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ASSESSMENT OF LINEAR HYDRAULIC ENGINE RELIABILITY OF HANDLING THE MACHINES BUCKET FOR LOADING, TRANSPORTATION AND STORAGE USED IN MINING

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ABSTRACT: The purpose of this study is to estimate the reliability features for linear hydraulic engines of handling the machines bucket for loading, transportation and storage used in performing underground and surface hydrotechnical works. The input data required for the study of reliability comes from machines user and characterizes the functionality of the elements for five machines for a period of four years.

Keywords: reliability, hydraulic motor, distribution.

1. OVERVIEW OF MACHINES FOR LOADING, TRANSPORTATION AND STORAGE SUBJECT TO RELIABILITY ANALYSIS

Machines for loading, transportation and storage are complex machines used to load the material resulting from the process of drilling-blasting, transportation on relatively small distances and its storage. They are used for both material disposals from the work front, in case of useful minerals mining, as well as for digging galleries, including within the hydrotechnical structures.

They are also being used on the surface for loading, transportation and storage of various materials, particularly in the construction field.

In Tables 1 and 2 are presented the main technical characteristics of two types of machines for loading and transportation of goods by the Sandvik company.

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For the case of the reliability study carried out was taken into consideration the mechanical actuator model used in hydrotechnical structures.

In Figures 1 and 2 is presented model with bucket capacity of 3000 kg.

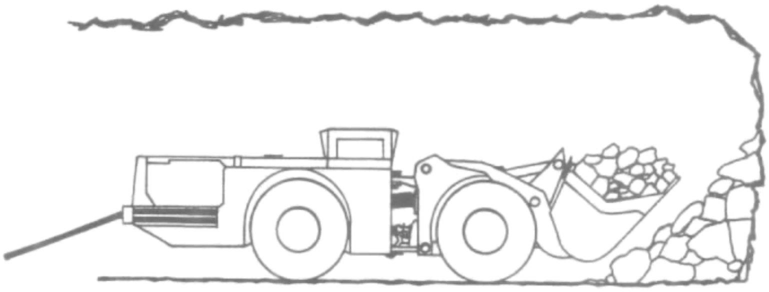

Fig. 1. TORO 151 model manufactured by Sandvik company during the loading of the material

Fig. 2. Overview of the machine for loading, transportation and storage, TORO 151 model manufactured by Sandvik company

A preliminary study of reliability and maintainability performed on the fleet of machines for loading, transportation and storage existing at the operators of hydrotechnical structures has shown that the bucket handling hydraulic engine is the most critical subsystem.

Based on these considerations, further on the study, will be done a reliability study on the linear hydraulic engine for bucket handling.

Table 1. **The main technical characteristics of machines for loading, transportation and storage with mechanical actuator manufactured by Sandvik company**

Model	Name	Bucket capacity, kg	Weight, kg	Length, mm	Width, mm
LH201	Microscoop 100	1000	3650	4650	1055
LH203	TORO 151	3500	8700	7040	1480
LH307	TORO 6	6700	18020-19600	8631	2236
LH410	TORO 7	10000	26200	9591	2647
LH514	TORO 9	14000	38100	10870	2920
LH517	TORO 0010	17200	44000	11120	3000
LH621	TORO 11	21000	56800	11993	3100

Table 2. **The main technical characteristics of machines for loading, transportation and storage with electrical actuator manufactured by Sandvik company**

Model	Name	Bucket capacity, kg	Weight, kg	Length, mm	Width, mm
LH203E	TORO 151E	3500	9400	6995	1480
LH306E	EJC 145E	6600	17237	8407	2159
LH409E	TORO 400E	9600	24500	9736	2525
LH514E	TORO 1400E	14000	38500	10950	2880
LH625E	TORO 2500E	25000	77500	14011	3900

Operational reliability study is being carried out based on data obtained from the mechanical energy compartment regarding subassembly functionality for five machines for loading and transporting over four calendar years of operation.

