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LOST PRODUCTION COSTS OF THE OVERBURDEN EXCAVATION SYSTEM CAUSED BY RUBBER BELT FAILURE

KOSZTY UTRACONEJ PRODUKCJI WYWOŁANE USZKODZENIEM GUMOWEJ TAŚMY TRANSPORTOWEJ W UKŁADZIE MASZYNOWYM DO ZDEJMOWANIA NADKŁADU

In this paper the average malfunction costs (lost production) of the overburden excavation system on the Tamnava - East field open-pit mine caused by the failure of belt conveyor rubber belts which work on the bucket wheel excavator, belt wagon and spreader are determined, i.e. the unit cost of system malfunction per hour of belt conveyor work during belt lifetime. The basis for the calculation of malfunction costs is presented by the proposed methodology for the analysis of rubber belt working time to failure based on the fact that working time until sudden failure (tear, breakthrough) can be described by exponential distribution while working time until gradual failure can be described by normal distribution. The proposed methodology as well as the expression for malfunction cost determination can be used, with appropriate adoptions, in the analysis of the functioning of other open-pit mines for better planning of malfunctions, requirements for spare rubber belts as well reductions in working costs, i.e. they can indicate better (optimal) maintenance strategy.

Keywords: *Malfunction costs, Rubber belt failure, Failure time distribution.*

W prezentowanym artykule wyznaczono średnie koszty awarii (utraconej produkcji) układu maszynowego do zdejmowania nadkładu, wykorzystywanego w kopalni odkrywkowej Tamnava - East field, spowodowanej uszkodzeniem przenośnikowych taśm gumowych zastosowanych w koparce wielonaczyniowej, samobieżnym przenośniku taśmowym oraz zwałowarce. Koszt zdefiniowano jako jednostkowy koszt awarii układu na godzinę pracy przenośnika taśmowego podczas cyklu życia taśmy. Podstawę obliczeń kosztów awarii stanowiła zaproponowana metoda analizy czasu pracy taśmy gumowej do uszkodzenia, oparta na fakcie, iż czas pracy do nagłego uszkodzenia (rozerwanie, przebicie) można opisać za pomocą rozkładu wykładniczego, natomiast czas pracy do stopniowego uszkodzenia – za pomocą rozkładu normalnego. Proponowana metodologia, jak również równania do wyznaczania kosztów awarii mogą być wykorzystywane, przy odpowiedniej adaptacji, do analizy funkcjonowania innych kopalni odkrywkowych służąc lepszemu planowaniu awarii, zapotrzebowania na zapasowe pasy gumowe oraz redukcji kosztów pracy. Mogą one, innymi słowy, wskazywać (optymalną) strategię utrzymania ruchu.

Słowa kluczowe: *Koszty awarii, uszkodzenie taśmy gumowej, rozkład czasu uszkodzenia.*

1. Introduction

Within the public company - Electric Power Industry of Serbia (EPS), during the observed period (1991-2009), coal (lignite) was excavated from six open-pit mines in two basic basins, Kolubara and Kostolac. Continuous mechanisation was used for the excavation of lignite and overburden on all of the open-pit mines. The work of the Tamnava – East field open-pit mine located in the Kolubara basin, with an average annual lignite production of 7.5 million tons and excavation of 10 million m^3lm (cubic meters of loose material) of overburden, is observed for the gathering and analysis of data about the work of mechanisation in the sense of malfunctions caused by failures of the rubber belts on the belt conveyors. It is important to underline that almost all the lignite production from the Tamnava – East field open-pit mine was used for the production of electric energy.

The excavation, removal and disposal of overburden are prerequisites for lignite exploitation. The composition of overburden which has to be excavated is heterogeneous and consists of gravel and several types of clay. From 1979 continuous mechanisation was used for overburden excavation on the Tamnava – East field open-pit mine. Mechanisation consisted of several machines such as: a bucket wheel excavator (theoretical capacity Q=4100 m^3lm/h), mobile transfer conveyors (belt wagons), spreaders and a belt conveyor system. The rubber belts with iron cord (St=1600 N/cm), which are used on the conveyors on the machines are 1600 mm wide. While receiving excavated material, in addition to the expected wearout, sudden rubber belt failures occur due to the impact caused by large excavated pieces. Transported material also has a dominant influence on both the reliability and durability of rubber belts (of the same quality). Namely, the lifetime of rubber belts is from 4 to 5 times longer during the transportation of lignite than in the case of overburden transportation [13].

Due to those facts and the subsequent the lack of data for analysing rubber belt failure during lignite transportation in the observed period, in this paper only rubber belt failure on belt conveyors in the case of overburden transportation, which arise more often than in the case of lignite transportation, will be analysed.

In this paper the methodology for the analysis of the rubber belts working time to failure, based on the fact that the working time until sudden failure (tear, breakthrough) can be described by exponential distribution while that until gradual failure can be described by normal distribution, is proposed and verified. Using the proposed methodology the data related to the failure of belt conveyor rubber belts, which work in the overburden excavation system (bucket wheel excavator, belt wagon, spreader), are analysed (statistically processed) for the period from 1991 to 2009.

