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STUDIES OF THE INFLUENCE OF INDEPENDENT VARIABLES (COVARIANTS) ON THE RELIABILITY CHARACTERISTICS OF EQUIPMENT

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ANNOTATION
In this article, the study of the influence of independent variable covariants on the reliability characteristics of equipment.

Basic phrases : covariate, mechanical factor, vibration, SWORD-B, ENV-CON, censored TBF, STATA 13.0, electrical, WM- I subsystem.

INTRODUCTION
All those factors which may have an influence on the reliability characteristics of a system are called covariates. Covariates are also called explanatory variables. Examples of covariates are the operating environment (dust, temperature and humidity, etc.), the skill of operators.
The PSW machine has been extensively used in assembling car bodies. The PSW machine consists of the following sub-systems: electrical sub-system, the pneumatic sub-system (for machines with pneumatic actuators), and hydraulic (cooling) sub-system. The automobile company where machines operate specializes in the manufacturing of stampings and welding parts that constitutes the body of the car. The production facility consists of stamping and assembling shops. The stamping-shop consists of storage area for a steel coil, blanking machine, press machines, and the PSW machines. The assembling-shop consists of spot-welding guns, the PSW machines, repair shop and the storage of finish products. The item welding is carried out in the two shops. In the first shop, press sub-assemblies are fastened with bolts and nuts on the projection welding machines. These items then moved to the storage area as a finished product. Some individual stamping parts are first sent to the assembling-shop, where parts are fastened with bolts and nuts on the similar projection machine, and then supplied to the spot welding line where final assembling is carried out. Because of the JIT inventory policy, the factory produces parts only when it receives an order from a customer. Therefore, storage area contains only 1-2 day’s stock of finished product. The machines are key elements in the production process; any breakdown of the machine can cause the fluctuation in the upstream demand chain. Therefore, ensuring the reliable and continuous operation of the machines is very important. The assembling shop has two main gates with dimensions of 6 × 8 m, both outputs are designed for the import of empty pallets and the export of finished products from the shop. Regardless of the season, the gates remain open. As a result, equipment and workers

are exposed to the harsh environment condition. This case study considered reliability performance of two similar welding machines from the stamping-shop (WM- I) and assembling-shop (WM- II).

In the first step of the proposed method, data from two machine WM- I and WM- II was collected. Both machines were manufactured by the same equipment supplier and operate for two shifts, 14 hours a day and 25 days a month. The loading coefficient and working cycle of both machines are almost the same. The time before failure (TBF) and event data for a period of 1 year were obtained from the maintenance logbook records. The maintenance records depict the exact time of the failure, time to repair, and failed component of the machine. With the support of maintenance and quality control engineers, the factors that can affect machines reliability identified and classified into several groups.

The next step is to formulate covariates that may have an influence on the reliability/hazard rate of the PSW machine and its sub-systems. The data analysis in the previous section shows that the reliability of the PSW can be influenced by different factors, which can conditionally be classified into three groups: mechanical factor (mechanical vibration), environmental condition and human factor.

Mechanical vibration (MECH-V). The main source of mechanical failures is movable parts of the machine. The reciprocating motion of the movable clamp can cause the strong mechanical vibration, which can significantly reduce the reliability of individual elements of the sub-system and the entire machine. The mechanical vibration can result in weakening electrical connection and accelerates wear and tear of the machine structure.

Environmental condition (ENV-CON). The reliability of the machine can be affected by the adverse conditions of the environment. The effects of an environmental condition such as polluted air, moisture, high and low ambient temperatures, climate etc. can cause variation in weld properties and reliability characteristics of the machine. In addition, the environmental condition has a direct impact on a workers performance [1]. In the southern part of Uzbekistan where the equipment is operating, climatic conditions are harsh and severe with large amplitude fluctuations in temperatures ranging from -20° to + 45 °. Therefore, the ENV-CON is an important covariate to be examined.

