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ANALYTICAL DETERMINATION OF THE AVAILABILITY OF A ROTARY EXCAVATOR AS A PART OF COAL MINING SYSTEM - CASE STUDY: ROTARY EXCAVATOR SchRs 800.15/1.5 OF THE DRMNO OPEN PIT[****]

Abstract

Rotary excavators as the basic machines at the open pits of lignite operate in very difficult working conditions, where they are constantly expected to be highly productive, reliable, available and safe as the production carriers. Determining the availability as well as the duration and number of failures using the analytical methods allows to analyze the key influencing factors on their occurrence and values of these parameters and to determine the essential elements of system maintenance and management in order to optimize them.

Keywords: *rotary excavator, reliability, convenience of maintenance, availability*

1 INTRODUCTION

Coal is the basic energy fuel in electricity production. Rotary excavators are used to excavate coal at the open pits of the Electric Power Industry of Serbia. Coal exploitation in the Kostolac basin began in 1870. The open pit "Drmno" is the only active mine in the Kostolac basin. The open pit “Drmno” produces 25% of coal (lignite) in Serbia.

A growth of capacity on coal from the current $9x10^6$ to $12x10^6$ t/year and overburden from $40x10^6$ to the maximum $55x10^6$ m^3/year is designed at the open pit “Drmno“. Coal mining takes place with two BTD systems with one export conveyor, with occasional engagement of dragline excavator as necessary auxiliary equipment. The mined coal from both systems is transported by a groupage conveyor to the distribution bunker and further to the crushing plant, landfill and thermal power plant. The BTD systems are systems that consist of the following elements: a rotary excavator, series of conveyors and crushing plant. These systems are connected in a series connection as it can be seen in Figure 1. If one element of the BTD system fails, the entire system stops working.

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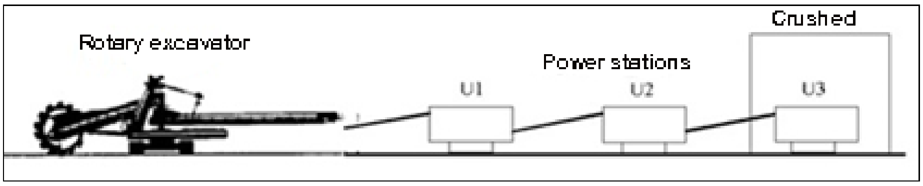


Figure 1 *Overview of the BTD system (rotary excavator-conveyor-crusher)*

Equipment on the BTD systems:
I BTD system:
- excavator SchRs 800.15/1,5;
- excavator SRs 400.14/1;
- 2 self-propelled conveyors BRs 2400;
- 2 level conveyors, width 1800 mm.

II BTD system:
- excavator ERs 710.17,5/13-16;
- excavator SRs 400.14/1;
- self-propelled conveyor BRs 2400;
- self-propelled conveyor BRs 1400;
- conveyor, width 1400 mm;
- conveyor, width 1800 mm. [5]

Figure 2 *View of the I BTD system at the open pit "Drmno"*

This paper presents an analytical determination of the reliability and availability of the SchRs 800.15/1.5 rotary excavator based on the collected data related to delays (mechanical, electrical and other delays) on the I BTD system of the open pit "Drmno".

1.1 Characteristics of an excavator

The SchRs 800.15/1.5 rotary excavator works within the I BTD system. The manufacturer of this rotary excavator is the German company O&K. The excavator was purchased in 1995.

A rotary excavator is in itself a very complex machine system. Like any system, it is composed of a number of subsystems:

1. Excavation subsystem
2. Subsystem for excavator movement
3. Receiving conveyor subsystem
4. Storage conveyor subsystem
5. Subsystem for rotating the upper structure [4]

According to the German classification, the rotary excavators are divided into classes A (compact excavator), B (C frame excavator) and C (giant excavator) according to the basic construction characteristics. [3]

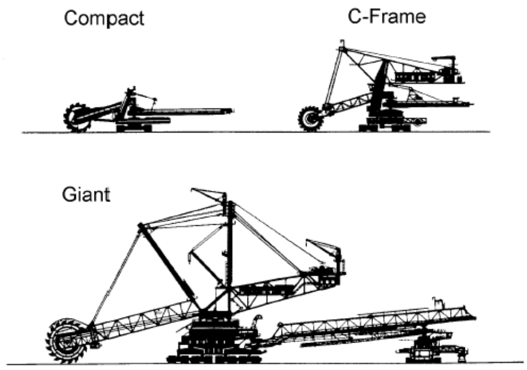


Figure 3 *Types of rotary excavators* [3]