Six rubber belts of different lengths which work on specified machines are analysed in order to determine the average malfunction costs (lost production) of the overburden excavation system on the Tamnava - East field open-pit mine caused by the failure of belt conveyor rubber belts, i.e. the unit cost of system malfunction per hour of belt conveyor work during belt lifetime.

The overburden excavation systems work 24 hours a day 7 days a week i.e. round the clock, and maximum production can only be achieved through the maximum usage of equipment. However, poor design solutions and other unexpected problems limit their performance and effectiveness. Those problems, caused by inadequate reliability, maintainability characteristics and poor maintenance strategy, lead to unexpected breakdowns and failures which result in huge economic losses [5, 9].

1.1. Literature review

Mining equipment complexity and size are continually increasing and therefore unplanned failures of mining equipment cause higher repair (replacement) costs than the planned maintenance or repair. On the other side, lost production costs are even more important. Those facts underline the importance of a reliability study into the operation of mining equipment [2].

With the beginning of the development of systems sciences, practically after World War II, reliability engineering as one of the main concepts of technical systems assessment experienced the most progressive development. Barabady and Kumar [2] performed reliability analysis for each subsystem of two analysed chrushing plants by using failure data in order to estimate the parameters of theoretical distributions which provide the best fit for characterizing the failure pattern. Uzgoren and Elevli [16] showed that the times between successive failures for the mechanical systems of a dragline are not independent and identically distributed and use the nonhomogeneous Poisson process to describe the trend; i.e. the time between failures as a function of time, in order to predict the time to the next failure and thus determine the expected number of failures and reliability for different time periods. Hoseine et al. [7] analysed the reliability of the water system which plays a critical role in the work of longwall shearer machines. The water system is modelled as a system of three serially connected subsystems. The empirical data about the functioning of the water system are statistically analysed in order to determine which subsystem has the highest reliability importance. In that sense, Uzgoren et al. [15] claim that the reliability function is the base of reliability investigations and hence perform a comparative analysis of twenty studies of mining machinery and equipment reliability, which emphasizes the importance of reliability research especially in the mining industry. There has been no analysis of conveyor rubber belts.

Reliability research and failure analyses of the belt conveyors are very important, due to the costs of the technological processes in which belt conveyors are an integral element. Belt puncture resistance, slit resistance, belt fatigue testing, and the investigation of belt splices are the basic experimental methods of assessment of reliability and remaining rubber belt capabilities – resources [6]. Bindzar et al. [3] propose several numerical methods in order to assess the remaining capabilities of rubber belts due to service quality.

Chookah et al. [4], used the superposition of the probability functions to compose the degradation effects (phenomena: fatigue, corrosion) on oil pipelines. The super-position of the probability functions model unites various phenomena that have the same effect. The same applies in the case of different categories of rubber belt failure and degradation.

The influence factors on the maintenance costs are analysed and investigated by Yue et al. [17], in order to establish reasonable maintenance strategies, improve the efficiency of equipment operation, reduce costs and optimize the design of mining machines. Based on the time-to-failure density function, Huang et al. [8] analysed the influence of the maintainability and the maintenance policy in general on service life. Liu et al. [10] used the Weibull probability density function for reliability simulation so as to optimize the design and reduce the maintenance costs of chain conveyors. Elevli and Demirci [5] analysed the impact of corrective, preventive and mixed maintenance activities (strategies) of mining equipment on reliability and profitability, defining the relationship between reliability and profitability. The common conclusion reached in these articles is a well-known fact – increasing reliability (up to a certain level) can reduce maintenance costs. For rubber belts, it is significant to observe this fact in relation to belt length; i.e. to find the mathematical dependence between maintenance costs, failure rates and belt length.

2. Methodology for failure analysis and indexes of excavation system functioning

From the reliability point of view an overburden excavation system can be considered as a serial system, meaning that the failure of any machine or sub-system leads to the malfunction of the whole system.

Data pertaining to the malfunction of the overburden excavation system caused by rubber belt failure are taken from the maintenance diary (plant records) of the Tamnava – East field open-pit mine for a 19 year period (from 1991 to 2009). Six closed rubber belts of different lengths, which work on the bucket wheel excavator, belt wagon and spreader, are taken into consideration. The lengths of those rubber belts are: L_1=27.6 m, L_2=51.6 m, L_3=75 m, L_4=81.5 m, L_5=106.1 m and L_6=158.2 m.

The basis of the proposed methodology is the idea that the causes of rubber belt failure can be divided into two categories i.e. that the distributions of working time to failure caused by different failure categories are not the same.

Depending on the nature of the cause which leads to the malfunction of the overburden excavation system, the data about rubber belt failure are divided into two categories. The first category “gradual failures” comprises failure caused by:

- worn out belt,
- belt runout,
- belt replacement due to annual maintenance, and
- belt replacement due to capital maintenance,

while the second category “sudden failures” comprise failure caused by:

- damage to junctions,
- breakthrough,
- impact, and
- belt tearing.

Since the data from the maintenance diary only tells us when the failure of each rubber belt occurred (date) and which cause lead to such failure, additional computation to determine the time each rubber belt worked until failure has to be carried out.