It is noted that the product under study is considered irreparable, in the meaning that at its failure, the loading machine is stopped and the defective subassembly is replaced in its entirety. If that analyzed item is considered suitable to be repaired, depending on the state of failure, it will be analyzed, diagnosed and repaired in specialized workshops.

2. ESTIMATION OF THE LINEAR HYDRAULIC ENGINE FOR BUCKET HANDLING RELIABILITY

Fig. 3. Overview of linear hydraulic engine

Tracking the functionality in operation was performed on ten linear hydraulic engines (hydraulic cylinders), two on each of the five machines for loading, transportation and storage under study. Figure 3 presents an overview of one of the linear hydraulic engines with double effect, with which the bucket is being handled.

The main defects that appear at the linear hydraulic engines consisted in hydraulic oil loss due to damage of seals, especially the appearance of the pronounced wears of engine fasteners, which is an unavoidable phenomenon, due to high loads, to the frequency of occurrence of these loads, taking into account the multitude of maneuvers that have to be performed with the bucket and the working principle with this machine.

The database that was available is indicating good operation times, *TBF*, noted t_i, in *h*, of linear hydraulic engines, values which, in the order of their counting, over time, are shown in Table 3. Time values of good functioning, t_i, represent a statistical number of the form (S1), that contains *n*= 20 disjoint values, sorted in ascending order, as follows: 272; 644; 916; 1004; 1196; 1200; 1216; 1380; 2312; 2368; 2536; 2564; 2640; 2776; 2964; 3060; 3108; 3652; 3696; 3920. Table 4 presents the values of the empirical distribution function used for estimation of reliability parameters.

Table 3. **Time values of good functioning for linear hydraulic engines**

Nr. crt.	*TBF, t_i, h*	*Nr. crt.*	*TBF, t_i, h*	*Nr. crt.*	*TBF, t_i, h*	*Nr. crt.*	*TBF, t_i, h*
1	2536	6	644	11	2964	16	3696
2	1200	7	1380	12	272	17	3108
3	3060	8	2776	13	1196	18	1216
4	3652	9	1004	14	3920	19	2368
5	2564	10	916	15	2312	20	2640

Table 4. **Values of the empirical distribution function** $\hat{F}(t_i)$

1	0,034314	5	0,230392	9	0,426471	13	0,622549	17	0,818627
2	0,083333	6	0,279412	10	0,475490	14	0,671569	18	0,867647
3	0,132353	7	0,328431	11	0,524510	15	0,720588	19	0,916667
4	0,181373	8	0,377451	12	0,573529	16	0,769608	20	0,965686

Exponential distribution **-** Method of least squares

Table 5. **Calculation elements specific for exponential distribution using the method of least squares and its verification**

i	t_i, *h*	t_i^2	$\ln\left[1-\hat{F}(t_i)\right]\cdot t_i$	λ, 1/*h*	$F(t_i)$	$\left\|F(t_i)-\hat{F}(t_i)\right\|$	$\left\|F(t_i)-\hat{F}(t_{i-1})\right\|$
1	272	73984	-9,497224	0,000495	0,126057	0,091743	0,126057
2	644	414736	-56,035327	0,000495	0,273136	0,189803	0,238822
3	916	839056	-130,044759	0,000495	0,364762	0,232409	0,281429
4	1004	1008016	-200,926686	0,000495	0,391858	0,210486	0,259506
5	1196	1430416	-313,201529	0,000495	0,447034	0,216641	0,265661
6	1200	1440000	-393,224888	0,000495	0,448128	0,168716	0,217736
7	1216	1478656	-484,137107	0,000495	0,452485	0,124054	0,173073
8	1380	1904400	-654,027412	0,000495	0,495206	0,117755	0,166775
9	2312	5345344	-1285,347289	0,000495	0,681867	0,255397	0,304416
10	2368	5607424	-1528,049465	0,000495	0,690571	0,215081	0,264101
11	2536	6431296	-1885,285263	0,000495	0,715280	0,190770	0,239790
12	2564	6574096	-2185,071248	0,000495	0,719202	0,145672	0,194692
13	2640	6969600	-2572,190470	0,000495	0,729577	0,107028	0,156047
14	2776	7706176	-3090,874391	0,000495	0,747195	0,075626	0,124646
15	2964	8785296	-3779,303704	0,000495	0,769675	0,049087	0,098107
16	3060	9363600	-4491,995520	0,000495	0,780372	0,010764	0,059784
17	3108	9659664	-5305,984068	0,000495	0,785533	0,033095	0,015925
18	3652	13337104	-7385,377983	0,000495	0,836195	0,031452	0,017567
19	3696	13660416	-9184,214978	0,000495	0,839726	0,076940	0,027921
20	3920	15366400	-13219,062592	0,000495	0,856560	0,109127	0,060107
		$\sum_{i=1}^{20} t_i^2 =$ 117395680	$\sum_{i=1}^{20} \ln\left[1-\hat{F}(t_i)\right] t_i =$ =-58153,8519			0,255397	D_{max}=**0,304416**