This excavator belongs to a group of compact rotary excavators. Compact excavators have a relatively short boom in relation to a diameter of the working wheel. [3] The advantages of compact rotary excavators are primarily in their low weight; therefore, they have a lower purchase price and are characterized by the outstanding maneuverability. The disadvantages are reflected in the lower coefficient of utilization, high load of a ball and frequent damage to the supporting structure. The basic technical characteristics of the SchRs 800.15/1.5 rotary excavator are given in Table 1. In general, the operation technology of rotary excavators, including this specific one, depends on three basic factors: technological characteristics, geomechanical properties of the excavated material and deposit conditions. The basic technology of SchRs 800.15/1.5 excavator operation is work in a height block (height work in a block with vertical cuts, excavation the entire block height in several cuts). The maximum floor height is up to 15 m.

Figure 4 *Rotary excavator SchRs 800.15/.5 in operation*

Table 1 *Basic technical characteristics of the rotary excavator SchRs 800.15/15 [5]*

Theoretical capacity (m^3/h)	3024
Guaranteed capacity (m^3/h)	1350
Impeller diameter (m)	9.1
Installed drive power RT (kW)	800
Specific excavation force (N/cm)	1200
Nominal bucket volume (m^3)	0.8
Number of buckets	14
Number of bucket shakes (1/min)	79
Excavation height (m)	15
Excavation depth (m)	1.2
Boom length RT (m)	14.5
Unloading belt length (m)	25.5
Height of the boom suspension point RT (m)	8.3
Suspension point distance from the vertical rotary axis of the excavator (m)	1.2
Boom angle RT (°)	19.5/15.5
Excavator weight in operation (t)	560

The rotary excavator works in very difficult conditions, where a high productivity, reliability, availability and safety at work are constantly expected from it as a carrier of production. The effects of operation the mining machines depend on the reliability, their functioning, technical and technological performance, handling, maintenance, logistical support, adaptability-compliance of the relationship between the performance of machines and characteristics of the working environment. [2]

Reliability of systems with series connected elements. Basic terms. Availability

Reliability is the probability with a certain level of confidence that the system, machine will successfully perform the function for which it is intended, without failure and within defined performance limits, taking into account the previous time of the system use, during the given time of task duration. [1]

The reliability of a system of n series-connected elements is equal to the product of reliability of all these elements. [1].

$$R = R_1 \cdot R_2 \cdot R_3 \cdot \ldots R_n$$

where: R_1, R_2,... R_n - reliability of system elements. [1]

Structure of a system with a series connection of elements is the simplest model of the system.

When there is a large amount of data on failures of system elements, as is the case in this paper, there is a possibility to determine the theoretical distribution of failure probability and repair of system elements.

If the system has N series-connected elements with different constant failure intensities $\lambda_1, \lambda_2,..., \lambda_n$, with exponential distribution of element operating time to failure, then the distribution of system operating time to system failure is also exponential, with intensity $\lambda = \lambda_1 + \lambda_2 + \cdots + \lambda_n$. [1]

One of the most important indicators of reliability is the intensity of failure. In a large number of technical systems, the change in failure rate over time appears as in Figure 5. [7]

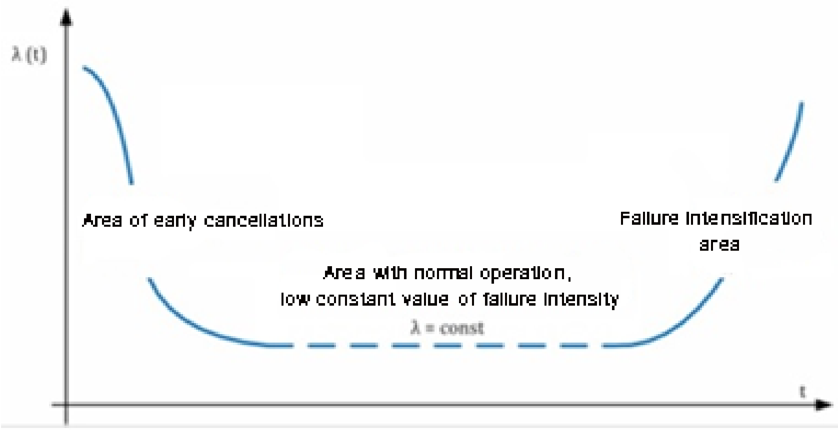


Figure 5 *Function of failure interval density [7]*

The curve in Figure 5, the so-called Bathtube curve, shows 3 areas in the lifetime of the technical system:

1. Area of early failures
2. Area with normal operation (period of exploitation) - constant failure rate,
3. Area of failure intensification of failures - end of lifetime, [7]

Maintenance convenience function

In order for the machine (rotary excavator) to meet the high requirements when it comes to reliability, availability and safety in operation, it is necessary to perform a maintenance process. Convenience of maintenance is a very important feature of the machine. It is a feature of an element or system that the maintenance measures can easily prevent, detect or eliminate faults and malfunctions. [1].

The more complex the machine, the harder it is to detect failures. A large percentage of maintenance time is taken up by a fault finding and thus increases maintenance costs and production losses.

The maintenance function is defined as the distribution of time that the machine (technical system) spends "in failure".

Determining the availability makes it possible to optimize the maintenance function, identify the important parameters that affect the maintenance function and represent the basic indicators of the production system efficiency.

The availability of technical systems

The availability is calculated based on a time state picture, in which the times when the system in a good condition, the "up-time" state, is changed with the times when the system is out of order, the "down-time" state). The time picture of the state can be shown in Figure 6. The time when the system is in a good condition can be divided into an inactive time, i.e. the time while the system is waiting for work (stand-by) (t_{11}) and the time when the system is working (t_{12}). The time when the system is in failure is divided into: organizational time (t_{21}), logistic time (t_{22}) and active repair time (t_{23}) which can be the time for corrective repairs (t_{231}) and time for preventive repairs (t_{232}). [6]

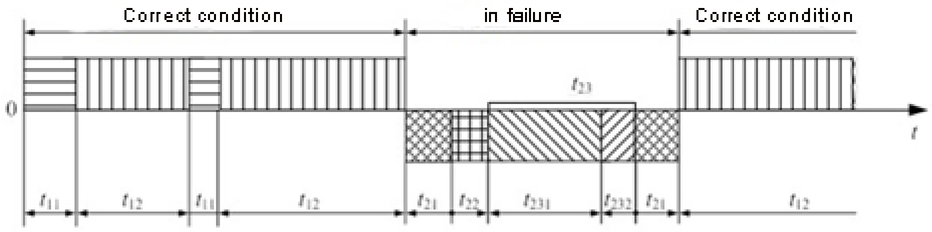


Figure 6 *Time image condition* [6]

The availability is determined as the quotient of the total time during which the system is in a good condition and the total time that makes the time in a good condition and time in failure (Operational availability). [6]

$$A(t) = \frac{\sum t_{11}, t_{12}}{\sum t_{11}, t_{12}, t_{21}, t_{22} t_{231}, t_{232}} \quad [6]$$

2 DATA STRUCTURE OF FAILURE. STATISTICAL PROCESSING OF FAILURE DATA

There is no machine (rotary excavator) that works without failure. Failures on rotary excavators have negative production and economic effects, and the goal of maintenance and operation function is to minimize these negative consequences.

A failure or malfunction is the cessation of an element ability to perform its function. There is a complete (stoppage of the machine operation) and partial failure (the machine operates but with worsened characterristics). [1]

Based on the data obtained from Elektroprivreda Srbije, which also includes the open pit "Drmno", databases related to the mechanical (damage to the superstructure bearings, cracking of caterpillars, tooth replacement, etc.), electrical (cable breakdown, TT connection interruption, interruption of blockage, etc.) were formed as well as the other failures (overhaul, service, conditional stop due to the bad weather conditions, etc.) of the SchRs 800.15/1.5 rotary excavator for a period of 3 years (2016, 2017 and 2018).

Figure 7 shows the layout of one of database. In each cancellation database there is a column in which the date, the object on which the failure occurred (delay), the beginning of delay, the end of delay and the total time in delay.

Determining the affiliation of sample to the theoretical distribution can be done by applying the χ^2 - test, i.e. the agreement of empirical function *F*(x)* with the assumed theoretical distribution function *F(x)* is checked. [8]

The Hi-square test was used to determine whether there was a significant difference between the expected frequency distributions and observed frequency distributions in one or more data categories.

