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Application of Weibull Distribution Method for Aircraft Component Life Estimation in Civil Aviation Sector

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Abstract—**The continuous monitoring of fleet reliability has been made compulsory by the aviation authorities, due to the maintenance program for civil aviation aircrafts has been prepared on MSG-3 philosophy. In this context, task card and maintenance intervals must be set according to the reliability of aircraft components and systems. Approximately 90 percent of the maintenance programs prepared according to the MSG-3 philosophy contain task cards for finding defects or faults, and these do not have a relevant use in the absence of a defect or fault. In this study, reliability of the aircraft parts is estimated according to the Weibull distribution by using maintenance data, and the probability of failure for each part is calculated.**

Index Terms—**weibull, weibull analysis, civil avation, MSG-3, reliability analysis, life data analysis**

I. INTRODUCTION

With the advancements in the science and technology, the capabilities of the modern equipment increased substantially. Along with the increase in capabilities, increased complexity of equipment or subsystems of equipment pose problems for maintainability. Due to the ever changing market conditions, several industries require increasingly cost efficient measures. As the maintenance and support get more and more complex, optimization of maintenance and support get even more important.

Cost efficiency is critical for an airline's ability to compete and survive. Low cost operation is very important issue for airlines within today's competitive airline industry. In the commercial aviation industry, maintenance costs are responsible for 10 percent of the total operating costs. For a given flight network and fleet, it is either out of control of airlines to reduce costs in areas such as fuel and oil costs, or not much room is left for reducing labor and distribution costs [1]. As the average net profit margin of the airline industry is about 5 percent [2], cost efficiency is critical for an airline's ability to compete and survive. Therefore, reducing the maintenance cost is essential for the sustainability and growth of an airline.

In the aircraft industry, maintenance activities are essential part of airworthiness. The purpose of maintenance is to restore an item to a serviceable condition. It consists of servicing, repair, modification, overhaul, inspection and determination of condition [3].

Maintenance can be broadly categorized into four types. These are corrective maintenance, preventive maintenance, predictive maintenance, and condition-based maintenance.

In corrective maintenance, actions are only performed when a break-down occurs. It is also known as unscheduled maintenance [3], [4]. Although it eases the burden of constant monitoring in some cases, it increases the critical risks during operation, which may result in dangerous outcomes.

In preventive maintenance, actions are performed at defined intervals. It is also known as scheduled maintenance. This type of maintenance is closely related to the expected wear-out time of components [3], [4]. Although regular inspection and maintenance in set intervals decrease the risk of break-out during operation when compared to corrective maintenance, it doesn't take unexpected break-outs into consideration.

In predictive maintenance, statistical methods are used for estimation of life of components and systems. Acquired data after the operation is used for predicting the condition of components [4]. Although, required maintenance intervals can be predicted beforehand, there is no real-time analysis.

In condition-based maintenance, component and system performance are monitored in real-time. An abnormal situation can be predicted beforehand, and necessary actions can be taken [3]. However, in terms of data acquisition and constant monitoring systems, as well as labor requirements, it adds extra complexity and cost to the system, and may not be feasible for simple use scenarios.

Life estimation of components are one of the building blocks of maintenance. These can be given as in

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preventive maintenance, or can be calculated by using statistical methods as in predictive maintenance. Weibull distribution is a continuous probability distribution. Developed by Waloddi Weibull, the distribution is used in several areas such as wind speed distribution [5], insurance analysis [6], and reliability analysis. It can model a wide diversity of hazard rates, and can be approximated to other types of distributions under special conditions [7].

This paper is about the application of Weibull distribution to component life analysis in the airline industry, and will give a brief information about the project done with THY Technic.

