The Effects of Aircraft Preventive Maintenance on Reliability

E. Kiyak

***Abstract*—**Preventive maintenance can be described as maintenance of equipment or systems before fault occurs. The main goal of maintenance is to avoid or mitigate the consequences of failure of equipment. It also improves reliability, decreases cost of replacement and system downtime. Preventive maintenance helps provide high level of availability of system function and obtains great return on investments of hardware and software. However, very frequent application of preventive maintenance is not economical though. In order to obtain optimum benefit, this maintenance should be done at proper times. This study aims at explaining the importance of preventive maintenance mathematically. The mean time to failure (MTTF) or the mean time between failures (MTBF) is taken as the reliability criteria. The reliability values obtained when preventive maintenance is applied and not applied are compared to the MTTF.

***Keywords*—**Mean time to failure, Preventive maintenance, Reliability, Strategic decision making.

I. Introduction

Maintenance involves all the procedures and operations carried out to keep the aircraft ready for flight in suitable conditions between a period starting from the purchase of the aircraft and its being out of service [1]. Based on this definition, it is essential to use various systems, components and parts of the aircraft continuously free from any malfunctions. Such a maintenance application on these elements is carried out as scheduled maintenance procedures, which can be classified:

Proactive maintenance,

Preventive maintenance [2].

Unscheduled maintenance is an undesired situation in which unprecedented sudden problems are solved. Such a downtime can interrupt many plans and schedules and might cause even more damage to the company in terms of the loss of prestige and reputation, let alone financial burden it brings to the company.

Reliability is defined as the possibility of a system to work properly to perform desired functions during a specified period of time under predetermined conditions [3].

Manuscript received October 3, 2011. This work was supported in part by the Anadolu University under Grant 1102F029.

E. Kiyak is with the Anadolu University, Eskisehir, TURKEY (corresponding author to provide phone: +90 222 335 05 80/6879; fax: (+90 222 322 16 19; e-mail: ekiyak@anadolu.edu.tr).

The aim of preventive maintenance applied to an aircraft is to ensure that the parts of the aircraft have higher reliability than a certain level. By doing this, it is possible to reduce the number of unexpected downtimes and therefore the number of unscheduled maintenance practices. Others are [4]:

- Increased Automation
- Business loss due to production delays
- Reduction of insurance inventories
- Production of a higher quality product
- Just-in-time manufacturing
- Reduction in equipment redundancies
- Cell dependencies
- Minimize energy consumption
- Need for a more organized, planned environment.

There are also some risks [4]:

- Damage to an adjacent equipment during a preventive maintenance task.
- Damage to the equipment receiving the preventive maintenance task to include such things as: Damage during the performance of an inspection, repair, adjustment, or installation of a replacement part. Installing material that is defective, incorrectly installing a replacement part, or incorrectly reassembling material.
- Reintroducing infant mortality by installing new parts or materials.
- Damage due to an error in reinstalling equipment into its original location.

The effective implementation of a reliability and maintenance program must take into consideration some factors [5]:

- The customer's requirements,
- The business strategy of the company,
- The size of the project.

Reliability Centred Maintenance has three part process [6]:

- Systems Analysis,
- Zonal Analysis,
- Structural Analysis.

These three parts are three distinctly different methodologies. The outputs from each are combined to form an integrated packaged preventive maintenance schedule as shown in the Figure 1.

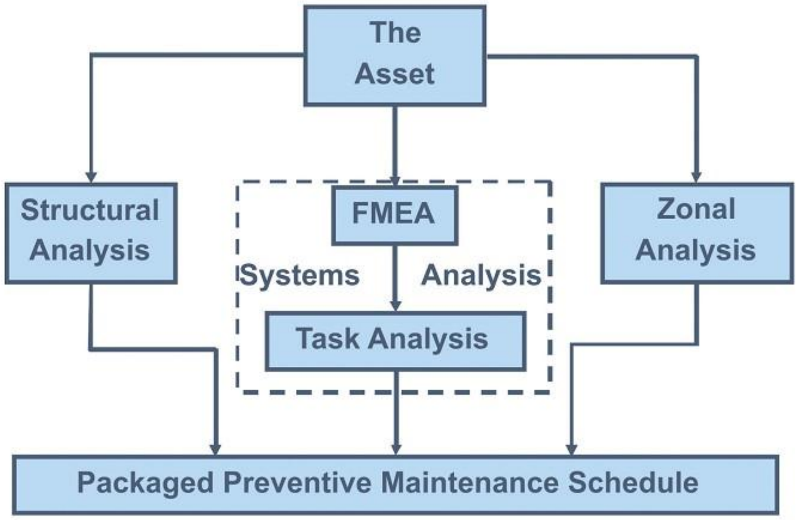

Fig. 1 Preventive Maintenance Schedule [6]

Each of the three parts of the analysis is utilized to address specific aspects of the maintenance.