In order to obtain the “effective working time per year [h]” for each analysed rubber belt regardless of the nature of failure (Tables 2, 3, 4, 5, 6, 7 and 10), the number of days the rubber belt functioned properly in a specific year is multiplied by the appropriate annual coefficient of time utilisation k_t (Table 1) of the overburden excavation system. The coefficient of time utilisation k_t is calculated based on 8760 working hours per year.

In addition to the values for k_t, Table 1 also shows: the values for the coefficient of capacity utilization k_q, the annual quantities of excavated overburden Q_{ob} [m3lm/year] as well as the annual quantities of excavated lignite Q_l [t/year] on the Tamnava – East field open-pit mine in the observed period (from 1991. to 2009.), which are necessary for the calculation of the average malfunction costs of the overburden excavation system.

2.1. Analysis of rubber belt working time to "gradual failures"

The effective working time per year (obtained as described in the previous chapter), the total working time between failures (interventions) and the mean time to failure caused by gradual failures – $MTTF_{gf}^{L_i}$, for each of the analysed rubber belts, are shown in Tables 2, 3, 4, 5, 6 and 7.

In the same time period the shorter rubber belts receive material more often and perform more deflections around the pulleys then their longer counterparts. In the case of gradual failures those facts lead to faster wearout and therefore to shorter working (mean) time to failure i.e. shorter lifetime, which is shown in Table 8.

Table 1. Indexes of overburden excavation system functioning [1]

Year	Coefficient of time utilisation (k_t)	Coefficient of capacity utilisation (k_q)	Quantity of excavated overburden *Qob* [m³lm/year]	Quantity of excavated lignite *Ql* [t/year]
1991	0.53	0.55	10501264.80	10133116.00
1992	0.47	0.51	9730550.70	11709953.00
1993	0.56	0.56	11381546.80	10650709.00
1994	0.53	0.48	9019914.80	11549667.00
1995	0.48	0.46	8016591.70	11911686.00
1996	0.54	0.41	8875252.10	8510809.00
1997	0.52	0.44	9319011.00	9160856.00
1998	0.38	0.37	7524601.50	8115122.00
1999	0.37	0.44	7945520.70	8127768.00
2000	0.32	0.39	6676672.60	8014754.00
2001	0.33	0.43	7856667.00	5616794.00
2002	0.31	0.53	9574307.60	3239635.00
2003	0.43	0.56	10237852.30	5870371.00
2004	0.43	0.45	7911295.60	4798317.00
2005	0.41	0.44	10213457.80	4859044.00
2006	0.59	0.43	10196516.20	4805146.00
2007	0.58	0.49	10086417.90	5036367.00
2008	0.61	0.44	10397788.70	5029341.00
2009	0.47	0.43	3318868.80	3479869.00
	Average: $\bar{k}_t = 0.466$	Average: $\bar{k}_q = 0.464$	Total: $Q_{ob}^{tot} = 168784098.6$	Total: $Q_l^{tot} = 140619324$

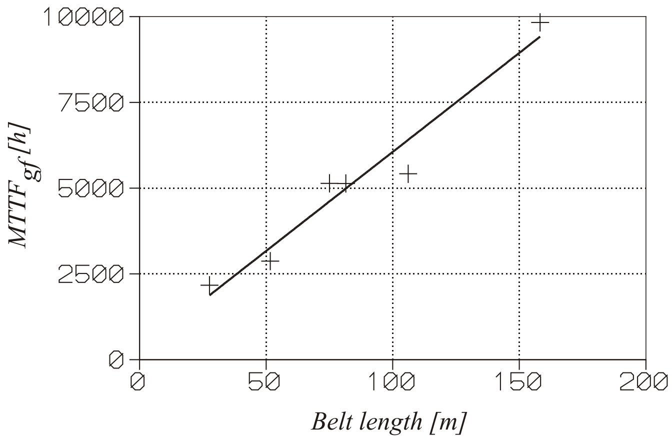

Fig. 1. Mean time to gradual failures as a function of rubber belt length

The analysed rubber belts have different lengths and in order to obtain a homogenous (representative) sample for further analysis, it is necessary to recalculate the total working time of the shorter rubber belts according to the longest rubber belt (L_6=158.2 m). Therefore, the mean time to failure ($MTTF_{gf}^{L_i}$) caused by gradual failures, as a function of the rubber belt length is determined (L_i) (Table 8). For that purpose the linear regression model is assumed.

The parameters of linear regression and the correlation coefficient are determined using statistical software SPSS [14].

The required linear regression, shown on Figure 1, has the following form:

$$MTTF_{gf} = 281.41+57.734\cdot L. \qquad (1)$$

The correlation coefficient, the measure of the strength of linear dependence, has the following value $r = 0.976$.

The value of the correlation coefficient is very close to one, which means that the dependence between the mean time to failure, caused by gradual failures – $MTTF_{gf}^{L_i}$ and rubber belt length – L_i is absolute (strong). [11]

In order to identify whether the recalculation of the total working time of the shorter rubber belts according to the longest rubber belt makes sense, the existence of statistical dependence between the mean time to failure, caused by gradual failures and rubber belt length also needs to be checked.