The human factor can have a significant influence on the reliability performance of the machine. According to 30% of all equipment failure occurs due to inappropriate handling and inadequate maintenance which in turn mainly occurs due to the inadequate skill of the workers. In the automotive industry, standards ISO requires that welders and maintenance stuff be properly skilled in performing weld and service work. Hence, poor human performance has not been the only cause associated with inadequate skill and qualification of the workers. There are different factors that are known to affect the human performance such as psychological and mental conditions, operational conditions and environmental conditions. The human factor consists of operator performance (OP) covariate and maintenance performance (MP) covariate. For each sub-system, the data tables with failure time, codified covariates and failure indicator are modelled. Due to the space constraints, the data table is shown only for WM- I electric sub-system in Table (see Appendix). The first column of the table shows calculated time before failure (TBF) of the sub-system. The second column indicates censored TBF. The censored TBF with value (0) occurs when the machine is stopped for routine or preventive maintenance inspection and with value (1) when a failure occurs due to the effect of the covariates. The remaining columns are covariates, with the values (-1) if the covariate is a reason of the failure and with value (+1) if covariate was not a reason of the failure.

In the next step, the PH assumption of the covariates must be checked. The statistical test, based on Schoenfield residuals, was carried out on WM- I and WM- II machines subsystems covariates using STATA 13.0 software. According to the test, if the **p**-value is statistically significant (i.e. greater than 0.10), it can be concluded that the tested covariates independent of time and thus satisfy the PH assumption. For example **Table 1** shows the results of the statistical test for the WM- I electrical sub-system. As can be seen from the table **p**-value > 0.10 for all covariates of WM - I electrical sub-system, this suggests that covariates satisfy the PH assumption. The result of the statistical test has shown that covariates are time independent for all WM- I and WM- II machines sub-systems.

Table 1

Covariates	Chi-square	Degree of freedom	p-value
MP	0.06	1	0.806
ENV-CON	0.00	1	0.999
MECH-V	0.30	1	0.872

The next step in the PH model is to determine covariates that have a significant influence on the hazard rate of the welding machines sub-systems. The corresponding regression parameters α was obtained by step-down (backward elimination) method, that uses the Wald statistic. The step-down regression analysis first considers all possible variables in the model. The least significant covariates (i.e. with **p**-value > 0.05) are excluded from the analysis and the model reiterates procedure until all covariates with significant coefficient identified. The estimation of regression coefficients was performed using XLSTAT software. For example, **Table 2** demonstrates step-down selection procedure for the WM- I electrical sub-system. In this table, the covariates MECH-V and ENV-CON are found to have a statistically significant influence (p=0.024) and (p=0.004) respectively, whereas the covariates OP and MP were not found to have statistically significant influence at the 0.05 level. The final selected covariates and corresponding estimated regression coefficients **α** for WM- I and WM- II sub-systems are presented in **Table 3 and 4**. From the **Table 3**, substituting estimated **α** values of the covariates into Equation the actual hazard rate of the WM- I electrical sub-system, considering influence covariates is expressed as

Table 2

Step	Covariates	α	SE	Wald	p-value	Hazard ratio

Step 1	OP	0.319	0.685	0.217	0.641	1.376
	MP	1.030	0.566	3.314	0.069	0.357
	ENV-CON	0.907	0.432	4.407	0.036	0.404
	MECH-V	0.018	0.429	0.002	0.967	1.018
Step 2	OP	0.304	0.566	0.287	0.592	1.355
	MP	1.043	0.478	4.765	0.029	0.352
	ENV-CON	0.918	0.334	7.580	0.006	0.399
Step 3	MECH-V	1.078	0.476	5.128	0.024	0.340
	ENV-CON	0.954	0.330	8.343	0.004	0.385

Table 3

Sub-system	Covariate	α	SE	Wald statistics	p-value	Hazard ratio
Electric	MECH-V	1.078	5.128	5.128	0.024	0.340
	ENV-CON	0.954	8.343	8.343	0.004	0.385
Pneumatic	ENV-CON	0.602	0.260	5.390	0.020	0.547
	MECH-V	0.472	0.275	2.952	0.086	0.624
Hydraulic	ENV-CON	1.216	0.425	8.168	0.004	0.296
	MEC H-V	0.518	0.271	3.661	0.056	0.596