Systems Analysis

This part of the analysis focuses on the functional systems within the equipment such as control system, brake system, pneumatic system. The analysis comprises two stages: a Functional Failure Modes and Effects Analysis (FMEA) and a Task Analysis. These are used to identify the potential failure modes, the consequences of those failures and then identify the most applicable and effective maintenance task to mitigate the failure mode. The analysis also identifies the appropriate frequency at which the maintenance task should be undertaken.

Structural Analysis

This part of the analysis concentrates on the structural aspects of the equipment. This is a focused and efficient analysis technique that identifies maintenance tasks to address structural failure modes associated with fatigue, environmental deterioration and accidental damage.

Zonal Analysis

This part of the analysis is used to derive requirements for Zonal Inspections. A Zonal Inspection is a General Visual On Condition (GVOC) maintenance task used to identify non-specific failures that are too inconsequential to be considered in the Systems and Structural parts of the RCM process. In addition, Zonal Inspections provide a mechanism to maintain against failure modes that are random in nature and therefore cannot be predicted by the other techniques (e.g. vandalism damage). The output of the three parts of the process is a set of maintenance tasks with a range of raw frequencies. The tasks are packaged together to build a maintenance regime comprising groups of maintenance task that can be undertaken at set and convenient frequencies.

Knezevic points out that it is possible to facilitate maintenance practices by applying some tactics during the design of the aircraft. In addition, aircraft might be flown with the help of substitute systems in case of a malfunction [7].

Alper also mentions about the necessity of making maintenance plans suitable according to the conditions in the country. To illustrate with, he suggests that it is necessary to carry out reliability analyses of two parts of engines of F-16 fighters in Turkey that fail very often [8].

Wilmeth and Usrey suggest that there will be a relatively higher improvement than the existing maintenance program when reliability-centered maintenance is applied to DC power supplies. In addition, they claim that reliability-centered maintenance will be effective in overcoming a considerable number of problems when it is not possible to prevent certain critical failures or when other maintenance practices do not work to end downtime [9].

Kipersztok is described a diagnosis decision support approach using Bayesian belief networks for facilitating airplane maintenance at an airport gate. The approach combines engineering and mechanic’s knowledge with statistical component reliability data. It is argued that Bayesian network contain a rich representation language that permits to encode the different types of knowledge needed for airplane diagnosis. The high degree of system integration in an airplane typically results in ambiguous diagnoses. The inference engine of a Bayesian network provides a consistent probability update mechanism to help disambiguate between the possible causes of a failure. Sensitivity analysis of the networks to noisy priors justifies the use of simple probability models from Mean Time Between Unscheduled Removal data, and also shows reasonable robustness of the network diagnosis due to a reasonably limited sensitivity of the network to prior noise [10].

Wu et. al also suggest some methods to cut down on direct operating costs for commercial aircrafts. The key role in these suggested methods is the design and the diagnosis of the malfunction. Similarly, Boeing 777 is claimed to have relatively lower direct operating costs than its similars since its design is based on the principle mentioned above [11].

Wiksten and Johansson, in their study, point out the importance of improvement in decision making process regarding the maintenance based on the available maintenance data. Considering this principle in mind, they analyzed operation and maintenance data for reliability, cost and usability [12].

Leung et. al propose an innovative reliability algorithm program which supports technical reliability analyses and makes simple, fast and effective calculations. They also claim that if this program is improved, certain downtimes can be predicted in advance and necessary precautions can be taken accordingly [13]. Similarly, Miah and Hinton develop a reliability-centered maintenance program against corrosion. The idea behind the program is to observe the indications of corrosion and to make preventive maintenance plans accordingly [14].

