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An Application on Estimation of Machine Failure Times in Cement Production Process

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Abstract

This study aims at developing a model that would enable us to predict the failure times of machines in cement manufacturing process. The knowledge of machine failures is very vital in maintenance of machines in order to enhance production and minimize on costs of maintenance. In this context, Weibull distribution, Least Squares (LS) method and Maximum Likelihood Estimation (MLE) method are applied to assess failure distributions. 167 machine failure data were used in this study and analyzed with Minitab software. It was concluded that the failure times follow Weibull distribution and the LS and MLE methods were used to estimate the parameters of the distribution in order to check the fitness. Thus, applying LS method, it is possible to get $\beta = 2.07$ and $\eta = 971.7$, while applying MLE method, results obtain as $\beta = 2.17$ and $\eta = 966$. It was noted that these values are rather close and both methods gave almost the same results.

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1 INTRODUCTION

The cement production process is one of the most exemplary production systems as it depends on the of proper the functioning machinery to ensure efficiency and control the costs. This process is complex and it includes several steps such as extraction and grinding of raw materials, clinker production and cement batching. All these stages involve the use of equipment that is interdependent and any failure of any of the equipment can cause a slow down of the whole process thus affecting quality of the product. Failure of a single machine in this system can have a domino effect and may lead to shutdown of the entire production line and extremely high financial losses.

Since cement industry cannot afford any interruption in operation, it is crucial to know machine failure times. Predictive maintenance which is based on the accurate failure time estimation enables plant managers to plan for the maintenance activities before the actual need arises thus avoiding the unexpected down time and effective resource management. These predictions can be made using various data such as past maintenance record, real time sensor data. This paper aims at presenting how such predictive maintenance strategies can help to reduce manufacturers costs associated with maintenance works, increase overall equipment effectiveness, increase machine's lifetime, and therefore increase sustainability and competitiveness of cement manufacturing in an energy intensive industry.

The study applies the Weibull distribution, Least Squares (LS) method, and Maximum Likelihood Estimation (MLE) method for analyzing machine failure times in cement production. The following statistical techniques are used on a dataset of 167 machine failures with the help of Minitab software for data analysis. This is because Weibull distribution is very flexible and can be used to model a wide variety of failure distributions in reliability engineering and failure analysis. Thus, analyzing the failure data with this distribution, the researchers will be able to understand the causes of failures and make better predictions of future failures.

Therefore, the application of both LS and MLE methods ensures that the parameter estimation is done accurately and consistently, thus enabling a comparison of the results obtained. The findings of the study consist of identifying probability distributions for both failure and maintenance times which are very vital in the development of maintenance strategies. These findings along with certain suggestions provide beneficial recommendations for the cement production companies for enhancing their maintenance policies. Through the implementation of these data-driven strategies, companies can be able to minimize on downtime, increase equipment reliability and hence increase efficiency in the cement production process [1].

2 LITERATURE REVIEW

When the literature is examined, it is seen that there are various studies about Weibull distribution and the current issue. Aljeddani and Mohammed suggest an improved method for estimating wind speed with the help of Weibull distribution. The authors have developed new modified maximum likelihood (MML) techniques, energy pattern factor and method of moment (MOM) for enhancing parameter estimation. The study also emphasizes on the importance of proper wind energy prediction as is one of the vital components of renewable energy integration. The proposed method provides more accurate and effective estimates as compared to the conventional methods for estimating the parameters thereby supporting the right decision making on the investment in wind energy projects [2].

In the study by Kamberi et al., the performance of the parameter estimation methods for the three distributions namely the Weibull, Weibull-Rayleigh and Exponentiated Weibull is assessed. The authors employ MLE and implement it with real data in R language. The study determines the best estimators of these distributions and the capabilities of MLE in giving the most efficient and accurate estimations of parameters. Also, the practical utilization of the three-parameter Weibull distribution is underscored in various disciplines including engineering and natural sciences [3].