Table 2 shows the results of applying the χ^2 - test.

	A	B	C	D	E	F	G	H	I	J
1										
2	Datum	Mesec	Godina	Sistem	Objekat	Zastoj	Početak zastoja	Kraj zastoja	Vreme zastoja	Ukupno vreme zastoja u minutima
944	5/8/2016	MAJ	2016	BTD SchRs-800	BAGER SchRs-800	ELEKTRO	7:00:00 AM	9:40:00 AM	2:40	160
965	5/11/2016	MAJ	2016	BTD SchRs-800	BAGER SchRs-800	ELEKTRO	3:00:00 PM	6:30:00 PM	3:30	210
966	5/11/2016	MAJ	2016	BTD SchRs-800	BAGER SchRs-800	ELEKTRO	11:00:00 PM	11:35:00 PM	0:35	35

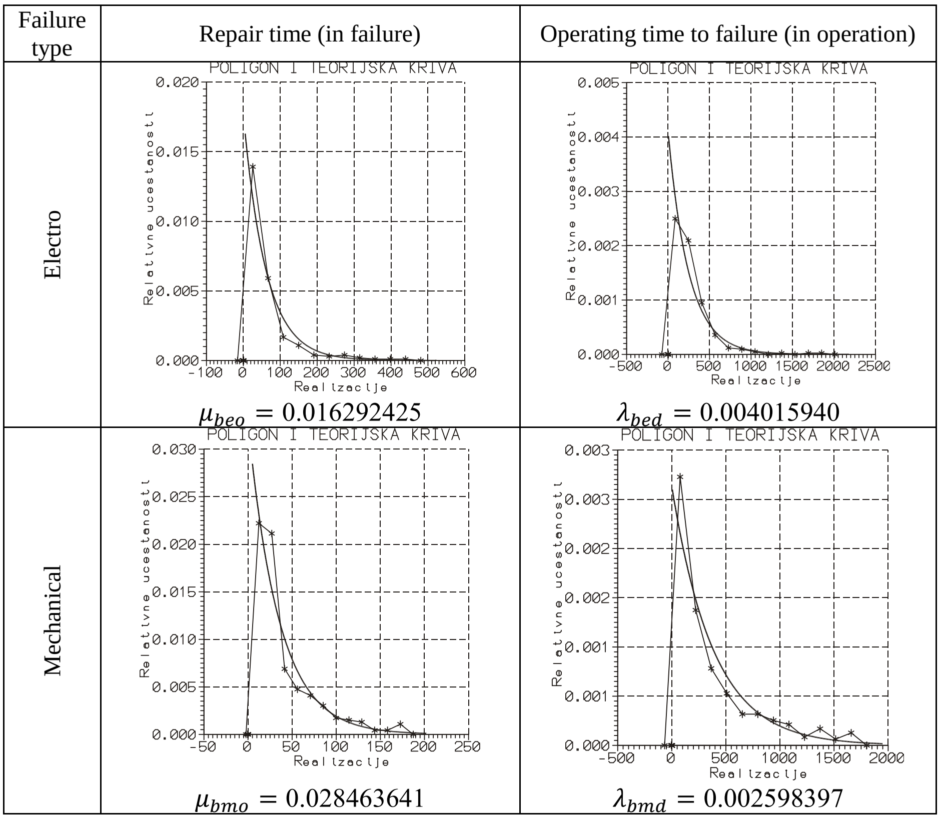
Figure 7 *Database form - electrical downtime*

Table 2 *Results of application the $\chi 2$ test*

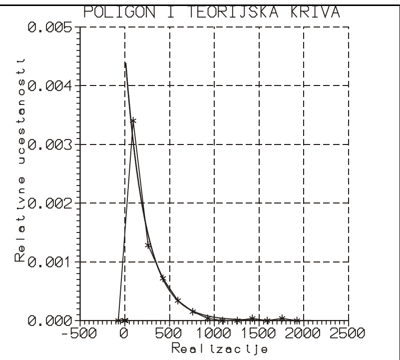
Ord. No.	Object	Delay type	Sample size	Distribution of repair time		Distribution between failure times	
				Type	**Parameter μ**	**Type**	**Parameter λ**
1.	EXCAVATOR SchRs-800.15/1,5	Electro	262	E1	0.016292425	E1	0.004015940
2.	EXCAVATOR SchRs-800.15/1,5	Mechanical	359	E1	0.028463641	E1	0.002598397
3.	EXCAVATOR SchRs-800.15/1,5	Others	161	E1	0.004390628	E1	0.004407482
4.	EXCAVATOR SchRs-800.15/1,5	E+M+O	782	E1	0.019389661	E1	

