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Reliability Analysis and Maintenance Optimization of Projection Spot Welding Machine in the Automotive Industry

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Abstract

This study analyzed the operational characteristics of the reliability and maintainability of the Projection Spot Welding (PSW) machine in the automotive industry. The components of the machine were grouped into three sub-systems: electrical, pneumatic, and hydraulic, and they were ordered into a hierarchical structural model for calculating reliability characteristics. The obtained maintenance lists and failure and repair data were studied and classified. Trend and serial correlation tests were carried out to select a proper modeling technique for each sub-system. Then, the reliability-maintainability model was constructed to estimate the failure behavior of the sub-systems, identify the best-fit distribution model, and calculate reliability characteristics. Finally, based on the calculated reliability characteristics, the preventive maintenance intervals for a different reliability level were calculated and requirements for increasing reliability were suggested. The analysis of the main structural sub-systems of the RSW machine showed that the hydraulic sub-system significantly affects the overall reliability level of the machine. However, the mean time to repair (MTTR) of the hydraulic sub-system is the lowest among other sub-systems. The analysis also found that the reliability of the electric and pneumatic sub-systems decreases by up to 50% after approximately 80h and 40h, respectively. The results of the study concluded that the reliability and maintainability analysis can improve the accuracy of preventive maintenance intervals and assess the reliability of each component of the RSW machine, which in turn can help reduce operating costs and extend the life of machine components.

Keywords: reliability; maintainability; projection spot-welding machine; statistical analysis

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1. Introduction

The PSW machine has been widely used in the automotive industry, where good quality of welds and high reliability of machines are required [1]. The PSW machine imposes special requirements on reliability because welding points and weldments are located in critical places in the body of a car, the inadequate quality of which can lead to large financial expenses or even risks associated with the safety and lives of humans. Therefore, safety and quality standards like MVSS (Motor Vehicle Safety Standard) and ISO/TS 16949 pay particular attention to weld quality and require strict monitoring of welding processes from manufacturers. Unfortunately, the low degree of equipment exploitation and violation of technological discipline lead to extensive failures and inconsistencies of welded structures even with the established requirements. In this regard, ensuring the reliable and failure-free operation of the PSW machine becomes an important task for both designers and plant engineers. In engineering practices, ensuring the reliable operation of the welding machine can be achieved by analyzing its reliability and maintainability [2]. This analysis helps determine the weak spots of the machine, establish proper maintenance intervals, and formulate requirements for reliability in relation to operating conditions.

Different applications of reliability and maintainability analysis have been developed and presented in many research papers [3] proposed an analytical reliability-maintainability model for a pneumatic system of the rotary drilling machine. The model was applied to investigate the influence of the reliability parameters on system performance [4] proposed a reliability and maintainability application for improving the productivity of Dragline [5] developed an approach based on reliability analysis that supports the maintenance decision process in Aircraft systems [6] developed a methodological framework for modeling the reliability and maintainability of the electrical drum shearer. The paper described the

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methodology for identifying critical components of the system and analyzed failure probabilities of the components of the machine. Methods that access reliability characteristics of the welding machine and can be applied in industrial environments have not been presented in literature so far, as the welding machine is a complex technical product. Additionally, in many practical cases, it is very difficult to analyze its reliability characteristics. However, authors [7], [8], and [9] presented the application of reliability analysis of the welding processes and welding machines' different components. The methodology used in these studies is based on statistical methods of analysis. At present, in both the theory and the practice of reliability analysis, the use of statistical methods to obtain reliability and maintainability characteristics has been proven to be relevant [10].

This study aims to analyze the operational reliability and maintainability characteristics of the RSW machine in the automotive industry. The obtained reliability characteristics can help determine the contribution of each component to the overall reliability of the PSW machine and select the most effective maintenance approach that can improve its reliability performance.

2. The Projection Spot Welding Machine

The PSW machine can be clearly distinguished between the electrical and mechanical parts. The mechanical part of the PSW machine may vary considerably depending on the welding operation and design. According to these features, dozens of different types of PSW machines have been used industrially.