In the work of Atamer and Çavdar, a single-stage cylindrical gear mechanism is assessed for its reliability with the help of failure data. They use a simplified FMEA and a block diagram for the identification of system reliability structure. Failure data is estimated with the help of available historical data and Maximum Likelihood Estimation (MLE) is applied for parameter estimation using MATLAB function "wblfit". The study also provides an analysis of the system reliability enhancements and how the failure modes can be identified and the measures that can be taken to improve the system reliability as well [4].

Alkan et al. wants to estimate the diameter distribution of oriental beech stands in the Almus area and then use Weibull distribution for this purpose. In this study two estimation methods are applied namely Seemingly Unrelated Regression (SUR) and Modified Cumulative Distribution Function Regression (MCDF). In this study, four different methods of parameter estimation are used and the findings indicate that the MCDF method outperforms the SUR method. The hybrid method is also determined to be the most effective method in parameter estimation. This work has its application in the domain of sustainable forest management and the planning of forestry resources [5].

Yanıktepe and Kara estimate the wind energy potential with three different statistical distribution methods, namely Graphical Method (GM), Maximum Likelihood Estimation (MLE Method), and Modified Maximum Likelihood Method (MMLM). The wind speed data are collected at the roof of Osmaniye Korkut Ata University and the data are examined in the present research. According to the GM method the best fit is achieved with an R^2 of 0.9409 and this is better than the MLE and MMLM methods. The findings of this study are useful in the determination of the wind energy potential and hence enhance the wind energy planning [6].

Oral evaluates the wind energy potential of Bitlis Province using wind data recorded at every ten minutes interval. To analyse the data, Weibull distribution is used and the average wind speed and power density are computed from the measured and estimated data. The study also shows that the Weibull distribution adequately estimates the data with an annual average wind speed and power density of 3.26m/s and 49.77 W/m² respectively. This study also reveals the potential of wind energy generation in Bitlis and the efficiency of Weibull distribution in energy planning [7].

Bingöl and Bulut use Weibull distribution parameters to analyze the wind energy potential and features of the Dinar region in Turkey. Wind data used in the study are collected from the year 2015 to 2020 and six different methods for parameter estimation are used such as moment, graphical, Justus empirical, energy trend, energy pattern and MLE methods. The most reliable methods for the determination of the parameters are the MLE and energy trend methods. This paper gives important information about the wind energy potential and the turbine characteristics for the Dinar region [8].

Shu and Jesson study the wind speed characteristics in the UK during the period 1981-2018 distribution with is the employed help for of the 38 analysis observation of stations' wind data. Differences in wind speed scale parameters are noticed from one site to another with values of 4.96 m/s to 12.06 m/s. The results also show that there are distinguishable variations in the wind potential across the UK which substantiates the need to have strategic placement of wind energy projects and the use of regional wind power density assessment [9].

Hussain et al. have tried to determine the possibility of applying wind power density in four coastal areas of Pakistan namely Jiwani, Gwadar, Pasni and Ormara and to estimate the Weibull shape and scale parameters using eight numerical methods. These methods include the empirical, graphical and MLE method. The efficiency of these methods was evaluated and compared with each other by the analysis of variance (R^2), root mean square error (RMSE), and chi-square (X^2). Based on the results, energy trend and graphical methods provided low performance while it was concluded that Ormara is the best location for wind power generation. The paper presents a review of the most effective methods for determining the wind power density and, therefore, will be useful for future wind energy projects in the coastal areas of Pakistan [10].

Yalçınkaya and Birgören considered a problem of how to establish lower confidence bounds for Weibull lower percentiles or A-basis and B-basis material properties which are very vital in identification of failure prone parts and minimization of risk in material reliability analysis. Since testing of materials is expensive, it is done only to a certain extent and hence the parameter estimation is not very precise. The authors compared the following estimation methods namely, MLE method, Menon's method and Weighted/Unweighted LS methods. Their Monte Carlo simulations showed that for small sample size ($n < 20$) MLE method provided more accurate results as compared to other methods. The authors also stressed that the LS methods provide convenient computations if the differences in performance are not crucial [11].