Verifying the statistical dependence between the mean time to failure and rubber belt length, for a small sample case ($n<30$), is done by using Student's *t*-test. Statistical dependence exists if [11]:

$$|t_0|>t_{\alpha/2,n-2}, \qquad (2)$$

where:

$t_0 = \dfrac{r\sqrt{n-2}}{\sqrt{1-r^2}}$ = 9.02169 – decision statistics ($r = 0.976$ – correlation coefficient, n= 6),

$t_{\alpha/2,n-2}$ – theoretical value of Student's t distribution (for α= 0.05), i.e. $t_{\alpha/2,n-2}=t_{0.025,4}$= 2.776.

According to the previous expressions, it can be concluded that statistical dependence between the mean time to failure, caused by gradual failures – $MTTF_{gf}^{L_i}$ and rubber belt length – L_i exists because

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[1] Source: Public company Electric Power Industry of Serbia.

Table 2. Rubber belt working time to gradual failure – L_1= 27.6 m

No.	Year	No. of days	Effective working time per year [h]	Total working time [h]
1	1992	37	417.36	2258.64
	1993	137	1841.28	
2	1994	242	3078.24	3078.24
3	1994	53	674.16	2010.48
	1995	116	1336.32	
4	1997	114	1422.72	1422.72
5	1998	122	1112.64	1112.64
6	2007	96	1336.32	2361.12
	2008	70	1024.80	
7	2008	88	1288.32	1288.32
8	2008	113	1654.32	1654.32
9	2008	95	1390.80	4323.60
	2009	260	2932.80	
			$MTTF_{gf}^{L_1}$ [h]	**2167.79**

Table 3. Rubber belt working time to gradual failure – L_2= 51.6 m

No.	Year	No. of days	Effective working time per year [h]	Total working time [h]
1	1992	135	1522.80	3095.28
	1993	117	1572.48	
2	1993	248	3333.12	4134.48
	1994	63	801.36	
3	1995	238	2741.76	6111.36
	1996	260	3369.60	
4	1996	51	660.96	660.96
5	1996	55	712.80	3208.80
	1997	200	2496.00	
6	1998	107	975.84	1482.00
	1999	57	506.16	
7	2008	254	3718.56	3718.56
8	2009	48	541.44	541.44
			$MTTF_{gf}^{L_2}$ [h]	**2869.11**

Table 4. Rubber belt working time to gradual failure – L_3= 75 m

No.	Year	No. of days	Effective working time per year [h]	Total working time [h]
1	1993	149	2002.56	4304.88
	1994	181	2302.32	
2	1995	101	1163.52	1163.52
3	1995	72	829.44	9254.40
	1996	366	4743.36	
	1997	295	3681.60	
4	1997	70	873.60	3618.72
	1998	301	2745.12	
5	1999	143	1269.84	8377.68
	2000	366	2810.88	
	2001	365	2890.80	
	2002	189	1406.16	
6	2007	67	932.64	5310.00
	2008	299	4377.36	
7	2008	67	980.88	3924.96
	2009	261	2944.08	
			$MTTF_{gf}^{L_3}$ [h]	**5136.31**

Table 5. Rubber belt working time to gradual failure – L_4= 81.5 m

No.	Year	No. of days	Effective working time per year [h]	Total working time [h]
1	1991	155	1971.60	10038.00
	1992	366	4128.48	
	1993	293	3937.92	
2	1993	72	967.68	4440.24
	1994	273	3472.56	
3	1997	134	1672.32	3186.24
	1998	166	1513.92	
4	1998	197	1796.64	1796.64
5	1999	143	1269.84	7670.88
	2000	366	2810.88	
	2001	365	2890.80	
	2002	94	699.36	
6	2007	35	487.20	4527.84
	2008	276	4040.64	
7	2008	90	1317.60	
	2009	263	2966.64	4284.24
			$MTTF_{gf}^{L_4}$ [h]	**5134.87**

the calculated value of decision statistics is greater than the theoretical value of Student's *t* distribution.

In order to obtain a representative sample, the correction (recalculation) of the working times to the gradual failures (TTF) of the rubber belts is done in the following way: each working time to gradual failure of the shorter rubber belts (L_1, L_2, L_3, L_4, L_5) is multiplied by the quotient of mean times to gradual failure, obtained using the linear dependence (1), of the longest (L_6) and the given rubber belt. The obtained results are shown in Table 9.

The verification of the assumption that the corrected sample, shown in Table 9, can be represented by normal distribution:

$$f(t) = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot \exp\left[-\frac{(t-\bar{t})^2}{2 \cdot \sigma^2} \right] \tag{3}$$

Table 6. Rubber belt working time to gradual failure - L_5= 106.1 m

No.	Year	No. of days	Effective working time per year [h]	Total working time [h]
1	1992	284	3203.52	5542.08
	1993	174	2338.56	
2	1994	285	3625.20	3625.20
3	1994	7	89.04	1183.44
	1995	95	1094.40	
4	1995	270	3110.40	5793.12
	1996	207	2682.72	
5	1996	159	2060.64	5055.84
	1997	240	2995.20	
6	1997	125	1560.00	12421.92
	1998	365	3328.80	
	1999	365	3241.20	
	2000	366	2810.88	
	2001	187	1481.04	
7	2008	94	1376.16	4297.68
	2009	259	2921.52	
			$MTTF_{gf}^{L_5}$ [h]	**5417.04**

