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Probabilistic methods in the reliability assessment of power units

The paper presents results of reliability analysis made for a lignite-fired 370 MW rated power units installed in the Bełchatów Power Station. The concept of a standardized power unit and the method of a histogram with a set number of observations in each class were applied. The study includes analysis of probability distributions of operation times and repair times for the main power unit components. Empirical probability distribution functions have been identified and their parameters estimated in the study. The final forecast includes an estimation of such reliability measures like expected operation time, expected failure rate, average repair time and expected annual failure duration.

1 Introduction

Contemporary industry based on complex technological processes sets high requirements concerning an electrical power quality and continuity of supply. The complexity of the power system as well as power concentration in power stations make difficult the realization of these requirements. Rated power of a single units under construction still grows and this causes the rise of the emergency of peak power shutdown and limitations in power supply in consequence.

Electric power blackouts experienced in United States, Great Britain and Italy reminded the importance of power system reliability. These incidents have shown that the occurrence of a massive outage is feasible and can happen in each country. The superior target of the power system is to guarantee the continuity of supply for all consumers as well as required power quality at lowest generation costs.

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2 Mathematical basis of the reliability estimation of power units by the method of a histogram

The operation practice of power system demonstrates that failure frequency of power units is many times higher than other power system components (i.e. overhead lines, transformers, switchgear, protections etc.) [1,11]. The characteristic feature of power unit reliability, directly resulting from the redundancy of an auxiliary systems is the possibility to appear failures of different kind, i.e. power unit continues operation with its rates, power units operates with power limitation or power unit must be shut-down. This means that power unit is a multi-stage object in sense of its reliability, on the contrary to the two-stage installations staying in ability or inability to operate, which refers to many power transmission and distribution devices.

Estimation of reliability in power generation process requires the knowledge of reliability rates both power unit components and entire power plant. One should point out that power unit components have various durability. Some of them could be in the lifetime period with decreasing or stable failure frequency when others have achieved ageing period characterizing with growth of failure frequency. Complicated power installations are processed by intensive fatigue or wear and tear (metal erosion, moisture, temperature, pressure) which affect on installation elements in a different degree.

The Bełchatów Power Station, which is the subject of the study, is the largest lignite fueled power station in Europe with capacity of 5298 MW. The power station consists of twelve 370 MW and one 858 MW power unit and has around 20reliability analysis is focused on twelve 370 MW power units which technological structure is typical for thermal power station and include steam boiler, turbine, generator, auxiliaries etc. All units are homogenous in several respects such as constructional uniformity and similar conditions in which units operate. Since the first of dozen 370 MW units was commissioned in the Bełchatów Power Station (Poland) in 1982, a systematic research on power units reliability was initiated by the Institute of Electrical Power Engineering at Technical University of Łódź [5–7]. The principal target of analyses prepared yearly has been estimation of actual reliability measures of main generating devices of power units and their most defective elements, especially heating surfaces in steam boiler BB-1150. Statistical data files of the successive years of the power station operation have been systematically complemented and verified. The verification of statistical data consist in elimination of events which are not of random origin (i.e. actively influenced by operation and maintenance staff) and these, which were not qualified as break downs only because there was enough ready-reserve power during failure. Using reliability model (Fig. 1) and computer database worked out for the 370 MW power unit, the most defective elements of the boiler, turbine, generator and auxiliary systems have been identified [3,4]. For selected elements, empirical probability density functions of operation times, repair times have been determined with use of the histogram with a set number of observations in each class.