II. UNDERSTANDING MSG-3

Airlines for America (A4A), formerly Air Transport Association of Americal (ATA) is an American organization that helps shaping policies and measures about safety, security, and health of the U.S. airline industry. The document MSG-3 (Maintenance Steering Group) 'Operator/Manufacturer Scheduled Maintenance Development' prepared by A4A develops a framework for scheduled maintenance tasks and intervals. These scheduled maintenance tasks and intervals are developed in tandem with operators, manufacturers, and the regulatory authorities. As non-scheduled maintenance is not covered in this document, it can be seen as a guideline for preventive maintenance [8]. As this guideline is also used in Turkey, it leaves an opportunity to increase maintenance procedures.

III. WEIBULL DISTRIBUTION

Cumulative distribution function of the three parameter Weibull distribution can be written as follows:

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

where t is time, η is the characteristic life or scale parameter, β is the Weibull slope or shape parameter, and γ is the location or time delay parameter. When $t - \gamma = \eta$, 63.2 % of the product population will fail irrespective of the value of β.

Probability density function of a three parameter Weibull distribution can be written as follows:

$$f(t) = \beta\eta^{-\beta}(t-\gamma)^{\beta-1}e^{-((t-\gamma)/\eta)^{\beta}} \tag{2}$$

When $\gamma = 0$, Weibull distribution becomes a two-parameter Weibull distribution. For component life estimation in this paper, two parameter Weibull distribution is used.

A. Parameter Estimation

For doing a life analysis, parameters η and β must be estimated using failure data. In a simple data, for each component, there is a time to failure or time to suspension. Depending on the problem, different metrics can be used for time, such as total rev count for a motor, or flight count for landing gear components.

Not all of the components are changed due to failure. Some components are changed due to the recommended replacement time, or are still in operation. These components are suspended items, because their time to failure is not known, however it is known that they didn't fail for a specified time. It is logical that they effect life estimation of components.

For estimation of parameters, cumulative distribution function can be rearranged by the steps given below [9]:

$$F(t) = 1 - e^{-((t)/\eta)^{\beta}} \tag{3}$$

$$\frac{1}{1-F(t)} = e^{-(t/\eta)^{\beta}} \tag{4}$$

$$ln\left(\frac{1}{1-F(t)}\right) = \left(\frac{t}{\eta}\right)^{\beta} \tag{5}$$

$$ln\left(ln\left(\frac{1}{1-F(t)}\right)\right) = \beta ln(t) - \beta ln(\eta) \tag{6}$$

The equation is similar to equation $Y = AX + B$, where $Y = ln\left(ln\left(\frac{1}{1-F(t)}\right)\right)$, $X = ln(t)$, $A = \beta$, and $B = \beta ln(\eta)$.

For finding the estimation of the parameters, median ranks of the failed components should be calculated. The procedure will be shown by using a sample, which is a box control component, with part number 0006648-801.

TABLE I. TABLE OF THE PN NUMBER INSTALLATION HOURS

	AIRCRAFT PART SAMPLE DATA		
#	***PN***	***SCHEDULE CATEGORY***	***HOURS***
1	0006648-801	FAILURE	1187
2	0006648-801	FAILURE	1222
3	0006648-801	FAILURE	5436
4	0006648-801	FAILURE	6077
5	0006648-801	FAILURE	6298
6	0006648-801	SUSPENSION	9840
7	0006648-801	FAILURE	14180
8	0006648-801	FAILURE	14737
9	0006648-801	FAILURE	16054
10	0006648-801	FAILURE	21771
11	0006648-801	FAILURE	27297
12	0006648-801	FAILURE	35229
13	0006648-801	FAILURE	40238
14	0006648-801	SUSPENSION	47062
15	0006648-801	SUSPENSION	54785
16	0006648-801	FAILURE	57838
17	0006648-801	SUSPENSION	58349
18	0006648-801	FAILURE	62333

For finding the median ranks of the components in the presence of suspended data, the given approach can be used.