Marusic et. al focus on the problems related to the reliability program designed for small fleets. They state that when there is not sufficient data to carry out statistical analyses for such small fleets, it is necessary to increase the number of fleets virtually to avoid wrong decisions due to wide distribution. The calculations should be made according to these new numbers and alarm levels should be determined in order to make decisions for preventive activities [15].

Jula et. al present a case of an actual aircraft electric power system analysis. They define a conceptual fault tree using the Boolean logical structures The fault tree is expressed all the combination of factors that can lead to system failure in the onboard electric system and the goal is to improve the fault-tolerance behavior of the system [16].

Guizzi et. al propose a model of a productive system subject to a condition based maintenance policy which has to be optimized by modifying the maintenance thresholds to reach the lowest level of global system cost. A simulation approach is proposed that take in count all the cost related both to production and to maintenance. They propose a parametric study to determine how some critical parameters can influence the achievement of the system and the maintenance policy to be adopted [17].

Viorel presents to address two maintenance modern methods of maintenance activities, maintenance and reliability-based total productive maintenance to analyze the main characteristics of these methods [18].

Gherghinescu and Popescu claim by applying a complete and functional predictive maintenance can be obtained the following results [19]:

• depreciation with more than 10 times of the investment cost,

• decrease between 25 and 30% of the total maintenance costs for monitored equipment,

• reducing the stationary time between 35 and 45%

Among the various aspect of the maintenance related to economic aspects two key parameters have to be properly estimated [20]:

MTBF: Mean Time Between Failure,

MTTR: Mean Time To Repair

This study tries to explain the importance of preventive maintenance for aircrafts mathematically. The MTTF is taken as reliability criteria. The reliability values obtained when preventive maintenance is applied and not applied are compared to the MTTF.

II. Reliability Analysis

Among basic reliability criteria are MTTF and MTBF, the number of failures during a certain period of time and the repair cost [21]. MTTF is used for non-repairable component as electronic equipment while MTBF is used for repairable component.

MTTF is defined by [22]:

$$MTTF = \int_0^{\infty} t f(t) dt = \int_0^{\infty} R(t) dt \quad (1)$$

Here, f(t) is defined probability density function (PDF) and R(t) is defined reliability.

PDF is defined by:

$$f(t) = \frac{dF(t)}{dt} \quad (2)$$

Here, F(t) is the cumulative distribution function. F(t)+R(t)=1 is used for non-repairable components.

Another function which is used in reliability is failure rate or hazard function:

$$\lambda(t) = \frac{f(t)}{R(t)} \quad (3)$$

λ(t) provides an instantaneous rate of failure.

On the other hand, total failure density function of the repairable component is defined by:

$$L(t) = \sum_{k=1}^{\infty} f_k \quad (4)$$

Here, f_k is the failure density function of the kth.

f_k is defined by:

$$f_k = \int_0^t f_{k-1}(\varphi) f(\varphi) d\varphi \quad (5)$$

Repair frequency of the repairable component is defined by:

$$f_R = \frac{1}{T_M} \int_0^{T_M} L(t) dt \quad (6)$$

In order to increase the reliability of the systems, certain operations requiring extra investment might be necessary such as increasing component reliability, backing up the components, to reduce the maintenance time, increasing the options and the frequency of measurements and observations. By evaluating the financial dimension of the method to follow, the cost of reliability in general or per unit can be calculated. The cost of reliability per unit decreases when it reaches a certain value. When the risk of insufficient reliability for those using this system is considered, the dotted lines given in Figure 1 can be calculated as the minimum cost to ensure a certain level of reliability.

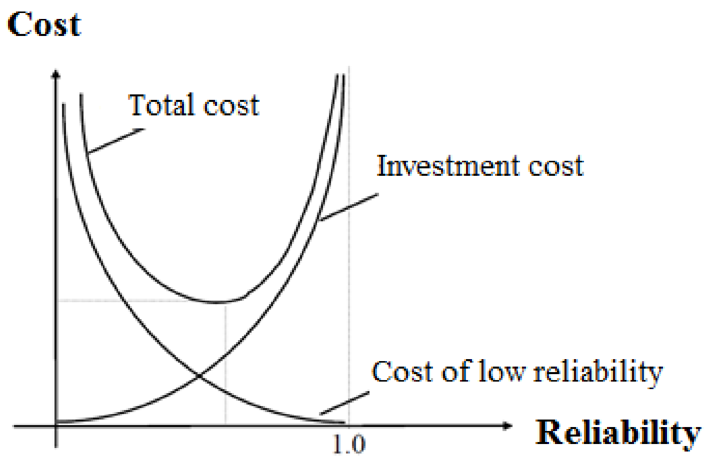

Fig. 1 The relationship between reliability and cost

The total cost per unit time is defined by:

$$C = C_R f_R + C_M f_M \quad (7)$$

Here, C_R is defined the cost of repair, C_M is defined the cost of maintenance and f_M is defined maintenance frequency.

