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Optimization of Maintenance Task Interval of Aircraft Systems

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Abstract: Maintenance accounts for approximately 20% of the operational cost of aircraft; a margin higher than cost associated with fuel, crew, navigation, and landing fees. A significant percentage of maintenance cost is attributed to failures of aircraft components and systems. These failures are random and provide a database which can further be analyzed to aid decision-making for maintenance optimization. In this paper, stochastic mathematical models which can potentially be used to optimize maintenance task intervals of aircraft systems are developed. The initial data for this research are diagnostic variables and reliability parameters which formed the basis for selecting the probability density function for time between failures according to the exponential and Erlang models. Based on the probability density functions, the efficiency of the maintenance processes was calculated using average operational cost per unit time. The results of the analysis were further tested using the Monte Carlo simulation method and the findings are highlighted in this paper. The simulation results compared favorably with analytical results obtained using already existing Monte Carlo techniques to about 82% accuracy. The proposed mathematical optimization models determine the optimal aircraft maintenance task interval which is cost effective while considering safety and reliability requirements; our results can also be applied during the development, design, and operation phases of aircraft systems.

Index Terms: Maintenance, Optimization, Data Processing, Operation Systems, Operational Costs, Aircraft Systems.

1. Introduction

Recent research highlights that statistical data processing algorithms can be related to intelligence-based information technologies which use the principles of adaptivity, system and process approach, and robustness to improve efficiency [1-6]. Statistical data processing algorithms [7] can be used to improve the efficiency of aircraft operations given diagnostic variables and reliability parameters as initial data. In general, the trends of these variables and parameters are non-stationary random processes [8]. The trends contain quasi-stationary intervals for the period of normal operation of aircraft components and systems. During the deterioration phase of aircraft systems, there are changes to statistical characteristics of observed trends. Such changes can occur due to different reasons: personnel errors, aging of components and systems, etc. [9-15]. Statistical data processing algorithms estimate the time of possible failure with the aim of preventing it based on correct and timely operational actions.

The Maintenance Steering Group (MSG) logic is a decision process for cost-effective and efficient routines acceptable to aircraft manufacturers, operators, and regulators. Its evolution from MSG to MSG-2 and MSG-3 shows that aircraft data processing algorithms should be based on the principles of artificial intelligence [16-19]. To implement these principles, the operational system (OS) can be used. The structural diagram of the operational system of an aircraft using artificial intelligence-based principles is presented in Fig. 1.

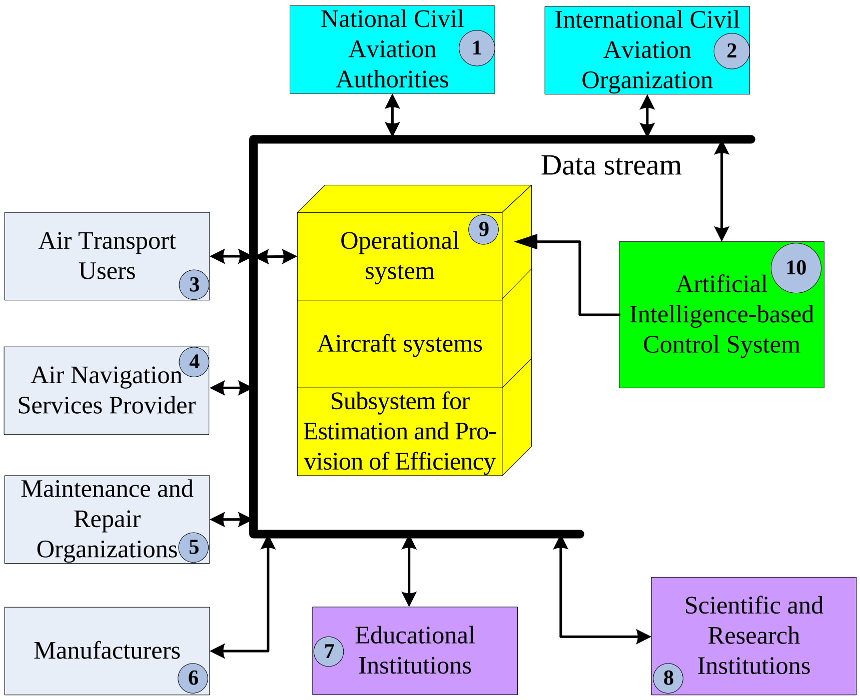

Fig.1. Structural diagram of the operational system of an aircraft.