Table 4

Sub-system	Parameters	
	β	η
Electric	2.85	139.7
Pneumatic	2.09	42.8
Hydraulic	1.79	22.8

$$\boldsymbol{\lambda(t,z) = \lambda_0(t)\exp(-1.078MECHV - 0.954ENVCON)} \quad (4\text{-}12)$$

using estimated values from **Table 4-4** and Equation (2) the actual hazard rate of the WM-II electrical sub-system, considering influence covariates expressed as

$$\boldsymbol{\lambda(t,z) = \lambda_0(t)\exp(-1.138ENVCON - 0.619MECHV - 0.699MP - 0.521OP)} \quad (4\text{-}13)$$

Equation (6) and (7) showed that hazard rates of WM-I and WM-II electrical sub-systems have an impact of covariates equal $\mathbf{exp(-1.078)} = 0.34$, $\mathbf{exp(-0.954) = 0.38}$ and $\mathbf{exp(-1.138) = 0.32}$ $\mathbf{exp(-0.619) = 0.53, exp(-0.699) = 0.49, exp(-0.521) = 0.59}$ respectively.

From the **Table 3** and **4**, it can be seen that covariates MECH-V and ENV-CON have a statistically significant influence on the hazard rate of the WM-I and WM-II electric, pneumatic and hydraulic sub-systems. The covariates such as OP and MP appears to have significant influence mainly on the hazard rate of the WM-II sub-systems. The result of the analysis has shown that reliability performance of the PSW machine significantly dependent on the mechanical stresses and environmental condition which accelerate the failure rate and degradation of the machines technical performance. Therefore, engineers and maintenance workers should control vibration parameters of the machine and eliminate harmful influence of the environmental factors.

After obtaining significant covariates and their regression coefficients, the next step is to estimate baseline hazard rate $\boldsymbol{\lambda_0(t)}$. The two-parameter Weibull distribution is selected in this research to estimate baseline hazard rate of the PSW machines sub-systems. To examine the adequacy of selected distribution as a model for the failure data, the least squares method (LSM) is used [5][6]. This method calculates the best-fitting regression line for the failure data by minimizing the sum of squared residuals. For example, **Figure 1** shows the Weibull probability plot of the WM- I electrical sub-system failure data. The data points follows the straight line, which suggest that the failure data follow Weibull distribution. The LSM regression analysis has shown an approximately straight line for all WM- I and WM-II sub-systems TBF data. Thus, it can be concluded that the Weibull distribution is an appropriate choice for modelling hazard rate. The estimated parameters $\boldsymbol{\beta}$ and η for each WM- I and WM-II sub-systems are shown in **Table 3 and 4**. Using corresponding parameters from **Table 4** and Equation, the baseline hazard rate of the WM- I electrical, pneumatic and hydraulic sub-systems can be estimated as