The mechanical part of the machine consists of the machine frame (on which the lower and upper console are fixed), drive force system (for closing electrodes), and water cooling system (for cooling current-carrying parts of the machine). The drive force system can also be pneumatic (air cylinder), hydraulic, and electromechanical (servomotor). Among them, the pneumatically operated drive force system is mainly used due to its simplicity of construction [11]. The drive force system of the PSW machine under the study of this work is pneumatically operated. The pneumatically operated drive force system consists of a three-chamber cylinder with two pistons, a filtering system, and lubrication system. The hydraulic system of the PSW machine is designed to remove heat from current-carrying parts of the machine. It consists of a pump, hoses, water tubes, valves, hydraulic relays, and filtering system. Generally, the electrical system of the PSW machine is not as different in structure as the mechanical system. The electrical system of the PSW machine is very similar to other types of spot welding machines [12]. It mainly includes a transformer, rectifier unit with capacitor banks, converter, and welding controller. The electrode holders and electrodes also relate to the electrical system of the machine, but they have a very short useful life cycle and therefore were not included in the analysis. The hierarchical structure of the PSW machine is presented in Figure 1.

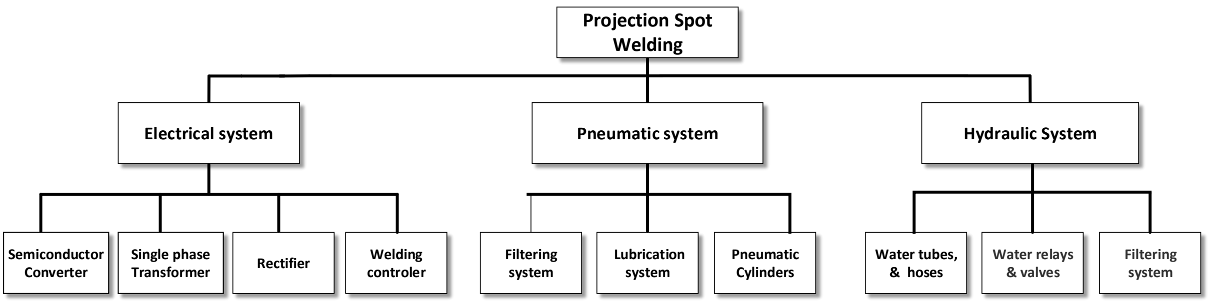

Figure 1. Projection Spot Welding machines structure

3. Theoretical Concept

The reliability analysis of the PSW machine is based on the estimation of reliability characteristics, which are represented by analytical expressions of reliability function $R(t)$, maintainability function $M(t)$, failure density function $f(t)$, mean time to failure (*MTBF*), and mean time to repair (*MTTR*). These functions are discussed in detail in the sections below.

3.1. Reliability

Reliability is a property of a system/component to perform its required functions under a specified time interval.

It is mathematically defined as

$$R(t) = 1 - \int_0^t f(t)dt \quad (1)$$

Where $R(t)$ is the reliability function at time t and $f(t)$ is the failure density function.

3.2. Maintainability

Maintainability is one of the main properties of reliability, defined as the ability of the system to prevent and detect the causes of its failures and also the ability to be restored to an operational condition [13]. It is defined as

$$M(t) = \int_0^t f(t)dt \quad (2)$$

Where $M(t)$ is the maintainability function at time t and $f(t)$ is the repair density function.

The MTTR is a maintainability parameter, defined as the average restoration time of a system/component after failure. It is defined as

$$MTTR = \int_0^t (1 - M(t))dt \quad (3)$$

3.3. Failure Rate

The failure rate (denoted by λ) is the frequency with which a system/component fails at time *t*. It is expressed as the robability of failure per unit of time. It can be defined with the reliability function $R(t)$

$$\lambda(t) = \frac{f(t)}{R(t)} = -\frac{1}{R(t)} \times \frac{dR(t)}{dt} \quad (4)$$

Where $f(t)$ is a failure density function at time t and $R(t)$ is a reliability function at time t.

