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ABSTRACT

CONTRIBUTIONS TO THE STUDY OF RELIABILITY, MAINTAINABILITY AND AVAILABILITY OF NEW MINING TRANSPORTATION SYSTEMS

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CONTENT

INTRODUCTION

In this paper, a complex reliability, maintainability and availability study is acknowledged as RMA study. The denomination comes from the initials of the three entities, which interpenetrate, Reliability, Maintainability, and Availability, respectively.

The first stage in the performing of a RMA study is related to the primary data base available. In order to be useful, the data base should include chronological series of functioning times between failures or re-establishing system functioning. This involves establishing moments of occurrence and remedy of defaults with sufficient accuracy. These effective functioning or repair times represent the absolutely necessary input data for an efficient study to be performed.

Processing a primary data base that does not reflect reality leads to results, which in their turn are not real. Implementation of these results leads to making erroneous decisions, which result in considerable economic losses.

The last of the stages of performing a RMA study is results interpretation, which totally depends on the technical abilities of the technological engineers and reliability specialists. Results interpretation is made in strict agreement with production, development and maintenance management applied at organizational level.

Intermediary stages, mainly referring to reliability, maintenance and availability indicators quantification, are relatively easy to be solved by efficient technologies.

Solving the first and the last stage exclusively depends on the skill of the human operator, on his/her expertise, which cannot be replaced by anything else.

Referring to the technical systems used in mining industry, relatively few RMA studies had been conducted. For underground and above ground coal industry, the results obtained by the team of mechanical engineers of the University of Petroșani are acknowledged. Similarly, the approaches in the extractive industry section of the Nord University of Baia Mare should be mentioned.

In the field of coal industry, the classic reliability studies, in order, had been directed to: power support, specifically SMA-2 power support. These are equipment intended to extract bituminous coal in longwalls; TR-3 and TR-5 scraper belts; various equipments used in bituminous coal processing; bucket wheel excavators, specifically EsRc-1400 excavator, used to extract lignite in Oltenia coal field; high capacity conveyers used to haul coal in quarries.

The aim of this paper is to carry out a reliability, maintainability and availability study on two transportation system categories. RMA studies refer to complex LHD machines and roller belt conveyors. The paper does not particularly approach design of reliable systems for the field under consideration. The principal contents are related to the way of assessment, measuring and prediction of reliability and maintainability of a system.

The importance of the subject theme is highlighted by the concrete results obtained by the studies carried out on the analyzed products. Equally, from a theoretical point of view, the paper can constitute an analysis guide of the functionality of any type of electrical-mechanical element, machine or equipment.

The results obtained by the paper can be used by economic agents exploiting technical systems of this type, Meanwhile, the results can be in the attention of all those that have preoccupation in the design and implementation of RMA studies.

CHAPTER I. GENERAL CHARACTERIZATION OF TECHNICAL SYSTEMS LIFE

The aim of this chapter is to present concepts defining and quantifying an RMA study of a product of electrical-mechanical nature.

A RMA study includes more or less complete information regarding reliability, maintainability and availability of the analyzed product.

In the first part the function of failure intensity for the life of a technical system is presented. This function is acknowledged in the literature of speciality as ‘bathtub curve’, the shape of this curve is strictly influenced by the four entities listed.

The four concepts used in industrial practice, reliability, maintainability, maintenance and availability, are defined.

From these definitions the structural connections between them result, all of them equally leading to the characterization of the functionality of a product. The complexity of the reliability concept is highlighted, which in a complete presentation should include approaches of technical, operational, commercial and management nature.

Reliability and maintainability assessment of a product can be done in four ways:

- using the data base regarding specific values of reliability and maintainability indicators for component elements and knowledge of the system’s architecture;
- starting from the information coming after the use of the product or from the complaints made by the beneficiary, this being about an analysis of the operational reliability and maintainability. This way is applied in extensor along this paper;
- trials performed on the new product, in view of verifying its functioning before launching its production;
- starting from the opinion of some experts, when there are no information regarding reliability and maintainability of a component or of a new system.

CHAPTER II RELIABILITY STUDY OF COMPLEX LHD MACHINES

This chapter is intended to study the reliability of complex LHD machines, which are widely used in various sectors of industrial activities. In the first part, the reliability of the whole load machine is studied, with direct applicability on maintenance activities. In the second part, quantitative indicators specific to operational reliability for three component systems of the machine are quantified and interpreted. The reliability study performed represents a mirror of the machine functionality indicating its quality level at the moment of the study. The study justifies on the one hand the proposals for improving and modernizing the product, but especially the use of predictive maintenance strategy, depending on the state of the equipment.

Evaluation of reliability indicators for the entirety of load and haul machines.

In order to determine the empirical function of failure distribution, the 169 failures occurred in load and haul machines for a period of 2,5 years are highlighted. Only significant failures are taken into consideration, with adverse effects on nominal functioning parameters of the machines, minor failures being excluded. The failures considered did not cause significant damage and did not present significant risks for people. In order to establish the effective operation, it is considered that the load and haul machine effectively works 400 *hours/month*. These are uniform time periods, making up the duration of the reliability study.

Reliability function, $R(t)$, Fig. 2.5, quantifies the probability of good functioning in time of the load machine, in underground conditions and application of preventive maintenance. If the dynamic of failure occurrence follows Weibull's biparametric distribution, the reliability function is expressed by the equation

$$R(t/10196;\,1{,}998) = e^{-\left(\frac{t}{10196}\right)^{1{,}998}}\ ,\ \ t > 0. \qquad (2.12)$$

Failure time probability density indicator, Fig. 2.6, also called good functioning time distribution density, $f(t)$, in h^{-1}, signifies the instantaneous failure occurrence speed. For normalized biparametric Weibull distribution is expressed by the equation

$$f\,(t/10196;\,1{,}998) = 1{,}959\cdot 10^{-4}\left(\frac{t}{10196}\right)^{0{,}998} e^{-\left(\frac{t}{10196}\right)^{1{,}998}},\ \ t > 0\ ,\ \ h^{-1}. \qquad (2.14)$$

Failure rate indicator, written $z(t)$, in h^{-1}, Fig. 2.7, describes the probability of load machine failure at a certain time. The calculus relation of the indicator for normalised biparametric Weibull distribution is

$$z(t/10196;\,1{,}998) = 1{,}959\cdot 10^{-4}\left(\frac{t}{10196}\right)^{0{,}998}\ ,\ \ t > 0\ ,\ \ h^{-1}. \qquad (2.16)$$

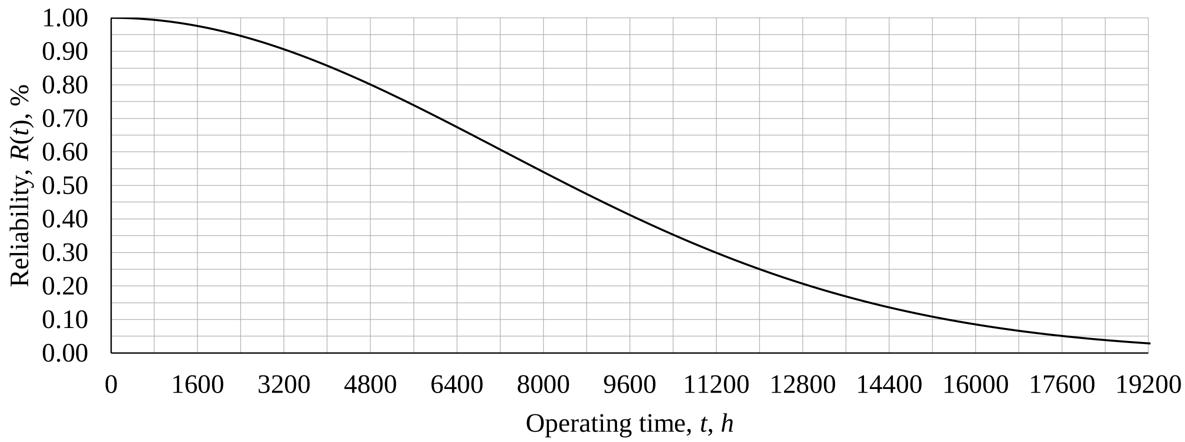

Fig. 2.4. Reliability function for LHD machine

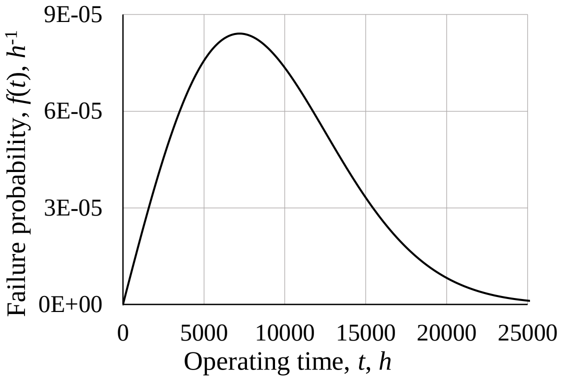

Fig. 2.6. Density function

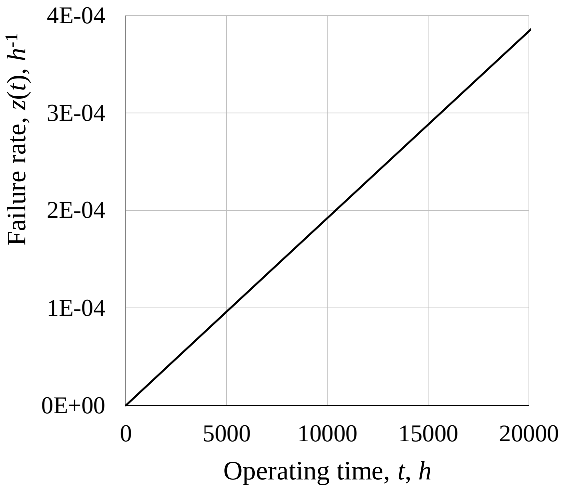

Fig. 2.7. Failure rate function

Results obtained in determining principal reliability indicators lead to a series of conclusions and predictions. The conclusions mainly refer to quantitative reliability indicators, characterizing the functionality of the complex load and haul machine. Equally, appreciations are made regarding the determination of the empirical function of failure distribution, as well as on the estimation methodology of distribution parameters.

1. The empirical distribution function has been determined based on absolute significant failures considered over uniform time intervals for 400 *hours*. This value is consistent with he effective work time for a calendar *month*. Mathematically, the empirical distribution function represents the relative cumulated frequency of failure occurrence. To determine distribution functions only mechanical failures have been considered, for which the main cause if occurrence is wear. This manner of assessment of the function of empirical distribution is determined by the precarious data base regarding load and hauls machines exploitation

2. Application of Kolmogorov-Smirnov (KS) concordance test proves that the dynamic of failure occurrence and manifestation follows Weibull's normalized biparametric distribution law. This shows that this distribution law characterises the best the load and haul machines' functionality. The parameters of normalized biparametric Weibull distribution are shape parameter, β = 1,998, and real scale parameter, η = 10196 *h*. It should be specified that exponential and normal distribution laws are not validated, which is suggested by β parameter of Weibull distribution as well.

3. Weibull biparametric normalized distribution parameters are estimated by the method of least squares. This is a statistic parametric method allowing punctual calculus of parameters of an indicated distribution. Literature of speciality shows that by the use of analytical method of least squares, the most realistic results are obtained. Equally, graphic method is used as well, also based on linearization of distribution function as well as the presented analytical method. Weibull distribution with parameters calculated by maximum likelihood method, and by the one of moments is not validated. Non-validation of these distributions substantiates the known idea that, by the application of punctual parametric statistical methods of parameter evaluation, their indicative values are obtained.

4. Reliability and failure functions allow an overall appreciation of the load and haul machine functionality. These indicators cannot make reference to the machine's component element or sub-units, which would allow their quality level to be indicated. According to Fig. 2.4, the probability for the load machine not to fail after 4800 *hours* of effective exploitation is 80%. It should be noted that the value is real in the conditions of adequate exploitation of the machine, especially respecting the conditions imposed by preventively planned maintenance. In other words, we should anticipate with an 80% certainty that the machine would not fail after 4800 *hours* of operation. It should be mentioned that this effective operating period means 12 calendar *months*, one *year*, respectively.

5. A slow decrease of the reliability function curve is noticed, suggesting an instantaneous speed of low failure. According to probability density curve, Fig. 2.5, instantaneous failure speed is of 10^{-5} *failures/hour* magnitude, suggesting a relatively high reliability level.

6. Evolution in time of the failure intensity or rate, Fig. 2.6, offers the most information regarding the functionality of the load machine. First, a quasi-linearity of failure rate evolution is noticed, characteristic of a parameter of $\beta = 1{,}998$ shape. In reliability, Rayleigh distribution is acknowledged, for which failure intensity increase is linear. The 10^{-4} order of magnitude for failure rate indicates an acceptable quality level for the load machine unit. The level is considered acceptable, considering the wear degree after a considerable functioning time. The linearity of the failure intensity function shows that the process increases proportionally with a very low factor, which according to Fig. 2.7 has the value $2 \cdot 10^{-8}$ (*failure*/*h*)/*h*. This shows that the machine is made up of homogeneous elements with close reliability characteristics. Evolution in time of the failure intensity shows that the load machine, according to the life span curve, is placed in the principal functioning period. In this stage, failures occur mainly due to wear. To this fatigue of the materials is added, considering that, at the moment of performing the reliability study, the machine has a considerable number of hours of operation. Corrosion and abrasion, processes that are amplified in underground working conditions, should also be taken into consideration.

7. For a 50% reliability level, the mean failure time is approximately 8500 *hours*, which suggests that half of the total failures occurs until this moment. This can be construed as an indicator for planning preventive maintenance activity. The average time of good functioning between two failures, is also approximately 9000 *hours*, representing 1,8 calendar *years*.

Evaluation of reliability indicators for load machine bucket manoeuvring hydraulic cylinder

Table 2.11. **Estimated values of the theoretical distribution parameters**

Distribution, symbol	Parameter					
	λ, h^{-1}	m, h	σ, h	β	η, h	γ, h
Exponential negative, *Ep*	5,130E-04					
Normal normalized, *Nv*		2098,421	1026,384			
Weibull biparametric normalized, *Wp*				1,915	2410,605	
Weibull biparametric normalized, *Wv*				2,008	2313,752	
Weibull triparametric, *Wm*				2,153	2369,473	1,831E-06

Table 2.12. **Testing the theoretical distributions of time between failures**

Distribution, symbol	Distribution function, $F(t)$	K-S test, $D_{max} < D_{cr} = D_{\alpha,\,19}$			
		Maximum deviation, D_{max}	Risk, α, %	Critical value, $D_{\alpha,\,19}$	Validation
Exponential negative, *Ep*	$F(t) = 1 - e^{-\lambda t} = 1 - e^{-5{,}130 \cdot 10^{-4}\, t}$ (2.25)	**0,303597**	2,5	$D_{\alpha;\,19}$=**0,320607**	YES
			0,5	$D_{\alpha;\,19}$=0,383792	
Normal normalized, *Nv*	$F(t) = \frac{1}{2} + \Phi\left(\frac{t-m}{\sigma}\right) = \frac{1}{2} + \Phi\left(\frac{t-2098{,}421}{1026{,}384}\right)$ (2.26)	**0,199908**	20	$D_{\alpha;\,19}$=**0,237346**	YES
	$F(t) = \mathrm{NORMSDIST}\left(\frac{t-m}{\sigma}\right) = \mathrm{NORMSDIST}\left(\frac{t-2098{,}421}{1026{,}384}\right)$ (2.27)		0,5	$D_{\alpha;\,19}$=0,383792	
Weibull biparametric normalized, *Wp*	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t}{2410{,}605}\right)^{1{,}915}}$ (2.28)	**0,217284**	20	$D_{\alpha;\,19}$=**0,237346**	YES
			0,5	$D_{\alpha;\,19}$=0,383792	
Weibull biparametric normalized, *Wv*	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t}{2313{,}752}\right)^{2{,}008}}$ (2.29)	**0,246697**	10	$D_{\alpha;\,19}$=**0,271357**	YES
			0,5	$D_{\alpha;\,19}$=0,383792	

Table 2.12. **Testing the theoretical distributions of time between failures**

Distribution, symbol	Distribution function, $F(t)$	K-S test, $D_{max} < D_{cr} = D_{\alpha,19}$			
		Maximum deviation, D_{max}	Risk, α, %	Critical value, $D_{\alpha,19}$	Valida-tion
Weibull triparametric, *Wm*	$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t-1{,}831E\text{-}06}{2369{,}473}\right)^{2{,}153}}$ (2.30)	**0,228676**	20	$D_{\alpha;19}$=**0,237346**	YES
			0,5	$D_{\alpha;19}$=0,383792	

Table 2.14. **Quantitative indicators of reliability for hydraulic cylinder.**
Normal normalized distribution *Nv*

