.
2. Calculation of the percentage of time spent in technological downtime per day.
3. Calculation of cumulative time spent in technological downtime.
4. For the obtained rank time in technological downtime, calculate the daily machine work done.
5. For the obtained rank time in technological downtime, calculate the percentage of machine work done.
6. For the obtained rank time in technological downtime, calculate the cumulative machine work done.
7. For the generated cumulative times of daily technological downtime and cumulative machine work done, generate histograms, Fig. 2.
8. Observe the surface that represents the difference between the cumulative times of daily technological downtime and the cumulative machine work done.

Calculation for technological time in downtime and machine work done will be:

For 220 monitoring days, the formulas will be:

$$T'_{cti} = T'_{t0} + \frac{T'_{ti}}{\sum_{i}^{n-1} T'_{ti}} = 3.34 + \frac{T'_{ti}}{43155}, \qquad (18)$$

$$W_{cT'_f i} = W_{T'_f 0} + \frac{W_{T'_f i}}{\sum_{i}^{n-1} W_{T'_f i}} = 0 + \frac{W_{T'_t i}}{5821829}. \qquad (19)$$

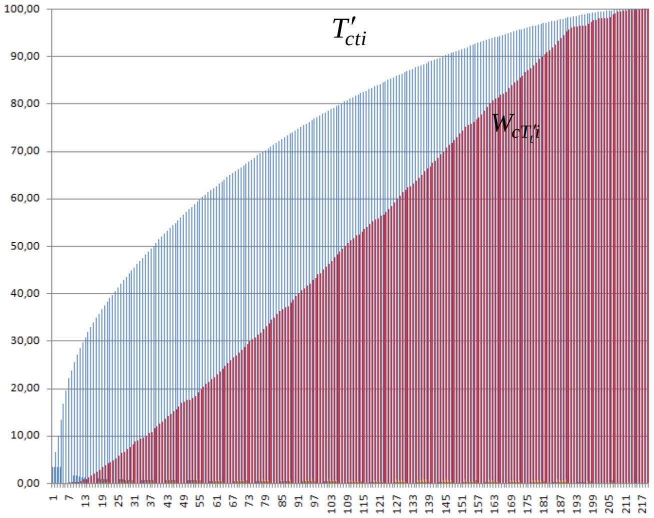

Figure 2. Cumulative curve of technological faults frequency and machine work done.

Mechanical faults

The methodological steps for examination of the effect of the frequency of mechanical downtime on the operating volume of the observed machine are as follows:
1. Rank the frequency of mechanical downtime by day, so that the first-ranked day is the day with the highest number of downtime caused by mechanical nature.
2. Calculation of the percentage fraction of daily frequencies of mechanical downtime.
3. Calculation of cumulative daily frequencies of mechanical downtime.
4. For the obtained rank of daily frequencies of the mechanical downtime, calculate the daily work done by the machine.
5. For the obtained rank of daily frequencies of the mechanical downtime, calculate the percentage of daily machine work done.
6. For the obtained rank of daily frequencies of mechanical downtime, calculate the cumulative daily machine work done.
7. For the obtained rank of daily frequencies of the mechanical downtime and cumulative daily machine work done, generate histograms, Fig. 3.
8. Observe the surface that represents the difference between the cumulative frequencies of daily mechanical downtime and the cumulative daily machine work done.

   For 220 monitoring days, formulas will be:

$$M'_{cfi} = M'_{f0} + \frac{M'_{fi}}{\sum_{i}^{n-1} M'_{fi}} = 1.24 + \frac{M'_{fi}}{1052}, \qquad (20)$$

$$W_{cM'_f i} = W_{M'_f 0} + \frac{W_{M'_f i}}{\sum_{i}^{n-1} W_{M'_f i}} = 0.54 + \frac{W_{M'_f i}}{5821829}. \qquad (21)$$