3.4. The Exponential Distribution

For the exponential distribution $Exp(\lambda)$, the reliability of the system or probability of failure free operation at time t is defined as

$$\lambda R(t) = \lambda e^{-\lambda(t-\gamma)} \quad (5)$$

Where λ is the failure rate and γ is the location parameter. In this distribution failure rate, λ occurs in successive random intervals and is commonly used in the reliability to describe the period of "useful life" in the bathtub curve [14]. The failure rate function is given by

$$f(t) = \frac{\lambda e^{-\lambda t}}{e^{-\lambda t}} \quad (6)$$

3.5. The Weibull Distribution

The Weibull distribution is used when the failure flow is non-stationary and the failure rate varies with time [15]. It is capable of describing all three forms of failure rate, which are decreasing, increasing, and stationary. For a two-parameter Weibull distribution, the reliability is written as

$$R(t) = \frac{\beta}{\theta}(\frac{t}{\theta})^{\beta-1} \ exp[-\frac{t}{\theta}]^{\beta} \quad (7)$$

Where β and θ are the shape and scale parameters, respectively. The parameter $\beta=1$ signifies the stationary failure rate of a system/component. The failure rate is given by

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\theta}(\frac{T-\gamma}{\theta})^{\beta-1} \quad (8)$$

3.6. The Gamma Distribution

The gamma distribution is a continuous distribution with two parameters, β and λ. If parameter β = 1, the gamma distribution coincides with the exponential distribution. The gamma distribution in the reliability analysis can be written as

$$R(t) = \frac{\lambda^{\beta} t^{(\beta-1)}}{\Gamma(\beta)} exp(-\lambda t) \tag{9}$$

Where β is a shape parameter and λ is a failure rate.

3.7. The Log-Normal Distribution

The reliability function for the log-normal distribution is

$$R(t) = \frac{1}{\sqrt{2\pi\sigma}} \int_0^t \frac{1}{t} exp\left(\frac{(Ln(t) - \mu)^2}{2\sigma^2}\right) dt \tag{10}$$

Where σ is a standard deviation and μ is a mean. The log-normal distribution is successfully used in reliability engineering to describe the operating event of the electrical devices.

4. Case Study

4.1. Failure and Repair Data Collection

In this case study, the reliability data for analysis was collected from the automobile manufacturing company JV LLC "UzSungwoo" in Uzbekistan, Fergana. The company specializes in the manufacturing of stamping and welding parts that constitutes the body of a car. The operational information on equipment failures and technical maintenance reports were preliminarily studied and analyzed. The maintenance reports depict the time before failure (TBF), time to repair (TTR), type of failed component, and time for waiting of the maintenance team. Initially, the failure of welding equipment was considered a failure of an individual element. The failure modes and TBF and TTR data of each component of the machine were classified and grouped into sub-systems. The failure modes associated with a "human factor" were excluded from the PSW machine reliability analysis in the current study. This type of failure occurred due to an unauthorized interference of operators in the operation of the machine, causing long downtimes for reconfiguration. The statistical data on failures were analyzed for four PSW machines that are operated for two shifts, 14 hours a day and 25 days a month. Figure 2 shows the results of the statistical failure analysis. The figure clearly shows that 39% and 35% of all failures are related to hydraulic and pneumatic sub-systems, respectively. The figure also shows that 20% of all failures occurred in the electric sub-system. The failures associated with a "human factor" only make up 6% of all failures.