In the study conducted by Zeytinoğlu, the different statistical estimation techniques for the parameters of Weibull distribution, which is one of the most frequently applied distribution in lifetime and failure rate analysis, are examined. There are four main methods which are discussed in the paper: graphical method, LS method, MLE method and moment method. The effectiveness of each method in estimating the scale and shape factors of Weibull distribution is evaluated with the help of lifetime data of a material used in a photocopier printing unit. The results of the comparison show how these methods compare and perform and such findings can be useful to those who are implementing them in engineering and reliability analysis [12].

This paper by Doğanşahin, Uslu, and Kekezoğlu offers a detailed review of wind speed distributions and applies a two component Weibull model to address the uncertainties pertaining to wind energy conversion. Wind speed and power output data of a wind energy plant are examined and different techniques for estimating parameters of probability density function are used. It was observed that the two component Weibull distribution better described the variability of wind speed than the single component Weibull distributions. The authors state that the two-component Weibull model is more effective in the estimation of wind energy potential and for a better comparison with the actual plant data [13].

In the paper by Danacı, Birgören, and Ersöz, the authors present a structure for determining Weibull distribution parameters and percentiles with emphasis on the cases when the sample size is limited. The paper puts forward methods for determining the point and interval estimates of Weibull parameters with the help of the MLE method and weighted LS methods. The following algorithms are written in the C++ and all the outputs are coupled with the graphical user interface that enables the user to calculate the point estimates and confidence intervals for any sample size, confidence failure level probability. Unlike other works that employed rigid parameter sets, the current approach allows for more flexibility and improved accuracy for the small sample size, which is quite important in reliability analysis and material testing [14].

Seal and Sherry discuss the behaviour of brittle failure in ferritic steels and how the probability of failure in the transition region between brittle and ductile fracture can be estimated using Weibull distribution. The Weibull stress approach based on the two-parameter Weibull distribution shows that the Weibull modulus does not change in the lower transition region but when the temperature approaches the upper transition region it becomes less constant. This shift is due to growth of the zone plastic ahead of a defect which leads to trial of more number of potential failure sites along with increased possibility of blunting and subsequent ductile tearing. The authors also discuss the relevance of these findings with relation to fracture toughness and the creation of models for brittle failure [15].

3 METHODS

In this section, the Weibull distribution, LS method and MLE method used in this study are explained in detail. This chapter presents the analysis tools and techniques that are employed for the prediction of failure in the context of maintenance planning.

3.1 Weibull distribution

The Weibull distribution is one of the most popular distributions which are employed life data in reliability modeling. Due to the ability of its and parameters to change, it can easily fit many data sets of different types. If it is a random variable which is distributed following Weibull distribution then the probability density function of the distribution can be written as:

$$f(t;\beta,\eta) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-(t/\eta)^{\beta}}, \quad t > 0 \tag{1}$$

The cumulative distribution function of the distribution is given by:

$$F(t;\beta,\eta) = 1 - e^{-(t/\eta)^{\beta}} \tag{2}$$

The shape parameter (β) of the Weibull distribution controls the appearance of the distribution graph. When β = 1, then the distribution is said to be an exponential distribution. If $\beta > 1$ then the failure rate increases with time and if $\beta < 1$ then a decreasing failure rate is noted. The scale parameter (η) is the characteristic lifetime of the distribution and it is the size or scale of the data set in question. In this research these two parameters of Weibull distribution will be estimated from the failure times data set that will be obtained [1].

3.2 Least squares method

The LS method is one of the most popular and straightforward methods of parameter estimation. For the Weibull distribution, LS estimates are often based on distributional transformations. The parameter estimation process can be summarized as follows:

1. Failure times data are sorted. (t_1, t_2, …., t_n)

2. The empirical cumulative distribution function is computed for each event.

3. Starting from the transformation based on the cumulative distribution function of the Weibull distribution, a linear relationship of the form $\ln(-\ln(1-F_i))=\beta\ln(t_i)-\beta\ln(\eta)$ is obtained.

4. A linear regression model is then constructed based on the y-axis ($\ln(-\ln(1-F_i))$) and x-axis ($\ln(t_i)$) in this linear form.

5. Coefficients of this linear model are estimated using the LS method and thus parameters β and η are obtained. Here, the slope is equal to β and the intercept is -βln(η).