No.	Name and symbol of the indicator	Relationship	Value, Unit
1	Reliability function, $R(t)$	$R(t) = \frac{1}{2} - \Phi\left(\frac{t-m}{\sigma}\right) = 1 - \text{NORMSDIST}\left(\frac{t-m}{\sigma}\right) = 1 - \text{NORMSDIST}\left(\frac{t-2098{,}421}{1026{,}384}\right)$ (2.38)	Fig. 2.12
2	Failure function, $F(t)$	$F(t) = \frac{1}{2} + \Phi\left(\frac{t-m}{\sigma}\right) = \text{NORMSDIST}\left(\frac{t-m}{\sigma}\right) = \text{NORMSDIST}\left(\frac{t-2098{,}421}{1026{,}384}\right)$ (2.39)	Fig. 2.13
3	Failure probability function, $f(t)$	$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-m}{\sigma}\right)^2} = \frac{1}{1026{,}384\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-2098{,}421}{1026{,}384}\right)^2}$ (2.40)	Fig. 2.14
4	Failure rate function, $z(t)$	$z(t) = \frac{f(t)}{R(t)} = \frac{\frac{1}{1026{,}384\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-2098{,}421}{1026{,}384}\right)^2}}{1 - \text{NORMSDIST}\left(\frac{t-2098{,}421}{1026{,}384}\right)}$ (2.41)	Fig. 2.15
5	Mean time between failures, *MTBF*, $E(t)$	$MTBF = m = 2098{,}421$ (2.42)	2098 *h*
6	Median operating time, $t_{0,5}$, t_{med}	$t_{0,5} = m = 2098{,}421$ (2.43)	2098 *h*
7	Dispersion of operating time, D	$D = \sigma^2 = (1026{,}384)^2$ (2.44)	1053464 h^2

Tabelul 2.17. **Quantitative indicators of reliability for hydraulic cylinder.**
Weibull triparametric distribution *Wm*

No.	Name and symbol of the indicator	Relationship	Value, Unit
1	Reliability function, $R(t)$	$R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} = e^{-\left(\frac{t-1{,}831E\text{-}06}{2369{,}473}\right)^{2{,}153}}$ (2.59)	Fig. 2.12
2	Failure function, $F(t)$	$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t-1{,}831E\text{-}06}{2369{,}473}\right)^{2{,}153}}$ (2.60)	Fig. 2.13
3	Failure probability function, $f(t)$	$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} = 9{,}086\cdot10^{-4}\left(\frac{t-1{,}831E\text{-}06}{2369{,}473}\right)^{1{,}153} e^{-\left(\frac{t-1{,}831E\text{-}06}{2369{,}473}\right)^{2{,}153}}$ (2.61)	Fig. 2.14
4	Failure rate function, $z(t)$	$z(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} = 9{,}086\cdot10^{-4}\left(\frac{t-1{,}831E\text{-}06}{2369{,}473}\right)^{1{,}153}$ (2.62)	Fig. 2.15
5	Mean time between failures, *MTBF*, $E(t)$	$MTBF = \gamma + \eta\,\Gamma\left(\frac{1}{\beta}+1\right) = 1{,}831\cdot10^{-4} + 2369{,}473\,\Gamma\left(\frac{1}{2{,}153}+1\right)$ (2.63)	2098 *h*

Tabelul 2.17. **Quantitative indicators of reliability for hydraulic cylinder. Weibull triparametric distribution *Wm***

No.	Name and symbol of the indicator	Relationship	Value, Unit
6	Median operating time, $t_{0,5}$, t_{med}	$t_{0,5} = \gamma + \eta \sqrt[\beta]{-\ln 0,5} = 1,831 \cdot 10^{-4} + 2369,473 \sqrt[2,153]{-\ln 0,5}$ (2.64)	1999 *h*
7	Dispersion of operating time, *D*	$D = \eta^2 \left\{\Gamma\left(\frac{2}{\beta}+1\right) - \left[\Gamma\left(\frac{1}{\beta}+1\right)\right]^2\right\} = 2369,473^2 \left\{\Gamma\left(\frac{2}{2,153}+1\right) - \left[\Gamma\left(\frac{1}{2,153}+1\right)\right]^2\right\}$ (2.65)	1053872 h^2

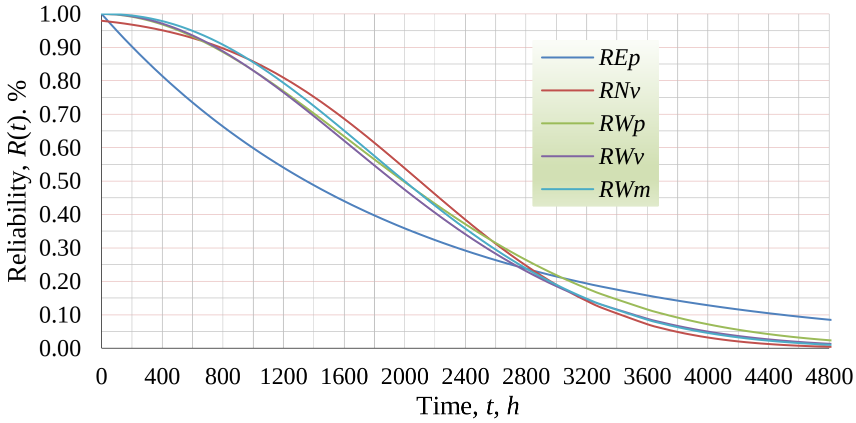

Fig. 2.12. Reliability functions for hydraulic cylinder

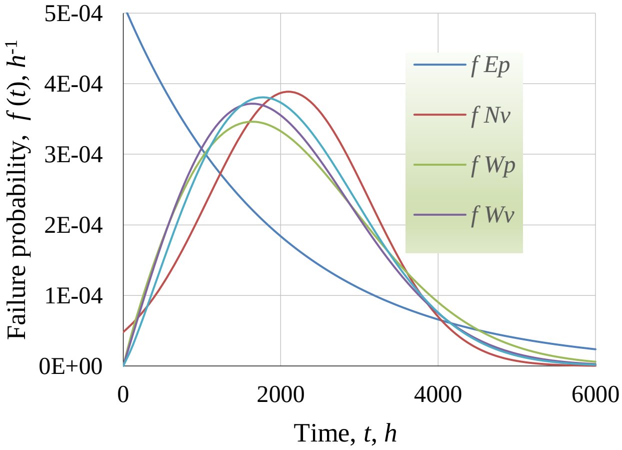

Fig. 2.14. Failure probability functions

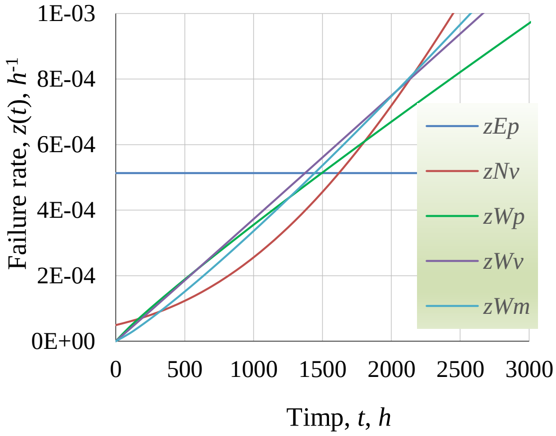

Fig. 2.15. Failure rate functions

The results obtained in determining the main reliability indicators lead to a series of conclusions and predictions regarding the functionality of the hydraulic cylinder.

1. The empirical failure distribution function has been determined based on the statistical series made up of good functioning times between failures. The empirical data meet the criteria of independence and distribution according to the same law.

Mathematically, the empirical distribution function has been calculated using the most usual estimator indicated by the literature of specialty for Weibull distributions. The good functioning time of cylinders matches the effective work time of the haul machines for a calendar *month* of 400 *hours*. To determine the distribution function, only significant mechanical failures have been considered. The main causes of occurrence of these failures are wear, deformation, tear and fatigue.

2. From Figs. 2.12 and 2.13 the trend of grouping results, even overlapping reliability and non-reliability curves, for normal and Weibull distribution in the three forms. For these distributions, the maximum distances between the empiric time distribution law until failure and the theoretical laws are the smallest. The distance reaches approximately 20% for normal distribution, for Weibull distribution being higher by maximum 5%. The smallest value of the distance and good functioning time dispersion proves that normal distribution characterizes the best the functionality of the hydraulic cylinder. Due to the relatively small differences it is considered that normal and Weibull distribution laws can equally well characterize the functionality of the product. It is considered that, although validated, the exponential model underestimates the good functioning of the analyzed product.

3. The reliability and failure functions allow an overall appreciation of the functionality of the hydraulic cylinder. These indicators cannot refer to component elements of the cylinder that would allow indication of their quality level.

4. According to Fig. 2.12, the probability that the hydraulic cylinder would not fail after 1200 *hours* of effective functioning is 80%. In other words, we should anticipate, with 80% certainty that the hydraulic cylinder would not fail after 1200 *hours* of functioning. It is mentioned that this period of effective functioning matches three calendar *months*.

5. For a 2000 *hours* functioning period, corresponding to five calendar months, the reliability of the motor becomes equal to its non-reliability, namely 50%. The value is consistent with an average good functioning time, and it is confirmed by the indicator calculus for the validated distribution laws. This value of five *months* can be taken into consideration for including in the revision plan the verification of the cylinder integrity, or even its replacement. It is necessary to check the integrity or seals, the wear degree of the cylinder mounting elements and the level of rod deformation.

6. Reliability decrease from 80% to 50% is consistent with a functioning duration of 800 *hours*. This proves that the failure speed has a relatively large value, which is confirmed by the smoothly decreasing slope of the reliability function. This is also proved by the graphics of probability density and failure intensity or rate.

7. Analysis of failure intensity shows its increasing trend, explicable by manifestation in time, especially of wear and fatigue processes. Its value, of 10^{-3} *failures/hour*, for the average time of functioning is still a modest value.

According to Weibull distribution, where shape parameter *ß*=2, the increase of failure rate is linear with $4\cdot10^{-7}$ (*failure*/*h*)/*h* factor of proportionality. This also proves that the cylinder is made up of homogeneous elements with close reliability levels.

8. The approximately symmetrical shape of the probability density curve shows the equality of the good functioning average time with its median, around the value of 2000 *hours*. This suggests that 50% of the failures occur before this date and the other half afterwards. This influences the planning of revisions and repairs.

9. The values of reliability indicators obtained for the analyzed hydraulic cylinders lead to the necessity of reducing the number and frequency of significant failures. This intention can be achieved by reconsidering the cylinder design, considering that it represents an obsolete solution. The sealing gaskets quality and the mechanical characteristics of the materials for the cylinder bar and the fixing elements should be reconsidered.

Evaluation of reliability indicators for hydraulic pumps in brake systems

Table 2.19. **Estimated values of the failure distribution laws parameters**

Distribution, symbol	Parameter					
	λ, h^{-1}	*m*, *h*	σ, *h*	β	η, *h*	γ, *h*
Exponential negative, *Ep*	$1{,}488\cdot10^{-4}$					
Normal normalized, *Nv*		7030,417	1541,101			
Weibull biparametric normalized, *Wp*				5,125	7641,913	
Weibull biparametric normalized, *Wv*				4,998	7706,140	
Weibull triparametric, *Wm*				5,246	7635,829	6,24E-06

Table 2.20. **Testing the theoretical distribution laws of time between failures**

Distribution, symbol	Distribution function, $F(t)$	K-S test, $D_{max} < D_{cr} = D_{\alpha,\,12}$ Maximum deviation, D_{max}	Risk, α, %	Critical value, $D_{\alpha,\,19}$	Va-lida-tion
Exponential negative, *Ep*	$F(t) = 1 - e^{-\lambda t} = 1 - e^{-1{,}488 \cdot 10^{-4}\, t}$ (2.66)	**0,544472**	0,5	$D_{\alpha;12}$=**0,476715**	NOT
Normal normalized, *Nv*	$F(t) = \frac{1}{2} + \Phi\left(\frac{t-m}{\sigma}\right) = \frac{1}{2} + \Phi\left(\frac{t-7030{,}417}{1541{,}101}\right)$ (2.67)	**0,141006**	20	$D_{\alpha;\,12}$=**0,295770**	YES
	$F(t) = \mathrm{NORMSDIST}\left(\frac{t-m}{\sigma}\right) = \mathrm{NORMSDIST}\left(\frac{t-7030{,}417}{1541{,}101}\right)$ (2.68)		0,5	$D_{\alpha;\,12}$=0,476715	
Weibull biparametric, *Wp*	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t}{7641{,}913}\right)^{5{,}125}}$ (2.69)	**0,163483**	20	$D_{\alpha;\,12}$=**0,295770**	YES
			0,5	$D_{\alpha;\,12}$=0,476715	
Weibull biparametric, *Wv*	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t}{7706{,}140}\right)^{4{,}998}}$ (2.70)	**0,178514**	20	$D_{\alpha;\,12}$=**0,295770**	YES
			0,5	$D_{\alpha;\,12}$=0,476715	
Weibull triparametric, *Wm*	$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t-6{,}24E-06}{7635{,}829}\right)^{5{,}246}}$ (2.71)	**0,162262**	20	$D_{\alpha;\,12}$=**0,295770**	YES
			0,5	$D_{\alpha;\,12}$=0,476715	

Table 2.22. **Quantitative indicators of reliability for the hydraulic pump.**
Weibull biparametric normalized distribution *Wp*

No.	Name and symbol of the indicator	Relationship	Value, U
1	Reliability function, $R(t)$	$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} = e^{-\left(\frac{t}{7641{,}913}\right)^{5{,}125}}$ (2.79)	Fig. 2.18
2	Failure function, $F(t)$	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t}{7641{,}913}\right)^{5{,}125}}$ (2.80)	Fig. 2.19
3	Failure probability function, $f(t)$	$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 7{,}944 \cdot 10^{-4}\left(\frac{t}{7641{,}913}\right)^{4{,}125} e^{-\left(\frac{t}{7641{,}913}\right)^{5{,}125}}$ (2.81)	Fig. 2.20
4	Failure rate function, $z(t)$	$z(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} = 6{,}706 \cdot 10^{-4}\left(\frac{t}{7641{,}913}\right)^{4{,}125}$ (2.82)	Fig. 2.21
5	Mean time between failures, *MTBF*, $E(t)$	$MTBF = \eta\,\Gamma\left(\frac{1}{\beta}+1\right) = 7641{,}913\,\Gamma\left(\frac{1}{5{,}125}+1\right)$ (2.83)	7026 *h*
6	Median operating time, $t_{0,5}$, t_{med}	$t_{0,5} = \eta \sqrt[\beta]{-\ln 0{,}5} = 7641{,}913 \sqrt[5{,}125]{-\ln 0{,}5}$ (2.84)	7114 *h*
7	Dispersion of operating time, D	$D = \eta^2\left\{\Gamma\left(\frac{2}{\beta}+1\right) - \left[\Gamma\left(\frac{1}{\beta}+1\right)\right]^2\right\} = (7641{,}913)^2\left\{\Gamma\left(\frac{2}{5{,}125}+1\right) - \left[\Gamma\left(\frac{1}{5{,}125}+1\right)\right]^2\right\}$ (2.85)	2473270 h^2

Table 2.23. **Quantitative indicators of reliability for the hydraulic pump.**
Weibull biparametric normalized distribution *Wv*

No.	Name and symbol of the indicator	Relationship	Value, U
1	Reliability function, $R(t)$	$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} = e^{-\left(\frac{t}{7706{,}140}\right)^{4{,}998}}$ (2.86)	Fig. 2.18

Table 2.23. **Quantitative indicators of reliability for the hydraulic pump. Weibull biparametric normalized distribution *Wv***

No.	Name and symbol of the indicator	Relationship	Value, U
2	Failure function, $F(t)$	$F(t) = 1- e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1- e^{-\left(\frac{t}{7706,140}\right)^{4,998}}$ (2.87)	Fig. 2.19
3	Failure probability function, $f(t)$	$f(t)=\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} =$ $=6,485\cdot 10^{-4}\left(\frac{t}{7706,140}\right)^{3,998} e^{-\left(\frac{t}{7706,140}\right)^{4,998}}$ (2.88)	Fig. 2.20
4	Failure rate function, $z(t)$	$z(t)=\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}=6,485\cdot 10^{-4}\left(\frac{t}{7706,140}\right)^{3,998}$ (2.89)	Fig. 2.21
5	Mean time between failures, *MTBF*, $E(t)$	$MTBF = \eta\,\Gamma\left(\frac{1}{\beta}+1\right) = 7706,140\cdot\Gamma\left(\frac{1}{4,998}+1\right)$ (2.90)	7075 *h*
6	Median operating time, $t_{0,5}$, t_{med}	$t_{0,5} = \eta\sqrt[\beta]{-\ln 0,5} = 7706,140\sqrt[4,998]{-\ln 0,5}$ (2.91)	7161 *h*
7	Dispersion of operating time, D	$D = \eta^2\left\{\Gamma\left(\frac{2}{\beta}+1\right)-\left[\Gamma\left(\frac{1}{\beta}+1\right)\right]^2\right\} =$ $= 7706,140^2\left\{\Gamma\left(\frac{2}{4,998}+1\right)-\left[\Gamma\left(\frac{1}{4,998}+1\right)\right]^2\right\}$ (2.92)	2628378 h^2