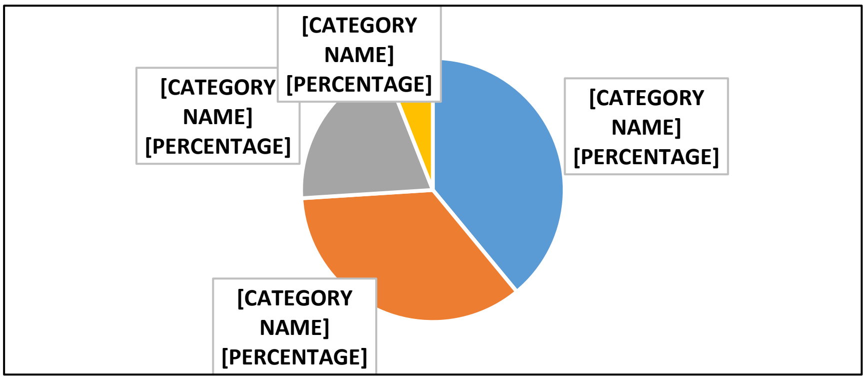

Figure 2. Statistical failure analysis of the RSW machine

4.2. Trend and Serial Correlation

The second step of reliability analysis involves selecting the optimal modeling technique for TBF and TTR data. Generally, the time between failure/repair in the reliability analysis is modeled based on a nonhomogeneous Poisson process (NHPP) and renewal process (RP) [16]. The time between failures in the RP is independent and identically distributed (idd), implying that the data has no trends and there is no relationship among failures. This process is usually used in reliability analysis to model repairable systems, where the repair will restore the system to “as good as new condition”. If the data is not idd, then RP is not valid and NHPP must be used. The NHPP is used to model “non-repairable systems” with “as bad as old restoration”. The powerful analytical techniques “trend test” and “serial correlation test” are commonly used to verify the assumption that TBF/TTR data is iid.

The “trend test” is a statistical test that determines the trend in reliability data, and it can be accomplished graphically by plotting a cumulative number of failures/repairs against a cumulative number of TBF/TTR data. If the plot exhibits a straight line, then the reliability data can be considered as iid and thus has no evidence of trends. The “serial correlation test” is used to detect randomness in data samples and can be accomplished by plotting the i^{th} TBF/TTR against the $(i-1^{th})$ TBF/TTR for $i = 1, 2, \cdots, n$, where n is the total number of failures. If the TBF/TTR data is iid, then the points in the graph should be randomly scattered. Figure 3 shows the results of the “trend test” and “serial correlation test” of the PSW machine electric sub-system, pneumatic sub-system, and hydraulic sub-system. From Figure 3, it is observed that trend lines for all sub-systems are approximately straight and data points in the scatter plot are distributed randomly. This provides significant evidence that reliability data for all sub-systems is iid and has no correlation. The results of the tests verified the assumption that the data iid is valid for all sub-systems of the machine and therefore the RP model can be used to estimate reliability and maintainability functions.