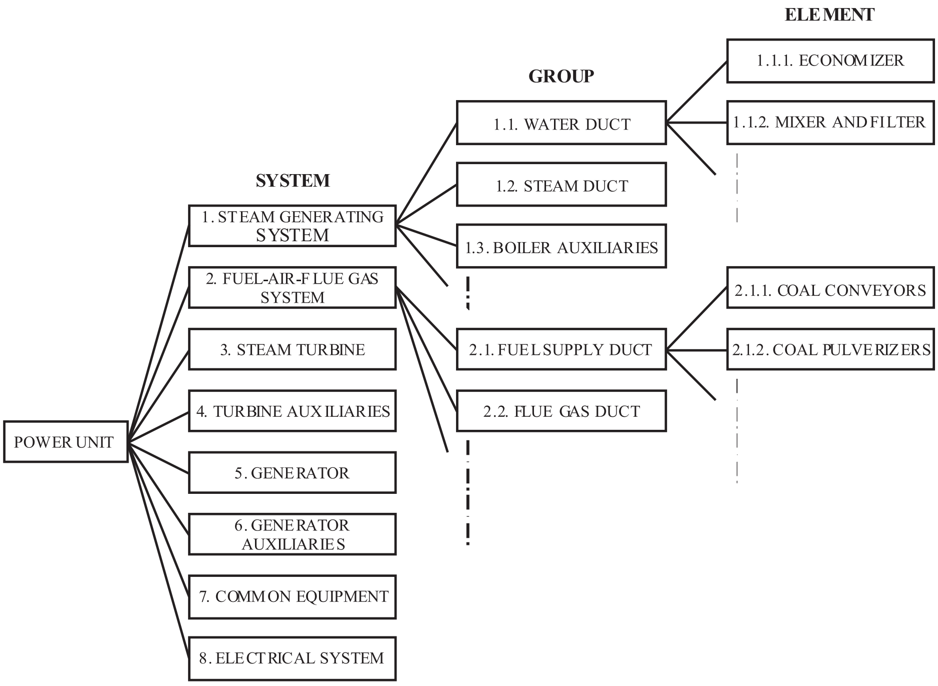


Figure 1. Schematic diagram of the three-step decomposition of the power unit for reliability model.

This histogram is prepared according to the following steps [12]:

- sorting numbers in a data set of n observations in an ascending order t_1, t_2, t_3, ... t_n;
- calculating number of classes r by the formula

$$r = 2\ln(n) \tag{1}$$

  and rounding down r to the nearest integer;

- calculating number of observations m in each class by the formula

$$m = \frac{n}{r} \tag{2}$$

  and rounding down m to the nearest integer;

- assigning all observations to each class in such a way that equal numbers from a data set are included in the same class; therefore the number of observations in the i-th class, n_i, can vary from an assumed value m;

- determining the lower and upper bound of each class; for example the upper bound of the 4th class (lower bound of the 5th class) is an arithmetic mean of the greatest number included in the 4th class and the lowest number included in the 5th class;

- calculating the i-th class interval width, Δt_i as the difference of its upper and lower bound; determining the i-th class midvalue, $\bar{t}_i$, as an arithmetic mean of its lower and upper bounds;

- calculating the value of an empirical probability density function by the formula

$$f^x(\bar{t}_i) = \frac{n_i}{n\Delta t_i}\ . \tag{3}$$

The histogram is completed by drawing a bar for each class. The main advantage of this histogram is the possibility to apply for the amount of classes $r \geq 7$ and less numerous data sets. If take into account the minimum required amount of observations in a single class ($n_i \geq 5$), the minimum statistical sample ($n \geq 35$) is easy to achieve in practice.

Calculation unit was implemented in computer database to identify probabilistic models for empirical distributions of operational times and shutdown times of standardized 370 MW power unit. Considering times of failures recorded in a computer database, times to failure and times of failure duration have been calculated. An empirical probability density function $f^x(t)$ is compared with the shape of the density function of different theoretical distributions (exponential, Weibull, normal, log-normal), and subjectively best distribution is selected as the one representing the random variable under investigation [8,10]. The hypothesis thus constructed is verified by means of (Pearson and Kolmogorov) statistical tests of goodness of fit, and only on this basis is the decision made to accept or reject it. All calculations are performed for the standard significance level $\alpha = 0.05$. Probability density functions $f(t)$, cumulative distribution functions $F(t)$ and means $E(T)$ for considered distributions are presented in Tab. 1. Estimators of distribution parameters are presented respectively in Tab. 2 [9].

Table 1. Probability density functions $f(t)$, cumulative distribution functions $F(t)$ and means $E(T)$ for considered distributions.

Distribution	$f(t)$	$F(t)$	$E(T)$
Exponential $\lambda > 0$	$\lambda \exp(-\lambda t)$	$1 - \exp(-\lambda t)$	$\frac{1}{\lambda}$
Weibull $a > 0$ $b > 0$	$\frac{b}{a}\left(\frac{t}{a}\right)^{b-1} \exp\left[-\left(\frac{t}{a}\right)^b\right]$	$1 - \exp\left[-\left(\frac{t}{a}\right)^b\right]$	$a\Gamma\left(\frac{1}{b} + 1\right)$
Normal $m \geq 0$ $\sigma > 0$	$\frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(t-m)^2}{2\sigma^2}\right]$	$0.5 + \Phi\left(\frac{t-m}{\sigma}\right)$	m
Log-normal $m > 0$ $\sigma > 0$	$\frac{\lg e}{t\sigma\sqrt{2\pi}} \exp\left[-\frac{(\lg t-m)^2}{2\sigma^2}\right]$	$0.5 + \Phi\left(\frac{\lg t-m}{\sigma}\right)$	$\exp\left[\frac{m}{\lg e} + \frac{\sigma^2}{2(\lg e)^2}\right]$

Explanations: Γ – gamma function, Φ – Laplace's function, λ – reciprocal of the scale parameter, σ – shape parameter, t, T – operation time or repair time as a random variable continuous and discrete respectively, a – scale parameter, b – shape parameter.