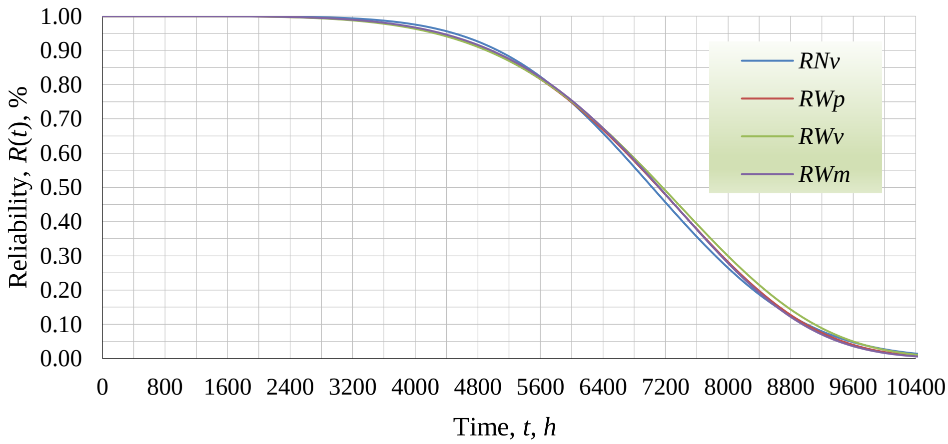

Fig.2.18. Reliability functions for hydraulic pump

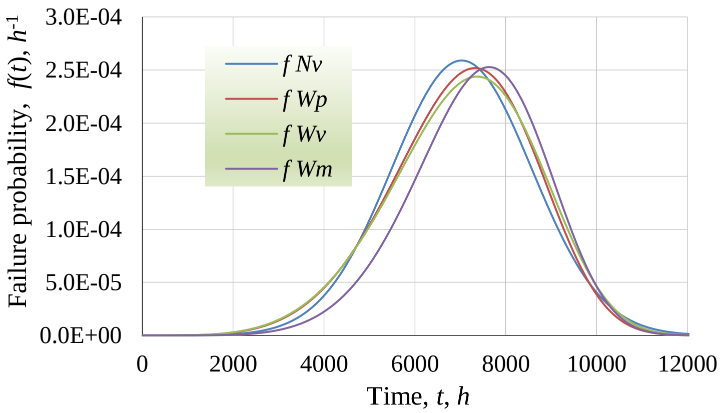

Fig. 2.20. Failure probability functions

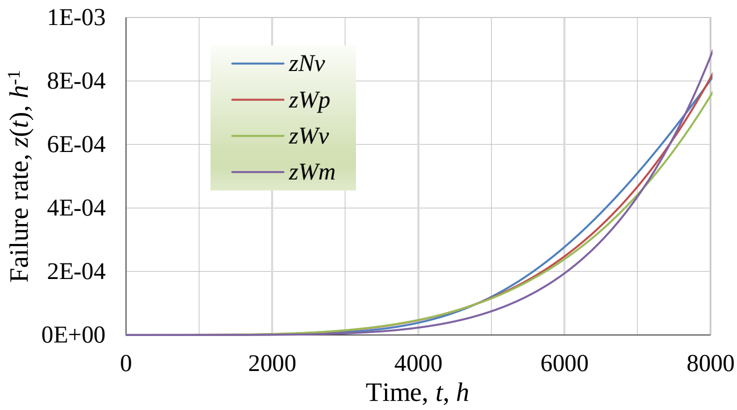

Fig. 2.21. Failure rate functions

The results obtained in the determination of the main reliability indicators lead to a series of conclusions and prediction regarding hydraulic plunger pumps functionality.

1. Empirical failure distribution function is determined based on a statistical series made up of good functioning times between failures. The data meet independence and identical distribution criteria. Mathematically, empirical distribution is calculated using the most usual estimator indicated in literature for Weibull distribution. To determine distribution function, only significant failures, of mechanical nature have been considered. The main failure causes are the processes of wear and deformation of piston and cylinder surfaces. Good functioning times of pumps are in agreement with the effective time of 400 *hours* of work for the haul machine in a calendar *month*.

2. Fig. 2.18 shows the trend of reliability and non-reliability curves overlapping, for normal and Weibull distribution in the three forms. For normal distribution, the 14% distance between empirical and theoretical distribution has the least value. This shows that normal distribution characterizes the best pump functionality. This is supported by the least value of good functioning times dispersion.

For Weibull distribution the distance varies between 16-18%, which is very close. The relatively close distance values support the idea that any of the four distributions can characterize hydraulic pumps' functionality very well.

3. Reliability and failure functions allow an overall appreciation of hydraulic pumps functionality. These indicators cannot refer to the pump's component elements, which would allow indication of their qualitative level.

4. According to Fig. 2.18, before 3200 *hours* of functioning pumps do not practically fail. The probability for the hydraulic pumps not to fail after 5400 *hours* of effective functioning is 80%. In other words, we should anticipate, with 80% certainty that hydraulic pumps would not fail after 5600 *hours* of functioning. To be mentioned that this period of effective functioning represents 14 calendar months, 1,2 *years*, respectively.

5. For 7200 *hours* functioning time, corresponding to 18 calendar *months* (1,5 *years*), pump reliability becomes equal to non-reliability, namely 50%. The value is consistent with average good functioning time, and it is confirmed by the indicator calculation for the validated distribution laws. This 18 *months* value can be taken in consideration for the inclusion of the pump integrity verification in the revision plan, or even its replacement.

6. Reliability decrease from 80 to 50% corresponds to a functioning duration of 1600 *hours*. This proves that the failure speed is high, according to the functioning time probability density graph, of 10^{-4} *failures /hour*. This is confirmed by the great slope of reliability function and the failure probability and intensity density graphs.

7. The analysis of failure intensity variation shows its increasing trend, explicable by manifestation in time, especially of the pump functional surfaces wear and deformation.

Its value is 10^{-3} *failures/hour*, for the average functioning time is a very high value.

8. The approximately symmetrical shape of the probability density curve shows the equality

between good functioning average time and its median, around the value of 7000 *hours*. This suggests that 50% of the failures occur before that date, and the other half afterwards. This influences revision and repair planning.

9. Reliability indicators values obtained lead to the necessity of reducing the number and frequency off significant failures occurrence. This can be achieved by reconsidering the pump construction, considering that it is an obsolete solution. Overall design of the pump piston and cylinder conjugated surfaces should be reconsidered, regarding material quality and execution technology.

Evaluation of average duration of utilization of friction pads in the brake system

Table 2.26. **Estimated values of the theoretical distribution parameters for friction pads**

Distribution, symbol	Parameter					
	λ, h^{-1}	m, h	σ, h	β	η, h	γ, h
Exponential negative, *Ep*	$1{,}014 \cdot 10^{-3}$					
Normal normalized, *Nv*		1494,167	245,630			
Weibull biparametric, *Wp*				6,811	1599,153	
Weibull biparametric, *Wv*				7,026	1605,691	
Weibull triparametric, *Wm*				7,166	1595,352	2,447E-04

Table 2.27. **Testing the theoretical distribution laws of friction pads operating times**

Distribution, symbol	Distribution function, $F(t)$	K-S test, $D_{max} < D_{cr} = D_{\alpha,\,24}$			
		Maximum deviation, D_{max}	Risk, α, %	Critical value, $D_{\alpha,\,19}$	Validation
Exponential negative, *Ep*	$F(t) = 1 - e^{-\lambda t} = 1 - e^{-1{,}014 \cdot 10^{-3}\, t}$ (2.100)	**0,697183**	0,5	$D_{\alpha;\,24}$=**0,343184**	NOT
Normal normalized, *Nv*	$F(t) = \frac{1}{2} + \Phi\left(\frac{t-m}{\sigma}\right) = \frac{1}{2} + \Phi\left(\frac{t-1494{,}167}{245{,}630}\right)$ (2.101)	**0,131922**	20	$D_{\alpha;\,24}$=**0,212048**	YES
	$F(t) = \text{NORMSDIST}\left(\frac{t-m}{\sigma}\right) = \text{NORMSDIST}\left(\frac{t-1494{,}167}{245{,}630}\right)$ (2.102)		0,5	$D_{\alpha;\,24}$=0,343184	
Weibull biparametric, *Wp*	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t}{1599{,}153}\right)^{6{,}811}}$ (2.103)	**0,148327**	20	$D_{\alpha;\,24}$=**0,212048**	YES
			0,5	$D_{\alpha;\,24}$=0,343184	
Weibull biparametric, *Wv*	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t}{1605{,}691}\right)^{7{,}026}}$ (2.104)	**0,163513**	20	$D_{\alpha;\,24}$=**0,212048**	YES
			0,5	$D_{\alpha;\,24}$=0,343184	
Weibull triparametric, *Wm*	$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t-2{,}447\text{E-}04}{1595{,}352}\right)^{7{,}166}}$ (2.105)	**0,156463**	20	$D_{\alpha;\,24}$=**0,212048**	YES
			0,5	$D_{\alpha;\,24}$=0,343184	

Table 2.28. **Quantitative indicators of reliability for friction pads. Normal normalized distribution *Nv***

No.	Name and symbol of the indicator	Relationship	Value, U
1	Reliability function, $R(t)$	$R(t) = \frac{1}{2} - \Phi\left(\frac{t-m}{\sigma}\right) = 1 - \text{NORMSDIST}\left(\frac{t-m}{\sigma}\right) = 1 - \text{NORMSDIST}\left(\frac{t-1494{,}167}{245{,}630}\right)$ (2.106)	Fig. 2.24
2	Failure function, $F(t)$	$F(t) = \frac{1}{2} + \Phi\left(\frac{t-m}{\sigma}\right) = \text{NORMSDIST}\left(\frac{t-m}{\sigma}\right) = \text{NORMSDIST}\left(\frac{t-1494{,}167}{245{,}630}\right)$ (2.107)	Fig. 2.25

Table 2.28. **Quantitative indicators of reliability for friction pads.**
Normal normalized distribution *Nv*

No.	Name and symbol of the indicator	Relationship	Value, U
3	Failure probability function, $f(t)$	$f(t)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{t-m}{\sigma}\right)^2}=\frac{1}{245,630\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{t-1494,167}{245,630}\right)^2}$ (2.108)	Fig. 2.26
4	Failure rate function, $z(t)$	$z(t)=\frac{f(t)}{R(t)}=\frac{\frac{1}{245,630\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{t-1494,167}{245,630}\right)^2}}{1-\text{NORMSDIST}\left(\frac{t-1494,167}{245,630}\right)}$ (2.109)	Fig. 2.27
5	Mean time between failures, *MTBF*, $E(t)$	$MTBF = m = 1494,$ (2.110)	1494 *h*
6	Median operating time, $t_{0,5}$, t_{med}	$t_{0,5} = m = 1494,167$ (2.111)	1494 *h*
7	Dispersion of operating time, D	$D=\sigma^2=(245,630)^2$ (2.112)	60334 h^2

Tabelul 2.30. **Quantitative indicators of reliability for friction pads.**
Weibull biparametric normalized distribution *Wv*

No.	Name and symbol of the indicator	Relationship	Value, U
1	Reliability function, $R(t)$	$R(t)=e^{-\left(\frac{t}{\eta}\right)^{\beta}}=e^{-\left(\frac{t}{1605,691}\right)^{7,026}}$ (2.120)	Fig. 2.24
2	Failure function, $F(t)$	$F(t)=1-e^{-\left(\frac{t}{\eta}\right)^{\beta}}=1-e^{-\left(\frac{t}{1605,691}\right)^{7,026}}$ (2.121)	Fig. 2.25
3	Failure probability function, $f(t)$	$f(t)=\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}e^{-\left(\frac{t}{\eta}\right)^{\beta}}=$ $=4,375\cdot10^{-3}\left(\frac{t}{1605,691}\right)^{6,026}e^{-\left(\frac{t}{1605,691}\right)^{7,026}}$ (2.122)	Fig. 2.26
4	Failure rate function, $z(t)$	$z(t)=\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}=4,375\cdot10^{-3}\left(\frac{t}{1605,691}\right)^{6,026}$ (2.123)	Fig. 2.27
5	Mean time between failures, *MTBF*, $E(t)$	$MTBF=\eta\,\Gamma\left(\frac{1}{\beta}+1\right)=1605,691\,\Gamma\left(\frac{1}{7,026}+1\right)$ (2.124)	1502 *h*
6	Median operating time, $t_{0,5}$, t_{med}	$t_{0,5}=\eta\sqrt[\beta]{-\ln 0,5}=1605,691\sqrt[7,026]{-\ln 0,5}$ (2.125)	1524 *h*
7	Dispersion of operating time, D	$D=\eta^2\left\{\Gamma\left(\frac{2}{\beta}+1\right)-\left[\Gamma\left(\frac{1}{\beta}+1\right)\right]^2\right\}=$ $=(1605,691)^2\left\{\Gamma\left(\frac{2}{7,026}+1\right)-\left[\Gamma\left(\frac{1}{7,026}+1\right)\right]^2\right\}$ (2.126)	63280 h^2

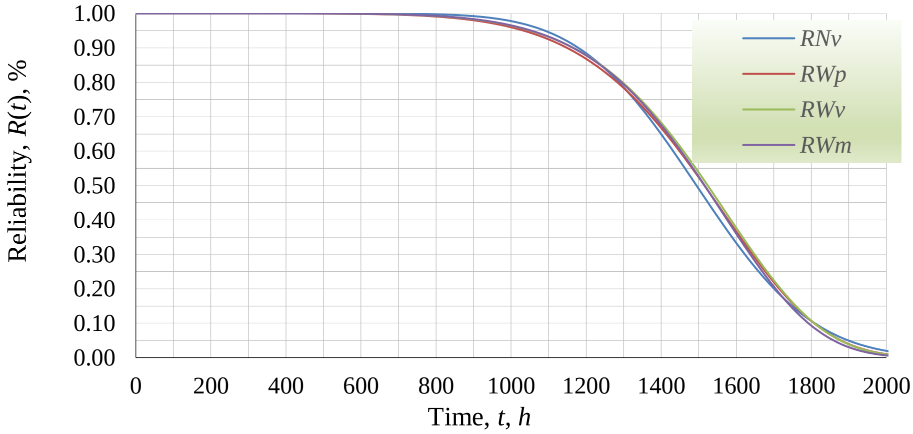

Fig. 2.24. Reliability functions for friction pads

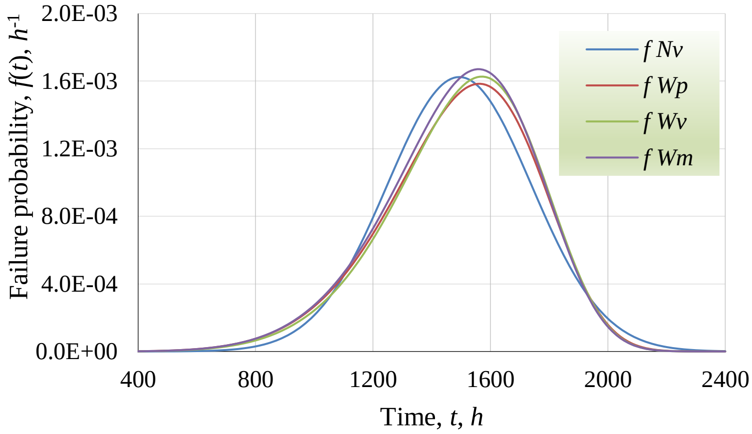

Fig. 2.26. Failure probability functions

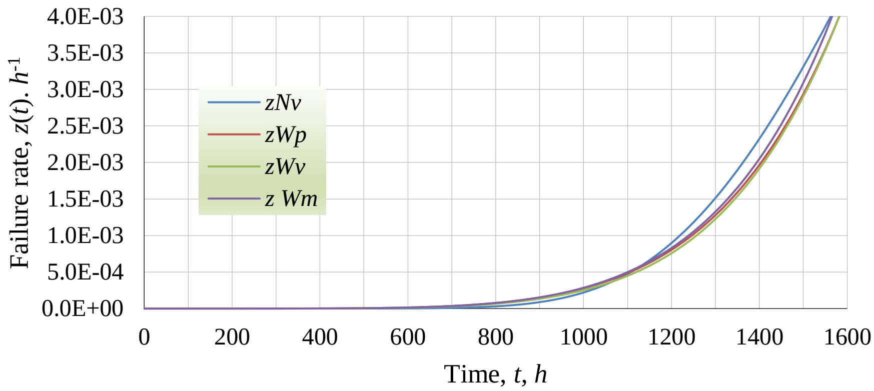

Fig. 2.27. Failure rate functions

1. The empirical failure distribution function is determined based on a statistic series made up of the times before the friction pads are removed. The data meet the independence and identical distribution criteria. Mathematically, the empirical distribution function is calculated using the most usual estimator indicated in literature for Weibull distribution. To determine the distribution function, only significant failures caused by over the admitted limit plate wear was taken into consideration. The good functioning time of the plates is consistent with the effective 400 *hours* work time of the haul machine for one calendar *month*. It is estimated however, that for one calendar *month*, the effective work time for the plates is 200 *hours*.