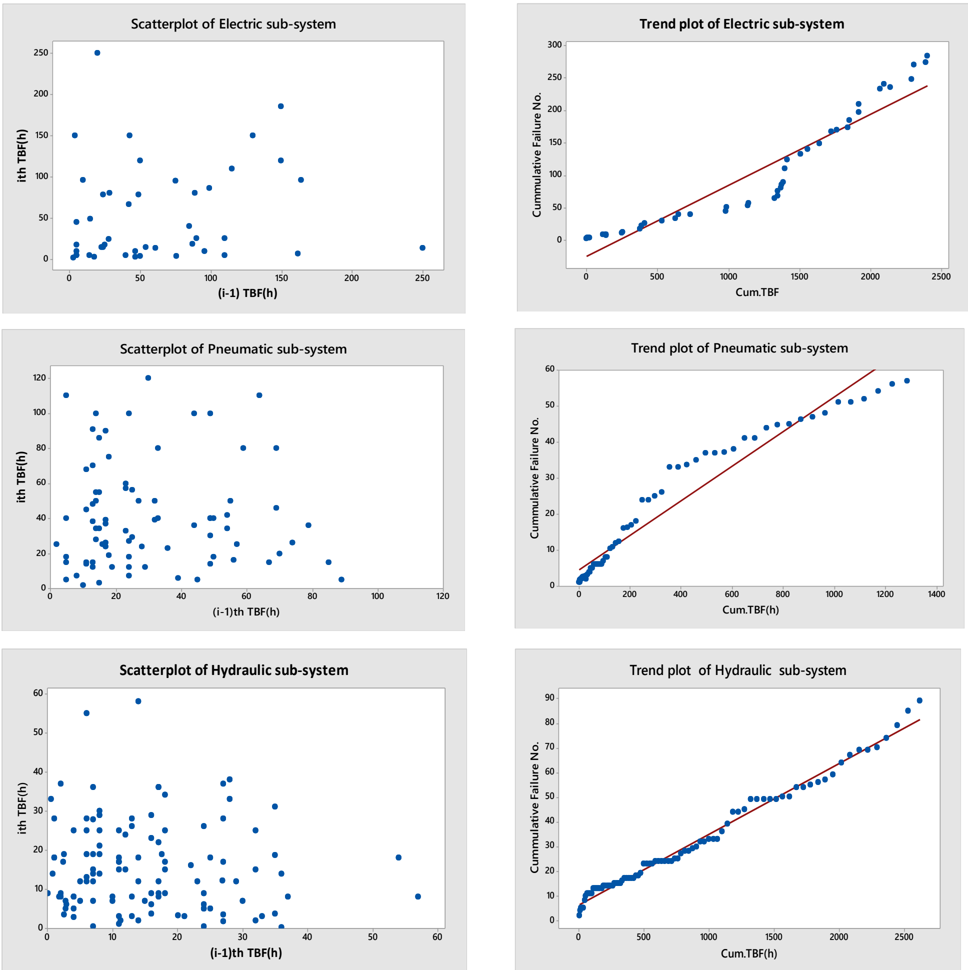

Figure 3. Results of tests for trend and serial correlation of TBF and TTR data

4.3. Determination of the Best Fit Distribution

4.3.1. Maximum Likelihood Method

The determination of the best-fit distribution of the TBF and TTR data for the machine sub-systems is based on the hypothesis H_0 that the data sample belongs to the parametric family of probability distributions specified as $f(x;\theta)$. The unknown parameters $f(x;\theta)$ can be estimated by using the maximum-likelihood estimation (MLE) method.

The likelihood function $f(x)$ is called the function of θ when

$$L(x_1, x_2, \cdots, x_n, \theta) = p\left(x_{1,}\theta\right) \cdots p(x_{n,}\theta) \tag{11}$$

Where x_i are samples from the X. Thus, maximizing the likelihood function $L(\theta)$, we get

$$lnL(\theta) = max \sum_{i=1}^{n} ln(f(R_i; \theta) - (f(L_i; \theta)) \tag{12}$$

4.3.2. Anderson-Darling Goodness-of-Fit Test

The assessment of the hypothesis for the best-fit distribution was completed using the Anderson-Darling (A-D) goodness-of-fit test. The AD goodness-of-fit test assumes the specific distribution of selected data and calculates its statistical values. The hypothesis H_0 is rejected if statistical values are larger than the threshold value [17]. The A-D goodness-of-fit test is defined as

$$AD = -n\frac{1}{n}\sum_{i=1}^{n}(2i-1)[ln\,F(X_i) + ln(1 - F(X_{n-1+1}))] \tag{13}$$

Where n is the sample size and $F(X)$ is the cumulative distribution function.

Table 1 shows calculated statistical values of the AD goodness-of-fit test for all the sub-systems' TBF and TTR data. According to the AD test, the estimated statistical values for the electrical sub-system are as follows: two-parameter Weibull distribution = 0.08655, Exponential distribution = 0.09175, Lognormal distribution = 0.13417, and Log-logistic distribution = 0.14829. The Weibull distribution has the smallest statistical value compared with the other distributions, indicating the best fit for the data. In addition, a graphical test using Easy-Fit software was performed and presented in Figure 4. The graphical test enables a visual comparison of the fitness of distributions and selection of the most valid model. As can be seen from Figure 4, the Weibull model describes the failure distribution more accurately, confirming the appropriateness of the selected distribution. In the same manner, the best-fit distributions for the pneumatic and hydraulic sub-systems were identified and highlighted in bold (Table 1).