Normal distribution - maximum likelihood method

$$m_n = \frac{\sum_{i=1}^{n} t_i}{n} = 2171{,}2 \text{ h}; \ \sigma_n = \sqrt{\frac{1}{n-1}\sum_{i-1}^{n}\left(t_i - m_n\right)} = 1102{,}950378 \text{ h}.$$

Table 6. **Calculation elements specific for normal distribution on its validation**

i	t_i, h	m_n, h	σ_n, h	$\frac{t_i - m_n}{\sigma_n}$	$F(t_i)$	$\left\|F(t_i) - \hat{F}(t_i)\right\|$	$\left\|F(t_i) - \hat{F}(t_{i-1})\right\|$
1	272	2171,2	1102,950378	-1,721927	0,042541	0,008228	0,042541
2	644	2171,2	1102,950378	-1,384650	0,083080	0,000254	0,048766
3	916	2171,2	1102,950378	-1,138039	0,127552	0,004801	0,044219
4	1004	2171,2	1102,950378	-1,058253	0,144970	0,036402	0,012617
5	1196	2171,2	1102,950378	-0,884174	0,188301	0,042091	0,006929
6	1200	2171,2	1102,950378	-0,880547	0,189281	0,090130	0,041111
7	1216	2171,2	1102,950378	-0,866041	0,193234	0,135197	0,086178
8	1380	2171,2	1102,950378	-0,717349	0,236579	0,140871	0,091852
9	2312	2171,2	1102,950378	0,127658	0,550790	0,124319	0,173339
10	2368	2171,2	1102,950378	0,178431	0,570808	0,095317	0,144337
11	2536	2171,2	1102,950378	0,330749	0,629583	0,105073	0,154093
12	2564	2171,2	1102,950378	0,356136	0,639131	0,065601	0,114621
13	2640	2171,2	1102,950378	0,425042	0,664597	0,042048	0,091067
14	2776	2171,2	1102,950378	0,548347	0,708273	0,036705	0,085724
15	2964	2171,2	1102,950378	0,718799	0,763868	0,043279	0,092299
16	3060	2171,2	1102,950378	0,805839	0,789832	0,020224	0,069244
17	3108	2171,2	1102,950378	0,849358	0,802159	0,016468	0,032551
18	3652	2171,2	1102,950378	1,342581	0,910296	0,042649	0,091669
19	3696	2171,2	1102,950378	1,382474	0,916587	0,000080	0,048940
20	3920	2171,2	1102,950378	1,585565	0,943581	0,022105	0,026914
						0,140871	D_{max}=**0,173339**