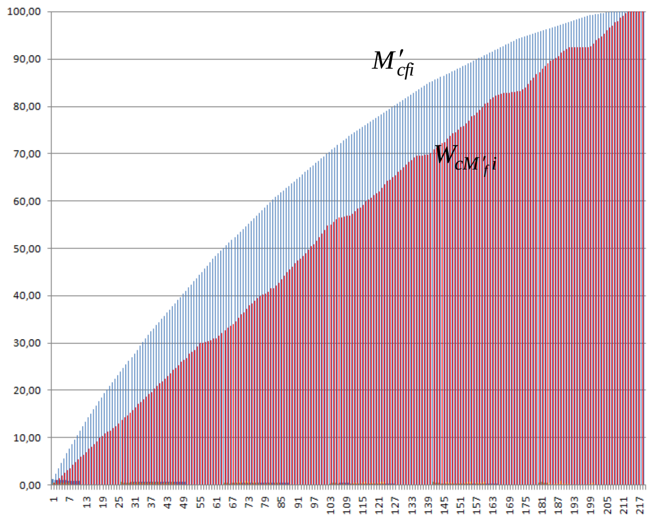

Figure 3. Cumulative curve of mechanical faults frequency and machine work done.

The methodological steps for the examination of time spent in mechanical downtime and the operating volume of the observed machine are as follows:
1. Ranking mechanical downtime by day, so that the first-ranked day is the day with the longest downtime caused by mechanical nature.
2. Calculation of the percentage of time spent in mechanical downtime per day.
3. Calculation of cumulative time spent in mechanical downtime.
4. For the obtained rank of time spent in mechanical downtime, calculate the daily work done by the machine.
5. For the obtained rank of time spent in mechanical downtime, calculate the percentage of daily machine work done.
6. For the obtained rank of time spent in mechanical downtime, calculate the cumulative daily machine work done.
7. For the generated cumulative times of daily mechanical downtime and cumulative daily machine work done, generate histograms, Fig. 4.
8. Observe the surface that represents the difference between cumulative times of daily mechanical downtime and the cumulative daily machine work done.

   For 220 monitoring days, the formulas will be:

$$M'_{cti} = M'_{t0} + \frac{M'_{ti}}{\sum_{i}^{n-1} M'_{ti}} = 2.09 + \frac{M'_{ti}}{66415}, \qquad (22)$$

$$W_{cM'_t i} = W_{M'_t 0} + \frac{W_{M'_t i}}{\sum_{i}^{n-1} W_{M'_t i}} = 0.03 + \frac{W_{M'_t i}}{5821829}. \qquad (23)$$

For the obtained histograms in Figs. 1-4, it is possible to generate cumulative curves, as best fitting curves, in explicit form, Table 1.

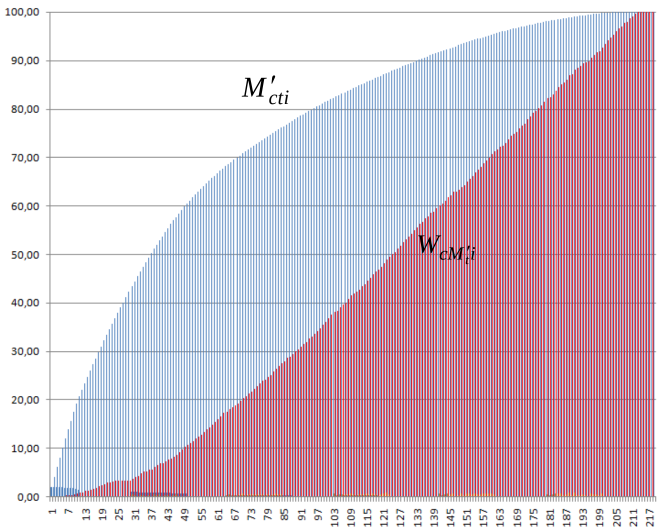

Figure 4. Cumulative curve of mechanical time in faults and machine work done.