Assuming, $C_0 = C / C_R$ Equation (7) can be written as:

$$C_0 = f_R + \frac{C_M}{C_R} f_M = \frac{1}{T_M}\int_0^{T_M} L(t)dt + \frac{C_M}{C_R}\frac{1}{T_M} \quad (8)$$

If Equation (8) is satisfied, the solution provides optimum maintenance interval.

Probability distributions can be classified [23]:

Discrete distributions,

Continuous distributions.

A random variable is a discrete variable, its probability distribution is called a discrete probability distribution while random variable is a continuous variable, its probability distribution is called a continuous probability distribution.

1. Some discrete distributions:

a) Binomial probability distribution:

A binomial random variable is the number of successes x in n repeated trials of a binomial experiment. The probability distribution of a binomial random variable is called a binomial distribution.

b) Hypergeometric probability distribution:

A hypergeometric random variable is the number of successes that result from a hypergeometric experiment. The probability distribution of a hypergeometric random variable is called a hypergeometric distribution.

c) Multinomial probability distribution:

A multinomial distribution is the probability distribution of the outcomes from a multinomial experiment. The multinomial formula defines the probability of any outcome from a multinomial experiment.

d) Poisson probability distribution:

A Poisson random variable is the number of successes that result from a Poisson experiment. The probability distribution of a Poisson random variable is called a Poisson distribution.

2. Some continuous distributions:

a) Normal probability distribution:

The normal distribution refers to a family of continuous probability distributions described by the normal equation. The random variable X in the normal equation is called the normal random variable. The normal equation is the probability density function for the normal distribution.

b) Student's t distribution:

The distribution of the t statistic is called the t distribution or the Student t distribution.

c) Chi-square distribution:

Suppose we conduct the following statistical experiment. We select a random sample of size n from a normal population, having a standard deviation equal to σ. We find that the standard deviation in our sample is equal to s. Given these data, we can define a statistic, called chi-square.

d) F distribution:

The f statistic, also known as an f value, is a random variable that has an F distribution.

The random variables and their distributions are important in reliability analysis. Although there are numerous distribution types, some basic information about homogenous distribution in the study is provided to make numerical calculations easier. Figure 2 presents density function of a random "x" variable between the interval $[x_1, x_2]$.

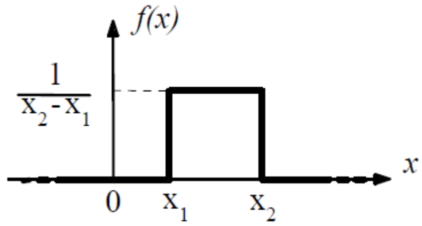

Fig. 2 Density function for a variable having a homogenous distribution

The function in Figure 2 is shown as follows [21]:

$$f(x) = \begin{cases} \frac{1}{x_2 - x_1}\ time^{-1};\ x_1 \le x \le x_2 \\ 0; otherwise \end{cases} \quad (9)$$

III. Preventive Maintenance in terms of Reliability in Aviation Sector

In order to illustrate the importance of preventive maintenance, a simple application is presented below. The application involves the comparison of reliability and the mean time values when maintenance is not applied and when preventive maintenance is applied.

Assume that the distribution function of a component to which preventive maintenance can be applied as follows:

$$f(t) = \begin{cases} \frac{1}{5}\ year^{-1};\ 0 \le t \le 5\ year \\ 0; otherwise \end{cases} \quad (10)$$