6. Thus, the parameters β and η are estimated by the LS approach.

Due to the fact that the LS method is easy to implement and can be accompanied by graphical representations, it is more appropriate to use it. However, there is a possibility that the estimation results may be biased if there are outliers in the data distribution.

3.3 Maximum likelihood estimation method

The MLE method is one of the most common statistical techniques used in parameter estimation and produces efficient estimators that are consistent. This method is based on the search of parameters that make the occurrence of the observed data set possible.

Considering the probability density function for Weibull distribution, likelihood function for data $t_1, t_2, \ldots, t_n$ is given by:

$$L(\beta,\eta)=\prod_{i=1}^{n} f(t_i;\beta,\eta)=\prod_{i=1}^{n}\frac{\beta}{\eta}\left(\frac{t_i}{\eta}\right)^{\beta-1} e^{-(t_i/\eta)^{\beta}} \quad (3)$$

Taking natural logarithm of this function results in the log-likelihood function as follows:

$$\ln L(\beta,\eta)=n\ln(\beta)-n\ln(\eta)+(\beta-1)\sum_{i=1}^{n} ln(t_i)-\sum_{i=1}^{n}\left(\frac{t_i}{\eta}\right)^{\beta} \quad (4)$$

For parameter estimation, partial derivatives are taken and the equations obtained by setting these derivatives equal to zero are solved:

$$[\frac{\partial \ln L}{\partial\beta}=\frac{n}{\beta}+\sum_{i=1}^{n} ln(t_i)-\sum_{i=1}^{n}\left(\frac{t_i}{\eta}\right)^{\beta}\ln\left(\frac{t_i}{\eta}\right)=0] \quad (5)$$

$$[\frac{\partial \ln L}{\partial\eta}=-\frac{n}{\eta}+\frac{\beta}{\eta}\sum_{i=1}^{n}\left(\frac{t_i}{\eta}\right)^{\beta}=0] \quad (6)$$

These equations can’t be solved mathematically and thus numerical approaches such as the Newton-Raphson method is used to estimate the parameters β and η. Although the MLE method is regarded as one of the most statistical reliable methods there are some computational problems may occur. However, due to the development of computer facilities, these problems can be easily solved.

4 RESULTS AND DISCUSSION

In the cement factory considered in this study, the past failure records of the machines in a specific production line are analyzed. The data set obtained includes the downtime that was recorded during some time period and every failure is logged. The data set used in the present study was collected from the previous maintenance records of the above mentioned critical machines in the production line, which include grinding mill, cement kiln, conveyor belts, mixer for raw material mixing etc.

At this point, the downtimes of these machines were modeled with a Weibull distribution. Both LS and MLE approaches were employed in order to identify the shape parameter (β) and scale parameter (η) of the distribution based on the data collected. Checking the data in a linear form on logarithmic axes made it possible to check the data conformity to the Weibull distribution visually. The machine failure data used in the study are given in Table 1.

Table 1. Machine failure data [1]

No	Data	No	Data	No	Data	No	Data	No	Data	No	Data
1	140	29	351	57	630	85	774	113	546	141	1400
2	902	30	738	58	808	86	1150	114	1407	142	512
3	539	31	493	59	1103	87	577	115	1058	143	420
4	1113	32	1117	60	1031	88	474	116	1234	144	836
5	1968	33	1638	61	1448	89	1528	117	1046	145	542
6	918	34	1099	62	825	90	1004	118	564	146	661
7	807	35	1425	63	1151	91	243	119	1568	147	1607
8	1423	36	700	64	697	92	474	120	888	148	487
9	1340	37	1090	65	618	93	330	121	1200	149	1259
10	883	38	1311	66	304	94	829	122	969	150	150
11	1294	39	469	67	1338	95	1284	123	850	151	397
12	1223	40	1100	68	760	96	1329	124	931	152	1538
13	450	41	660	69	546	97	473	125	771	153	946
14	410	42	1901	70	844	98	861	126	235	154	983
15	1678	43	1756	71	544	99	487	127	967	155	973
16	37	44	878	72	1130	100	724	128	238	156	993
17	914	45	833	73	901	101	571	129	856	157	579
18	1216	46	395	74	667	102	1322	130	1282	158	1090
19	337	47	593	75	1033	103	614	131	459	159	371
20	248	48	934	76	708	104	938	132	546	160	595
21	687	49	395	77	1278	105	661	133	730	161	890
22	1209	50	987	78	1006	106	474	134	1209	162	1258
23	497	51	1778	79	492	107	1400	135	858	163	804
24	1148	52	762	80	1320	108	229	136	358	164	464
25	78	53	729	81	1910	109	199	137	1131	165	432
26	571	54	1095	82	292	110	672	138	467	166	335
27	1055	55	1235	83	1271	111	677	139	299	167	506
28	1946	56	483	84	765	112	1027	140	529	168	