3 Histograms of operation times and repair times for the 370 MW power unit, its main components and selected elements of the BB-1150 steam boiler

The idea of a standardized unit has been introduced into the reliability study of the 370 MW units. All units are homogenous in several respects such as constructional uniformity and similar conditions in which units operate. The standarized unit is the unit in its useful life with stabilized failure rate that substitutes a dozen of power station units. The assumption that a standarized unit is in its useful life requires to exclude a period of an early life from an operation time of respective power units. The concept of a standardized unit allows to obtain an appropriately numerous population of failures not only for a power unit but also for its main generating devices (boiler, turbine, generator) and boiler elements. While establishing the population, the cases of incidental failures that occurred in the initial period of the power plant operation were neglected. It particularly refers to units 1 and 2 during the first three years of the power plant operation. The cases of failures that occurred in first year of operation were also skipped for remaining units. One can state that a higher failure frequency of a 370 MW power units in

Table 2. Estimators of distribution parameters for considered distributions.

Distribution	Parameter	Estimator
Exponential	λ	$\lambda^* = \frac{n}{\sum_{i=1}^{n} t_i}$
Weibull	$\theta = a^b$	$\theta^* = \frac{1}{n} \sum_{i=1}^{n} t_i^{b^*}$
	b	$b^* = \frac{n\theta^*}{\sum_{i=1}^{n} t_i^{b^*} \ln t_i - \theta^* \sum_{i=1}^{n} \ln t_i}$
Normal	m	$m^* = \frac{1}{n} \sum_{i=1}^{n} t_i$
	σ	$\sigma^* = \sqrt{\frac{\sum_{i=1}^{n} (t_i - m^*)^2}{n-1}}$
Log-normal	m	$m^* = \frac{1}{n} \sum_{i=1}^{n} \lg t_i$
	σ	$\sigma^* = \sqrt{\frac{\sum_{i=1}^{n} (\lg t_i - m^*)^2}{n-1}}$

the initial period of their operation was caused mainly by a design, construction and assembly defects. All these factors are distinctive for an adaptation of new generation power units. Therefore this period was excluded while population of failures for a standardized 370 MW unit was selected.

An investigated probability distribution functions were identified as Weibull distributions with parameter $b < 1$ (Fig. 2). In emergency states, strong dependence of the time of damage liquidation on the cause of its occurrence was found. Average times of shut down, in the case of permanent defects of the installations clearly differ from the times of shut down caused by the incorrect operation of the automatic control systems and safety devices, the operational staff mistakes etc. So, the values of times are as follows: 41.3 h and 1.75 h for the boiler; 59.7 h and 1.27 h for the turbine; 78.9 h and 1.48 h for the generator; 40.1 h and 1.95 h for feed water pump, respectively. Thus, it should be concluded that the times of long-term failures and short-term defects belong to two statistically different populations and that it is advisable to study their distributions separately. Generally speaking, the distributions of failure duration times are log-normal distributions (Fig. 3).