Table 7. Rubber belt working time to gradual failure - L_6= 158.2 m

No.	Year	No. of days	Effective working time per year [h]	Total working time [h]
1	1991	324	4121.28	10709.28
	1992	366	4128.48	
	1993	183	2459.52	
2	1993	182	2446.08	5130.00
	1994	211	2683.92	
3	1994	154	1958.88	10077.60
	1995	365	4204.80	
	1996	302	3913.92	
4	1997	6	74.88	14035.44
	1998	365	3328.80	
	1999	365	3241.20	
	2000	366	2810.88	
	2001	365	2890.80	
	2002	227	1688.88	
5	2003	288	2972.16	16748.16
	2004	366	3777.12	
	2005	365	3591.60	
	2006	365	5168.40	
	2007	89	1238.88	
6	2007	276	3841.92	5862.24
	2008	138	2020.32	
7	2008	228	3337.92	6248.16
	2009	258	2910.24	
			$MTTF_{gf}^{L_6}$ [h]	**9830.13**

Table 8. Rubber belt lifetime due to gradual failures

i	Belt length L_i [m]	$MTTF_{gf}^{L_i}$ [h]
1	27.6	2167.79
2	51.6	2869.11
3	75	5136.31
4	81.5	5134.87
5	106.1	5417.04
6	158.2	9830.13

where $\overline{t}$ and σ represent the arithmetic mean and standard deviation of the sample, is done by applying the χ^2 – test, using software specially designed for analysing stochastic variables in transport systems [12]. The cumulative value of the test statistic is χ^2_{ts} = 13.404, obtained by dividing the sample shown in Table 9 into 8 classes. The critical value, i.e. the table value for chi-square distribution for 5 degrees of freedom and significance level α = 0.01 is χ^2_{cr} = 15.086. Therefore the corrected sample (Table 9) can be represented (described) by normal distribution, with the arithmetic mean $\overline{t}$ = 9556.69 and standard deviation σ = 4967.05. (Figure 2)

Verification that the corrected sample given in Table 9 fits normal distribution is also done by the one sample Kolmogorov-Smirnov test, where the p-value of the test is 0.464 and the significance level is 0.05, using SPSS statistical software [14].

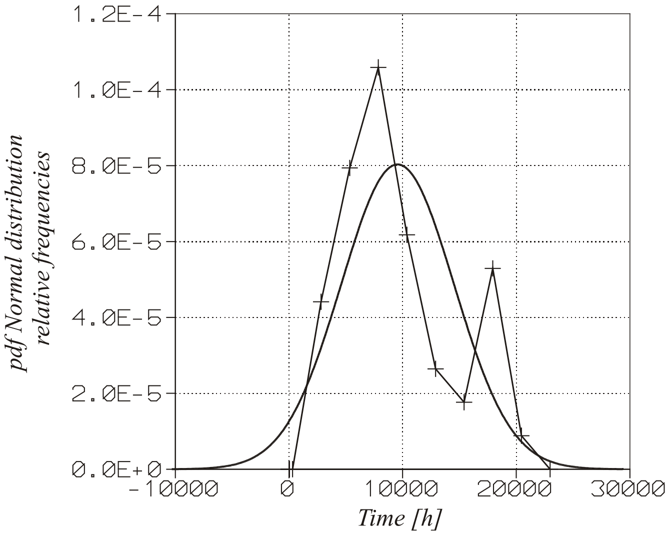

Fig. 2. Pdf of rubber belt working times to gradual failures – normal distribution

2.2. Analysis of rubber belt working time to „sudden failures“

The causes of failure in the second category “sudden failures” are breakthrough, impact, tearing and other damage which in the majority of cases are the result of the stroke exerted by large excavated pieces on the rubber belt. Sudden failures can occur at any moment during the operating of the belt conveyor, regardless of rubber belt length and the time the rubber belt has been in use (new, regenerated etc.). Due to the nature of sudden failures, there is no dependence between the

Table 9. Corrected working times to gradual failures

L_i		TTF [h]	L_i		TTF [h]	L_i		TTF [h]
$L_1 = 27.6$ m	1	11342.09	$L_2 = 51.6$ m	1	8937.88	$L_3 = 75$ m	1	8789.00
	2	15457.82		2	11938.66		2	2375.49
	3	10095.91		3	17647.07		3	18894.12
	4	7144.39		4	1908.58		4	7388.11
	5	5587.28		5	9265.68		5	17104.18
	6	11856.70		6	4279.40		6	10841.09
	7	6469.48		7	10737.66		7	8013.34
	8	8307.41		8	1563.45			
	9	21711.58						
$L_4 = 81.5$ m	1	18951.70	$L_5 = 106.1$ m	1	8143.97	$L_6 = 158.6$ m	1	10709.28
	2	8383.15		2	5327.15		2	5130.00
	3	6015.61		3	1739.04		3	10077.60
	4	3392.05		4	8512.86		4	14035.44
	5	14482.59		5	7429.45		5	16748.16
	6	8548.54		6	18253.74		6	5862.24
	7	8088.63		7	6315.35		7	6248.16

working time and length of the rubber belts and therefore there is no need for sample correction (recalculation).