Table 1. The results of the A-D test for TBF and TTR data of the RSW machine sub-systems

	TBF estimation				TTR estimation			
	Weibull	Lognormal	Exponential	Log-logistic	Weibull	Lognormal	Exponential	Gamma
Electrical	***0.08655***	0.13417	0.09175	0.14829	***0.53073***	0.95228	0.87355	1.11790
Pneumatic	***0.71314***	1.11620	1.11620	0.81551	0.80246	0.62269	1.22650	***0.59708***
Hydraulic	0.53643	0.68642	0.40984	0.92797	0.92797	1.50420	1.10060	***0.75699***

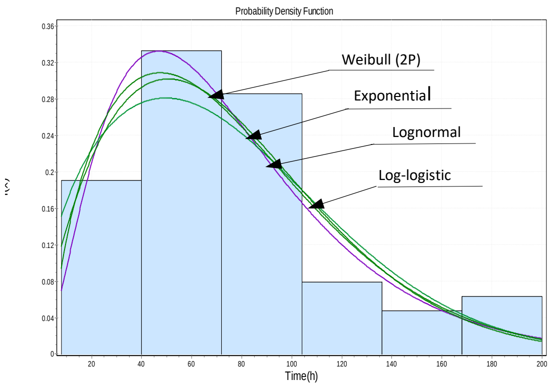

Figure 4. The result of the graphical test of best-fit distribution for electric –sub-system TBF data

Table 2 shows the estimated parameters of the best-fit distributions obtained by the MLE method. From Table 2, it can be seen that the failure rates of the electric sub-system and pneumatic sub-system follow a two-parameter Weibull distribution with parameters β =1.68, $\theta = 84.55$ and $\beta = 1.36$, $\theta = 21.56$ respectively. The failure intensity of the sub-systems clearly shows that the components of the sub-systems are in the wear-out phase. This indicates the presence of hidden defects, which without proper maintenance can ultimately lead to a complete breakdown of the machine. The failure rate of the hydraulic sub-system exhibits exponential behavior with parameter $\lambda = 0.06$. Estimated parameters of TTR data showed that failures of the pneumatic sub-system and hydraulic sub-system follow a gamma distribution with parameters $\alpha = 1.41$, $\beta = 1.38$ and α =1.53, β = 0.43, respectively. The TTR of the electrical sub-system follows a Weibull distribution with two parameters $\beta = 1.34$ and $\theta = 3.21$.

Table 2. Estimated parameters of the goodness of fit-test for TBF and TTR data of the RSW machine sub-systems

	TBF estimation		TTR estimation	
Sub-system	Best-fit	Parameters	Best-fit	Parameters
Electrical	2-Parameter Weibull	β = 1.68 θ = 84.55	Weibull	Shape = 1.34 Scale = 3.21
Pneumatic	2-Parameter Weibull	β = 1.044 θ = 21.56	Gamma	α = 1.41 β = 1.38
Hydraulic	Exponential	λ=0.061	Gamma	α = 1.53 β = 0.43

The parameters of the maximum likelihood estimations of the fitted distributions (Table 2) were substituted into Equations (6), (7), and (9) for Weibull, exponential and gamma distributions, in order to calculate the failure density function $f(t)$, reliability function $R(t)$, maintainability function $M(t)$, failure rate $\lambda(t)$, repair rate $\mu(t)$, and *MTBF* and *MTTR* of the sub-systems. The results of the calculations are presented in Table 2. From Table 1, the *MTBF* and *MTTR* of the electrical sub-system are estimated as $MTBF_e = 138.8$h and $MTTR_e = 3.05$h, respectively. The *MTBF* and *MTTR* of the pneumatic sub-system are $MTBF_p = 98.7$h and $MTTR_p = 1.37$h, respectively. Finally, the *MTBF* and *MTTR* of the hydraulic sub-system are $MTBF_h = 18.9$h. and $MTTR_h = 0.65$h, respectively.

4.3.3. Reliability and Maintainability Analysis

It can be seen from the analysis that the highest repair time is assigned to the electrical sub-system (*MTTR* = 3.05h.). For example, the repair of the transformer is not carried out on the machine itself but taken to repair shops that take a much longer time. It also can be seen that the hydraulic sub-system has the lowest repair time (*MTTR* = 0.65h). This indicates that maintenance of the hydraulic sub-system components does not require much time. However, the high frequency of hydraulic sub-system failures lowers the reliability level of the entire machine.