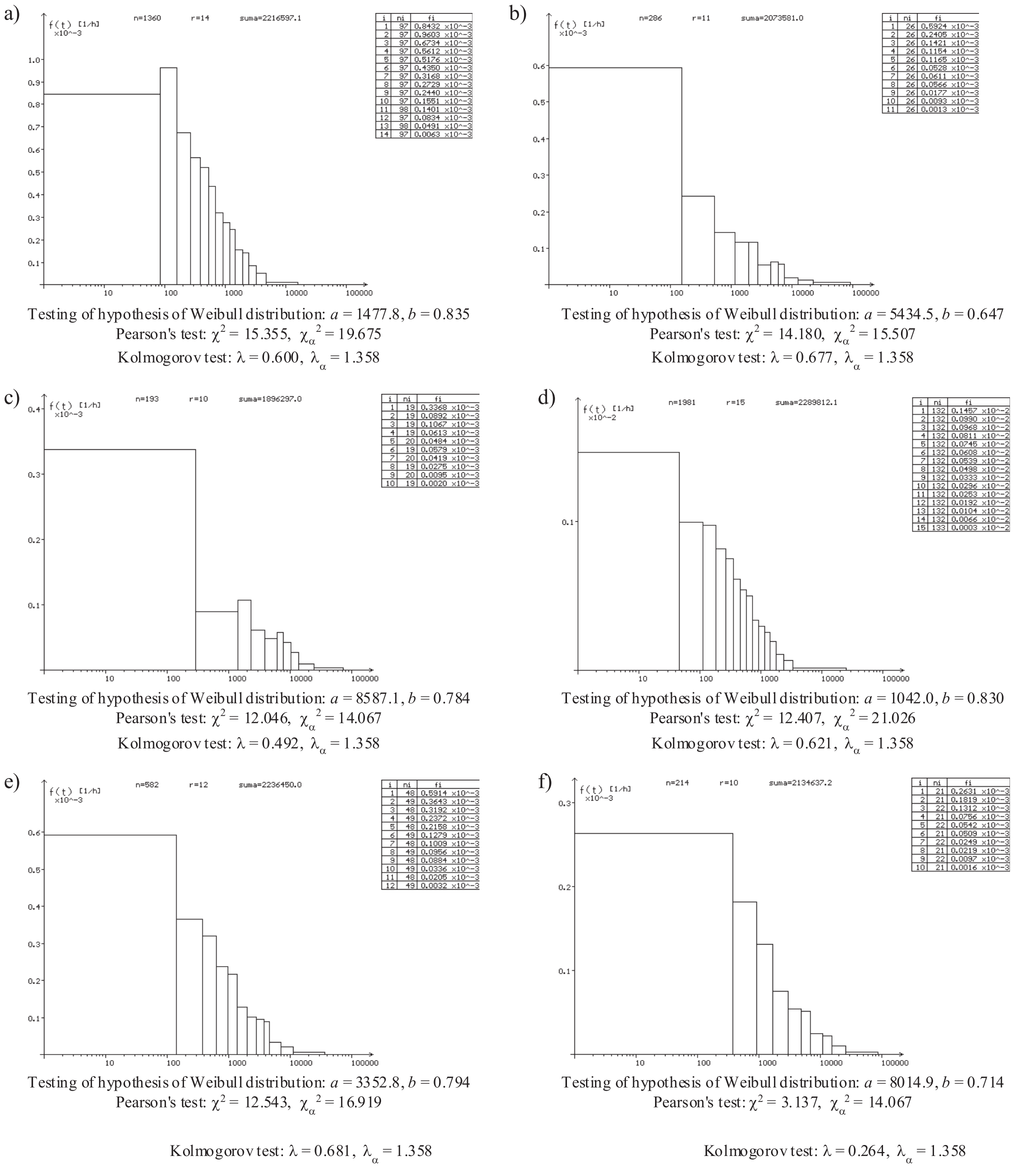
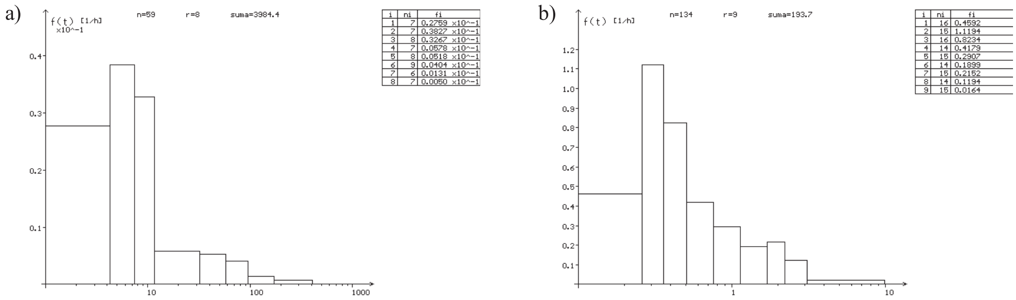


Figure 2. Probability density functions of times between failures identified as Weibull distributions: a) boiler BB-1150, b) turbine 18K370, c) generator GTHW-370, d) power unit, e) evaporator, f) P1B convection superheater. Explanations: a, b – estimated parameters of Weibull distribution, χ^2 – the value of Pearson's statistics, χ^2_α – the critical value of Pearson's statistics for the significance level $\alpha = 0.05$, λ – the value of Kolmogorov statistics, λ_α – the critical value of Kolmogorov statistics for the significance level equal to 0.05, i – the class number, n – the sample size, r – the number of classes, *suma* – the total value of all the observations in the sample, *ni* – the number of observations in the i-th class, *fi* – the value of empirical probability density function for the i-th class.