First, data is sorted from minimum to maximum with respect to failure/suspension time. Then, let M be the number of failed components, and N be the number of all components. Then, from the sorted list, rank increment for each failed component can be found by the given formula:

$$RI_m = \frac{(N+1) - AR_{m-1}}{2 + N - n} \tag{7}$$

where RI and AR are the rank increment and the adjusted rank of m^th failed component respectively, with $AR_1 = 0$. Adjusted rank can be found for each failed component by the given formula:

$$AR_m = RI_m + AR_{m-1} \tag{8}$$

Median ranks (MR) for failed components can be found by the given formula:

$$MR_m = \frac{AR_m - 0.3}{N + 0.4} \tag{9}$$

TABLE II. MEDIAN RANKS

#	***SCHEDULE CATEGORY***	***HOURS***	***MEDIAN RANK***
1	FAILURE	1187	0.0714
2	FAILURE	1222	0.1429
3	FAILURE	5436	0.2143
4	FAILURE	6077	0.2857
5	FAILURE	6298	0.3571
6	SUSPENSION	9840	-
7	FAILURE	14180	0.4286
8	FAILURE	14737	0.5000
9	FAILURE	16054	0.5714
10	FAILURE	21771	0.6429
11	FAILURE	27297	0.7143
12	FAILURE	35229	0.7857
13	FAILURE	40238	0.8571
14	SUSPENSION	47062	-
15	SUSPENSION	54785	-
16	FAILURE	57838	0.9286
17	SUSPENSION	58349	-
18	FAILURE	62333	1.0000

When these values given at Table II are put into the $Y = AX + B$, by using the median ranks for $F(t)$, an overdetermined system of equations can be created. Values of A and B can be found by using methods such as linear least squares method. Then, corresponding β and η values can be calculated. They are $\beta = 0.8686$ and $\eta = 12024.5503$ in this particular case.

B. Confidence Intervals and Confidence Bounds

Confidence interval is a type of interval estimation of a parameter or parameters in a statistical distribution. It is a function of confidence level and distribution parameters. Confidence level is determined by end user, and not by the data itself, and requires a know-how and intuition about the process. For example, for a given confidence level of 95%, one can say that different samples have a distribution that will fall between the confidence intervals 95% of the time [10].

For given β and η values, confidence intervals can be calculated using the procedure below:

$$u = \beta\big(ln(t) - ln(\eta)\big) \tag{10}$$

$$Var(u) = [1.168 + 1.10u^2 - 0.1913u]/N \tag{11}$$

$$u_1 = u - Z_{n/2}\sqrt{Var(u)} \tag{12}$$

$$u_2 = u + Z_{n/2}\sqrt{Var(u)} \tag{13}$$

$$1 - exp(-e^{u_1}) \leq F(t) \leq 1 - exp(-e^{u_2}) \tag{14}$$

$Z_{n/2}$ is the Z score for the standard normal distribution, and Z scores for commonly used confidence levels are given in Table III.

TABLE III. Z SCORES FOR DIFFERENT CINFIDENCE LEVELS

CONFIDENCE LEVEL	***Z score***
99%	2.58
98%	2.33
95%	1.96
90%	1.645

C. Interpretation of Parameters

In a two parameter Weibull distribution, β and η values can give insight about failure states of a component.

Hazard rate is defined as the rate of failure at time t, which can be formulated as follows:

$$h(t) = \frac{f(t)}{1 - F(t)} \tag{15}$$

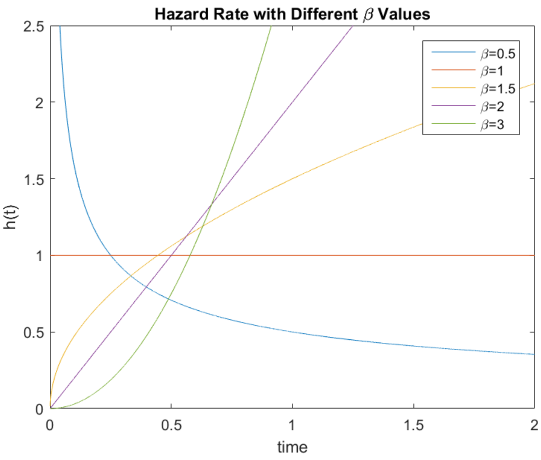

Figure 1.1. Hazard rate function

β value determine the shape, and can be classified for three types of failures.