Figure 5 shows the reliability and maintainability plots for the PSW machine and its sub-systems at the end of a different exploitation time. It can be observed from Figure 5(a) that the reliability of the electric sub-system decreases by up to 80% after 50 hours of operation. Furthermore, the plot indicates that the elements of the electric sub-system are most reliable among other sub-systems of the machine. Additionally, the maintainability plot of the electric sub-system in Figure 5(b) indicates that there is a 35% chance that the system will be restored after two hours. Figure 5(c) shows that the reliability of the elements of the pneumatic sub-system reaches almost 75% after 30 hours of operation. The maintainability plot of the pneumatic sub-system Figure 5(d) shows that there is a 90% chance that a failure in the system will be restored within 2.5 hours. According to Figure 5(e), the reliability of the hydraulic sub-system reached 35% within 25 hours of operation, indicating that the elements of the hydraulic sub-system have the lowest reliability level. However, the maintainability plot in Figure 5(f) shows that there is approximately a 95% chance that a failure in the system will be restored within only 1.5 hours.

Table 3. The reliability characteristics of the PSW machines sub-systems

Sub-system	Type of distribution	Failure density function TBF data	*MTBF* (hours)	*MTTR* (hours)	Failure rate (λ)	Repair rate (μ)
Electric	Two-parameter Weibull	$f(t) = \dfrac{1.72}{83.58}(t/83.58)^{-0.72}\exp[-(t/83.58)^{1.72}]$	38.8	3.05	0.031	0.3842
Pneumatic	Two-parameter Weibull	$f(t) = \dfrac{1.044}{22.58}(t/22.58)^{-0.044}\exp[-(t/22.58)^{1.044}]$	98.7	1.37	0.010	0.650
Hydraulic	Exponential	$f(t) = 0.061e^{-0.061(t-0.85)}$	18.9	0.65	0.882	1.520

5. Maintenance Scheduling

The obtained reliability characteristics allow us to determine the technical condition of the PSW machine and show the contribution of each sub-system component to the overall reliability level. The results of the analysis can also be used to establish the appropriate maintenance interval at the desired reliability level. Table 5 shows the maintenance operation intervals of the PSW sub-systems at 90% 80%, and 70% reliability levels. From the table, to achieve a 90% reliability level of the electric sub-system, maintenance must be scheduled after about 45 hours of operation. The maintenances inspection for the pneumatic sub-system must be scheduled after 19 hours or after about three shifts. Similarly, the maintenance interval of the hydraulic sub-system must be scheduled every 10 hours or after about one shift.