2. From Fig. 2.24 small differences result between reliability and non-reliability curves, for normal and Weibull distribution in the three shapes. For normal distribution, the 13% distance between the empirical and theoretical distribution has the smallest value. This shows that normal distribution characterizes the best the brake plate's functionality. The statement is supported by the least value of good functioning time's dispersion. For Weibull distribution the distance varies between 14,8-16,3 %, which are very close values. The relatively close values of distances support the idea that any of the four distributions can characterize very well the plates' functionality. The small value of dispersion, of standard deviation of plates' utilization times, respectively, show the homogeneity of the plates' production.

3. According to Fig. 2.24, the probability for the plates not to be removed after 1300 *hours* of effective functioning is 80%. In other words, we should anticipate, with 80% certainty, that the plates would not be removed after 1300 *hours*. This period is consistent with an effective functioning time of only 3,25 *months* for the machine, and 6,5 *months* for the plates.

4. For an 1500 *hours* functioning time, which is consistent with 7,5 calendar *months*, the plates'

reliability becomes equal to non-reliability, namely 50%. The value is consistent with the average good functioning time, and it is substantiated by the calculation of the indicator for validated distribution laws. This 7,5 *months* value can be taken into consideration in order to include plate integrity verification in the revision plan, or even for replacement.

5. Reliability decrease from 80% to 50% is consistent with a 200 *hours* functioning time. This proves that the failure speed is very high, according to the functioning time probability density being 10^{-3} *failures/hour*. This is confirmed by the great slope of the reliability function and the graphs of probability density and failure intensity.

6. The analysis of failure intensity variation shows that practically before 100 *hours* of utilization, five *months*, respectively, the brake plates are definitely in adequate functioning condition. After this period an increasing trend occurs, slower at first, followed by a significant increase. Its value of 10^{-3} *failure/hour*, for average functioning time is a very high value. This shows the very low quality level of the plates.

7. The obtained reliability indicators show the necessity of increasing the plates' utilization time. This can be achieved by reconsidering the overall design of the plates. First, the antifriction material of the plates should be reconsidered.

CHAPTER III DATA BASE FOR THE RMA STUDY OF ROLLER BELT CONVEYORS

The objective of this chapter is to establish the functional data foundation that would allow quantification of RMA indicators for the four roller belt conveyers. The functional data base is made up of statistical series that express, for each conveyer, the times between failures, as well as the adjustment times for each failure.

Primary data are recorded for a six *months* period. They include, separately for the four conveyers, the day and hour of the failure, and the day and hour of its remedy. These data, called gross data, come from the daily reports of the halts, as well as from the work order records created by the maintenance staff.

For Oltenia mine field quarries conditions are created to record these primary data at the open pit dispatchers. These primary data used in RMA studies are considered secondary data. This means that the data are collected by someone else than those who analyze the reliability and maintainability. The data are kept with the general aim of information supply about production and maintenance.

Primary data base allows chronological times to and effective times repair times to be determined between failures. To evaluate primary data, chronological times of functioning times between failures TBF_i, as well as repair times are established. Similarly, cumulative $CTBF_i$ functioning times repair times $CTTR_i$ are established.

Evaluation of chronological series of operational times

Evaluation of chronological series is done by application of functioning and repair times trend correlation test, as well as the one of serial correlation.

Trend correlation test is obtained by relating cumulative functioning and repair to the total number of failures. The approximately linear dependence between data shows that they are identically distributed. Trend correlation test application for the four conveyers shows that functional times are identically distributed. This shows that they can be quantified by the same law of distribution.

The serial correlation test, quantifying consecutive data dispersion, shows the connection between two consecutive failures, suggesting whether the data are independent or not. Application of serial correlation tests for the four conveyers shows that the data are independent. This shows that there is no connection between two consecutive failures, in other words, previous failure does not influence future failures.

The two correlation tests allow the use of the same theoretical distribution law governing failure manifestation for the four roller belt conveyers.

Distributions analyze times before failure or between failures, as well as repair times or times re-establishing conveyer functioning.

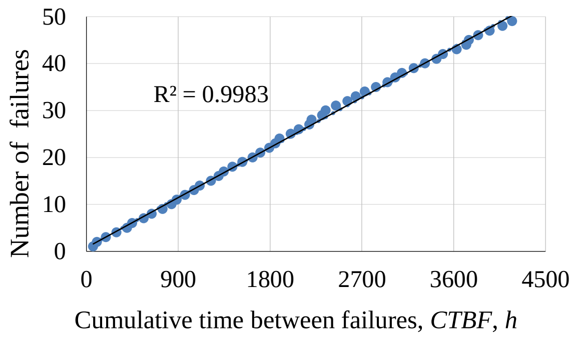

Fig. 3.3. Trend test for TBF_i, TB-1

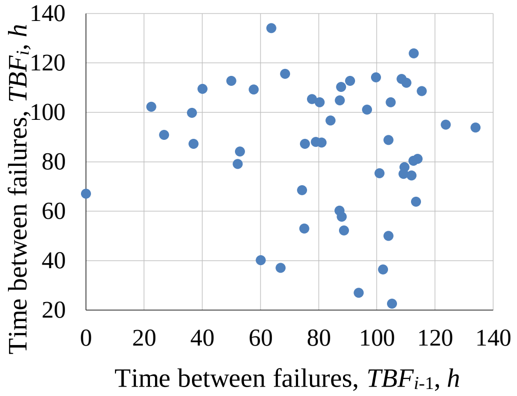

Fig. 3.4. Correlation test for TBF_i, TB-1

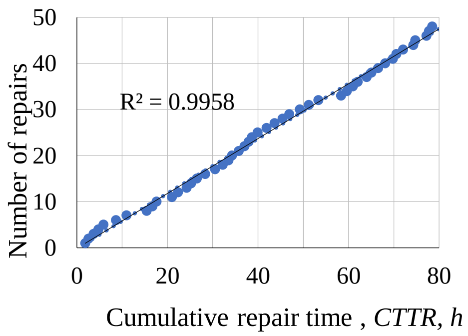

Fig. 3.5. Trend test for TTR_i, TB-1

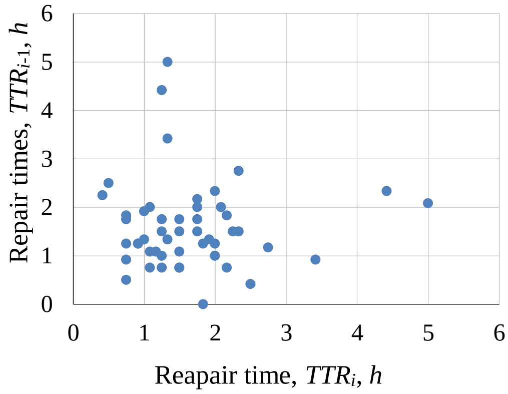

Fig. 3.6. Correlation test for TTR_i , TB-1

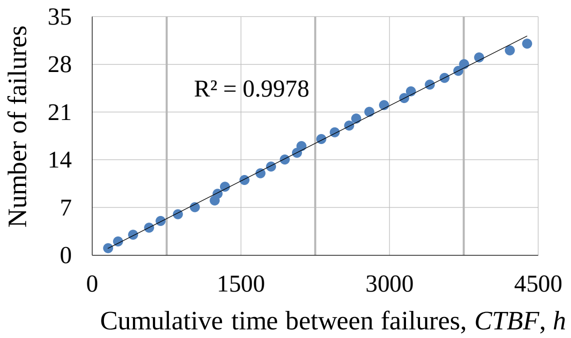

Fig. 3.7. Trend test for TBF_i, TB-2

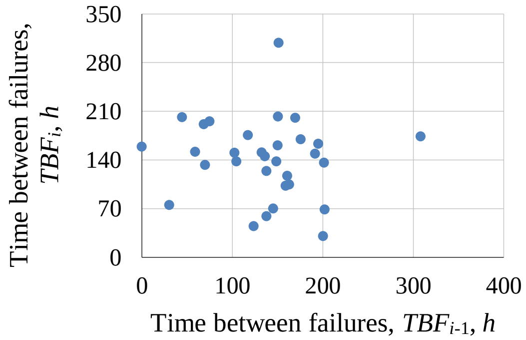

Fig. 3.8. Correlation test for TBF_{i-1}, TB-2

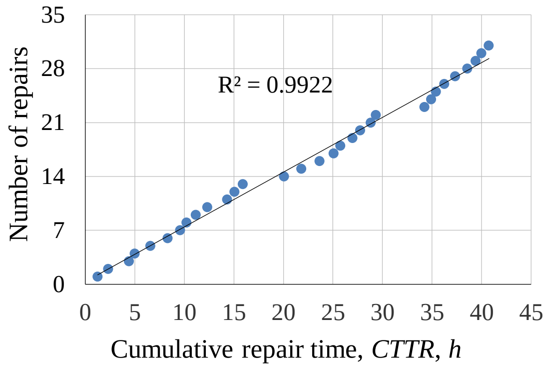

Fig. 3.9. Trend test for TTR_i, TB-2

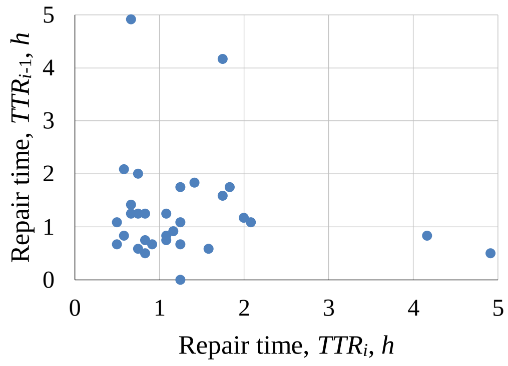

Fig. 3.10. Correlation test for TTR_i, TB-2

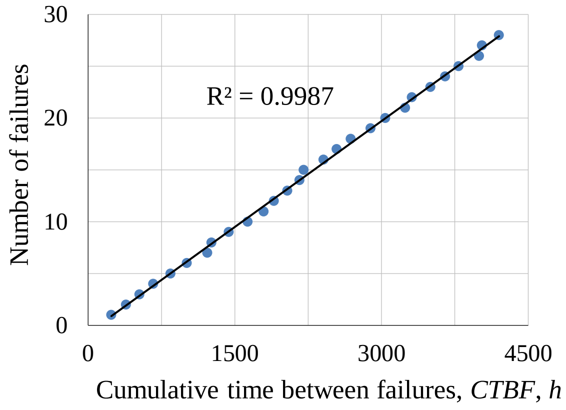

Fig. 3.11. Trend test for TBF_i, TB-3

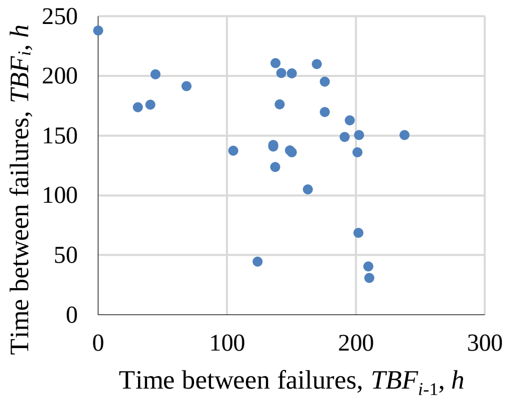

Fig. 3.12. Correlation test for TBF_i, TB-3

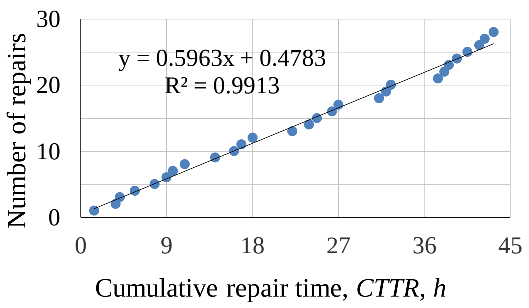

Fig. 3.13. Trend test for TTR_i, TB-3

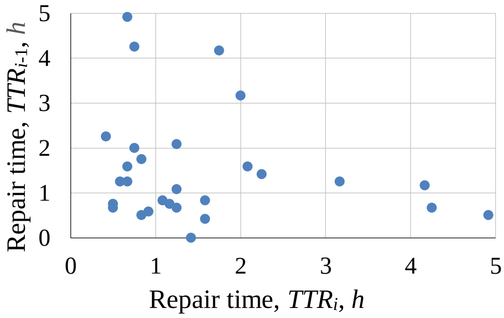

Fig. 3.14. Correlation test for *TTRi*, TB-3

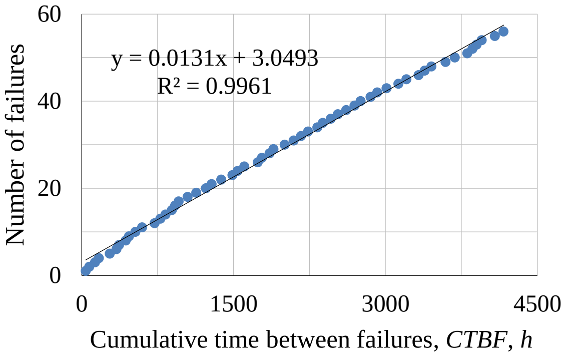

Fig. 3.15. Trend test for TBF_i, TB-4

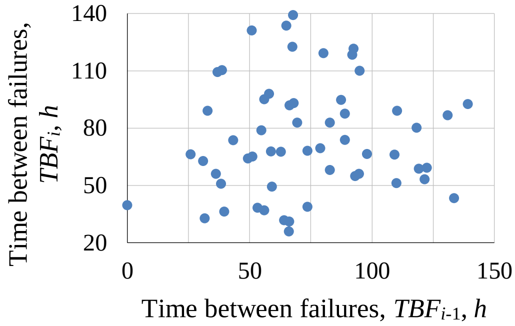

Fig. 3.16. Correlation test for TBF_i, TB-4

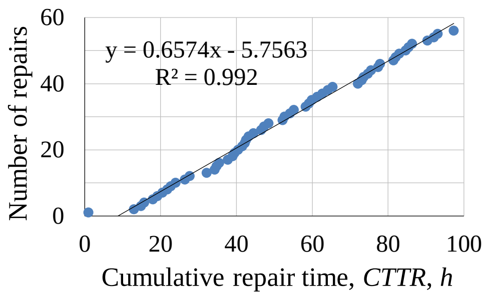

Fig. 3.17. Trend test for $CTTR_i$, TB-4

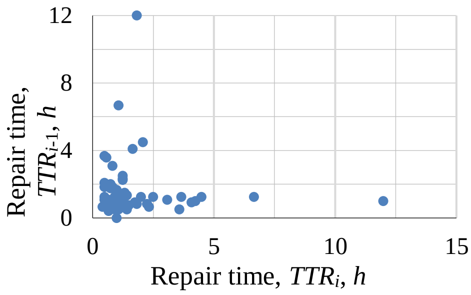

Fig. 3.18. Correlation test for $TTRi$, TB-4

Distribution of roller belt conveyors' failures

Table 3.13. **Roller belt conveyor TB-1. Statistical series of times between failures, TBF_i, t_i. Empirical distribution function $\widehat{F}(t_i)$**

i	TBF_i, t_i, h	$\widehat{F}(t_i)$	i	TBF_i, t_i, h	$\widehat{F}(t_i)$	i	TBF_i, t_i, h	$\widehat{F}(t_i)$	i	TBF_i, t_i, h	$\widehat{F}(t_i)$
1	22,500	0,014170	14	74,333	0,277328	27	90,833	0,540486	40	109,500	0,803644
2	26,917	0,034413	15	75,083	0,297571	28	93,750	0,560729	41	110,250	0,823887
3	36,416	0,054656	16	75,333	0,317814	29	95,000	0,580972	42	111,917	0,844130
4	37,000	0,074899	17	77,750	0,338057	30	96,667	0,601215	43	112,667	0,864372
5	40,083	0,095142	18	79,083	0,358300	31	99,750	0,621457	44	112,750	0,884615
6	50,000	0,115385	19	80,333	0,378543	32	101,000	0,641700	45	113,500	0,904858
7	52,167	0,135628	20	81,083	0,398785	33	102,167	0,661943	46	114,084	0,925101
8	52,917	0,155870	21	84,083	0,419028	34	104,000	0,682186	47	115,500	0,945344
9	57,750	0,176113	22	87,167	0,439271	35	104,083	0,702429	48	123,750	0,965587
10	60,167	0,196356	23	87,250	0,459514	36	104,750	0,722672	49	134,000	0,985830
11	63,750	0,216599	24	87,750	0,479757	37	105,250	0,742915			
12	67,000	0,236842	25	87,917	0,500000	38	108,500	0,763158			
13	68,500	0,257085	26	88,750	0,520243	39	109,250	0,783401			