The effective working times per year of rubber belt due to "sudden failures", as in the previous case, are obtained by multiplying the number of days the rubber belt functioned properly in a specific year by the appropriate annual coefficient of time utilisation K_t (Table 1) of the overburden excavation system.

The effective working time per year for each rubber belt is shown in Table 10, where the column "Total working time [h]" represents the sample which will be tested for consistence with exponential distribution. The mean time to sudden failures $MTTF_{sf}^{L_i}$ is shown in the far right column of Table 10.

The verification of the assumption that the sample, shown in Table 10 (sixth column), can be represented by exponential distribution:

$$f(t) = \lambda \cdot \exp\left[-\lambda \cdot t\right] \tag{4}$$

where λ represents the parameter of exponential distribution ("sudden failure" intensity), is done by applying of the χ^2 – test, using also software specially designed for analysing stochastic variables in transport systems [12].

The cumulative value of the test statistic is $\chi^2_{ts} = 1.881$, obtained by dividing the sample shown in Table 10 (sixth column) into 7 classes. The critical value, i.e. table value for chi-square distribution for 5 degrees of freedom and significance level $\alpha = 0.01$ is $\chi^2_{cr} = 15.086$. Therefore the sample shown in Table 10 can be represented (described) by exponential distribution, with the parameter $\lambda = 0.0005$. (Figure 3).

The verification that the sample given in Table 10 fits exponential distribution is also done by the one sample Kolmogorov-Smirnov test, where the p-value of the test is 0.888 and the significance level is 0.05, using SPSS statistical software [14].

3. Malfunction costs of the overburden excavation system caused by belt conveyor rubber belt failure

As shown in previous chapters, rubber belt failures which causes malfunctions in the belt conveyor i.e. the functioning of the overburden excavation system, can be divided into two categories: sudden failures (exponentially distributed working times to failure) and gradual failures (normally distributed working times to failure). In both cases it is assumed that such failures are instantaneous while failure clear up is carried out by belt replacement. In the case of gradual failures belt replacements can be planned in advance (smaller replacement costs) which cannot be done in the case of sudden failures. Furthermore, when sudden failures occur the rubber belt resource is not fully used.

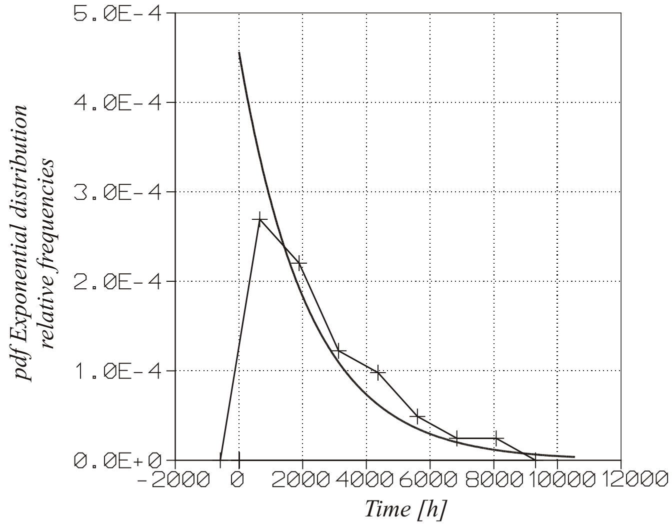

Fig. 3. Pdf of rubber belt working times to sudden failures – exponential distribution

The average malfunction costs (lost production) of the overburden excavation system caused by belt conveyor rubber belt failure, i.e. the unit cost of system malfunction per hour of belt conveyor work during belt lifetime can be calculated using the following expression [1]:

$$\bar{C}_{m_i} = \frac{c_{pm} + (c_{npm} + c_{nbr}^{L_i}) \cdot H(MTTF_{gf}^{L_i})}{MTTF_{gf}^{L_i}} \tag{5}$$

where:

Table 10. Rubber belt working times to sudden failure

L_i [m]	No.	Year	No. of days	Effective working time per year [h]	Total working time [h]	$MTTF_{sf}^{L_i}$ [h]
$L_i = 27.6$ m	1	1993	122	1639.68	1639.68	**1918.08**
	2	1993	106	1424.64		
		1994	70	890.40	2315.04	
	3	1995	83	956.16	956.16	
	4	1997	168	2096.64		
		1998	103	939.36	3036.00	
	5	1998	51	465.12	465.12	
	6	1998	37	337.44	337.44	
	7	1998	52	474.24		
		1999	87	772.56	1246.80	
	8	1999	32	284.16	284.16	
	9	1999	94	834.72	834.72	
	10	1999	145	1287.60	1287.60	
	11	1999	7	62.16		
		2000	366	2810.88		
		2001	365	2890.80		
		2002	365	2715.60		
		2003	21	216.72	8696.16	
$L_2 = 51.6$ m	1	1994	302	3841.44		3192.24
		1995	127	1463.04	5304.48	
	2	1997	165	2059.20		
		1998	211	1924.32	3983.52	
	3	1998	47	428.64	428.64	
	4	2008	96	1405.44		
		2009	146	1646.88	3052.32	
$L_3 = 75$ m	1	1992	216	2436.48		**1913.04**
		1993	121	1626.24	4062.72	
	2	1993	95	1276.80	1276.80	
	3	1994	184	2340.48		
		1995	192	2211.84	4552.32	
	4	1998	64	583.68		
		1999	222	1971.36	2555.04	
	5	2002	176	1309.44		
		2003	59	608.88	1918.32	
	6	2003	41	423.12	423.12	
	7	2003	23	237.36	237.36	
	8	2003	3	30.96	30.96	