Testing of hypothesis of log-normal distribution: $m = 1.446$, $\sigma = 0.626$
Pearson's test: $\chi^2 = 8.837$, $\chi_\alpha^2 = 11.070$
Kolmogorov test: $\lambda = 0.791$, $\lambda_\alpha = 1.358$

Testing of hypothesis of log-normal distribution: $m = -0.045$, $\sigma = 0.433$
Pearson's test: $\chi^2 = 12.059$, $\chi_\alpha^2 = 12.592$
Kolmogorov test: $\lambda = 0.817$, $\lambda_\alpha = 1.358$

Figure 3. Probability density functions of failures times identified as log-normal distributions: a) generator GTHW-370 (times of long-term failures), b) generator GTHW-370 (times of short-term failures).

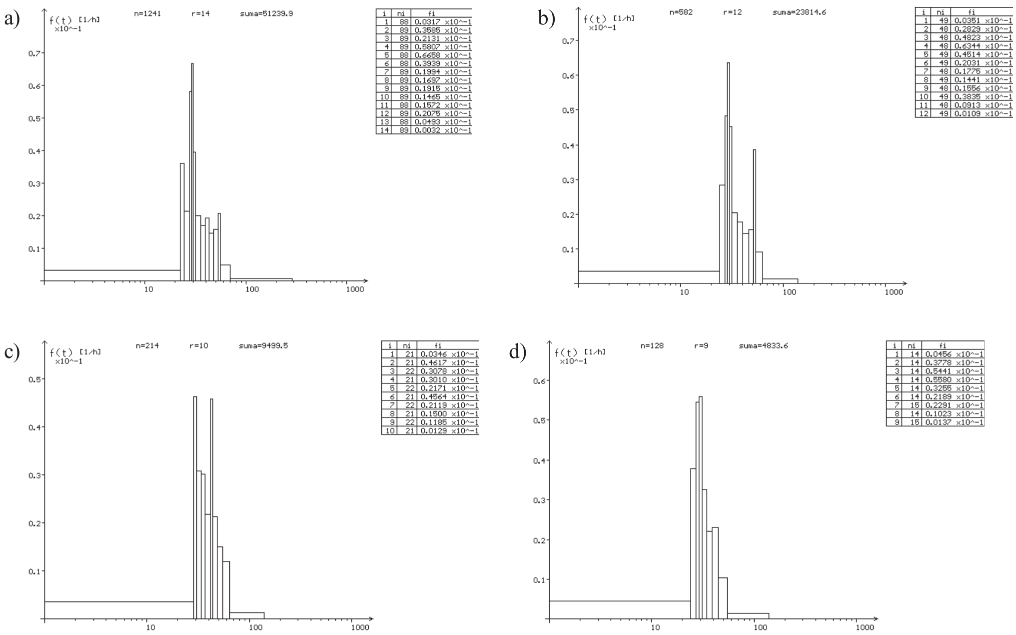


Figure 4. Probability density functions of failures times: a) boiler BB-1150 – distribution unidentified, b) evaporator – distribution unidentified, c) convection superheater P1B – distribution unidentified, d) economiser – distribution unidentified.

Probability density functions of failure times for the boiler (Fig. 4a) and its heat transfer surfaces (Figs. 4b–4d) have complicated shapes. An interesting feature of these distributions is an occurrence of two time intervals with high probability level of failure appearance with respective time duration. The first interval refers to failures with duration of 20–30 h, the second with duration of 40–60 h. The belongings of the failure to one of these groups is connected with the scope of leakages that steam boilers are affected. One can hypothesize that failures of the boiler with time duration out of these intervals have no relation to damages of heat transfer surfaces or that are composed by the superposition of failures of a few elements.

An empirical distribution functions of operation and failure times for each of dozen power units (Figs. 5 and 6) and steam boilers (Fig. 7) have been also examined.