Biparametric Weibull distribution – Method of least squares

Table 7. **Calculation elements specific for biparametric Weibull distribution standardized by using the least squares method and its verification**

i	t_i , h	$\ln t_i$	$(\ln t_i)^2$	$\ln\ln\frac{1}{\hat{R}(t_i)} \cdot \ln t_i$	$\ln\ln\frac{1}{\hat{R}(t_i)}$	$F(t_i)$	$\left\|F(t_i) - \hat{F}(t_i)\right\|$	$\left\|F(t_i) - \hat{F}(t_{i-1})\right\|$
1	272	5,605802	31,425017	-18,806359	-3,354803	0,025023	0,009291	0,025023
2	644	6,467699	41,831127	-15,792286	-2,441716	0,099682	0,016349	0,065368
3	916	6,820016	46,512623	-13,313611	-1,952138	0,171183	0,038830	0,087850
4	1004	6,911747	47,772251	-11,119669	-1,608807	0,196217	0,014844	0,063864
5	1196	7,086738	50,221855	-9,495457	-1,339891	0,252865	0,022473	0,071493
6	1200	7,090077	50,269190	-7,910364	-1,115695	0,254067	0,025345	0,023675
7	1216	7,103322	50,457184	-6,541832	-0,920954	0,258881	0,069551	0,020531

i	t_i, h	$\ln t_i$	$(\ln t_i)^2$	$\ln\ln\frac{1}{\hat{R}(t_i)}\cdot\ln t_i$	$\ln\ln\frac{1}{\hat{R}(t_i)}$	$F(t_i)$	$\lvert F(t_i)-\hat{F}(t_i)\rvert$	$\lvert F(t_i)-\hat{F}(t_{i-1})\rvert$
8	1380	7,229839	52,270569	-5,398445	-0,746690	0,308653	0,068798	0,019778
9	2312	7,745868	59,998475	-4,547475	-0,587084	0,578771	0,152300	0,201320
10	2368	7,769801	60,369808	-3,403590	-0,438054	0,593182	0,117692	0,166712
11	2536	7,838343	61,439626	-2,324139	-0,296509	0,634701	0,110191	0,159211
12	2564	7,849324	61,611884	-1,255265	-0,159920	0,641363	0,067834	0,116853
13	2640	7,878534	62,071301	-0,205008	-0,026021	0,659064	0,036515	0,085534
14	2776	7,928766	62,865335	0,851890	0,107443	0,689326	0,017758	0,066777
15	2964	7,994295	63,908752	1,942614	0,243000	0,728133	0,007545	0,056565
16	3060	8,026170	64,419408	3,081103	0,383882	0,746591	0,023017	0,026003
17	3108	8,041735	64,669497	4,301169	0,534856	0,755478	0,063150	0,014130
18	3652	8,203030	67,289705	5,776796	0,704227	0,840821	0,026826	0,022194
19	3696	8,215006	67,486331	7,477587	0,910235	0,846551	0,070115	0,021096
20	3920	8,273847	68,456543	10,057426	1,215568	0,873235	0,092451	0,043432
		$\sum_{i=1}^{20}\ln t_i=$ 150,0799	$\sum_{i=1}^{20}(\ln t_i)^2=$ 1135,3464	$\sum_{i=1}^{20}\ln\ln\frac{1}{\hat{R}(t_i)}\cdot\ln t_i=-$ 66,6249	$\sum_{i=1}^{20}\ln\ln\frac{1}{\hat{R}(t_i)}=-$ 10,88907		0,152300	*Dmax*=**0,201320**
		$\left(\sum_{i=1}^{20}\ln t_i\right)^2=$ 22523,99						
Parametrul de formă, β_1=1,649398								
Parametrul λ=2,44482·10^{-06}								
Parametrul de scară reală, η_1=2525,236790 *h*								

Tri-parametric Weibull distribution – Method of least squares
CV=0,507991; β_2=2,064592; K_β=0,885830; C_β=0,558483