RESULTS

By calculating the area that represents the difference between the cumulative curve corresponding to a certain type of downtime and the cumulative curve corresponding to the amount of work performed by the observed machine, we will obtain a parameter for evaluating the impact of this downtime on the efficiency of the machine. By comparing the surfaces in diagrams Figs. 5, 6, 7 and 8 (surface areas present the difference between cumulative curve of certain downtime and cumulative curve of machine work done), conclusions can be drawn as to what kind of machine fault has a primary impact on the machine working potential.

Diagrams given in Figs. 5-8 show that the surface obtained from the difference between the cumulative downtime curve and the cumulative work done curve is greatest at the time spent in mechanical downtime. The cumulative frequency curves of both technological and machine downtime do not show a high impact on the efficiency of operation, while the cumulative curves of downtime and technological and machine nature show a significant influence on the convexity of the cumulative curve of the machine efficiency.

Table 1. Equations.

Criteria	Subcriteria	Equations
mechanical	time in fault	$y = 2E\text{-}05x^3 - 0.007x^2 + 1.381x + 6.768$
	machine work done	$y = -1E\text{-}05x^3 + 0.004x^2 + 0.063x - 0.645$
mechanical	frequency	$y = -0.001x^2 + 0.843x + 2.985$
	machine work done	$y = -0.000x^2 + 0.548x - 0.682$
technological	time in fault	$y = -1E\text{-}07x^4 + 6E\text{-}05x^3 - 0.012x^2 + 1.424x + 11.39$
	machine work done	$y = -1E\text{-}05x^3 + 0.003x^2 + 0.232x - 1.665$
technological	frequency	$y = -2E\text{-}06x^3 - 0.000x^2 + 0.748x + 1.229$
	machine work done	$y = -8E\text{-}08x^4 + 3E\text{-}05x^3 - 0.002x^2 + 0.621x - 1.074$