Some of the illustrations of the findings are presented as Figure 1 and Figure 2 as shown below. These figures depict the Weibull model fits made with the LS and MLE of the parameters.

When the estimation results are analyzed, weibull distribution parameters are found to be β=2.07 η=971.7 according to the LS method and β=2.17 η=966 according to the MLE method. When we look at the Anderson Darling test statistic values, it is seen that these values are smaller than the critical value for both methods. This means that the current data set conforms to the weibull distribution with the calculated parameter values. Since the Anderson Darling test statistic value is smaller in the LS method, the parameter values calculated with this method are determined as the parameter values of the weibull distribution for the available data.

5 CONCLUSION

The aim of this research work is to develop a model of machine failures in the cement production process using the Weibull distribution, to estimate the distribution parameters of failures with LS and MLE methods and to analyze the obtained results. In the study, the failure times data collected from a certain production line in a cement factory are investigated and the shape parameter (β) and scale parameter (η) of Weibull distribution are estimated.

The outcomes of the study have implications for maintenance and reliability engineering functions in the cement sector. The Weibull plot is a method that provides a guide for determining the appropriate maintenance strategy, spare parts and materials requirements and the size of the workforce. In addition, knowing the variations in failure rate of a machine at different stages of its lifecycle will ensure the encouragement of the shift from preventive to predictive maintenance.