Table 3.14. **Roller belt conveyor TB-1. Estimated values of the theoretical distribution parameters for time between failures, *TBF*$_i$**

Distribution	Parameter					
	$\lambda(t)$, h^{-1}	$m(t)$, h	$\sigma(t)$, h	$\beta(t)$	$\eta(t)$, h	$\gamma(t)$, h
Exponential negative, *Ep*	$1{,}304 \cdot 10^{-2}$					
Normal normalized, *Nv*		85,184	26,591			
Weibull biparametric normalized, *Wp*				3,022	96,143	
Weibull biparametric normalized, *Wv*				3,031	91,669	
Weibull triparametric, *Wm*				3,553	94,598	4,278E-09

Table 3.15. **Roller belt conveyor TB-1. Testing the theoretical distribution laws of time between failures**

Distribution, symbol	Distribution function, $F(t)$	K-S test, $D_{max} < D_{cr} = D_{\alpha,\,49}$			
		Maximum deviation, D_{max}	Risk, α, %	Critical value, $D_{\alpha,\,19}$	Validation
Exponential, *Ep*	$F(t) = 1 - e^{-\lambda t} = 1 - e^{-1{,}304 \cdot 10^{-2}\, t}$ (3.1)	**0,383877**	0,5	$D_{\alpha;49}$=**0,242772**	NOT
Normal, *Nv*	$F(t) = \frac{1}{2} + \Phi\left(\frac{t-m}{\sigma}\right) = \frac{1}{2} + \Phi\left(\frac{t-85{,}184}{26{,}591}\right)$ (3.2)	**0,110700**	20	$D_{\alpha;49}$=**0,149870**	YES
	$F(t) = \text{NORMSDIST}\left(\frac{t-m}{\sigma}\right) = \text{NORMSDIST}\left(\frac{t-85{,}184}{26{,}591}\right)$ (3.3)		0,5	$D_{\alpha;49}$=0,242772	
Weibull biparametric, *Wp*	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t}{96{,}143}\right)^{3{,}022}}$ (3.4)	**0,131562**	20	$D_{\alpha;49}$=**0,149870**	YES
			0,5	$D_{\alpha;49}$=0,242772	
Weibull biparametric, *Nv*	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t}{91{,}669}\right)^{3{,}031}}$ (3.5)	**0,157141**	10	$D_{\alpha;19}$=**0,171279**	YES
			0,5	$D_{\alpha;49}$=0,242772	
Weibull triparametric, *Wp*	$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t-4{,}278E\text{-}09}{94{,}598}\right)^{3{,}553}}$ (3.6)	**0,107523**	20	$D_{\alpha;49}$=**0,149870**	YES
			0,5	$D_{\alpha;49}$=0,242772	

Table 3.16. **Roller belt conveyor TB-1. Statistical series of repair times, *TTR*$_i$, *tr*$_i$. Empirical distribution function $\widehat{M}(tr_i)$**

i	TTR_i, tr_i, h	$\widehat{M}(tr_i)$	i	TTR_i, tr_i, h	$\widehat{M}(tr_i)$	i	TTR_i, tr_i, h	$\widehat{M}(tr_i)$	i	TTR_i, tr_i, h	$\widehat{M}(tr_i)$
1	0,417	0,014170	14	1,083	0,277328	27	1,500	0,540486	40	2,167	0,803644
2	0,500	0,034413	15	1,167	0,297571	28	1,500	0,560729	41	2,167	0,823887
3	0,750	0,054656	16	1,250	0,317814	29	1,750	0,580972	42	2,250	0,844130
4	0,750	0,074899	17	1,250	0,338057	30	1,750	0,601215	43	2,333	0,864372
5	0,750	0,095142	18	1,250	0,358300	31	1,750	0,621457	44	2,333	0,884615
6	0,750	0,115385	19	1,250	0,378543	32	1,750	0,641700	45	2,500	0,904858
7	0,750	0,135628	20	1,250	0,398785	33	1,833	0,661943	46	2,750	0,925101
8	0,917	0,155870	21	1,333	0,419028	34	1,833	0,682186	47	3,417	0,945344
9	0,917	0,176113	22	1,333	0,439271	35	1,917	0,702429	48	4,417	0,965587
10	1,000	0,196356	23	1,333	0,459514	36	2,000	0,722672	49	5,000	0,985830
11	1,000	0,216599	24	1,500	0,479757	37	2,000	0,742915			
12	1,083	0,236842	25	1,500	0,500000	38	2,000	0,763158			
13	1,083	0,257085	26	1,500	0,520243	39	2,083	0,783401			

Table 3.17. **Roller belt conveyor TB-1. Estimated values of the theoretical distribution parameters for repair times**

Distribuția	Parameter												
	$\mu(tr)$, h^{-1}	$m(tr)$, h	$\sigma(tr)$, h	$m(lgtr)$, h	$t_{med}(lgtr)$, h	$\sigma(lgtr)$	$\beta(tr)$	$\eta(tr)$, h	$\beta(tr)$	$\eta(tr)$, h	$\beta(tr)_r$	$\eta(tr)$, h	$\gamma(tr)$, h
Exponential, *Ep*	0,691												
Normal, *Nv*		1,646	0,886										
Lognormal, *LNv*				0,376	1,457	0,499							
Weibull biparametric, *Wp*							2,378	1,844					
Weibull biparametric, *Wv*									2,022	1,882			
Weibull triparametric, *Wm*											1,935	1,856	2,148 E-10

Table 3.18. **Roller belt conveyor TB-1. Testing the theoretical distribution laws of repair times**

Distribution, symbol	Distribution function, $M(tr)$	K-S test, $D_{max} < D_{cr} = D_{\alpha,\,49}$			
		Maximum deviation, D_{max}	Risk, α, %	Critical value, $D_{\alpha,\,19}$	Validation
Exponential, *Ep*	$M(tr) = 1 - e^{-\mu\, tr} = 1 - e^{-0{,}691\, tr}$ (3.7)	**0,370109**	0,5	$D_{\alpha;49}$=**0,242772**	NOT
Normal, *Nv*	$M(tr) = \frac{1}{2} + \Phi\left(\frac{tr - m}{\sigma}\right) = \frac{1}{2} + \Phi\left(\frac{tr - 1{,}646}{0{,}886}\right)$ (3.8)	**0,126248**	20	$D_{\alpha;49}$=**0,149870**	YES
	$M(tr) = \text{NORMSDIST}\left(\frac{tr - m}{\sigma}\right) = \text{NORMSDIST}\left(\frac{tr - 1{,}646}{0{,}886}\right)$ (3.9)		0,5	$D_{\alpha;49}$=0,242772	
Lognormal, *LNv*	$M(tr) = \frac{1}{2} + \Phi\left(\frac{\ln tr - m}{\sigma}\right) = \frac{1}{2} + \Phi\left(\frac{\ln tr - 0{,}376}{0{,}499}\right)$ (3.10)	**0,082644**	20	$D_{\alpha;49}$=**0,149870**	YES
	$M(tr) = \text{NORMSDIST}\left(\frac{1}{\sigma} \ln \frac{tr}{t_{med}}\right) = \text{NORMSDIST}\left(\frac{1}{0{,}499} \ln \frac{tr}{1{,}457}\right)$ (3.11)		0,5	$D_{\alpha;49}$=0,242772	
Weibull biparametric, *Wp*	$M(tr) = 1 - e^{-\left(\frac{tr}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{tr}{1{,}844}\right)^{2{,}378}}$ (3.12)	**0,103087**	20	$D_{\alpha;49}$=**0,149870**	YES
			0,5	$D_{\alpha;49}$=0,242772	
Weibull biparametric, *Wv*	$M(tr) = 1 - e^{-\left(\frac{tr}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{tr}{1{,}882}\right)^{2{,}022}}$ (3.13)	**0,109716**	20	$D_{\alpha;49}$=**0,149870**	YES
			0,5	$D_{\alpha;49}$=0,242772	
Weibull triparametric, *Wm*	$M(tr) = 1 - e^{-\left(\frac{tr - \gamma}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{tr - 2{,}148E-10}{1{,}856}\right)^{1{,}935}}$ (3.14)	**0,124559**	20	$D_{\alpha;49}$=**0,149870**	YES
			0,5	$D_{\alpha;49}$=0,242772	

Table 3.19. **Roller Belt conveyor TB-2. Statistical series of times between failures, TBF_i, t_i. Empirical distribution function $\widehat{F}(t_i)$**

i	TBF_i, t_i, h	$\widehat{F}(t_i)$	i	TBF_i, t_i, h	$\widehat{F}(t_i)$	i	TBF_i, t_i, h	$\widehat{F}(t_i)$	i	TBF_i, t_i, h	$\widehat{F}(t_i)$
1	30,250	0,022293	9	117,167	0,277070	17	150,167	0,531847	25	175,750	0,786624
2	44,500	0,054140	10	123,750	0,308917	18	150,500	0,563694	26	191,417	0,818471
3	59,167	0,085987	11	132,583	0,340764	19	151,416	0,595541	27	195,250	0,850318
4	68,667	0,117834	12	135,917	0,372611	20	159,083	0,627389	28	200,500	0,882166
5	69,917	0,149682	13	137,667	0,404459	21	160,833	0,659236	29	201,333	0,914013
6	74,917	0,181529	14	137,917	0,436306	22	163,083	0,691083	30	202,083	0,945860
7	102,667	0,213376	15	145,250	0,468153	23	169,667	0,722930	31	308,340	0,977707
8	104,500	0,245223	16	148,916	0,500000	24	173,916	0,754777			

Table 3.20. **Roller belt conveyor TB-2. Estimated values of the theoretical distribution parameters for time between failures, TBF_i**

Distribution	Parameter					
	λ (*t*), h^{-1}	*m*(*t*), *h*	σ(*t*), *h*	β(*t*)	η(*t*), *h*	γ(*t*), *h*
Exponential negative, *Ep*	$7{,}896 \cdot 10^{-3}$					
Normal, *Nv*		141,519	56,505			
Weibull biparametric, *Wp*				2,391	161,799	
Weibull biparametric, *Wv*				2,355	154,278	
Weibull triparametric, *Wm*				2,701	201,020	– 39,494

Table 3.21. **Roller belt conveyor TB-2. Testing the theoretical distribution laws of time between failures**

Distribution, symbol	Distribution function, *F*(*t*)	K-S test, $D_{max} < D_{cr} = D_{\alpha,\,49}$			
		Maximum deviation, D_{max}	Risk, α, %	Critical value, $D_{\alpha,\,19}$	Va-lida-tion
Exponential, *Ep*	$F(t) = 1 - e^{-\lambda t} = 1 - e^{-7{,}896 \cdot 10^{-3}\, t}$ (3.15)	**0,373916**	0,5	$D_{\alpha;31}$=**0,303328**	NOT
Normal, *Nv*	$F(t) = \frac{1}{2} + \Phi\left(\frac{t-m}{\sigma}\right) = \frac{1}{2} + \Phi\left(\frac{t-141{,}519}{56{,}505}\right)$ (3.16)	**0,128254**	20	$D_{\alpha;31}$=**0,187316**	YES
	$F(t) = \mathrm{NORMSDIST}\left(\frac{t-m}{\sigma}\right) = \mathrm{NORMSDIST}\left(\frac{t-141{,}519}{56{,}505}\right)$ (3.17)		0,5	$D_{\alpha;31}$=0,303328	
Weibull biparametric, *Wp*	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t}{161{,}799}\right)^{2{,}391}}$ (3.18)	**0,153746**	20	$D_{\alpha;31}$=**0,187316**	YES
			0,5	$D_{\alpha;31}$=0,303328	
Weibull biparametric, *Wv*	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t}{154{,}278}\right)^{2{,}355}}$ (3.19)	**0,194417**	10	$D_{\alpha;31}$=**0,214125**	YES
			0,5	$D_{\alpha;31}$=0,303328	
Weibull triparametric, *Wm*	$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t+39{,}494}{201{,}020}\right)^{2{,}701}}$ (3.20)	**0,172736**	20	$D_{\alpha;31}$=**0,187316**	YES
			0,5	$D_{\alpha;31}$=0,303328	

*Table 3.22***. Roller belt conveyor TB-2. Statistical series of repair times, TTR_i, tr_i. Empirical distribution function $\widehat{M}(tr_i)$**

i	TTR_i, tr_i, *h*	$\widehat{M}(tr_i)$	*i*	TTR_i, tr_i, *h*	$\widehat{M}(tr_i)$	*i*	TTR_i, tr_i, *h*	$\widehat{M}(tr_i)$	*i*	TTR_i, tr_i, *h*	$\widehat{M}(tr_i)$
1	0,500	0,022293	9	0,750	0,277070	17	1,083	0,531847	25	1,750	0,786624
2	0,500	0,054140	10	0,750	0,308917	18	1,167	0,563694	26	1,750	0,818471
3	0,583	0,085987	11	0,833	0,340764	19	1,250	0,595541	27	1,833	0,850318
4	0,583	0,117834	12	0,833	0,372611	20	1,250	0,627389	28	2,000	0,882166
5	0,667	0,149682	13	0,833	0,404459	21	1,250	0,659236	29	2,083	0,914013
6	0,667	0,181529	14	0,917	0,436306	22	1,250	0,691083	30	4,167	0,945860
7	0,667	0,213376	15	1,083	0,468153	23	1,417	0,722930	31	4,917	0,977707
8	0,750	0,245223	16	1,083	0,500000	24	1,583	0,754777			

Table 3.23. **Belt conveyor TB-2. Estimated values of the theoretical distribution parameters for repair times**

Distribution	Parameter												
	μ(*tr*), h^{-1}	*m*(*tr*), *h*	σ(*tr*), *h*	*m*(*lgtr*), *h*	t_{med}(*lgtr*), *h*	σ(*lgtr*)	β(*tr*)	η(*tr*), *h*	β(*tr*)	η(*tr*), *h*	$\beta(tr)_r$	η(*tr*), *h*	γ(*tr*), *h*
Exponential, *Ep*	0,790												
Normal, *Nv*		1,314	0,976										

Table 3.23. **Belt conveyor TB-2. Estimated values of the theoretical distribution parameters for repair times**

Distribution	Parameter												
	$\mu(tr)$, h^{-1}	$m(tr)$, h	$\sigma(tr)$, h	$m(lgtr)$, h	$t_{med}(lgtr)$, h	$\sigma(lgtr)$	$\beta(tr)$	$\eta(tr)$, h	$\beta(tr)$	$\eta(tr)$, h	$\beta(tr)_r$	$\eta(tr)$, h	$\gamma(tr)$, h
Lognormal, *LNv*				0,100	1,105	0,555							
Weibull biparametric, *Wp*							1,867	1,284					
Weibull biparametric, *Wv*									1,573	1,482			
Weibull triparametric, *Wm*											1,362	1,436	–1,73E-12

Table 3.24. **Belt conveyor TB-2. Testing the theoretical distribution laws of repair times**

Distribution, symbol	Distribution function, $M(tr)$	K-S test, $D_{max} < D_{cr} = D_{\alpha,\,31}$			
		Maximum deviation, D_{max}	Risk, α, %	Critical value, $D_{\alpha,\,19}$	Validation
Exponential, *Ep*	$M(tr) = 1 - e^{-\mu\, tr} = 1 - e^{-0,790\, tr}$ (3.21)	**0,326176**	0,5	$D_{\alpha;31}$=**0,303328**	NOT
Normal, *Nv*	$M(tr) = \frac{1}{2} + \Phi\left(\frac{tr - m}{\sigma}\right) = \frac{1}{2} + \Phi\left(\frac{tr - 1,314}{0,976}\right)$ (3.22)	**0,217425**	5	$D_{\alpha;31}$=**0,237884**	YES
	$M(tr) = \text{NORMSDIST}\left(\frac{tr - m}{\sigma}\right) = \text{NORMSDIST}\left(\frac{tr - 1,314}{0,976}\right)$ (3.23)		0,5	$D_{\alpha;31}$=0,303328	
Lognormal, *LNv*	$M(tr) = \frac{1}{2} + \Phi\left(\frac{\ln tr - m}{\sigma}\right) = \frac{1}{2} + \Phi\left(\frac{\ln tr - 0,100}{0,555}\right)$ (3.24)	**0,103029**	20	$D_{\alpha;31}$=**0,187316**	YES
	$M(tr) = \text{NORMSDIST}\left(\frac{1}{\sigma}\ \ln \frac{tr}{t_{med}}\right) = \text{NORMSDIST}\left(\frac{1}{0,555}\ \ln \frac{tr}{1,105}\right)$ (3.25)		0,5	$D_{\alpha;31}$=**0,303328**	
Weibull biparametric, *Wp*	$M(tr) = 1 - e^{-\left(\frac{tr}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{tr}{1,284}\right)^{1,867}}$ (3.26)	**0,157795**	20	$D_{\alpha;31}$=**0,187316**	YES
			0,5	$D_{\alpha;31}$=**0,303328**	
Weibull biparametric, *Wv*	$M(tr) = 1 - e^{-\left(\frac{tr}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{tr}{1,482}\right)^{1,573}}$ (3.27)	**0,165634**	20	$D_{\alpha;31}$=**0,187316**	YES
			0,5	$D_{\alpha;31}$=0,303328	
Weibull triparametric, *Wm*	$M(tr) = 1 - e^{-\left(\frac{tr - \gamma}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{tr + 1,73E-12}{1,436}\right)^{1,362}}$ (3.28)	**0,211507**	10	$D_{\alpha;31}$=**0,214125**	YES
			0,5	$D_{\alpha;31}$=**0,303328**	