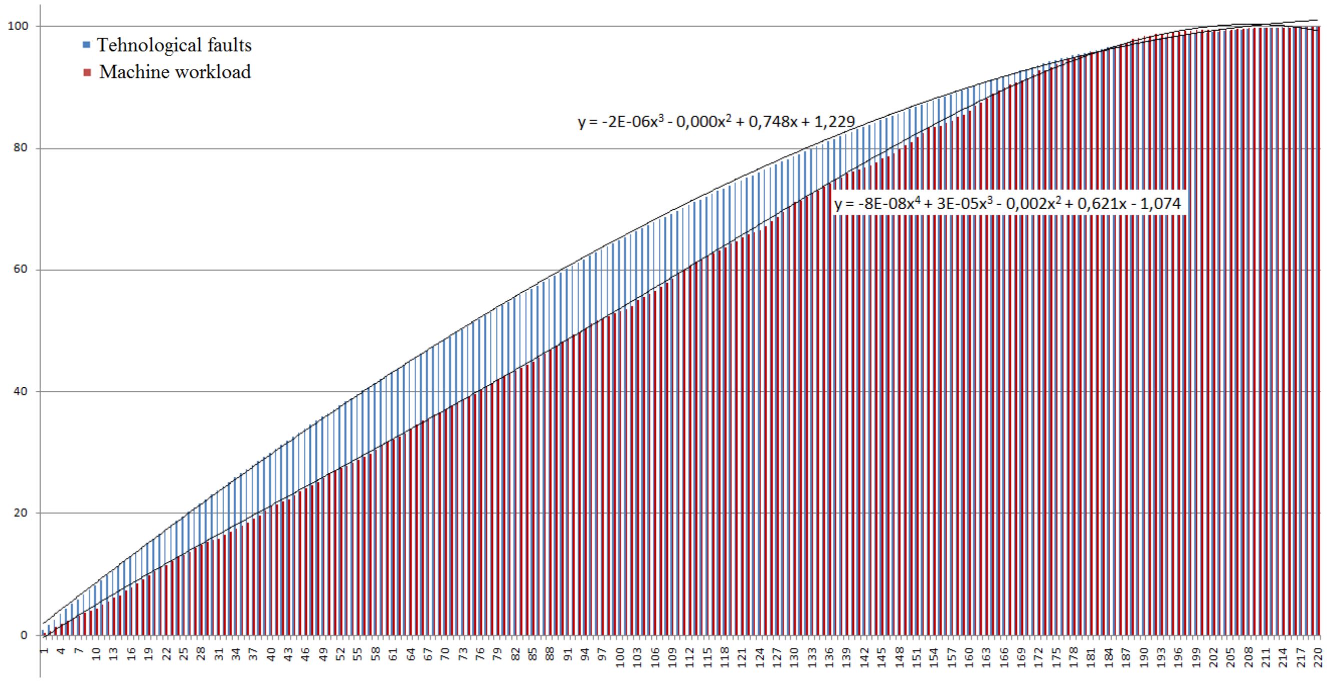

Figure 5. Curve fitting: technological frequency and machine workload.

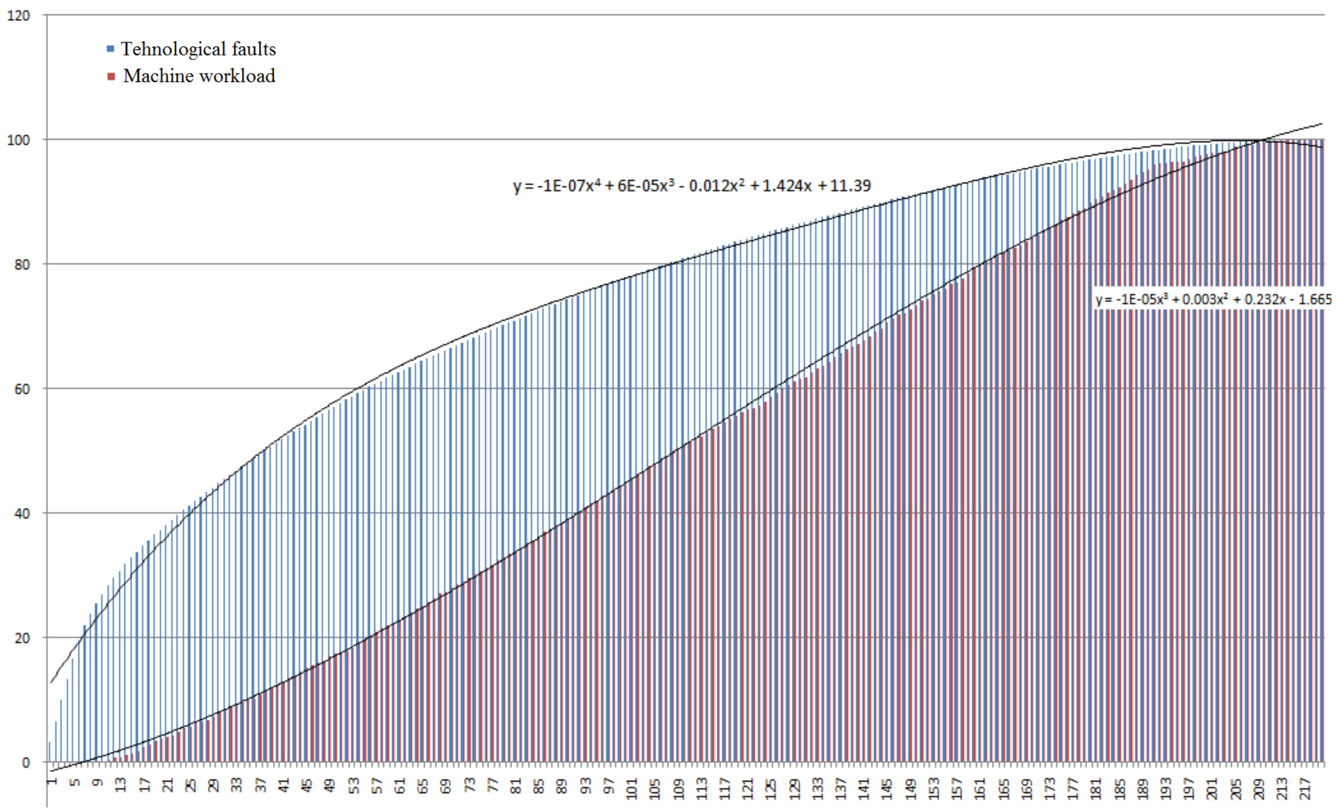

Figure 6. Curve fitting: technological time and machine workload.