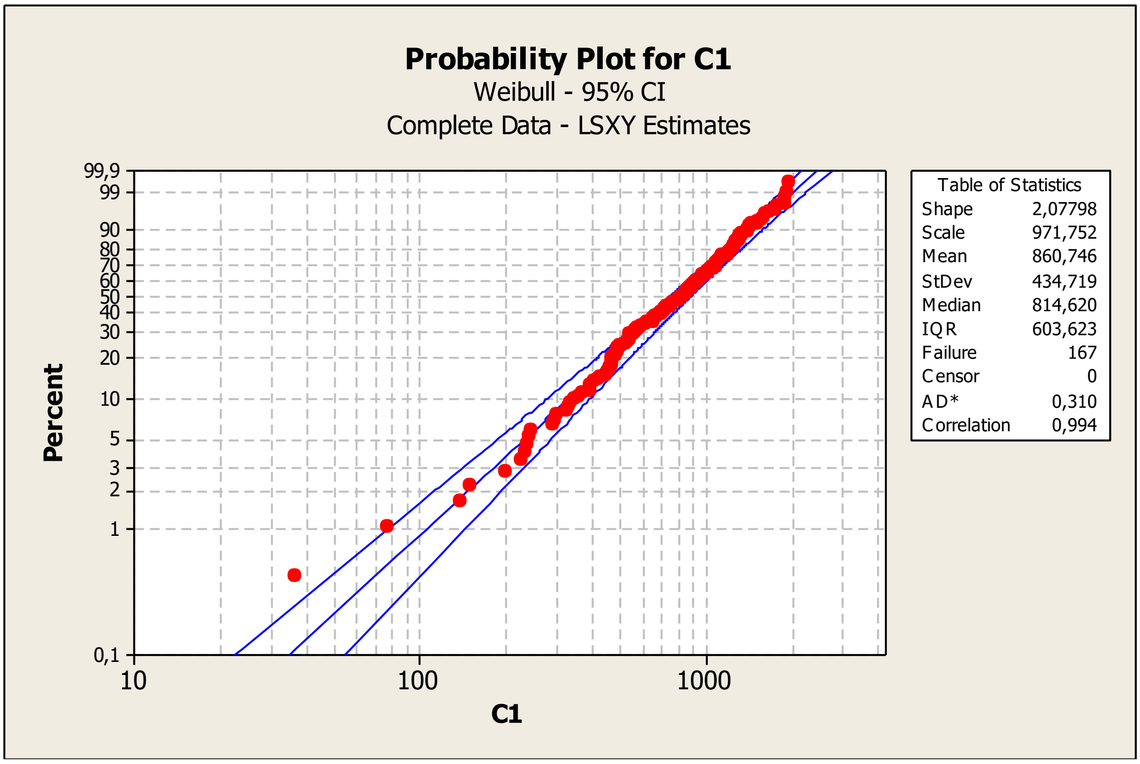

Figure 1. Parameter estimation by LS method

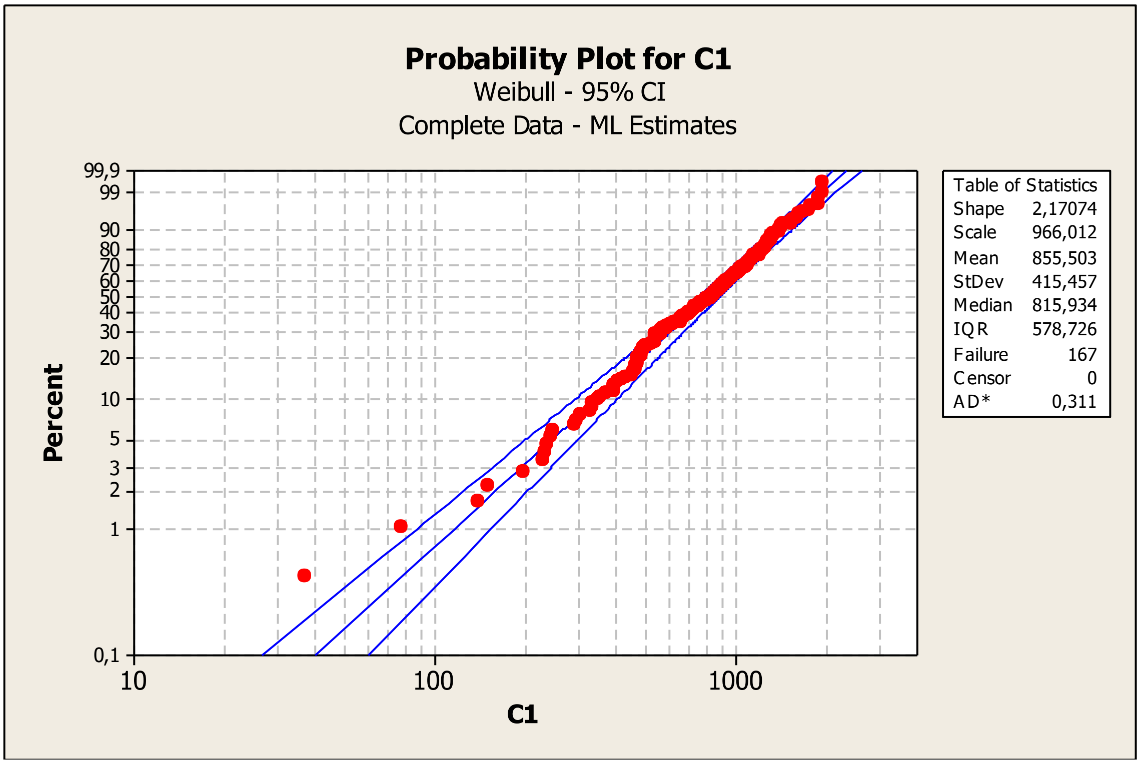

Figure 2. Parameter estimation by MLE method

Author Contributions

Çağatay TEKE: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - Original Draft, Writing - Review & Editing
Mümtaz İPEK: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing - Original Draft, Writing - Review & Editing

All authors read and approved the final manuscript.

Conflict of interest

No conflict of interest was declared by the authors.

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