If the following equation is used to calculate the reliability of the component when maintenance is not applied, the result is as follows:

$$R(t) = 1 - F(t) = 1 - t/5 \quad (11)$$

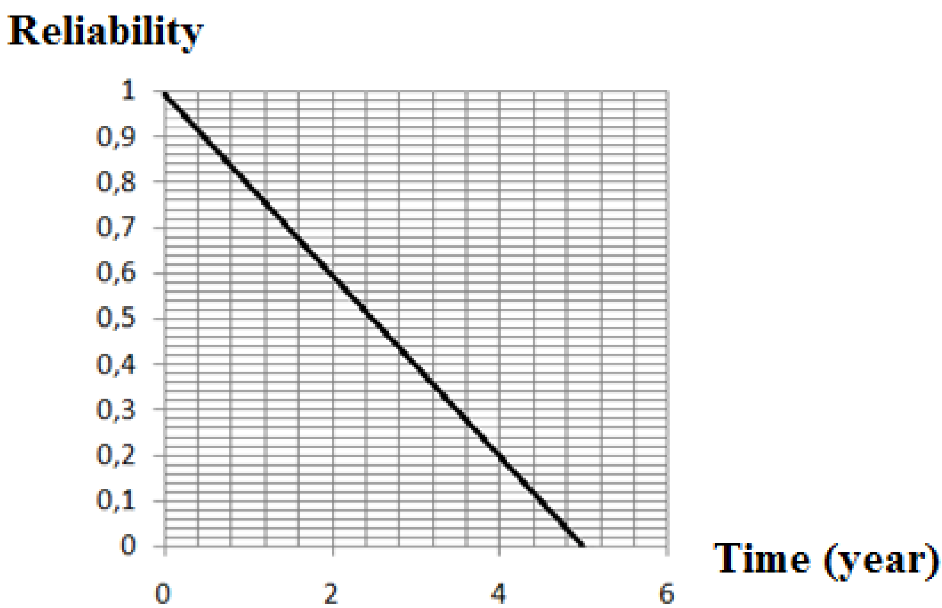

Fig. 3 The change of reliability in time when preventive maintenance is not applied

When Figure 3 is examined, it is observed that reliability will reduce to “0” in five years if no maintenance is applied during that time. As mentioned above, reliability should always be higher than a certain standard, so the value “0” cannot be allowed in aviation sector.

Using Equation (3), $\lambda(t) = 1/(5-t)$ is found. If t = 5 is used, hazard function goes to infinite asymptotically. This situation is not performed.

MTTF is calculated as follows:

$$\text{MTTF} = 5 \text{ year} \quad (12)$$

In the study, if we assume that preventive maintenance is later applied to this component periodically in one-year intervals to show the effect of preventive maintenance on reliability and MTTF, the following calculation can be made by using Equation (11):

$$R^*(1) = 0.8 \quad (13)$$

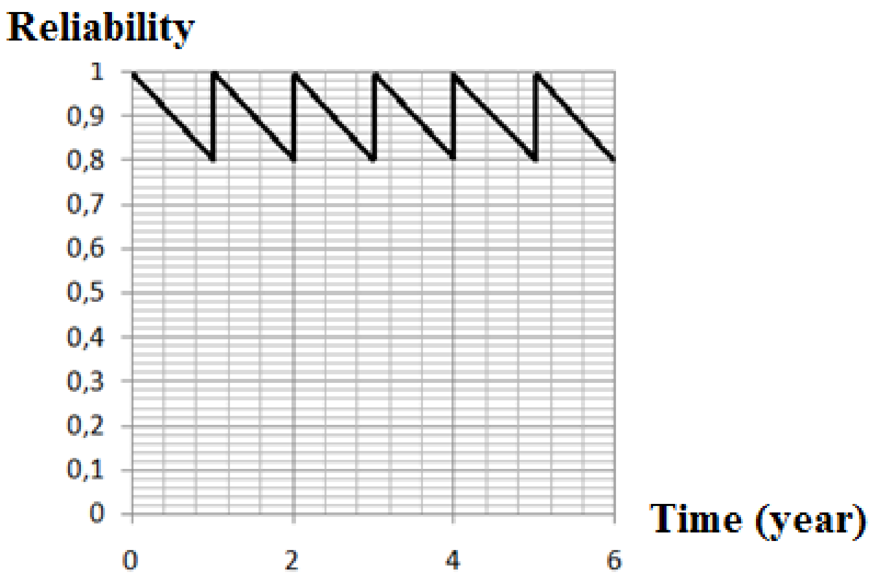

Fig. 4 The change of reliability in time when preventive maintenance is applied ($T_M = 1\ year$)

As shown in Figure 4, when preventive maintenance is applied regularly each year, reliability will never be less than 0.8. Here, it is assumed that maintenance is applied perfectly and the duration of the maintenance is ignored.