$\beta < 1$ means infant mortality, and it may be a result of things such as presence of de`fective components or poorly designed components for a given working condition. They are highly undesired types of failures, and requires a change in design, assembly, or quality control.

$\beta = 1$ means random failures, and they can happen anytime during the lifetime of a component, such as random bad landings for landing gear components.

$\beta > 1$ means wear-outs, and it helps in determining the expected life of a component.

For a component or a system, infant mortalities and random failures are not desired, and failures because of wear-out are desired. Although, β with high values are desired, one must become suspicious when β gets bigger than 6, as it means a sudden increase in breakdowns after a period of time, such as human mortality [11].

IV. APPLICATION TO AIRLINE MANAGEMENT INFORMATION SYSTEM

Weibull distribution is important in the fields such as aerospace industry, because of the increased risk with the failures, competitive environment that also effect design and maintenance of components and systems, and relative lack of samples compared to other industries such as automotive industry.

There are several software for reliability life data analysis, such as Weibull++ from ReliaSoft [12]. However, for easy access, easy maintenance and support, and custom requirements of THY Technic, a new web application is created, and will be actively developed. This web app is able to connect to Airline's Management Information System, and is able to directly put the results to the user without additional steps such as downloading and loading a file.

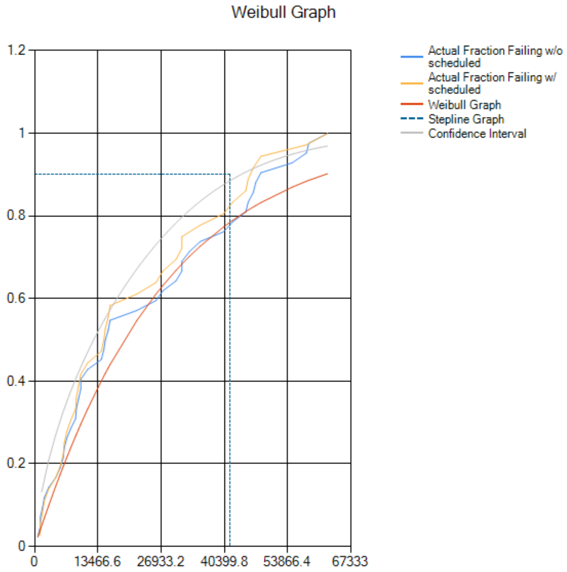

Figure 1.2 Cumulative distribution function for part 0006648-801.

In Fig. 1.2, cumulative distribution function for part 0006648-801 can be seen. Confidence level is chosen as 95%, and desired reliability is given as 85%. As found in the third section of this paper, this part has $\beta = 1.0234$, and $\eta = 27309.9195$. It means random failures for this component are potential problems, and the reasons for that must be investigated. The chosen confidence level is satisfying for this case, as most of the actual data are under the upper confidence bound.

By using the result of this analysis, one is able to have an oversight about potential problems about the part. The results can also be used for predicting required inventory after future flight data is added to the program.

In Fig 1.3, actual interface of the program can be seen.

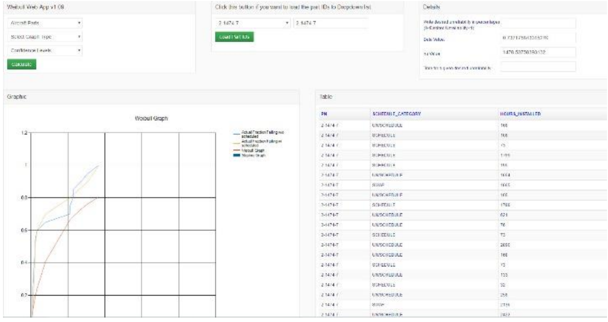

Figure 1.3 Weibull analysis program interface.

V. CONCLUSION

In this paper, a web based program to be used by Turkish Technic is explained. With this program, users will be able to predict the life of components, and can take necessary measurements according to results.

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