Table 3.25. **Belt conveyor TB-3. Statistical series of times between failures, TBF_i, t_i. Empirical distribution function $\widehat{F}(t_i)$**

i	TBF_i, t_i, h	$\widehat{F}(t_i)$	i	TBF_i, t_i, h	$\widehat{F}(t_i)$	i	TBF_i, t_i, h	$\widehat{F}(t_i)$	i	TBF_i, t_i, h	$\widehat{F}(t_i)$
1	30,834	0,024648	8	136,000	0,271127	15	150,500	0,517606	22	195,250	0,764085
2	40,583	0,059859	9	137,417	0,306338	16	162,750	0,552817	23	201,333	0,799296
3	44,500	0,095070	10	137,667	0,341549	17	169,667	0,588028	24	202,083	0,834507
4	68,667	0,130282	11	140,834	0,376761	18	173,750	0,623239	25	202,500	0,869718
5	104,833	0,165493	12	142,250	0,411972	19	175,917	0,658451	26	209,833	0,904930
6	123,750	0,200704	13	148,916	0,447183	20	176,083	0,693662	27	210,583	0,940141
7	135,917	0,235915	14	150,333	0,482394	21	191,417	0,728873	28	237,917	0,975352

Table 3.26. **Belt conveyor TB-3. Estimated values of the theoretical distribution parameters for time between failures TBF_i**

Distribuția	Parameter					
	$\lambda(t)$, h^{-1}	$m(t)$, h	$\sigma(t)$,h	$\beta(t)$	$\eta(t)$, h	$\gamma(t)$, h
Exponential negative, *Ep*	$7{,}263 \cdot 10^{-3}$					
Normal normalized, *Nv*		150,074	53,337			
Weibull biparametric, *Wp*				2,181	175,319	
Weibull biparametrică, *Wv*				2,438	159,828	
Weibull triparametrică, *Wm*				3,076	167,872	1,121E-06

Table 3.27. **Belt conveyor TB-3. Testing the theoretical distribution laws of time between failures**

Distribution, symbol	Distribution function, $F(t)$	K-S test, $D_{max} < D_{cr} = D_{\alpha,\,28}$			
		Maximum deviation, D_{max}	Risk, α, %	Critical value, $D_{\alpha,\,19}$	Validation
Exponential, *Ep*	$F(t) = 1 - e^{-\lambda t} = 1 - e^{-7{,}263 \cdot 10^{-3}\, t}$ (3.29)	**0,427435**	0,5	$D_{\alpha;28}$=**0,318625**	NOT
Normal, *Nv*	$F(t) = \frac{1}{2} + \Phi\left(\frac{t-m}{\sigma}\right) = \frac{1}{2} + \Phi\left(\frac{t-150{,}074}{53{,}337}\right)$ (3.30)	**0,194633**	20	$D_{\alpha;28}$=**0,196798**	YES
	$F(t) = \text{NORMSDIST}\left(\frac{t-m}{\sigma}\right) = \text{NORMSDIST}\left(\frac{t-150{,}074}{53{,}337}\right)$ (3.31)		0,5	$D_{\alpha;28}$=0,318625	
Weibull biparametric, *Wp*	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t}{175{,}319}\right)^{2{,}181}}$ (3.32)	**0,236001**	5	$D_{\alpha;28}$=**0,249934**	YES
			0,5	$D_{\alpha;28}$=0,318625	
Weibull biparametric, *Wv*	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t}{159{,}828}\right)^{2{,}438}}$ (3.33)	**0,289451**	1	$D_{\alpha;28}$=**0,299707**	YES
			0,5	$D_{\alpha;28}$=0,318625	
Weibull triparametric, *Wm*	$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t-1{,}121\text{E-}06}{167{,}872}\right)^{3{,}076}}$ (3.34)	**0,206150**	10	$D_{\alpha;28}$=**0,224974**	YES
			0,5	$D_{\alpha;28}$=0,318625	

Table 3.28. **Belt conveyor TB-3. Statistical series of repair times, TTR_i, tr_i. Empirical distribution function $\widehat{M}(tr_i)$**

i	TTR_i, tr_i, h	$\widehat{M}(tr_i)$	i	TTR_i, tr_i, h	$\widehat{M}(tr_i)$	i	TTR_i, tr_i, h	$\widehat{M}(tr_i)$	i	TTR_i, tr_i, h	$\widehat{M}(tr_i)$
1	0,417	0,024648	8	0,750	0,271127	15	1,250	0,517606	22	2,000	0,764085
2	0,500	0,059859	9	0,750	0,306338	16	1,250	0,552817	23	2,083	0,799296
3	0,500	0,095070	10	0,833	0,341549	17	1,250	0,588028	24	2,250	0,834507
4	0,583	0,130282	11	0,833	0,376761	18	1,417	0,623239	25	3,167	0,869718
5	0,667	0,165493	12	0,917	0,411972	19	1,583	0,658451	26	4,167	0,904930
6	0,667	0,200704	13	1,083	0,447183	20	1,583	0,693662	27	4,250	0,940141
7	0,667	0,235915	14	1,167	0,482394	21	1,750	0,728873	28	4,917	0,975352

Table 3.29. **Belt conveyor TB-3. Estimated values of the theoretical distribution parameters for repair times TTR_i**

Distribution	Parameter												
	$\mu(tr)$, h^{-1}	$m(tr)$, h	$\sigma(tr)$, h	$m(lgtr)$, h	$t_{med}(lgtr)$, h	$\sigma(lgtr)$	$\beta(tr)$	$\eta(tr)$, h	$\beta(tr)$	$\eta(tr)$, h	$\beta(tr)_r$	$\eta(tr)$, h	$\gamma(tr)$, h
Exponential, *Ep*	0,667												
Normal, *Nv*		1,545	1,205										

Table 3.29. **Belt conveyor TB-3. Estimated values of the theoretical distribution parameters for repair times TTR_i**

Distribution	Parameter												
	$\mu(tr)$, h^{-1}	$m(tr)$, h	$\sigma(tr)$, h	$m(lgtr)$, h	$t_{med}(lgtr)$, h	$\sigma(lgtr)$	$\beta(tr)$	$\eta(tr)$, h	$\beta(tr)$	$\eta(tr)$, h	$\beta(tr)_r$	$\eta(tr)$, h	$\gamma(tr)$, h
Lognormal, *LNv*				0,198	1,219	0,677							
Weibull biparametric, *Wp*							1,649	1,703					
Weibull biparametric, *Wv*									1,437	1,978			
Weibull triparametric, *Wm*											1,292	1,670	–5,035 E-10

Table 3.30. **Belt conveyor TB-3. Testing the theoretical distribution laws of repair times**

Distribution, symbol	Distribution function, $M(tr)$	K-S test, $D_{max} < D_{cr} = D_{\alpha,\,28}$			
		Maximum deviation, D_{max}	Risk, α, %	Critical value, $D_{\alpha,\,19}$	Va-lida-tion
Exponential, *Ep*	$M(tr) = 1- e^{-\mu\, tr} = 1- e^{-0{,}667\, tr}$ (3.35)	**0,259028**	2,5	$D_{\alpha;28}$=**0,272545**	YES
			0,5	$D_{\alpha;28}$=0,318625	
Normal, *Nv*	$M(tr) = \frac{1}{2}+\Phi\left(\frac{tr-m}{\sigma}\right) = \frac{1}{2}+\Phi\left(\frac{tr-1{,}545}{1{,}205}\right)$ (3.36)	**0,184591**	20	$D_{\alpha;28}$=**0,196798**	YES
	$M(tr)$ = NORMSDIST$\left(\frac{tr-m}{\sigma}\right)$= = NORMSDIST$\left(\frac{tr-1{,}545}{1{,}205}\right)$ (3.37)		0,5	$D_{\alpha;28}$=0,318625	
Lognormal, *LNv*	$M(tr)=\frac{1}{2}+\Phi\left(\frac{\ln tr-m}{\sigma}\right)=\frac{1}{2}+\Phi\left(\frac{\ln tr-0{,}198}{0{,}667}\right)$ (3.38)	**0,095652**	20	$D_{\alpha;28}$=**0,196798**	YES
	$M(tr)$ = NORMSDIST$\left(\frac{1}{\sigma}\ \ln\ \frac{tr}{t_{med}}\right)$= = NORMSDIST$\left(\frac{1}{0{,}677}\ \ln\ \frac{tr}{1{,}219}\right)$ (3.39)		0,5	$D_{\alpha;28}$=0,318625	
Weibull biparametric, *Wp*	$M(tr) = 1- e^{-\left(\frac{tr}{\eta}\right)^{\beta}} = 1- e^{-\left(\frac{tr}{1{,}703}\right)^{1{,}649}}$ (3.40)	**0,136695**	20	$D_{\alpha;28}$=**0,196798**	YES
			0,5	$D_{\alpha;28}$=0,318625	
Weibull biparametric, *Wv*	$M(tr) = 1- e^{-\left(\frac{tr}{\eta}\right)^{\beta}} = 1- e^{-\left(\frac{tr}{1{,}978}\right)^{1{,}437}}$ (3.41)	**0,184247**	20	$D_{\alpha;28}$=**0,196798**	YES
			0,5	$D_{\alpha;28}$=0,318625	
Weibull triparametric, *Wm*	$M(tr) = 1- e^{-\left(\frac{tr-\gamma}{\eta}\right)^{\beta}} = 1- e^{-\left(\frac{tr+5{,}035E\text{-}10}{1{,}670}\right)^{1{,}292}}$ (3.42)	**0,165202**	20	$D_{\alpha;28}$=**0,196798**	YES
			0,5	$D_{\alpha;28}$=**0,318625**	

Table 3.31. **Belt conveyor TB-4. Statistical series of times between failures, TBF_i, t_i. Empirical distribution function $\widehat{F}(t_i)$**

i	TBF_i, t_i, h	$\widehat{F}(t_i)$	i	TBF_i, t_i, h	$\widehat{F}(t_i)$	i	TBF_i, t_i, h	$\widehat{F}(t_i)$	i	TBF_i, t_i, h	$\widehat{F}(t_i)$
1	25,833	0,012411	15	54,833	0,260638	29	68,000	0,508865	43	93,083	0,757092
2	31,000	0,030142	16	55,916	0,278369	30	69,416	0,526596	44	94,750	0,774823
3	31,667	0,047872	17	56,000	0,296099	31	73,583	0,544326	45	95,000	0,792553
4	32,750	0,065603	18	57,917	0,313830	32	73,667	0,562057	46	97,917	0,810284

Table 3.31. **Belt conveyor TB-4. Statistical series of times between failures, TBF_i, t_i. Empirical distribution function $\hat{F}(t_i)$**

i	TBF_i, t_i, h	$\hat{F}(t_i)$	i	TBF_i, t_i, h	$\hat{F}(t_i)$	i	TBF_i, t_i, h	$\hat{F}(t_i)$	i	TBF_i, t_i, h	$\hat{F}(t_i)$
5	36,167	0,083333	19	58,667	0,331560	33	78,834	0,579787	47	109,250	0,828014
6	36,833	0,101064	20	59,167	0,349291	34	80,166	0,597518	48	110,000	0,845745
7	38,250	0,118794	21	62,750	0,367021	35	82,750	0,615248	49	110,250	0,863475
8	38,667	0,136525	22	64,083	0,384752	36	82,750	0,632979	50	118,250	0,881206
9	39,583	0,154255	23	65,000	0,402482	37	86,667	0,650709	51	119,167	0,898936
10	43,250	0,171986	24	66,000	0,420213	38	87,417	0,668440	52	121,500	0,916667
11	49,333	0,189716	25	66,167	0,437943	39	89,000	0,686170	53	122,500	0,934397
12	50,833	0,207447	26	66,333	0,455674	40	89,000	0,703901	54	131,000	0,952128
13	51,167	0,225177	27	67,500	0,473404	41	91,917	0,721631	55	133,500	0,969858
14	53,167	0,242908	28	67,750	0,491135	42	92,500	0,739362	56	139,166	0,987589

Table 3.32. **Belt conveyor TB-4. Estimated values of the theoretical distribution parameters for time between failures TBF_i**

Distribution	Parameter					
	λ (t), h^{-1}	$m(t)$, h	$\sigma(t)$,h	$\beta(t)$	$\eta(t)$, h	$\gamma(t)$, h
Exponential negative, *Ep*	$1{,}545 \cdot 10^{-2}$					
Normal normalized, *Nv*		74,421	29,094			
Weibull biparametric normalized, *Wp*				2,897	83,367	
Weibull biparametric normalized, *Wv*				2,984	84,833	
Weibull triparametric, *Wm*				2,766	83,616	6,013E-08

Table 3.33. **Belt conveyor TB-4. Testing the theoretical distribution laws of time between failures**

Distribution, symbol	Distribution function, $F(t)$	K-S test, $D_{max} < D_{cr} = D_{\alpha,\,56}$			
		Maximum deviation, D_{max}	Risk, α, %	Critical value, $D_{\alpha,\,19}$	Va-lida-tion
Exponential, *Ep*	$F(t) = 1 - e^{-\lambda t} = 1 - e^{-1{,}545 \cdot 10^{-2}\, t}$ (3.43)	**0,368232**	0,5	$D_{\alpha;56}$=**0,227425**	NOT
Normal, *Nv*	$F(t) = \frac{1}{2} + \Phi\left(\frac{t-m}{\sigma}\right) = \frac{1}{2} + \Phi\left(\frac{t-74{,}421}{29{,}094}\right)$ (3.44)	**0,096204**	20	$D_{\alpha;56}$=**0,140398**	YES
	$F(t) = \text{NORMSDIST}\left(\frac{t-m}{\sigma}\right) = \text{NORMSDIST}\left(\frac{t-74{,}421}{29{,}094}\right)$ (3.45)		0,5	$D_{\alpha;56}$=0,227425	
Weibull biparametric, *Wp*	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t}{83{,}367}\right)^{2{,}897}}$ (3.46)	**0,083422**	20	$D_{\alpha;56}$=**0,140398**	YES
			0,5	$D_{\alpha;56}$=0,227425	
Weibull biparametric, *Wv*	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t}{84{,}833}\right)^{2{,}984}}$ (3.47)	**0,105281**	20	$D_{\alpha;56}$=**0,140398**	YES
			0,5	$D_{\alpha;56}$=0,227425	
Weibull triparametric, *Wm*	$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} = 1 - e^{-\left(\frac{t-1{,}121\text{E-}06}{83{,}616}\right)^{2{,}766}}$ (3.48)	**0,077472**	20	$D_{\alpha;56}$=**0,140398**	YES
			0,5	$D_{\alpha;56}$=0,227425	

Table 3.34. **Roller belt conveyor TB-4. Statistical series of repair times, TTR_i, tr_i. Empirical distribution function $\widehat{M}(tr_i)$**

i	TTR_i, tr_i, h	$\widehat{M}(tr_i)$	i	TTR_i, tr_i, h	$\widehat{M}(tr_i)$	i	TTR_i, tr_i, h	$\widehat{M}(tr_i)$	i	TTR_i, tr_i, h	$\widehat{M}(tr_i)$
1	0,417	0,012411	15	0,833	0,260638	29	1,250	0,508865	43	1,833	0,757092
2	0,500	0,030142	16	0,833	0,278369	30	1,250	0,526596	44	2,000	0,774823
3	0,500	0,047872	17	0,917	0,296099	31	1,250	0,544326	45	2,083	0,792553
4	0,500	0,065603	18	0,917	0,313830	32	1,250	0,562057	46	2,250	0,810284
5	0,500	0,083333	19	0,917	0,331560	33	1,250	0,579787	47	2,333	0,828014
6	0,500	0,101064	20	0,917	0,349291	34	1,250	0,597518	48	2,500	0,845745
7	0,583	0,118794	21	1,000	0,367021	35	1,333	0,615248	49	3,083	0,863475
8	0,667	0,136525	22	1,000	0,384752	36	1,333	0,632979	50	3,583	0,881206
9	0,667	0,154255	23	1,083	0,402482	37	1,417	0,650709	51	3,667	0,898936
10	0,667	0,171986	24	1,083	0,420213	38	1,417	0,668440	52	4,083	0,916667
11	0,750	0,189716	25	1,083	0,437943	39	1,500	0,686170	53	4,250	0,934397
12	0,750	0,207447	26	1,083	0,455674	40	1,667	0,703901	54	4,500	0,952128
13	0,750	0,225177	27	1,250	0,473404	41	1,750	0,721631	55	6,667	0,969858
14	0,833	0,242908	28	1,250	0,491135	42	1,833	0,739362	56	12,000	0,987589