E1 – Exponential distribution,
λ – *exponential distribution parameter - failure intensity,*
μ – *exponential distribution parameter - maintenance intensity.*

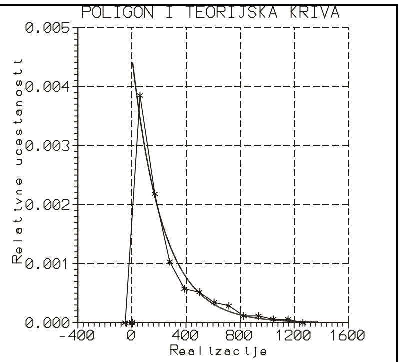
Figure 8 shows the exponential distributions of electrical, mechanical and other failures with the values of parameter λ (exponential distribution parameter - failure intensity) and parameters μ (exponential distribution parameter - maintenance intensity).



Others

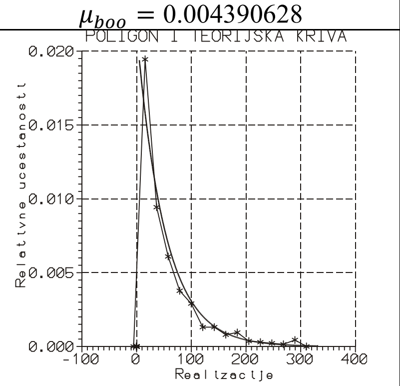


$\mu_{boo} = 0.004390628$



$\lambda_{bod} = 0.004407482$

Mechanical+Electro+Others



$\mu_{bo} = 0.019389661$

Figure 8 *Exponential distributions of electro, mechanical and other failures*

μ_{beo} – maintenance intensity of the electrical elements of excavator
μ_{bmo} – maintenance intensity of the excavator machine elements
μ_{boo} – maintenance intensity of the other failures
μ_{bo} – maintenance intensity of the SchRs 800.15/1.5 excavator
λ_{bed} – failure rate of the excavator electrical elements
λ_{bmd} – failure rate of the excavator machine elements
λ_{bod} – intensity of the other failures

3 ANALYTICAL EXPRESSION FOR THE SCHRS-800.15/1.5 EXCAVATOR AVAILABILITY

3.1 Reliability of the SchRs-800.15/1.5 excavator

Reliability of the electrical elements of excavator, based on the testing of sample of the operating time to failure, can be shown by the exponential distribution forms:

$$R_E(t) = e^{-\lambda_{bed} \cdot t} = e^{-0.004015940 \cdot t},$$

where: λ_{bed} $[1/h]$ - failure rate of the excavator electrical elements.

The average operating time between the failures, excavator electrical elements, $MTBF_{be}$ is equal to:

$$MTBF_{be} = \frac{1}{\lambda_{bed}} = \frac{1}{0.004015940} = = 249.01\ h.$$

The function of restoring the electrical elements of excavator $H_{be}(t)$ is of the form:

$$H_{be}(t) = \lambda_{bed} \cdot t.$$

For a period of one year (8760 h), the value of restoring function of the electrical elements of excavator has the value:

$$H_{be}(8760) = 0.004015940 \cdot 8760 = 35.18,$$

which means that the expected number of failures of the electrical elements of excavator SchRs-800.15/1.5 for one year is equal to ~ 36.

Reliability of the machine elements of excavator, based on the testing of sample of operating time to failure, can be shown by the exponential distribution form:

$$R_M(t) = e^{-\lambda_{bmd} \cdot t} = e^{-0.002598397 \cdot t},$$

where: λ_{bmd} [1/h] - failure rate of the excavator machine elements

The mean operating time between failures, excavator machine elements, $MTBF_{bm}$ is equal to:

$$MTBF_{bm} = \frac{1}{\lambda_{bmd}} = \frac{1}{0.002598397} = = 384.85\ h.$$

The function of restoring the mechanical elements of excavator $H_{bm}(t)$ is of the form:

$$H_{bm}(t) = \lambda_{bmd} \cdot t.$$

For a period of one year (8760 h), the value of restoring function of the mechanical elements of excavator has the value:

$$H_{bm}(8760) = 0.002598397 \cdot 8760 = = 22.76,$$

which means that the expected number of failures of the mechanical elements of excavator SchRs-800.15/1.5 for one year is equal to ~ 23.