Table 10. Rubber belt working times to sudden failure. (continue)

L_i [m]	No.	Year	No. of days	Effective working time per year [h]	Total working time [h]	$MTTF_{sf}^{L_i}$ [h]
$L_4 = 81.5$ m	1	1998	2	18.24		**2622.88**
		1999	222	1971.36	1989.60	
	2	2002	271	2016.24		
		2003	212	2187.84	4204.08	
	3	2009	102	1150.56		
		2010	95	524.40	1674.96	
$L_5 = 106.1$ m	1	1993	191	2567.04		**3883.32**
		1994	19	241.68	2808.72	
	2	1994	54	686.88	686.88	
	3	2001	178	1409.76		
		2002	365	2715.60		
		2003	250	2580.00	6705.36	
	4	2007	97	1350.24		
		2008	272	3982.08	5332.32	
$L_6 = 158.2$ m	1	1996	64	829.44		**2337.04**
		1997	132	1647.36	2476.80	
	2	1997	227	2832.96	2832.96	
	3	2002	138	1026.72		
		2003	77	794.64	1821.36	

$\overline{C}_{m_i}$ [€/h] the average malfunction costs of the overburden excavation system caused by failures of belt conveyor rubber belt of length L_i.

T_{pm} = 12 [h] the time needed for the planned replacement of the rubber belt (gradual failures).

T_{npm} = 30 [h] the time needed for the unplanned replacement of the rubber belt (sudden failures).

$c_{pm} = T_{pm} \cdot c_{m/h}$ = 12·9232.33 = 110787.96 [€] – the malfunction costs of the overburden excavation system with the planned replacement of the rubber belt.

$c_{npm} = T_{npm} \cdot c_{m/h}$ = 30·9232.33 = 276969.90 [€] – the malfunction costs of the overburden excavation system with the unplanned replacement of the rubber belt.

$c_{m/h}$ = 9232.33 [€/h] – the malfunction costs of the overburden excavation system per hour – see expression (6).

$MTTF_{gf}^{L_i}$ [h] the mean time to gradual failure of the rubber belt of length L_i, (Tables 2, 3, 4, 5, 6, 7).

$H(MTTF_{gf}^{L_i})$ the renewal function of the rubber belt of length (L_i), in the period of $MTTF_{gf}^{L_i}$ i.e. for the mean time to gradual failures.

$c_{nbr}^{L_i}$ [€] the unused rubber belt resource of length L_i.

In another words, expression (5) gives us the unit cost [€/h] of the overburden excavation system malfunction caused by belt conveyor rubber belt failure in the period of $MTTF_{gf}^{L_i}$ [h]. In that period one planned rubber belt replacement and $H(MTTF_{gf}^{L_i})$ unplanned rubber belt replacements will be carried out.

The malfunction costs of the overburden excavation system per hour $c_{m/h}$ [€/h], expressed through the price of the final product – lignite, can be calculated as:

$$c_{m/h} = Q_T \cdot \bar{k}_t \cdot \bar{k}_q \cdot r_e \cdot c_{l/t} = 4100 \cdot 0.466 \cdot 0.464 \cdot 0.833131 \cdot 12.5 = = 9232.33\ [€/h] \tag{6}$$

where:

Q_T =4100 [m³lm/h] – the theoretical digging capacity of the bucket wheel excavator, cubic meters of loose material per hour.

$\bar{k}_t$ = 0.466 – the average coefficient of time utilisation (Table 1.).

$\bar{k}_q$ = 0.464 – the average coefficient of capacity utilisation (Table 1.).

$r_e = \frac{Q_l^{tot}}{Q_{ob}^{tot}} = \frac{140619324}{168784098.6} = 0.833131$ [t/m³lm] – the ratio of overburden quantity which has to be removed (cubic meters of loose material) in order to excavate one ton of lignite (Table 1).

$c_{l/t}$ = 12.5 [€/t] – lignite price per ton (in Serbia in the last 20 years the price of electrical energy is a social category, therefore this lignite price is not real, i.e. the market price, because it is determined as a percentage of the price of one kWh of electrical energy).[2]

Rubber belt working time until sudden failure can be described by exponential distribution (see previous chapter), which means that the renewal function of the rubber belts has the following form:

$$H(MTTF_{gf}^{L_i}) = \lambda_i \cdot MTTF_{gf}^{L_i} \tag{7}$$

where:

$\lambda_i = 1 / MTTF_{sf}^{L_i}$ [1/h] – the sudden failure intensity of the rubber belt of length L_i, and

$MTTF_{sf}^{L_i}$ [h] – the mean (working) time to sudden failure of the rubber belt of length L_i, (Table 10).