According to Fig. 1, the OS of an aircraft is an organization of systems that includes equipment, facilities, organizational structure, processes, personnel, documentation, resources, information technologies etc. [20-23]. Unit 1 and 2 are international and national regulators, unit 3 is for the passengers and cargo. Unit 4 is a key component of flight safety, units 5 – 9 determine and maintain the reliability levels and efficiency of aircraft systems. Unit 10 provides an adaptive control of operation under conditions of prior uncertainty.

The OS of an aircraft contains subsystems, which evaluate the quality of maintenance [24, 25]. The results of this evaluation are used to generate and implement predictive and preventive maintenance actions. In addition, the OS is based on artificial intelligence principles, which allow for the processing of big data streams. This creates an organizational structure that provides required levels of flight safety and aircraft availability [26-29]. The OS of an aircraft contains the following data processing algorithms:

1. Detection algorithms.
2. Estimation algorithms.
3. Diagnostics.
4. Adaptive monitoring.
5. Heteroscedasticity analysis.
6. Correlation analysis.
7. Algorithms for the optimization of maintenance task intervals.
8. Algorithms for the development of mathematical models.
9. Regression analysis.
10. Heuristic algorithms.
11. Prognostics [30].

Maintenance optimization refers to the development and analysis of mathematical models for improving maintenance policies. In recent years, significant research is being focused on the development of various maintenance optimization strategies. However, as far as we know, no study has proposed reliability models based on time between failures, observed time and repair cost to improve the efficiency of the OS of aircraft.

This paper presents mathematical models for the optimization of aircraft maintenance task intervals. These models quantify the cost and benefits of maintenance with the goal of obtaining an optimum balance between both. The limitation of our study is that we considered only two failure models (exponential and Erlang models) which were used during the analytical calculations. For any arbitrary model of time between failures, the limitation is the non-analytical presentation of obtained results. The proposed model can significantly reduce average operational cost per unit time and is considered as the scientific and practical result of this research.

The paper is organized as follows. Section 1 introduces the topic. Section 2 discusses the motivation behind this research. Section 3 highlights the contribution of this Paper. Section 4 discusses related works. Section 5 presents the detailed algorithm for the optimization of maintenance task interval using different models of time between failures of aircraft systems. Section 6 explains the analysis of simulation results and Section 7 discusses the conclusions and future scope.

2. Motivation Behind this Work

Aircraft life cycle consists of four phases. The first phase is for design and development which consists of planning and conceptual design, preliminary design and system integration, detailed design. The second phase is the production and/or manufacturing stage. The third phase is for operation, and the final stage is disposal. The longest phase is the operation stage and provides the most statistical data for preventive, predictive and corrective maintenance actions [31].

As shown in Fig. 2, significant costs are incurred during the operational phase; maintenance, repair, and overhaul account for 20% of these costs [31, 32].