Reliability of the excavator connected to the other failures, based on the testing of sample of operating time to failure, can be shown by the exponential distribution form:

$$R_O(t) = e^{-\lambda_{bod} \cdot t} = e^{-0.004407482 \cdot t},$$

where: λ_{bod} [1/h] – intensity of the other failures.

The mean operating time between other failures of excavator, $MTBF_{bo}$ is equal to:

$$MTBF_{bo} = \frac{1}{\lambda_{bod}} = \frac{1}{0.004407482} = = 226.90\ h.$$

The function of restoring the other failures of excavator $H_{bo}(t)$ is of the form:

$$H_{bo}(t) = \lambda_{bod} \cdot t.$$

For a period of one year (8760 h), the value of restoring function of the other failures of excavator has the value:

$$H_{bo}(8760) = 0.004407482 \cdot 8760 = = 38.61,$$

which means that the expected number of other failures of the SchRs-800.15/1.5 excavator for one year is equal to ~ 39.

The adopted principle at the open pits of lignite of EPS, when it comes to consider the failure of rotary excavators, is that the electrical, mechanical and other failures are independent of each other. If any type of failure occurs, the excavator stops working. Based on this, the reliability of the SchRs-800.15/1.5 excavator can be shown by a serial connection. (Figure 9)

Figure 9 *Reliability of the SchRs-800.15/1.5 excavator - serial connection (electrical - mechanical - other)*

Reliability of the SchRs-800.15/1.5 excavator $R_b(t)$ is equal to:

$$R_b(t) = R_E(t) \cdot R_M(t) \cdot R_O(t),$$

$$R_b(t) = e^{-(\lambda_{bed}+\lambda_{bmd}+\lambda_{bod})\cdot t} =$$

$$= e^{-\lambda_{bd}\cdot t} = e^{-0.011021819\cdot t},$$

where: λ_{bd} $[1/h]$ – failure rate of the SchRs-800.15/1.5 excavator

The unreliability function of the SchRs-800.15/1.5 $F_b(t)$ excavator is equal to:

$$F_b(t) = 1 - R_b(t) = 1 - e^{-\lambda_{bd}\cdot t} =$$

$$= 1 - e^{-0.011021819\cdot t}.$$

The mean operating time of excavator between the failures, $MTBF_b$ is equal to:

$$MTBF_b = \frac{1}{\lambda_{bd}} = \frac{1}{0.011021819} = 90.73\ h.$$

The function of restoring the excavator $H_b(t)$ is of the form:

$$H_b(t) = \lambda_{bd} \cdot t.$$

For a period of one year (8760 *h*), the value of restoring function of excavator has the value:

$$H_b(8760) = 0.011021819 \cdot 8760 =$$

$$= 96.55,$$

which means that the expected number of failures of the SchRs-800.15/1.5 excavator for one year is equal to ~ 97

3.2 Maintenance convenience function of the SchRs-800.15/1.5 excavator

The maintenance convenience function of the SchRs-800.15/1.5 $M_b(t)$ excavator was determined by testing a sample consisting of the time required for repair due to electrical, mechanical and other failures. The maintenance convenience function is of the exponential shape:

$$M_b(t) = 1 - e^{-\mu_{bo}\cdot t} =$$

$$= 1 - e^{-0.019389661\cdot t},$$

where: μ_{bo} $[1/h]$ – maintenance intensity of the SchRs-800.15/1.5 excavator

The average repair time of the excavator, the failure time, MDT_b is equal to:

$$MDT_b = \frac{1}{\mu_{bo}} = \frac{1}{0.019389661} = 51.57\ h.$$

The mean repair times due to the failures of electrical and mechanical elements and other failures are:

Electrical:

$$MDT_{be} = \frac{1}{\mu_{beo}} = \frac{1}{0.016292425} =$$

$$= 61.38\ h.$$

Mechanical:

$$MDT_{bm} = \frac{1}{\mu_{bmo}} = \frac{1}{0.028463641} =$$

$$= 35.13\ h.$$

Others:

$$MDT_{bo} = \frac{1}{\mu_{boo}} = \frac{1}{0.004390628} =$$

$$= 227.76\ h.$$

3.3 Availability of the SchRs-800.15/1.5 excavator

Statistical processing of data on operating time to failure and repair time of the SchRs-800.15/1.5 excavator showed that the unreliability function of excavator can be described by the exponential distribution form $F_b(t) = 1 - e^{-\lambda_{bd} \cdot t}$, while the function of benefits the excavator maintenance can also be described by the exponential distribution form $M_b(t) = 1 - e^{-\mu_{bo} \cdot t}$.