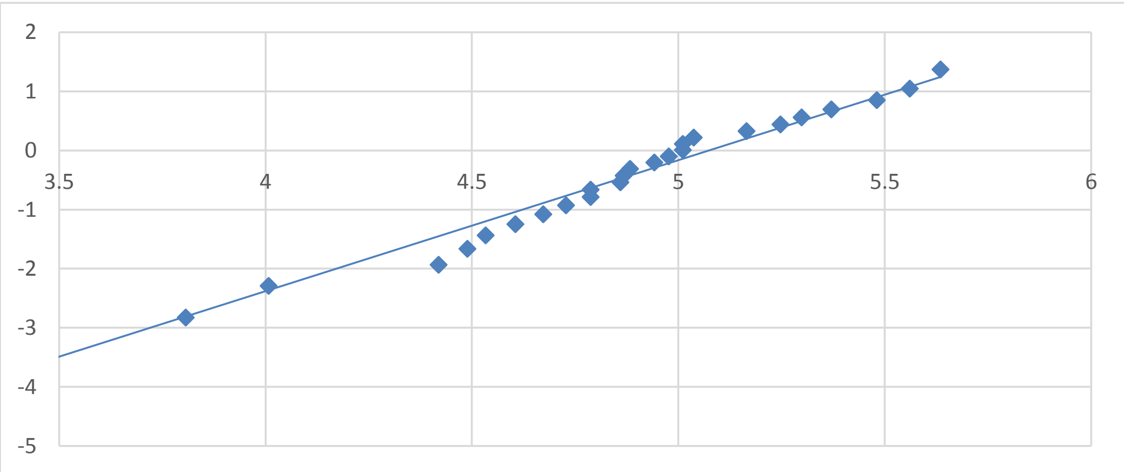

Figure 1: The Weibull plot of the WM- I electrical sub-systems TBF data

$$\boldsymbol{\lambda(t,z) = \frac{2.4}{166}\left(\frac{t}{166}\right)^{2.4-1} \exp \times (-1.078OMECHV - 0.954ENVCON)} \quad (1)$$

$$\boldsymbol{\lambda(t,z) = \frac{2.23}{78.47}\left(\frac{t}{78.47}\right)^{2.23-1} \exp \times (-0.602ENVCON - 0.441MECHV)} \quad (2)$$

$$\boldsymbol{\lambda(t,z) = \frac{1.71}{38.3}\left(\frac{t}{38.3}\right)^{1.71-1} \exp \times (-1.216ENVCON - 0.518MECHV - 0.614OP)} \quad (3)$$

Using parameters from **Table 4-4** and Equation (1) the baseline hazard rate of the WM-II electrical, pneumatic and hydraulic sub-systems is estimated as

$$\lambda(t,z) = \frac{2.85}{139.7}\left(\frac{t}{139.7}\right)^{2.85-1} \exp \times (-1.138MECHV - 0.619ENVCON - 0.699MP - 0.521OP) \quad (4)$$

$$\lambda(t,z) = \frac{2.23}{42.8}\left(\frac{t}{42.8}\right)^{2.23-1} \exp \times (-0.710ENVCON - 0.581MECHV) \quad (5)$$

$$\lambda(t,z) = \frac{1.79}{22.8}\left(\frac{t}{22.8}\right)^{1.79-1} \exp \times (-1.323ENVCON - 0.447MECHV - 0.423MP - 0.271OP) \quad (6)$$

CONCLUSION

The reliability of the PSW machine and its sub-systems can be improved by establishing appropriate maintenance planning system. Proposed reliability-based PHM application can plan maintenance intervals using the derived PHM reliability plots, which can optimize the level of reliability of the machine and estimate the optimal periodic maintenance intervals for machine sub-systems. For example, by using reliability plots **1**, and **4-7** maintenance intervals for the different reliability levels for WM- I electric sub-systems, is calculated and presented in **Table 5**. In order to estimate the optimal maintenance interval, the criticality of the PSW machines failures in the automobile industry is taken into account and 90% level of the reliability is suggested. From **Table 5,** to achieve 90% reliability for an electric sub-system of welding machine, the preventive inspection must be performed after every 70 hours operation. For pneumatic sub-system, 90% reliability can be achieved if inspection is carried out after 25h or almost after 4 shift operations. The interval for the hydraulic system is 15h or after 2 shift operation.

Table 5

Level of reliability	90%	80%	70%
Electric sub-system (h)	70	100	150
Pneumatic sub-system (h)	25	40	65
Hydraulic sub-system (h)	15	25	35

OUTPUT

1. A new algorithm has been developed for predicting the reliability of failures of welding equipment components and the accuracy of prediction has been improved using equipment monitoring data.
2. The nature of failures of machine components, types of failures and frequency are determined.
3. Various factors affecting the reliability of equipment have been studied, where the environmental factor is given special attention as the most significant.
4. A model based on the PHM (proportional hazard model) statistical method has been developed to analyze critical equipment components and determine the frequency of maintenance.

GENERAL CONCLUSIONS.

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