Table 3.35. **Roller belt conveyor TB-4. Estimated values of the theoretical distribution parameters for repair times TTR_i**

Distribuția	Parameter												
	$\mu(tr)$, h^{-1}	$m(tr)$, h	$\sigma(tr)$, h	$m(lgtr)$, h	$t_{med}(lgtr)$, h	$\sigma(lgtr)$	$\beta(tr)$	$\eta(tr)$, h	$\beta(tr)$	$\eta(tr)$, h	$\beta(tr)_r$	$\eta(tr)$, h	$\gamma(tr)$, h
Exponential, *Ep*	0,515												
Normal, *Nv*		1,738	1,844										
Lognormal, *LNv*				0,262	1,299	0,697							
Weibull biparametric, *Wp*							1,595	1,848					
Weibull biparametric, *Wv*									1,226	1,883			
Weibull triparametric, *Wm*											0,943	1,692	5,87 E-09

Table 3.36. **Belt conveyor TB-4. Testing the theoretical distribution laws of repair times**

Distribution, symbol	Distribution function, $M(tr)$	K-S test, $D_{max}<D_{cr}=D_{\alpha,\,56}$			
		Maximum deviation, D_{max}	Risk, α, %	Critical value, $D_{\alpha,\,19}$	Va-lida-tion
Exponential, *Ep*	$M(tr) = 1 - e^{-\mu\, tr} = 1 - e^{-0{,}515\, tr}$ (3.49)	**0,214684**	0,5	$D_{\alpha;56}$=**0,227425**	YES
Normal, *Nv*	$M(tr) = \frac{1}{2} + \Phi\left(\frac{tr - m}{\sigma}\right) = \frac{1}{2} + \Phi\left(\frac{tr - 1{,}738}{1{,}844}\right)$ (3.50) $M(tr) = \text{NORMSDIST}\left(\frac{tr - m}{\sigma}\right) =$ $= \text{NORMSDIST}\left(\frac{tr - 1{,}738}{1{,}844}\right)$ (3.51)	**0,238531**	0,5	$D_{\alpha;56}$=**0,227425**	NOT

Table 3.36. **Belt conveyor TB-4. Testing the theoretical distribution laws of repair times**

Distribution, symbol	Distribution function, $M(tr)$	K-S test, $D_{max}<D_{cr}=D_{\alpha,\,56}$			
		Maximum deviation, D_{max}	Risk, α, %	Critical value, $D_{\alpha,\,19}$	Va-lida-tion
Lognormal, *LNv*	$M(tr)=\frac{1}{2}+\Phi\left(\frac{ln\ tr-m}{\sigma}\right)=\frac{1}{2}+\Phi\left(\frac{ln\ tr-0{,}262}{0{,}697}\right)$ (3.52)	**0,119561**	20	$D_{\alpha;56}$=**0,140398**	YES
	$M(tr)=\text{NORMSDIST}\left(\frac{1}{\sigma}\ ln\ \frac{tr}{t_{med}}\right)=\text{NORMSDIST}\left(\frac{1}{0{,}697}\ ln\ \frac{tr}{1{,}299}\right)$ (3.53)		0,5	$D_{\alpha;56}$=**0,227425**	
Weibull biparametric, *Wp*	$M(tr)=1-e^{-\left(\frac{tr}{\eta}\right)^{\beta}}=1-e^{-\left(\frac{tr}{1{,}848}\right)^{1{,}595}}$ (3.54)	**0,188113**	2,5	$D_{\alpha;56}$=**0,194387**	YES
			0,5	$D_{\alpha;56}$=**0,227425**	
Weibull biparametric, *Wv*	$M(tr)=1-e^{-\left(\frac{tr}{\eta}\right)^{\beta}}=1-e^{-\left(\frac{tr}{1{,}883}\right)^{1{,}226}}$ (3.55)	**0,166366**	5	$D_{\alpha;56}$=**0,176694**	YES
			0,5	$D_{\alpha;56}$=**0,227425**	
Weibull triparametric, *Wm*	$M(tr)=1-e^{-\left(\frac{tr-\gamma}{\eta}\right)^{\beta}}=1-e^{-\left(\frac{tr-5{,}87E\text{-}09}{1{,}692}\right)^{0{,}943}}$ (3.56)	**0,258976**	0,5	$D_{\alpha;56}$=**0,227425**	NOT

CHAPTER IV STUDY OF AVAILABILITY OF ROLLER CONVEYOR BELT SYSTEMS

The final objective of this chapter is evaluation of the operational availability of transport systems made up of four roller belt conveyers mounted in series.

Operational availability is proved during exploitation and is quantified based on operational reliability and maintainability. Availability is given by the sum of two probabilities, the probability of functioning without failure, $R(t)$, and the probability of repair, expressed by maintainability function $M(tr)$. Availability of a technical system can be expressed by *KA* availability coefficient, also called *ration of active time* or *intrinsic availability*.

It represents the probability for a system to function adequately in any moment, during effective functioning and repair, in specified conditions. Intrinsic availability thus excludes times in which the system halts, although it is capable of functioning, called free times, as well as preventive maintenance times, those intended for logistic, administrative and depositing actions. The indicator is defined by the equation

$$KA=\frac{MTBF}{MTBF+MTTR}\ . \tag{4.3}$$

Reliability evaluation for roller belt conveyers

Optimization criteria used for to adopt distribution are dispersion and distance between empirical and theoretical distributions. Those distributions are adopted for which dispersion and distance has the least values. The tables presented synthesize the principal reliability indicators for the four roller belt conveyers. For each conveyer the distribution characterizing the best its functionality is adopted.

Table 4.4. **Quantitative indicators of reliability for belt conveyor TB-1. Weibull triparametric distribution *Wm***

No.	Name and symbol of the indicator	Relationship	Value, Unit
1	Reliability function, $R(t)$	$R(t)=e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}=e^{-\left(\frac{t-4{,}278E\text{-}9}{94{,}598}\right)^{3{,}553}}$ (4.25)	Fig. 4.1

Table 4.4. **Quantitative indicators of reliability for belt conveyor TB-1. Weibull triparametric distribution *Wm***

No.	Name and symbol of the indicator	Relationship	Value, Unit
2	Failure probability function, $f(t)$	$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} = \frac{3,553}{94,598}\left(\frac{t-4,278E{-}09}{94,598}\right)^{2,553} e^{-\left(\frac{t-4,278E{-}09}{94,598}\right)^{3,553}}$ (4.26)	Fig. 4.2
3	Failure rate function, $z(t)$	$z(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} = \frac{3,553}{94,598}\left(\frac{t-4,278E{-}09}{94,598}\right)^{2,553}$ (4.27)	Fig. 4.3
4	Mean time between failures, $MTBF$, $E(t)$	$E(t) = \gamma + \eta\,\Gamma\left(\frac{1}{\beta}+1\right) = 4,278\cdot10^{-9} + 94,598\,\Gamma\left(\frac{1}{3,553}+1\right)$ (4.28)	85 h
5	Median operating time, $t_{0,5}$, t_{med}	$t_{0,5} = \gamma + \eta\sqrt[\beta]{-ln\,0,5} = 4,278\cdot10^{-9} + 94,598\sqrt[3,553]{-ln\,0,5}$ (4.29)	85 h
6	Dispersion of operating time, D	$D = \eta^2\left\{\Gamma\left(\frac{2}{\beta}+1\right) - \left[\Gamma\left(\frac{1}{\beta}+1\right)\right]^2\right\} = 94,598^2\left\{\Gamma\left(\frac{2}{3,553}+1\right) - \left[\Gamma\left(\frac{1}{3,553}+1\right)\right]^2\right\}$ (4.30)	707 h^2

Table 4.5. **Quantitative indicators of reliability for belt conveyor TB-2. Normal normalized distribution *Nv***

No.	Name and symbol of the indicator	Relationship	Value, Unit
1	Reliability function, $R(t)$	$R(t) = \frac{1}{2} - \Phi\left(\frac{t-m}{\sigma}\right) = 1–\text{NORMSDIST}\left(\frac{t-m}{\sigma}\right) = 1–\text{NORMSDIST}\left(\frac{t-141,519}{56,505}\right)$ (4.31)	Fig. 4.4
2	Failure probability function, $f(t)$	$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-m}{\sigma}\right)^2} = \frac{1}{56,505\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-141,519}{56,505}\right)^2}$ (4.32)	Fig. 4.5
3	Failure rate function, $z(t)$	$z(t) = \frac{f(t)}{R(t)} = \frac{\frac{1}{56,505\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-141,519}{56,505}\right)^2}}{1-\text{NORMSDIST}\left(\frac{t-141,519}{56,505}\right)}$ (4.33)	Fig. 4.6
4	Mean time between failures, $MTBF$, $E(t)$	$MTBF = m = 141,519$ (4.34)	142 h
5	Median operating time, $t_{0,5}$, t_{med}	$t_{0,5} = t_{med} = m = 141,519$ (4.35)	142 h
6	Dispersion of operating time, D	$D = \sigma^2 = 56,505^2$ (4.36)	3193 h^2

Table 4.12. **Quantitative indicators of reliability for belt conveyor TB-3. Weibull triparametric distribution *Wm***

No.	Name and symbol of the indicator	Relationship	Value, Unit
1	Reliability function, $R(t)$	$R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} = e^{-\left(\frac{t-1,121E{-}06}{167,872}\right)^{3,076}}$ (4.73)	Fig. 4.7
2	Failure probability function, $f(t)$	$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} = \frac{3,076}{167,872}\left(\frac{t-1,121E{-}06}{167,872}\right)^{2,076} e^{-\left(\frac{t-1,121E{-}06}{167,872}\right)^{3,076}}$ (4.74)	Fig. 4.8
3	Failure rate function, $z(t)$	$z(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} = \frac{3,076}{167,872}\left(\frac{t-1,121E{-}06}{167,872}\right)^{2,076}$ (4.75)	Fig. 4.9
4	Mean time between failures, $MTBF$, $E(t)$	$E(t) = \gamma + \eta\,\Gamma\left(\frac{1}{\beta}+1\right) = 1,121E{-}6 + 167,872\cdot\Gamma\left(\frac{1}{3,076}+1\right)$ (4.76)	150 h

Table 4.12. **Quantitative indicators of reliability for belt conveyor TB-3. Weibull triparametric distribution *Wm***

No.	Name and symbol of the indicator	Relationship	Value, Unit
5	Median operating time, $t_{0,5}$, t_{med}	$t_{0,5} = \gamma + \eta \sqrt[\beta]{-ln\ 0,5} = 1{,}121E\text{–}6 + 167{,}872 \sqrt[3,076]{-ln\ 0,5}$ (4.77)	141 *h*
6	Dispersion of operating time, *D*	$D = \eta^2 \left\{\Gamma\left(\frac{2}{\beta}+1\right) - \left[\Gamma\left(\frac{1}{\beta}+1\right)\right]^2\right\} =$ $= 167{,}872^2 \left\{\Gamma\left(\frac{2}{3,076}+1\right) - \left[\Gamma\left(\frac{1}{3,076}+1\right)\right]^2\right\}$ (4.78	2845 h^2

Table 4.15. **Quantitative indicators of reliability for belt conveyor TB-4. Weibull biparametric normalized distribution *Wv***

No.	Name and symbol of the indicator	Relationship	Value, U
1	Reliability function, *R*(*t*)	$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} = e^{-\left(\frac{t}{84,833}\right)^{2,984}}$ (4.91)	Fig. 4.10
2	Failure probability function, *f* (*t*)	$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} =$ $= \frac{2,984}{84,833}\left(\frac{t}{84,833}\right)^{1,984} e^{-\left(\frac{t}{84,833}\right)^{2,984}}$ (4.92)	Fig. 4.11
3	Failure rate function, *z*(*t*)	$z(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} = \frac{2,984}{84,833}\left(\frac{t}{84,833}\right)^{1,984}$ (4.93)	Fig. 4.12
4	Mean time between failures, *MTBF*, *E*(*t*)	$E(t) = \eta\ \Gamma\left(\frac{1}{\beta}+1\right) = 84{,}833\ \Gamma\left(\frac{1}{2,984}+1\right)$ (4.94)	76 *h*
5	Median operating time, $t_{0,5}$, t_{med}	$t_{0,5} = \eta \sqrt[\beta]{-ln\ 0,5} = 84{,}833 \cdot \sqrt[2,984]{-ln\ 0,5}$ (4.95)	75 *h*
6	Dispersion of operating time, *D*	$D = \eta^2 \left\{\Gamma\left(\frac{2}{\beta}+1\right) - \left[\Gamma\left(\frac{1}{\beta}+1\right)\right]^2\right\} =$ $= 84{,}833^2 \left\{\Gamma\left(\frac{2}{2,984}+1\right) - \left[\Gamma\left(\frac{1}{2,984}+1\right)\right]^2\right\}$ (4.96)	765 h^2

Reliability function, Figs. 4.13 and 4.14, of the system made up of the four conveyers arranged in series is

$$R_S(t) = e^{-\left(\frac{t-4,278E\text{-}9}{94,598}\right)^{3,553}} \cdot \int_t^{\infty} \frac{1}{56,505\sqrt{2\pi}}\, e^{-\frac{1}{2}\left(\frac{t-141,519}{56,505}\right)^2} dt \cdot e^{-\left(\frac{t-1,121E-06}{167,872}\right)^{3,076}} \cdot e^{-\left(\frac{t}{84,833}\right)^{2,984}}. \qquad (4.108)$$

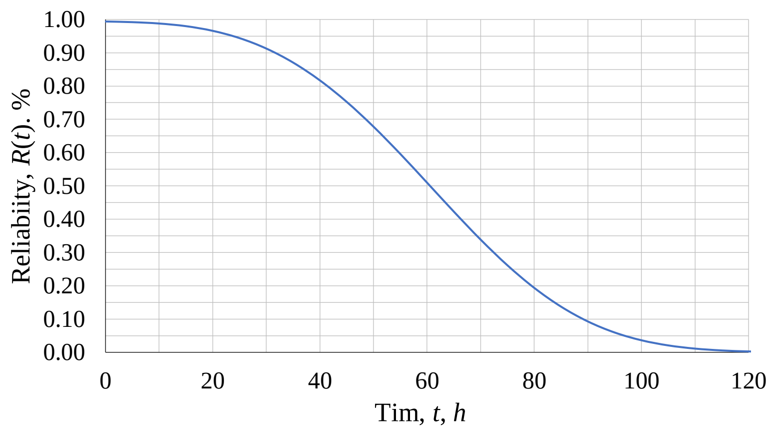

Fig. 4.13. Transport system reliability function

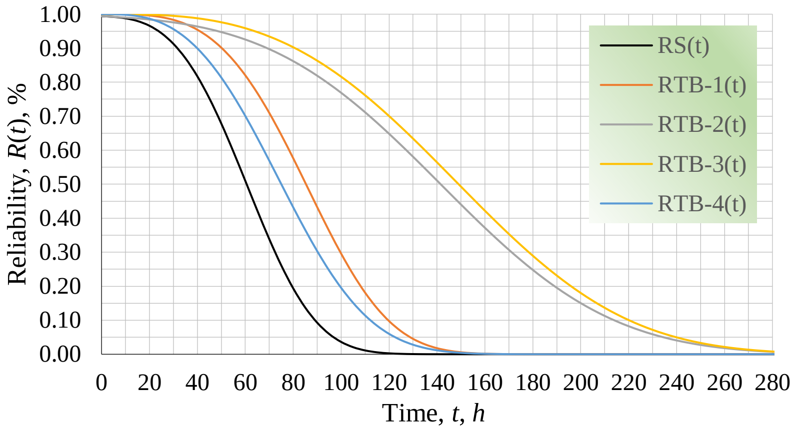

Fig. 4.14. System and subsystems reliability functions

Evaluation of the transport system maintainability

Optimization criteria used to adopt distributions are dispersion and distance between empirical and theoretical distributions. Those distributions are adopted for which dispersion and distance has the least values. The tables in this chapter synthesize the principal indicators of maintainability characterizing the conveyers' functionality.