The following calculation can be made by using Equation (3):

$$\lambda(1)^* = 0.25 \quad (14)$$

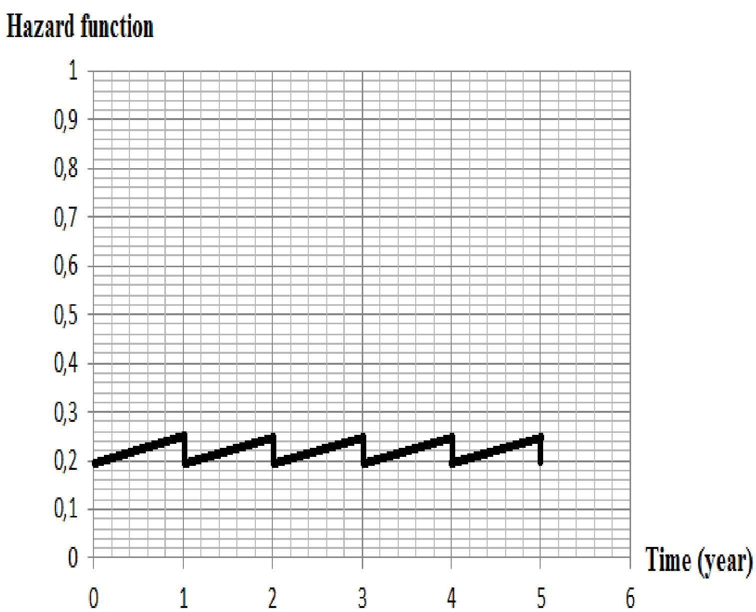

Fig. 5 The change of hazard function in time when preventive maintenance is applied ($T_M = 1\ year$)

As shown in Figure 5, when preventive maintenance is applied regularly each year hazard function will never goes to infinite. It remains in between 0.2 and 0.25. The average of the hazard function is obtained 0.225.

MTTF is calculated as follows:

$$MTTF^* = \frac{1}{\lambda_{avg}} = 4.45\ year \quad (15)$$

IV. Conclusion

This study deals with the importance of preventive maintenance in terms of reliability. After some basic concepts are explained, a simple application related to aviation sector is presented and the effects of preventive maintenance on reliability and the values of MTTF regarding this sample application are shown.

It is obvious that preventive maintenance has a cost, so the frequency of this type of maintenance should be determined carefully. Depending on the component on which maintenance is applied, unnecessary preventive maintenance might increase reliability at the beginning to some extent; however, the financial burden it creates in long term should not be ignored.

When various components of an aircraft are considered, it can be concluded that such calculations are not easy to make. However, it might be necessary to apply preventive maintenance for certain components. If a type of software designed based on the data obtained from the previous maintenance data is used, it is possible to make a list of optimum preventive maintenance times and the components to apply this type of maintenance.

A downtime in aviation sector can have dramatic effects in aviation sector. An aircraft that crashes can result in casualties and financial burden as well as the loss of prestige and reputation for the company, which may even lead to bankruptcies.

The use of reliability-centered software can bring advantages in the long term although it has a financial cost at the beginning. More importantly, it makes it possible to replace certain components and to provide logistic support when necessary with the help of regular maintenances applied before these problems give harm to the system.

Appendix

C: total cost

C_M: cost of maintenance

C_R: cost of repair

f(t): probability density function

f_k: failure density function of the kth

f_M: maintenance frequency

F(t): cumulative distribution function

F_R: repair frequency of the repairable component

L(t): total failure density function of the repairable component

R(t): reliability

λ(t): instantaneous rate of failure

Acknowledgment

The supported by Anadolu University Research Projects Committee (Project No. 1102F029) is gratefully acknowledged.

References

[1] M. Kayrak, “Aircraft Maintenance and Repair Lecture Notes”, Anadolu University, Civil Aviation School, Eskisehir, unpublished.

[2] F. Taskin, “Optimization of Buffer Inventory for Regular Preventive Maintenance Using Fuzzy Logic”, M.S. thesis, Sakarya University, 2006.

[3] J. Endrenyi, *Reliability Modeling in Electric Power Systems*, John Wiley and Sons, 1980.