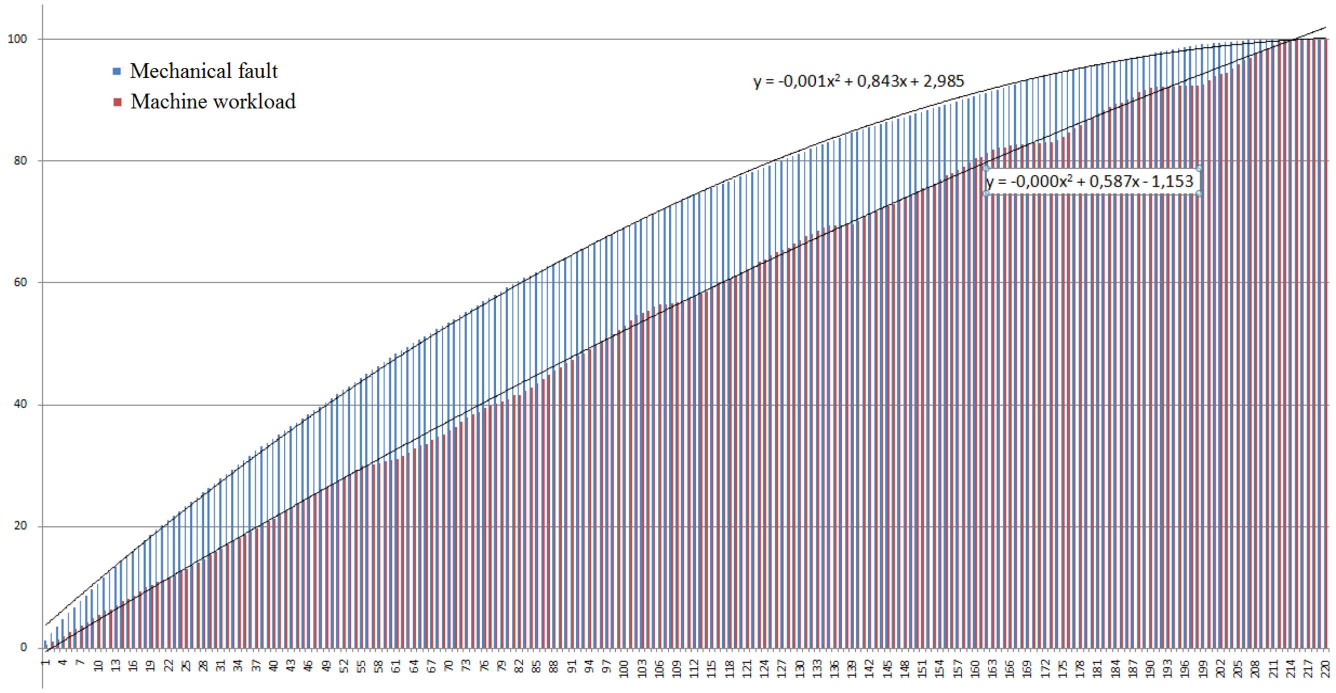

Figure 7. Curve fitting: technological and mechanical frequency and time.