Table 4.18. **Quantitative indicators of maintainability for belt conveyor TB-1. Lognormal normalized distribution *LNv***

No.	Name and symbol of the indicator	Relationship	Value, Unit
1	Maintainability function, $M(tr)$	$M(tr) = \frac{1}{2} + \Phi\left(\frac{ln\,tr - m}{\sigma}\right)$ = NORMSDIST$\left(\frac{1}{\sigma}\,ln\,\frac{tr}{tr_{med}}\right)$ = = NORMSDIST$\left(\frac{1}{0,499}\,ln\,\frac{tr}{1,457}\right)$ (4.120)	Fig. 4.15
2	Repair probability function, $f(tr)$	$f(tr) = \frac{1}{tr}\,\frac{1}{\sigma\sqrt{2\pi}}\,e^{-\frac{1}{2}\left(\frac{ln\,tr - m}{\sigma}\right)^2} = \frac{1}{tr}\,\frac{1}{0,499\sqrt{2\pi}}\,e^{-\frac{1}{2}\left(\frac{ln\,tr - 0,376}{0,499}\right)^2}$ (4.121)	Fig. 4.16
3	Repair rate function, $z(tr)$	$z(tr) = \frac{f(tr)}{1 - M(tr)} = \frac{\frac{1}{tr}\,\frac{1}{0,499\sqrt{2\pi}}\,e^{-\frac{1}{2}\left(\frac{ln\,tr - 0,376}{0,499}\right)^2}}{1 - \mathrm{NORMSDIST}\left(\frac{1}{0,499}\,ln\,\frac{tr}{1,457}\right)}$ (4.122)	Fig. 4.17
4	Mean time to repair, $MTTR$, $E(tr)$	$MTTR = E(tr) = e^{m + \frac{\sigma^2}{2}} = e^{0,376 + \frac{0,499^2}{2}}$ (4.123)	1,650 h
5	Median time to repair, $tr_{0,5}$, tr_{med}	$tr_{0,5} = tr_{med} = e^{m} = e^{0,376}$ (4.124)	1,457 h
6	Maximum corrective maintenance time for P=90%, $tr_{max;0,90}$	$tr_{max;0,90} = e^{m + 1,29\sigma} = e^{0,376 + 1,29 \cdot 0,499}$ (4.125)	2,772 h
7	Maximum corrective maintenance time for 95%, $tr_{max;0,95}$	$tr_{max;0,95} = e^{m + 1,64\sigma} = e^{0,376 + 1,64 \cdot 0,499}$ (4.126)	3,301 h
8	Repair time dispersion, D	$D = \left(e^{\sigma^2} - 1\right) e^{2m + \sigma^2} = \left(e^{0,499^2} - 1\right) e^{2 \cdot 0,376 + 0,499^2}$ (4.127)	0,769 h^2

Table 4.23. **Quantitative indicators of maintainability for belt conveyor TB-2. Lognormal normalized distribution *LNv***

No.	Name and symbol of the indicator	Relationship	Value, Unit
1	Maintainability function, $M(tr)$	$M(tr) = \frac{1}{2} + \Phi\left(\frac{ln\,tr - m}{\sigma}\right)$ = NORMSDIST$\left(\frac{1}{\sigma}\,ln\,\frac{tr}{tr_{med}}\right)$ = = NORMSDIST$\left(\frac{1}{0,555}\,ln\,\frac{tr}{1,105}\right)$ (4.160)	Fig. 4.18

Table 4.23. **Quantitative indicators of maintainability for belt conveyor TB-2. Lognormal normalized distribution *LNv***

No.	Name and symbol of the indicator	Relationship	Value, Unit
2	Repair probability function, $f(tr)$	$f(tr) = \frac{1}{tr}\,\frac{1}{\sigma\sqrt{2\pi}}\,e^{-\frac{1}{2}\left(\frac{ln\,tr-m}{\sigma}\right)^2} = \frac{1}{tr}\,\frac{1}{0{,}555\sqrt{2\pi}}\,e^{-\frac{1}{2}\left(\frac{ln\,tr-0{,}100}{0{,}555}\right)^2}$ (4.161)	Fig. 4.19
3	Repair rate function, $z(tr)$	$z(tr) = \frac{f(tr)}{1-M(tr)} = \frac{\frac{1}{tr}\,\frac{1}{0{,}555\sqrt{2\pi}}\,e^{-\frac{1}{2}\left(\frac{ln\,tr-0{,}100}{0{,}555}\right)^2}}{1-\text{NORMSDIST}\left(\frac{1}{0{,}555}\,ln\,\frac{tr}{1{,}105}\right)}$ (4.162)	Fig. 4.20
4	Mean time to repair, *MTTR*, $E(tr)$	$MTTR = E(tr) = e^{m+\frac{\sigma^2}{2}} = e^{0{,}100+\frac{0{,}555^2}{2}}$ (4.163)	1,289 *h*
5	Median time to repair, $tr_{0,5}$, tr_{med}	$tr_{0,5} = tr_{med} = e^m = e^{0{,}100}$ (4.164)	1,105 *h*
6	Maximum corrective maintenance time for P=90%, $tr_{max;0,90}$	$tr_{max;0,90} = e^{m+1{,}29\sigma} = e^{0{,}100+1{,}29\cdot 0{,}555}$ (4.165)	2,261 *h*
7	Maximum corrective maintenance time for 95%, $tr_{max;0,95}$	$tr_{max;0,95} = e^{m+1{,}64\sigma} = e^{0{,}100+1{,}64\cdot 0{,}555}$ (4.166)	2,746 *h*
8	Repair time dispersion, *D*	$D=\left(e^{\sigma^2}-1\right)\,e^{2m+\sigma^2}=\left(e^{0{,}555^2}-1\right)\,e^{2\cdot 0{,}100+0{,}555^2}$ (4.167)	0,600 h^2

Table 4.30. **Quantitative indicators of maintainability for belt conveyor TB-3. Weibull biparametric normalized distribution *Wp***

No.	Name and symbol of the indicator	Relationship	Value, Unit
1	Maintainability function, $M(tr)$	$M(tr) = 1-e^{-\left(\frac{tr}{\eta}\right)^\beta} = 1-e^{-\left(\frac{tr}{1{,}703}\right)^{1{,}649}}$ (4.215)	Fig. 4.21
2	Repair probability function, $f(tr)$	$f(tr) = \frac{\beta}{\eta}\left(\frac{tr}{\eta}\right)^{\beta-1} e^{-\left(\frac{tr}{\eta}\right)^\beta} = \frac{1{,}649}{1{,}703}\left(\frac{tr}{1{,}703}\right)^{0{,}649} e^{-\left(\frac{tr}{1{,}703}\right)^{1{,}649}}$ (4.216)	Fig. 4.22
3	Repair rate function, $z(tr)$	$z(tr) = \frac{\beta}{\eta}\left(\frac{tr}{\eta}\right)^{\beta-1} = \frac{1{,}649}{1{,}703}\left(\frac{tr}{1{,}703}\right)^{0{,}649}$ (4.217)	Fig. 4.23
4	Mean time to repair, *MTTR*, $E(tr)$	$MTTR = \eta\,\Gamma\left(\frac{1}{\beta}+1\right) = 1{,}703\,\Gamma\left(\frac{1}{1{,}649}+1\right)$ (4.218)	1,523 *h*
5	Median time to repair, $tr_{0,5}$, tr_{med}	$tr_{0,5} = \eta\sqrt[\beta]{-ln\,0{,}5} = 1{,}703\cdot\sqrt[1{,}649]{-ln\,0{,}5}$ (4.219)	1,364 *h*
6	Maximum corrective maintenance time for P=90%, $tr_{max;0,90}$	$tr_{max;0,90} = \eta\sqrt[\beta]{-ln\,0{,}1} = 1{,}703\cdot\sqrt[1{,}649]{-ln\,0{,}1}$ (4.220)	2,824 *h*
7	Maximum corrective maintenance time for 95%, $tr_{max;0,95}$	$tr_{max;0,95} = \eta\sqrt[\beta]{-ln\,0{,}05} = 1{,}703\cdot\sqrt[1{,}649]{-ln\,0{,}05}$ (4.221)	3,313 *h*
8	Repair time dispersion, *D*	$D = \eta^2\left\{\Gamma\left(\frac{2}{\beta}+1\right)-\left[\Gamma\left(\frac{1}{\beta}+1\right)\right]^2\right\} = 1{,}703^2\left\{\Gamma\left(\frac{2}{1{,}649}+1\right)-\left[\Gamma\left(\frac{1}{1{,}649}+1\right)\right]^2\right\}$ (4.222)	0,899 h^2

Table 4.35. **Quantitative indicators of maintainability for belt conveyor TB-4. Weibull biparametric normalized distribution *Wp***

No.	Name and symbol of the indicator	Relationship	Value, U
1	Maintainability function, $M(tr)$	$M(tr) = 1-e^{-\left(\frac{tr}{\eta}\right)^\beta} = 1-e^{-\left(\frac{tr}{1{,}848}\right)^{1{,}595}}$ (4.254)	Fig. 4.24

Table 4.35. **Quantitative indicators of maintainability for belt conveyor TB-4. Weibull biparametric normalized distribution *Wp***

No.	Name and symbol of the indicator	Relationship	Value, U
2	Repair probability function, $f(tr)$	$f(tr) = \frac{\beta}{\eta}\left(\frac{tr}{\eta}\right)^{\beta-1} e^{-\left(\frac{tr}{\eta}\right)^{\beta}} = \frac{1,595}{1,848}\left(\frac{tr}{1,848}\right)^{0,595} e^{-\left(\frac{tr}{1,848}\right)^{1,595}}$ (4.255)	Fig. 4.25
3	Repair rate function, $z(tr)$	$z(tr) = \frac{\beta}{\eta}\left(\frac{tr}{\eta}\right)^{\beta-1} = \frac{1,595}{1,848}\left(\frac{tr}{1,848}\right)^{0,595}$ (4.256)	Fig. 4.26
4	Mean time to repair, $MTTR$, $E(tr)$	$MTTR = \eta\,\Gamma\left(\frac{1}{\beta}+1\right) = 1,848\,\Gamma\left(\frac{1}{1,595}+1\right)$ (4.257)	1,657 h
5	Median time to repair, $tr_{0,5}$, tr_{med}	$tr_{0,5} = \eta\sqrt[\beta]{-ln\ 0,5} = 1,848\cdot\sqrt[1,595]{-ln\ 0,5}$ (4.258)	1,469 h
6	Maximum corrective maintenance time for P=90%, $tr_{max;0,90}$	$tr_{max;0,90} = \eta\sqrt[\beta]{-ln\ 0,1} = 1,848\cdot\sqrt[1,595]{-ln\ 0,1}$ (4.259)	3,117 h
7	Maximum corrective maintenance time for 95%, $tr_{max;0,95}$	$tr_{max;0,95} = \eta\sqrt[\beta]{-ln\ 0,05} = 1,848\cdot\sqrt[1,595]{-ln\ 0,05}$ (4.260)	3,677 h
8	Repair time dispersion, D	$D = \eta^2\left\{\Gamma\left(\frac{2}{\beta}+1\right)-\left[\Gamma\left(\frac{1}{\beta}+1\right)\right]^2\right\} = 1,848^2\left\{\Gamma\left(\frac{2}{1,595}+1\right)-\left[\Gamma\left(\frac{1}{1,595}+1\right)\right]^2\right\}$ (4.261)	1,131 h^2

Evaluation of the availability of transport system

For a component subsystem of the system, the indicator is expressed by the equation

$$A_i(t)=KA_i=\frac{MTBF_i}{MTBF_i+MTTR_i}, \quad (4.270)$$

where i means TB-1, TB-2, TB-3 or TB-4.

In this equation, $MTBF_i$ represents the average good functioning times (times between failures), and $MTTR_i$ the average time related to repairs.

Unavailability, $U_i(t)$, defined by the equation

$$U_i(t)=1-A_i(t), \quad (4.271)$$

expresses the time ratio where the system cannot be used.

For the system series made up of the four conveyers, availability is

$$A_S(t)=\prod_{i=1}^{4}A_i(t)=A_{TB\text{-}1}(t)\cdot A_{TB\text{-}2}(t)\cdot A_{TB\text{-}3}(t)\cdot A_{TB\text{-}4}(t) \quad (4.272)$$

Table 4.37. **Availability evaluation of roller belt conveyor**s and transport system

No.	Conveyor	Number failures, n	$MTBF_i$ Value, h	$MTBF_i$ Distribution/ Relationship	$MTTR_i$ Value, h	$MTTR_i$ Distribution/ Relationship	$A_i(t)$, $\frac{MTBF_i}{MTBF_i+MTTR_i}$	$U_i(t)$, $U_i(t)=1-A_i(t)$, *hours/year*; *days/year*
1	Conveyor TB-1	49	85,183	*Wm*/(4.28)	1,650	*LNv*/(4.123)	0,980998	166; 6,93
2	Conveyor TB-2	31	141,519	*Nv*/(4.34)	1,289	*LNv*/(4.163)	0,990974	79; 3,29
3	Conveyor TB-3	28	150,075	*Wm*/(4.76)	1,523	*Wp*/(4.218)	0,989954	88; 3,67
4	Conveyor TB-4	56	75,736	*Wv*/(4.94)	1,657	*Wp*/(4.257)	0,978590	188; 7,81
5	Transport system: $A_S(t)$ = 0,941773; $U_S(t)$ = 510 *hours/year*; $U_S(t)$ = 21 *days/year*							

In another variant, the system availability can be calculated knowing the system's reliability function, $R_S(t)$. In this case, availability $A_S(t)$ of the system results from the equation

$$A_S(t)=\frac{MTBF_S}{MTBF_S+MTTR_S}. \quad (4.273)$$

In this equation, $MTBF_S$ represents the average good functioning time for the system, and $MTTR_S$ the average of the repair of the system.

$MTBF_S$ indicator results from the equation

$$MTBF_S = \int_0^{\infty} R_S(t)\, dt \ =$$

$$= \int_0^{\infty} \left[e^{-\left(\frac{t-4,278E\text{-}9}{94,598}\right)^{3,553}} \cdot \int_t^{\infty} \frac{1}{56,505\sqrt{2\pi}}\, e^{-\frac{1}{2}\left(\frac{t-141,519}{56,505}\right)^2} dt \cdot e^{-\left(\frac{t-1,121E-06}{167,872}\right)^{3,076}} \cdot e^{-\left(\frac{t}{84,833}\right)^{2,984}} \right] dt \quad (4.274)$$

Solving with Mathcad software the integral leads to the parameter value for the system, $MTBF_S$= = 60,436 *hours*.

In order to determine $MTTR_S$ parameter, the unit made up of the four conveyers as a single product characterized by the 164 failures is considered.

The statistic series with 164 terms is made up of repair times tr_i, in *hours*: 0,500; 0,583; 0,667; 0,667; 0,667; 0,750; 0,7500; 0,833; 0,833; 0,917; 1,083; 1,167; 1,250; 1,250; 1,250; 1,417; 1,583; 1,583; 1,750; 2,000; 2,083; 2,250; 3,167; 4,167; 4,250; 4,917; 0,417; 0,500; 0,500, 0,500; 0,500; 0,500; 0,583; 0,667; 0,667; 0,667; 0,750; 0,750; 0,750; 0,833; 0,833; 0,833; 0,917; 0,917; 0,917; 0,917; 1,000; 1,000; 1,083; 1,083; 1,083; 1,083; 1,250; 1,250; 1,250; 1,250; 1,250; 1,250; 1,250; 1,250; 1,333; 1,333; 1,417; 1,417; 1,500; 1,667; 1,750; 1,833; 1,833; 2,000; 2,083; 2,250; 2,333; 2,500; 3,083; 3,583; 3,667; 4,083; 4,250; 4,500; 6,667; 12,000.

Statistic processing of the series shows that repair times of the entire system follow a lognormal distribution law, defined by the following parameters:

- average, $m(lg\ tr)$ = AVERAGE $ln(tri)$ (1:164) = 0,254417 *h*;
- median, $t_{med}\ (lg\ tr) = e^{m(lg\ tr)}$=1,289710 *h*;
- shape parameter, $\sigma(lg\ tr)$ = STDEV $ln\ (tri)$ (1:164) = 0,615947
- distribution function, $M(tri)$ = NORMSDIST $ln\left(\frac{tr_i}{tr_{med}}\right)\frac{1}{\sigma}$.

With these values, $MTTR_S$ parameter is

$MTTR_S = E(tr)_S = e^{m+\frac{\sigma^2}{2}} = e^{0,254417+\frac{0,615947^2}{2}} = 1,559\ h.$

This value of the repair time average for the system is not realistic, in reality it being much higher. For a 95% certainty level,

$MTTR_S = tr_{max;0,95} = e^{m+1,64\sigma} = e^{0,254417+1,64\cdot 0,615947}$=3,541 *h*.

With the average value of functioning and repair times $A_S(t)$availability of the system is

$A_S(t) = \frac{MTBF_S}{MTBF_S+MTTR_S} = \frac{60,436}{60,436+3,541}$ = 0,944652 = 94,4652%.

Reported to one *year*, $U_S(t)$ = 485 *hours*, respectively $U_S(t)$ = 20 *days* of unavailability result.

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