[4] W. C. Worsham, Is Preventive Maintenance Necessary?, 2011. http://www.maintenanceworld.com/Articles/worshamw/ispreventive.html

[5] Reliability and Maintainability Engineering Program Approach, 2011. http://www.mtain.com/prog/rmprog.htm

[6] Reliability Centred Maintenance – RCM, 2011. http://www.fleetech.com/?/1739/1303/2272

[7] J. Knezevic, “Chief mechanic: the new approach to aircraft maintenance by Boeing”, *Journal of Quality in Maintenance Engineering*, Vol. 5, No. 4, pp. 314-324, MCB University Press, 1999.

[8] M. Alper, “Devoloping Method Aircraft Maintenance Planning Reliability Analysis”, Ph.D. dissertation, Anadolu University, 2000.

[9] R. G. Wilmeth, M. W. Usrey, “Reliability-centered maintenance: A case study”, *Engineering Management Journal*, 2000.

[10] O. Kipersztok, “Diagnosis Decision Support for Airplane Maintenance”, *In Advances in Scientific Computing, Computational Intelligence and Applications, Mathematics and Computers in Science and Engineering*, 2001.

[11] H. Wu, Y. Liu, Y. Ding, J. Liu, “Methods To Reduce Direct Maintenance Costs For Commercial Aircraft”, *Aircraft Engineering and Aerospace Technology*, Volume 76, Number 1, pp. 15–18, 2004.

[12] J. Wiksten, M. Johansson, “Maintenance and Reliability with Focus on Aircraft Maintenance and Spares Provisioning”, Bachelor Thesis, Lulea University, 2006.

[13] T. Leung, T. Carroll, M. Hung, A. Tsang, W. Chung, “The Carroll-Hung Method For Component Reliability Mapping In Aircraft Maintenance”, *Quality and Reliability Engineering International*, Volume 23, Issue 1, pp. 137–154, 2007.

[14] S. Miah, B. Hinton, “A Corrosion Related Reliability Centred Maintenance Pilot Program For The Royal Australian Air Force C-130 J-30 Hercules Aircraft”, *Tri-Service Corrosion Conference*, 2007.

[15] Z. Marusic, B. Galovic, O. Pita, “Optimizing Maintenance Reliability Program For Small Fleets”, *Transport*, Vol. 22, No 3, pp. 174–177, 2007.

[16] N. Jula, C. Cepisca, M. Covrig, C. Racuciu, T. Ursu, “Boolean Applications in Aircraft Electric Power Systems Reliability Analysis”, *2nd European Computing Conference*, Malta, 2008.

[17] G. Guizzi, M. Gallo, P. Zoppoli, Condition Based “Maintenance: simulation and optimization”, *8th WSEAS International Conference on System Science and Simulation in Engineering*, 2009.

[18] P. Viorel, “Modern Management Concepts of Maintenance Activities”, *Recent Researches in Manufacturing Engineering*, pp. 138-140, 2011.

[19] S. Gherghinescu, G. Popescu, “In-situ predictive maintenance by vibration analysis for Cryogenic Pilot Plant for Tritium and Deuterium Separation”, *Recent Advances in Environment, Energy Systems and Naval Science*, 2011.

[20] E. Briano, C. Caballini, P. Giribone, R. Revetria, “Design of Experiment and Montecarlo Simulation as Support for Gas Turbine Power Plant Availability Estimation”, *Proceedings of the 12th WSEAS International Conference on Automatic Control, Modeling & Simulation*, 2010.

[21] R. Billington, R. N. Allan, *Reliability Evaluation of Engineering Systems*, Plenum Press, 1992.

[22] C. E. Ebeling, *An Introduction to Reliability and Maintability Engineering*, McGraw-Hill, USA, 1997.

[23] Statistics Tutorial: Discrete and Continuous Probability Distributions, 2011. http://stattrek.com/lesson2/discretecontinuous.aspx

E. Kiyak was born in Eskisehir in 1978. He graduated from Anadolu University, Turkey, in Civil Aviation School, Department of Avionics in 2001. He received the MSc degree from University of Anadolu in Civil Aviation in 2003, and he had his PhD in Anadolu University Science Technologies Institute in 2008.

He became a Research Assistant at Anadolu University Civil Aviation School in 2001. He has been working as Assistant Professor in the same school.

His research interest includes fault tolerant control, flight control systems, fuzzy logic, reliability analysis and maintenance.