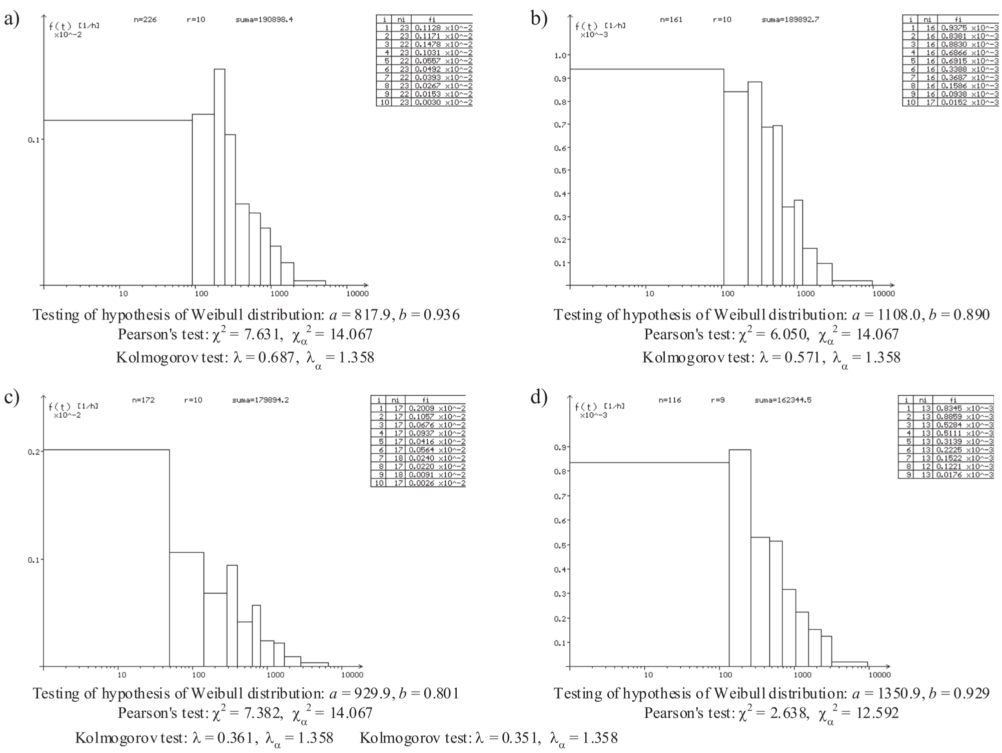
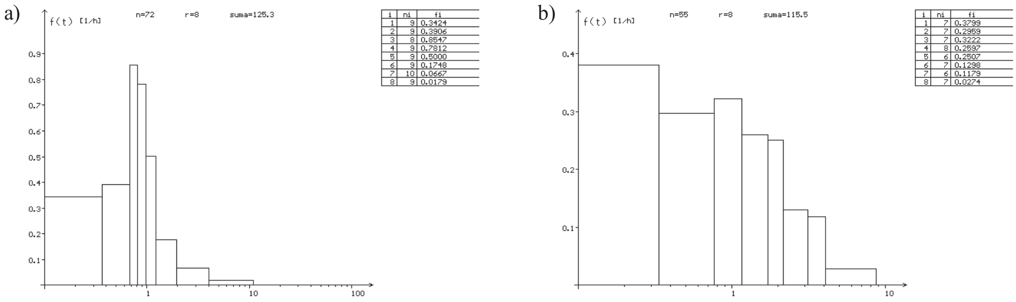
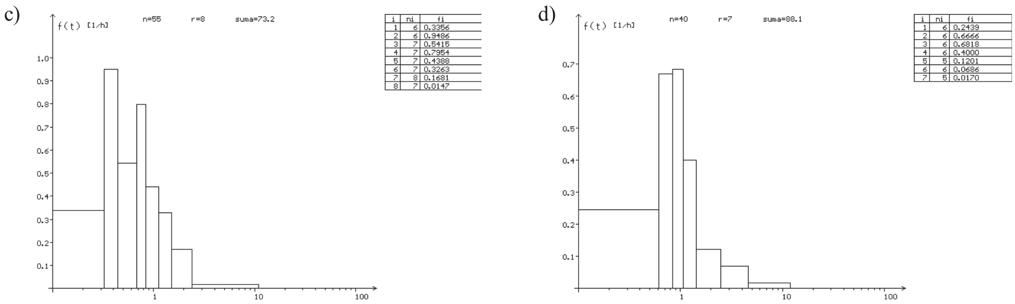


Figure 5. Probability density functions of times between failures identified as Weibull distributions: a) unit 1, b) unit 4, c) unit 8, d) unit 12.



a) Testing of hypothesis of log-normal distribution: $m = 0.055$, $\sigma = 0.388$
Pearson's test: $\chi^2 = 10.941$, $\chi_\alpha^2 = 11.070$
Kolmogorov test: $\lambda = 0.651$, $\lambda_\alpha = 1.358$