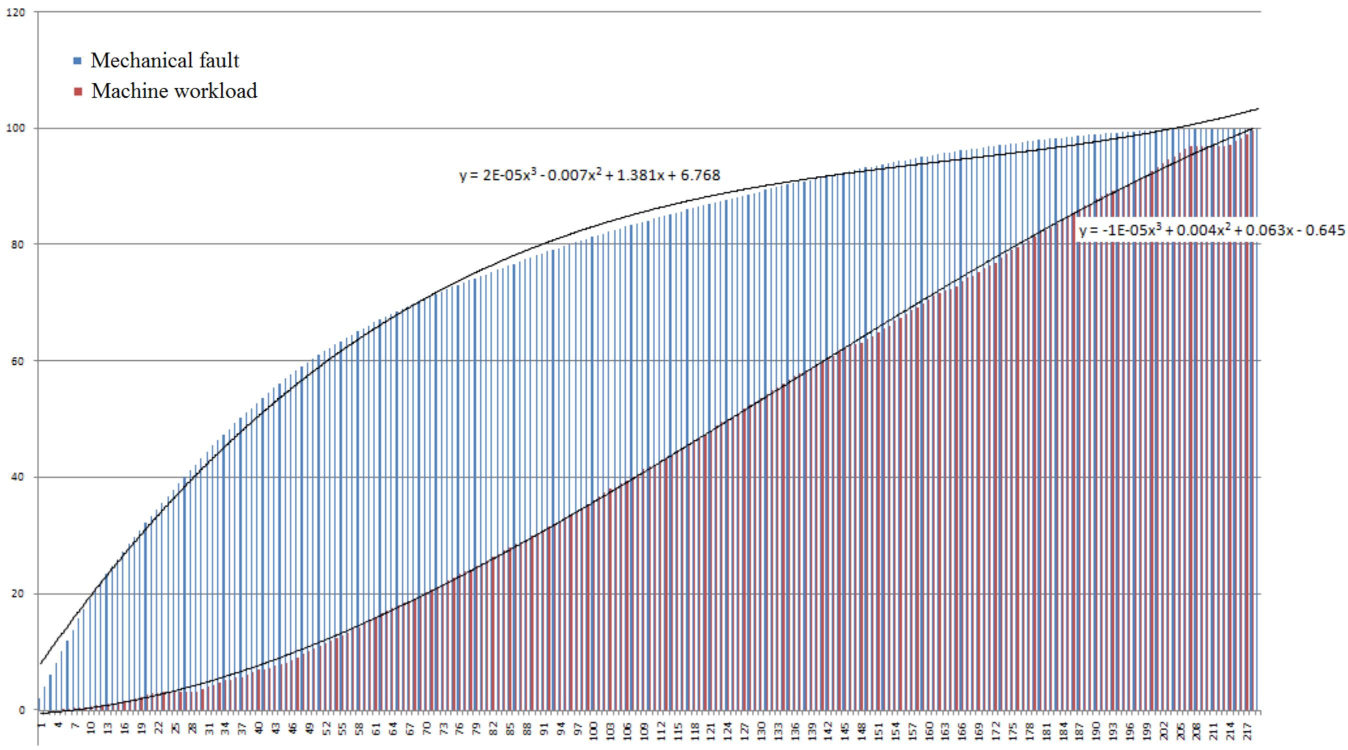

Figure 8. Curve fitting: technological and mechanical frequency and time.

CONCLUSIONS

The methodology of examining the impact of different types of downtime on the efficiency of the observed machine is presented in the paper. By observing and recording the downtimes that occur with the machine over a long period of time, it is possible to generate cumulative curves for each downtime. It is necessary to emphasize the monitoring of the machine downtimes over a longer time interval, in order to assess its increment in the cumulative curve. By comparing the increment of the cumulative downtime curve with the cumulative curve of the machine's operating volume, it can be assessed whether the observed downtime develops a cumulative curve of operating volume of concave or convex character, respectively, whether it makes significant losses.

The presented methodology analyses of the relationship between downtime and work done can largely serve as an indicator in selecting the critical causes of downtime on machine efficiency. A multi-criterion analysis, namely, analysis of the criteria - frequency and the time spent in downtime for each of the observed causes of downtime, clearly determines the critical pattern of downtime on the efficiency of the observed machine.

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