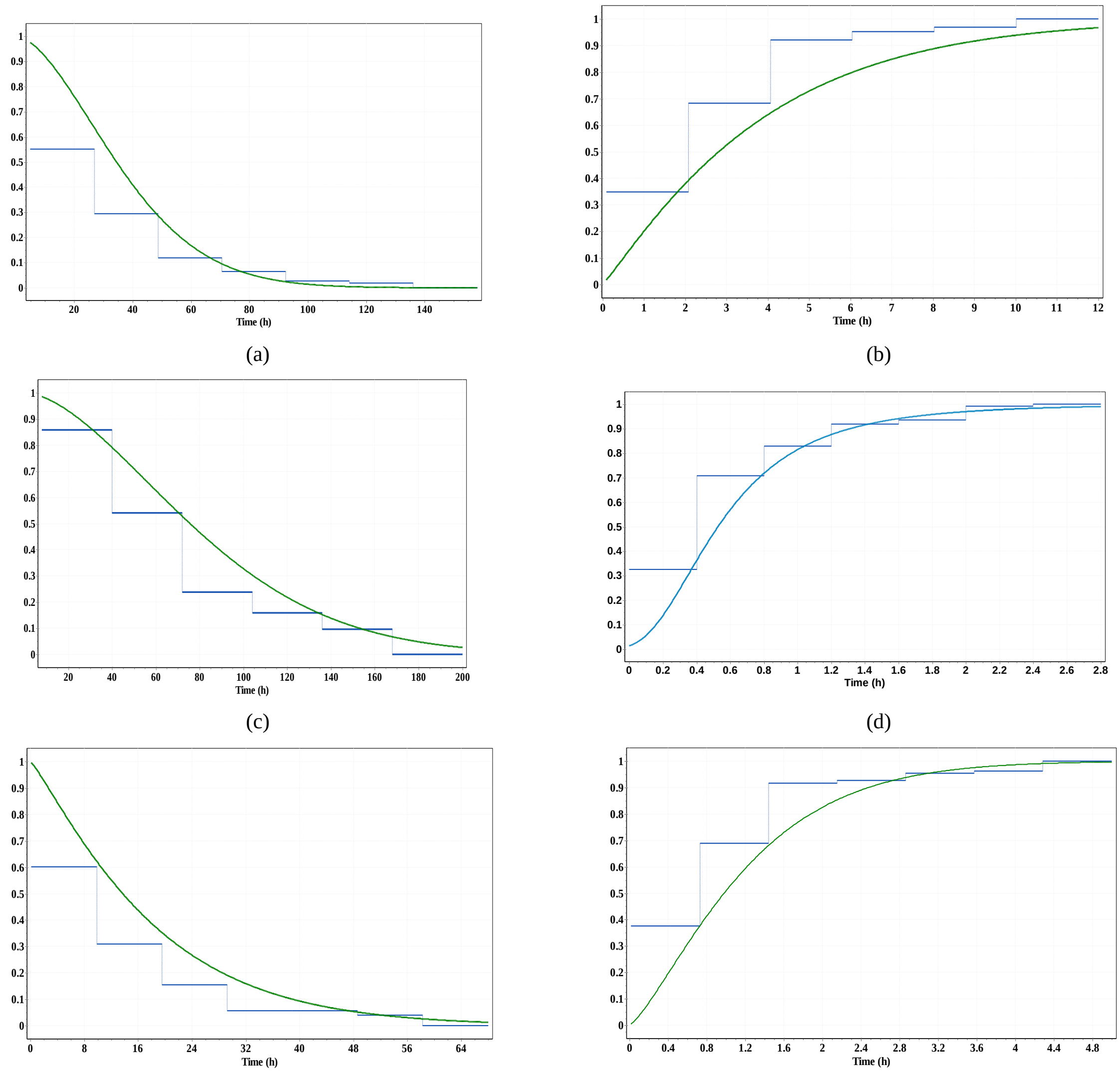

Figure 5. The reliability and maintainability function of the PSW machines sub-systems

Table 4. Different reliability levels and maintenance intervals for PSW machine sub-systems

Level of reliability (%)	**90**	**80**	**70**
Electric sub-system (h)	40	52	65
Pneumatic sub-system (h)	19	25	31
Hydraulic sub-system (h)	10	16	22

6. Discussion and Conclusions

This study presents the reliability and maintainability analysis of the PSW machine. The main aim of this paper is to estimate the operational reliability characteristics of the PSW machine sub-systems in the automotive industry. The results of the analysis have shown that the elements of the hydraulic sub-system are unreliable. According to the goodness-of-fit test failures, the hydraulic sub-system follows an exponential distribution. This clearly indicates that the failures have random characteristics. The statistical analysis of failure frequencies has shown that main failure modes of the hydraulic sub-system include clogging of water filters and tubes with dirt. This can lead to the reduction of water supply to the electrical parts of the machine. The electrical sub-system has been identified as the most reliable sub-system. The goodness-of-fit analysis showed that the failure rate of the electrical sub-system better fits the two-parameter Weibull distribution. The failure modes of the electrical sub-system are mainly caused by high vibrations (generated by the movable clamps of the machine) and external factors. The main failures of the electrical sub-system include over-heating and loosening and oxidation of the connections. According to the maintainability analysis, the electrical sub-system has the longest repair time ($MTTR$ = 3.05h) in comparison with other sub-systems. The goodness of fit test has shown that the TBF of the pneumatic sub-system better fits the Weibull distribution with two parameters: β = 1.044 and θ = 21.56. The failure frequency analysis has shown that 25% of all failures occurred in the pneumatic sub-system. The failures of the pneumatic sub-system include hose and pipe damage, which results in the leakage of lubricants and air.

The results of the analysis provide reliability characteristics that determine the operational reliability of the PSW machine in the automotive industry. Furthermore, obtained reliability characteristics can be used to determine the optimal periodicity of the replacement of machine elements, optimal spare parts level, and maintenance periodicity.

Acknowledgements

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