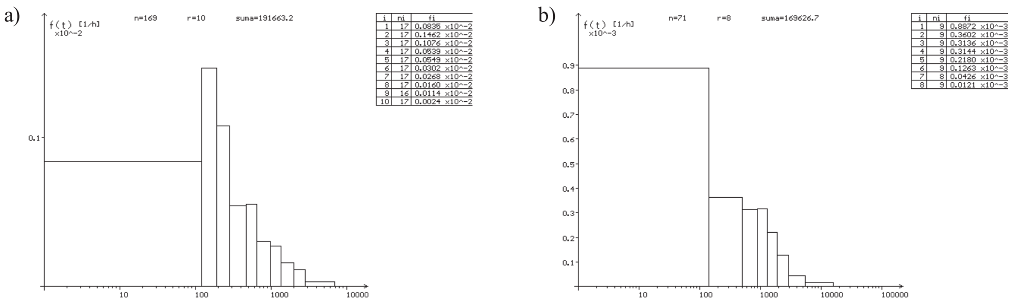
b) Testing of hypothesis of log-normal distribution: $m = 0.141$, $\sigma = 0.442$
Pearson's test: $\chi^2 = 5.172$, $\chi_\alpha^2 = 11.070$
Kolmogorov test: $\lambda = 0.425$, $\lambda_\alpha = 1.358$



c) Testing of hypothesis of log-normal distribution: $m = -0.044$, $\sigma = 0.375$
Pearson's test: $\chi^2 = 1.541$, $\chi_\alpha^2 = 11.070$
Kolmogorov test: $\lambda = 0.163$, $\lambda_\alpha = 1.358$

d) Testing of hypothesis of log-normal distribution: $m = 0.153$, $\sigma = 0.389$
Pearson's test: $\chi^2 = 4.915$, $\chi_\alpha^2 = 9.488$
Kolmogorov test: $\lambda = 0.607$, $\lambda_\alpha = 1.358$

Figure 6. Probability density functions of short-term failures times identified as log-normal distributions: a) unit 1, b) unit 4, c) unit 8, d) unit 12.



a) Testing of hypothesis of Weibull distribution: $a = 1075.1$, $b = 0.896$
Pearson's test: $\chi^2 = 10.746$, $\chi_\alpha^2 = 14.067$
Kolmogorov test: $\lambda = 0.534$, $\lambda_\alpha = 1.358$

b) Testing of hypothesis of Weibull distribution: $a = 2113.1$, $b = 0.810$
Pearson's test: $\chi^2 = 2.837$, $\chi_\alpha^2 = 11.070$
Kolmogorov test: $\lambda = 0.309$, $\lambda_\alpha = 1.358$

Figure 7. Probability density functions of times between failures identified as Weibull distributions: a) boiler 1, b) boiler 12.

4 An assesment of reliability indicies of the 370 MW power units and their main components

By means of estimation, parameters of identified probability distribution functions of operation and repair times have been calculated for investigated devices of 370 MW power units. Such reliability indices as expected failure rate, expected mean time of the shutdown, expected annual time of shutdowns have been estimated and expected failure-free time. Table 3 presents expected values of basic reliability indices for a standardized 370 MW power unit and its main components. Table 4 contains the results of reliability forecasts for shutdowns of important elements of the BB-1150 boiler, i.e. for an economizer, evaporator, inner suspended pipes P1A, convection superheater P1B, outlet superheater PIV, reheaters M1 and M2 and all superheaters summed up. Code symbols used for elements of the steam boiler BB-1150 remain in accordance with manufacturer specification and are applied in bibliography (for example [13]). Table 5 consist of expected values of reliability indices for respective power units of the power station whereas Tab. 6 for corresponding steam boilers.

Table 3. Reliability indices for main power plant components.

Failure location	Expected failure rate [1/a]	Mean time of a shutdown [h]	Total time of shutdowns [h/a]	Mean time between failures [h]
B	3.79	37.83	143.50	1626
T	0.83	13.31	11.00	7463
G	0.63	25.17	15.71	9874
F	0.34	11.11	3.73	18387
W	0.19	9.29	1.74	32914
O	0.52	9.36	4.85	11910
Unit	5.36	30.70	164.50	1151

Explanations: B – steam boiler and its auxiliaries, T – steam turbine and its auxiliaries, G – generator and its auxiliaries, F – system of feed water pumps, W – system of cooling water and service water pumps, O – others (including failures of electrical devices).

The results indicate that the evaporator is the most defective element in technological track of 370 MW power unit. The mean time of the shutdown duration is approx. 41 h, which – with the expected number of failures over the year of 1.62 – gives the total duration of shutdowns of approx. 66 h. The expected time between failures of 3820 h is, in this case, the shortest of all the elements under investigation.

Table 4. Forecasts for reliability indices of the most defective elements of the BB-1150 boiler.