Table 8. **Calculation elements specific for tri-parametric Weibull distribution using the method of moments and its verification**

i	t_i, h	β_2	η_2, h	γ	$F(t_i)$	$\lvert F(t_i)-\hat{F}(t_i)\rvert$	$\lvert F(t_i)-\hat{F}(t_{i-1})\rvert$
1	272	2,064592	2451,054034	-0,016813	0,010629	0,023685	0,010629
2	644	2,064592	2451,054034	-0,016813	0,061364	0,021969	0,027051
3	916	2,064592	2451,054034	-0,016813	0,122840	0,009513	0,039507
4	1004	2,064592	2451,054034	-0,016813	0,146487	0,034886	0,014134
5	1196	2,064592	2451,054034	-0,016813	0,203336	0,027057	0,021963
6	1200	2,064592	2451,054034	-0,016813	0,204587	0,074825	0,025805
7	1216	2,064592	2451,054034	-0,016813	0,209619	0,118813	0,069793
8	1380	2,064592	2451,054034	-0,016813	0,263213	0,114238	0,065218
9	2312	2,064592	2451,054034	-0,016813	0,587870	0,161400	0,210419
10	2368	2,064592	2451,054034	-0,016813	0,605965	0,130475	0,179495
11	2536	2,064592	2451,054034	-0,016813	0,657981	0,133471	0,182490
12	2564	2,064592	2451,054034	-0,016813	0,666292	0,092762	0,141782
13	2640	2,064592	2451,054034	-0,016813	0,688299	0,065750	0,114770
14	2776	2,064592	2451,054034	-0,016813	0,725580	0,054012	0,103031
15	2964	2,064592	2451,054034	-0,016813	0,772459	0,051871	0,100890

i	t_i, h	β_2	η_2, h	γ	$F(t_i)$	$\lvert F(t_i)-\hat{F}(t_i)\rvert$	$\lvert F(t_i)-\hat{F}(t_{i-1})\rvert$
16	3060	2,064592	2451,054034	-0,016813	0,794257	0,024649	0,073669
17	3108	2,064592	2451,054034	-0,016813	0,804610	0,014017	0,035003
18	3652	2,064592	2451,054034	-0,016813	0,897507	0,029860	0,078879
19	3696	2,064592	2451,054034	-0,016813	0,903188	0,013479	0,035541
20	3920	2,064592	2451,054034	-0,016813	0,928395	0,037291	0,011728
						0,161400	D_{max}=**0,210419**

Table 9. **Parameter values of the distribution functions that characterize the reliability of linear hydraulic engines**

Distribuţia	λ, 1/*h*	m_n, *h*	σ_n, *h*	β_1	η_1, *h*	β_2	η_2, *h*	γ
Exponenţială	0,000495							
Normală		2171,2	1102,95					
Weibull biparametrică, *Wp*				1,649	2525,237			
Weibull triparametrică, *Wm*						2,065	2451,052	-0,168

From Table 10 results that all four distributions, exponential, normal and both versions of Weibull distribution are validated, but the normal distribution function approximates the best the experimental (empirical) function, having the smallest maximum distance between them. However, this value of the maximum distance between the two distributions is very similar to the one that is characteristic for Weibull distributions, so it can be said that any of the three theoretical distribution functions can model very well the experimental function, as it would result from graphic representations described below.

Table 10. **Reliability functions characteristic for linear hydraulic engines and their comparison**

Theoretical distribution	Expression of reliability function, R(t)	Maximum deviation, D_{max}	Risk, α	Critical value, $D_{\alpha,20}$	Validation
Exponential	$e^{-0,000495\cdot t}$	0,304416	0,10	0,364734	Yes
Normal	$\frac{1}{2}-\Phi\left(\frac{t-2171,2}{1102,95}\right)$ or $1-\frac{1}{1102,95}\frac{1}{\sqrt{2\pi}}\int_0^t e^{-\frac{1}{2}\left(\frac{x-2171,2}{1102,95}\right)^2}dx$	**0,173339**	0,20	0,231555	Yes
Biparametric Weibull, Wp	$e^{-\left(\frac{t}{2525,237}\right)^{1,649}}$	0,201320	0,20	0,231555	Yes
Tri-parametric Weibull, Wm	$e^{-\left(\frac{t+0,168}{2451,054}\right)^{2,065}}$	0,210419	0,20	0,231555	Yes

The exponential model, according to the test (K-S) is validated, but the value of the maximum deviation is close to the critical value of the test, so that the reliability indicator values will be different, but not significantly, compared to the other distributions. With the help of the parameters determined for the four validated distribution laws were calculated and plotted the main quantitative indicators that characterize the reliability of linear hydraulic motor for bucket handling.