In the case of gradual failures, it is assumed that the complete rubber belt resource is used, while in the case of sudden failures one part of the rubber belt resource remains unused. The value of the unused rubber belt resource of length L_i, can be determined from the following expression:

$$c_{nbr}^{L_i} = c_{b/m} \cdot L_i \cdot \left(1 - \frac{MTTF_{sf}^{L_i}}{MTTF_{gf}^{L_i}}\right),\ [€] \tag{8}$$

where:

$c_{b/m}$ = 200 [€/m] – the rubber belt price (B1600) per meter [13].

The average malfunction costs (lost production) of the overburden excavation system caused by belt conveyor rubber belt failure, i.e. the unit cost of system malfunction per hour of belt conveyor work during belt lifetime, as a function of rubber belt length L_i are shown in Table 11 and Figure 4.

Figure 4 shows that the average malfunction costs of the overburden excavation system $\bar{C}_{m_i}$ per hour of belt conveyor work during belt lifetime decrease with the increase of rubber belt length L_i. Figure 4 shows that costs $\bar{C}_{m_i}$, depending on rubber belt length, range between 100 and 200 €/h.

Table 11.Average malfunction costs of the overburden excavation system $\bar{C}_{m_i}$ [€/h].

i	L_i [m]	λ_i [1/h]	$H(MTTF_{gf}^{L_i})$	$c_{npm}+c_{nbr}^{L_i}$ [€]	$(c_{npm}+c_{nbr}^{L_i}) \cdot H(MTTF_{gf}^{L_i})$ [€]	$\bar{C}_{m_i}$ [€/h]
1	27.6	0.000521	1.130187	277605.59	313746.36	195.84
2	51.6	0.000313	0.898776	276969.74	248933.86	125.38
3	75.0	0.000523	2.684894	286382.92	768907.85	171.27
4	81.5	0.000381	1.957722	284943.73	557840.63	130.21
5	106.1	0.000258	1.394951	282977.73	394739.98	93.32
6	158.2	0.000421	4.135450	300958.81	1244600.12	137.88

4. Conclusion

For large mining systems like overburden excavation systems, it is important to determine when the equipment in a system will breakdown, or how long it will perform in a reliable manner in order to take the necessary precautions to ensure continuity of the system operation due to huge lost production costs. Therefore the proposed methodology and its output –average malfunction (lost production) costs are designed to assist persons in charge in planning and adopting adequate maintenance strategies based on the prediction of failure intensities and lost production costs.

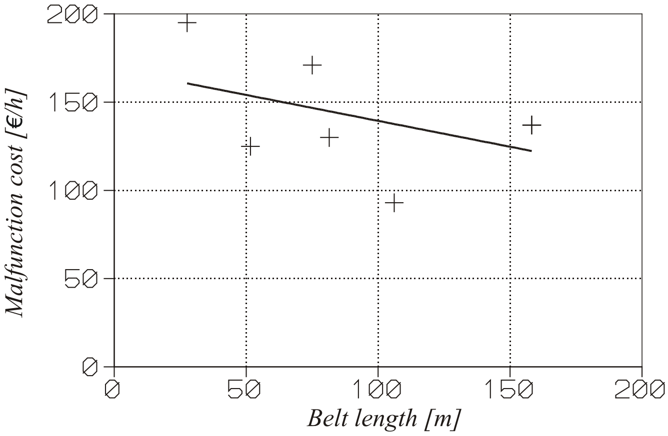

Fig. 4. Average malfunction costs

Statistical processing and analysis of the data pertaining to the malfunctions of the overburden excavation system caused by rubber belt failures taken from the maintenance diary (plant records) of the Tamnava – East field open-pit mine using the proposed methodology lead to the following conclusions.

The working time of the belt conveyor rubber belts, which work in the overburden excavation system (bucket wheel excavator, belt wagon, spreader) can be described by different theoretical distributions of time due to the nature of failure. In another words, rubber belt working time to failure presents a complex mathematical model, in which working time until sudden failure (tear, breakthrough) can be described by

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[2] Source: Public company Electric Power Industry of Serbia.

exponential distribution while working time until gradual failure can be described by normal distribution.

It is also shown that there is a strong linear dependence between mean time to failure, caused by gradual failures and rubber belt length. The obtained dependence indicates that the proposed methodology of analysis of rubber belt working time to failure can be applied to other rubber belts of different lengths working on similar machines.

The analysis of rubber belt working time to failure using the proposed methodology as a complex mathematical model enables the calculation of the average malfunction costs of the overburden excavation system (lost production) caused by belt conveyor rubber belt failure, i.e. the unit cost of system malfunction per hour of belt conveyor work during belt lifetime. Malfunction costs determined in this way facilitate better planning of malfunctions, requirements for spare rubber belts as well as a reduction of working costs in the open-pit mine.

The obtained results using the proposed methodology of analysis of belt conveyor rubber belt working time to failure are valid only for working conditions on the Tamnava – East field open-pit mine, while the proposed methodology as well as the expression for malfunction cost determination can be applied, with appropriate adoptions, in the analysis of other open-pit mines in order to indicate better (optimal) maintenance strategy.

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