Boiler element	Expected failure rate [1/a]	Mean time of a shutdown [h]	Total time of shutdowns [h/a]	Mean time between failures [h]
Economiser	0.40	37.76	14.97	15551
Evaporator	1.62	40.92	66.07	3819
Inner suspended pipes P1A	0.40	40.61	16.10	15619
Convection superheater P1B	0.62	44.39	27.49	9959
Outlet superheater PIV	0.26	51.32	13.56	23336
Reheater M1	0.35	39.75	14.05	17450
Reheater M2	0.18	46.20	8.22	34650
All superheaters (total)	1.46	43.61	63.67	4224

Table 5. Reliability indices for dozen power units of Belchatow Power Station.

Failure location	Expected failure rate [1/a]	Mean time of a shutdown [h]	Total time of shutdowns [h/a]	Mean time between failures [h]
Unit 1	7.31	30.36	222.06	843
Unit 2	7.36	29.85	219.55	838
Unit 3	4.41	31.75	140.03	1398
Unit 4	5.26	30.49	160.30	1173
Unit 5	5.98	31.67	189.49	1030
Unit 6	5.50	29.72	163.40	1121
Unit 7	6.09	35.70	217.39	1012
Unit 8	5.86	32.06	187.84	1052
Unit 9	4.83	32.14	155.07	1278
Unit 10	4.97	24.18	120.06	1241
Unit 11	3.88	28.87	111.95	1590
Unit 12	4.41	34.16	150.73	1398

5 Conclusions

Power system safety is determined by its weakest links related to large power units components. Optimal scheduling of the power unit maintenance, repairs and modernization becomes impossible without knowledge of failure reasons and

Table 6. Reliability indices for BB-1150 steam boilers installed in Bełchatów Power Station.

Failure location	Expected failure rate [1/a]	Mean time of a shutdown [h]	Total time of shutdowns [h/a]	Mean time between failures [h]
Boiler 1	5.44	—	207.41	1134
Boiler 2	5.22	36.90	192.62	1181
Boiler 3	2.43	45.14	109.53	2541
Boiler 4	3.65	38.65	141.24	1687
Boiler 5	4.72	39.51	186.37	1307
Boiler 6	3.81	36.38	138.59	1618
Boiler 7	4.11	37.63	154.61	1500
Boiler 8	3.91	35.86	140.30	1576
Boiler 9	3.56	40.74	144.84	1734
Boiler 10	3.42	31.37	107.31	1802
Boiler 11	2.19	35.05	76.81	2814
Boiler 12	2.60	39.64	103.00	2373

failure rates as well as giving reasonable guarantees of continuity of power supply. Reliability studies of power stations used to consider their weakest elements as an integrated part of the unit, i.e. turbine and boiler together with their auxiliaries and control systems. Consideration of the separate elements of the power unit leads to complicated reliability models which are labour-consuming or hard to analyze because of lack of information on failure rates of each element. Failures of many auxiliary systems have no significant influence on power plant operation but make it more difficult [2].

Reliability studies related to lignite fired power units rated at 370 MW and installed in domestic power system have been carried out systematically by authors for a number of years. The results allow to analyze a changeability of reliability indices in a long-term perspective and define reasons or effects of defective operation of generating devices. The knowledge of the current and forecast values of failure rates can be useful to determine modernization schedules or to rationalize repair and materials management. The failure rate is a reasonable measure for a durability of generating devices and an indication for economical effectiveness of repairs.

An acquisition of reliability indices proves that failure rate of the boiler makes it the weakest link in power unit reliability as well boiler failure rate is crucial for power plant availability. Therefore it is reasonable to reduce the amount of shutdowns related with boiler failures by the way of focusing the maintenance management on a lifetime improvement of the weakest links.

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Metody probabilistyczne w ocenie niezawodności bloków energetycznych

S t r e s z c z e n i e

W artykule dokonano oceny niezawodności pracy krajowych bloków 370 MW opalanych węglem brunatnym, zainstalowanych w Elektrowni Bełchatów. W oparciu o koncepcję bloku reprezentatywnego i metodę histogramu o założonej liczbie realizacji w klasach wyznaczono rozkłady prawdopodobieństwa występowania czasów pracy i czasów awarii dla głównych urządzeń bloku oraz ich najbardziej zawodnych elementów. Następnie na podstawie estymacji parametrów uzyskanych w ten sposób rozkładów empirycznych określono dla tych elementów wartości oczekiwane ich podstawowych wskaźników niezawodnościowych: intensywności awarii, średniego czasu wyłączenia, łącznego czasu wyłączeń w ciągu roku i czasu pracy bezawaryjnej.