In the graphic representations of Figures 4, 5, 6 and 7 are shown the variations, depending on the operating time, of the main reliability indicators.

The graphical representations in Figures 4 and 5 show the tendency to group, even overlapping, of the reliability and non-reliability curves for normal and Weibull distribution laws, in the two versions, that confirm the very close values of maximum distances between the experimental distribution and theoretical distributions. It also confirms once again that any of these distributions express with sufficient precision the closest reliability indicators closest to the real situation.

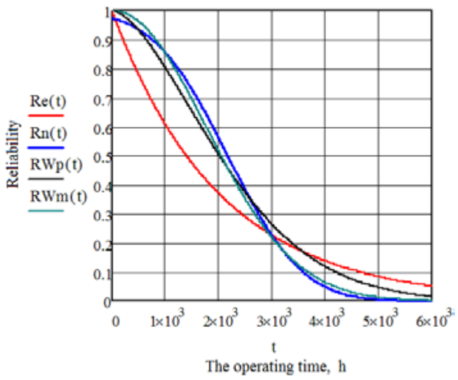

Fig. 4. Graphical representations of reliability functions for linear hydraulic engine

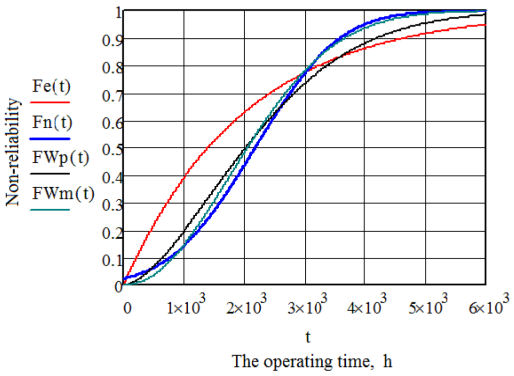

Fig. 5. Graphical representations of non-reliability functions for linear hydraulic engine

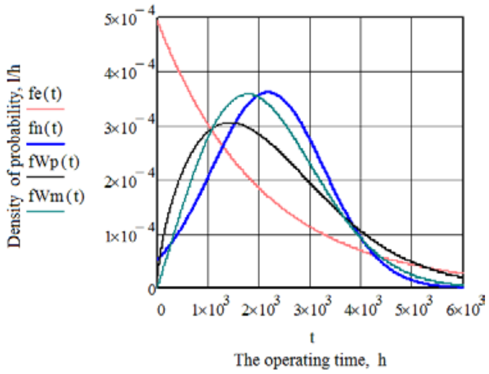

Fig. 6. Graphical representations for density of probability of linear hydraulic engine failure

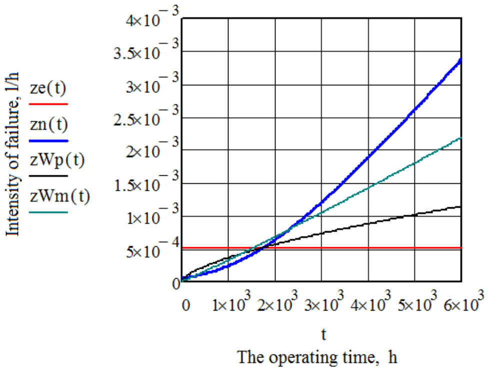

Fig. 7. Graphical representations for intensity of linear hydraulic engine failure

Overlapping almost entirely of the variation curves of reliability for normal and tri-parametric Weibull distributions is understandable, because of the value of the form factor of the Weibull distribution, β_2=2,065, since the theory states that the Weibull distribution is approaching to a normal distribution for β_2=3±0,5.