Finally, based on the results of statistical data processing on operating time to failure and repair time, the analytical expression for availability of the SchRs-800.15/1.5 excavator is of the following form:

$$A(t) = \frac{\mu_{bo}}{\lambda_{bd}+\mu_{bo}} + \frac{\lambda_{bd}}{\lambda_{bd}+\mu_{bo}} \cdot e^{-(\lambda_{bd}+\mu_{bo}) \cdot t},$$

$$A(t) = \frac{0.019389661}{0.011021819+0.019389661} + \frac{0.011021819}{0.011021819+0.019389661} \cdot e^{-(0.011021819+0.019389661) \cdot t},$$

$$A(t) = 0.637577027 + 0.362422973 \cdot e^{-0.0304114800 \cdot t},$$

where: $k_A = \frac{\mu_{bo}}{\lambda_{bd}+\mu_{bo}} = 0.637577027$ – availability coefficient, i.e. stationary availability value A.

The approximate time t_{stac} , when the excavator availability reaches a stationary value of A, can be determined based on the expression:

$$\frac{|A(t)-A|}{A} \times 100 \leq 1\% \quad \rightarrow \quad t_{stac} = t.$$

Solving the above inequality gives that: $t_{stac} = 133\ h$.

The change in availability of the SchRs-800.15/1.5 rotary excavator over time is shown in Figure 10.

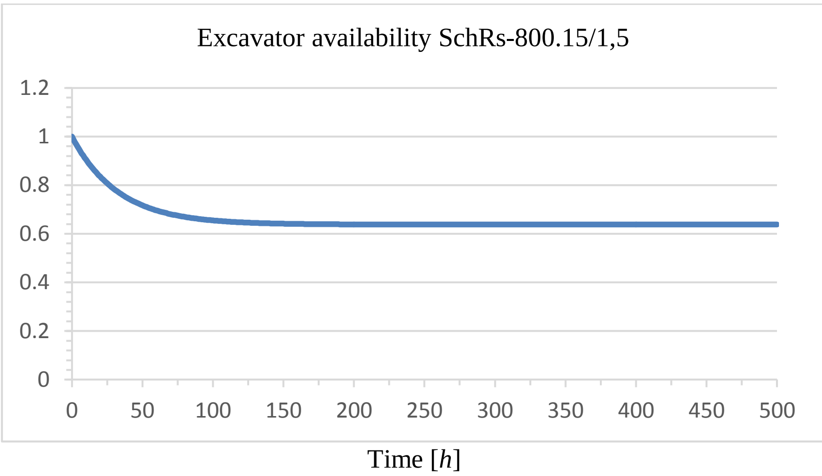


Figure 10 *The change in availability of the SchRs-800.15/1.5 excavator*

4 CONCLUSION

The application of analytical method for determining the availability and other parameters of the operation reliability of rotary excavators allows efficient determination the key factors of system operation as a function of time. By modeling the work process as a function of time, applying the appropriate statistical methods, the functional dependence of parameters such as availability, failure time, work time, etc. is defined. as a function of time.

In order to determine the relevant indicators, it is necessary to have data on the operation and failures of system for a longer period of time, and then to select the characteristic cases. Within the selected characteristic cases, it is necessary to determine a representative sample and perform the presented analysis on it.

Statistical analysis according to the presented methodology and performed on a representative sample, for the SchRs 800.15/1.5 rotary excavator, shows that the intensity of all failures (λ_{bd}) is 0.011021819 and the maintenance intensity (μ_{bo}) is 0.019389661.

The values of these parameters indicate at what stage of life time the rotary excavator is located. In the specific case, the rotary excavator SchRs 800.15/1.5, according to the curve of tub, is in the operation phase, which corresponds to the real situation. The calculated parameters serve to determine the availability of a specific rotary excavator and system as a whole, which is the basic input data for production planning at the lignite open pits of EPS, but also the other activities in the field of planning, monitoring of production or maintenance of equipment.

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