Also from these representations results that, the probability that the linear hydraulic engine will not fail after 1000 hours of effective operation is 85%. This means that, taking into account an effective working day of 16 hours, that is plausible for both underground and surface, and a total of 21 working days per month, is to be expected, with a probability of 85 %, that at three calendar months, the linear hydraulic engine will not fail.

For a period of 2000 hours of effective operation, which corresponds to six calendar months of operation, the engine reliability is equal to non-reliability, about 50%. This value of six months may be considered in the inclusion in the program of preventive planned revisions that needs careful check of the integrity of the linear hydraulic engines, even their replacement.

It should be noted that for an operating time of 1000 hours, the reliability of the hydraulic engine decreases linearly from 85% to 50%, which shows that the rate of failure is high, something which is supported by the graphical representations for density of the probability for failures and failure intensity, figures 6 and 7.

Analyzing the variation in time of intensity or rate of failure of the hydraulic engines it's observed that it has an increasing trend, understandable by showing the wear in time, at 2000 hours of operation its value being $z(2000)=5\cdot10^{-4}$ *failures/hour* which is still a modest value. Also, there is a linear increase of the failure intensity of tri-parametric Weibull distribution, for which the shape factor has the value β_2=2,065, with a value very close to 2, which in accordance with the theory is specific to Rayleigh distribution.

High failure rate values, certified by high values for density of probability and failure intensity, lead to the idea of reconsidering the construction of the whole engine, in respect to ensuring the tightness between the piston, stuffing gland and cylinder, as well as the fastening systems on the machine’s steel construction, in particular regarding the material and the applied heat treatment, giving the severe wear exposure of their bores.

Table 11 presents the values for a number of indicators that characterize the product's reliability analysis.

Analyzing the indicators presented in Table 11 it is confirmed again that the normal and tri-parametric Weibull distributions allow equally the calculation of the most appropriate reliability indicators to characterize the studied product, especially for having the lowest standard deviation value, being equal for the two distributions, being known the fact that, in the theory of experimental data processing it's demonstrated that if it has to be chosen between two distributions that are validated, for the assessment of reliability, is chosen the one that has the lowest value for standard deviation.

Table 11. **Reliability indicators on operating time until the linear hydraulic engine failure**

Item no.	Parameter		Parameter's value for distribution:			
	Name	MU	Exponential	Normal	Biparametric Weibull, Wp	Tri-parametric Weibull, Wm
1	Average, *m*, *MTTF*	h	2019	2171	2259	2171
2	Median, t_{med}	h	1399	2171	2021	2052
3	Module, t_{mod}	h	0	2171	1429	1778
4	Dispersion, *D*	h^2	4075188	1216499	1985865	1216499
5	Standard deviation, σ	h	2019	1103	1409	1103
6	Variation factor, *CV*	-	1	0,508	0,624	0,508

3. FINAL CONCLUSIONS

The main conclusions resulted from the survey of reliability of hydraulic engines for bucket handling are:

- Hydraulic engine function, described by time until failure is characterized by Weibull distribution law, with significant approaches on the normal law, this being considered a particular form of Weibull distribution law, something which is demonstrated by the shape parameter as well as by identical or very similar values of various indicators of reliability specific to the two distributions;

- The reliability of the hydraulic engine after 1000 hours of actual operation, corresponding to about three calendar month, is 85%, but for a period of 2000 hours it decreases to 50%, which shows that the rate of failure is high, confirmed by the values of the density of probability for failures and intensity of failure rate;

- The level of reliability of the linear hydraulic engines is low, which leads to a need to reconsider the whole construction of the engine, in respect to ensuring the tightness between the piston, stuffing gland and cylinder, as well as the fastening systems on the machine’s steel construction, in particular regarding the material and the applied heat treatment, giving the severe wear exposure of their bores.

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