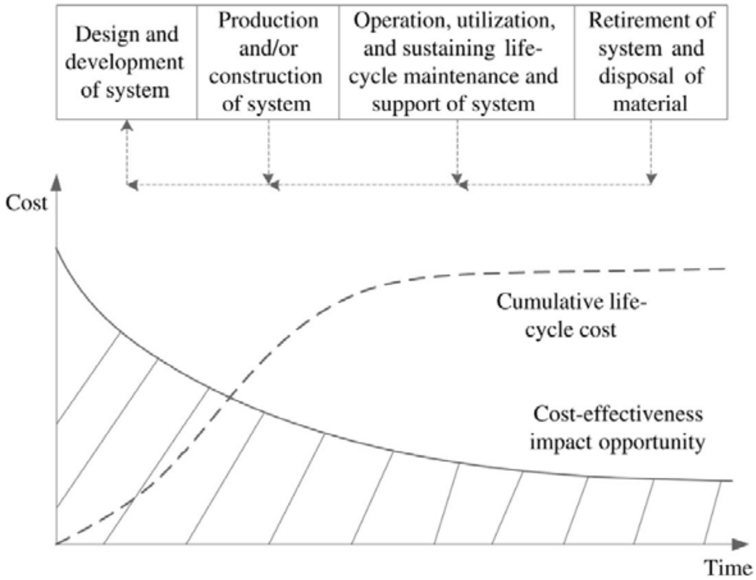

Fig.2. Cost of phases of aircraft life cycle

Aircraft maintenance is defined as a combination of all technical and administrative actions that retain or restore aircraft component parts, subsystems, and systems into a state in which it can perform its predetermined functions [33-35]. Objectives of aircraft maintenance can be summarized under three headings – ensuring aircraft availability, ensuring reliability of aircraft systems, and ensuring flight safety [36-38]. Direct aircraft maintenance costs include materials, equipment, facilities, spare parts supply, personnel etc. while indirect maintenance costs are from administrative and management staff, overhead expenditure, and loss of revenue due to aircraft downtime. Aircraft maintenance costs can be reduced by:

– using optimal maintenance task interval;
– using prognostic health management technologies;
– implementing artificial intelligence-based decision-making strategies;
– improving the organizational structure of the OS of the aircraft.

Maintenance costs to a large extent depend on the reliability of aircraft systems [39, 40]. The reliability of aircraft systems can be defined as the probability that an aircraft system performs its function for a required period, under specified environmental and operational conditions. In mathematical framework, reliability is formulated using random variables to model variability sources in product and process developments [41]. Considering that optimization of aircraft maintenance processes can potentially be carried out using reliability models, this study is devoted to the development of reliability models which can potentially be used to determine the optimal aircraft maintenance task interval per average unit cost.

3. Contribution of Paper

The goal of this paper is the optimization of maintenance task intervals of aircraft systems using a synthesis of data processing algorithms to reduce operational costs. The step-by-step procedure for determining the optimal maintenance task interval is shown in the methodology section and analytical equations are determined using exponential and Erlang models for time between failures of aircraft systems. Our results show that the Erlang model forms the basis for the analysis of any arbitrary model.

An optimal maintenance task interval is of paramount importance because:

1. As aircraft components and systems deteriorate, it is important to carry out maintenance actions and this results in an increase in operational cost. Therefore, there is the need for an optimal interval that balances the frequency of maintenance tasks and the failure rate.
2. Maintenance decisions are based on results of the analysis of operational data.
3. The proposed algorithm in our study can potentially be used to optimize aircraft operations.
4. The proposed algorithm can potentially be considered as a part of artificial intelligence-based OS of aircraft.

Our study is theoretical; our hypotheses were formed based on our research experience and knowledge of aircraft systems.

4. Related Works

There is currently an increased research interest in aircraft maintenance optimization since it directly impacts system availability and operational costs [42]. The main aircraft maintenance optimization techniques that have been researched recently are based on aircraft maintenance service scheduling, spare parts inventory, and aircraft maintenance planning.

Deng, Santos & Curran (2020) proposed a practical dynamic programming-based methodology for the optimization of long-term maintenance check schedules for a fleet of heterogeneous aircraft. This methodology integrates different check types (A, B, C and D checks) in a single schedule with the goal of reducing wasted flight hours interval between checks, thereby increasing aircraft availability and reducing maintenance cost. The proposed methodology follows a forward induction approach. It integrates a maintenance priority solution to work on the multi-dimensional action vector, uses a discretization and state aggregation strategy to lower outcome space at each time stage, and a thrifty algorithm to estimate the consequence of an action at the current stage on the remaining planning horizon. Forward induction means reasoning forward in time, determining the sequence of optimal actions from an initial state till the end of the time horizon [43].

Liu et al. (2019) presented an innovative design of an autonomous system that supports automatic decision-making for maintenance scheduling. The proposed design fuses aircraft condition, strategy, cost and planning [44]. Babar et al. (2019) designed a technique based on breadth first search and Dijkstra's Algorithms which produces maintenance feasible routes while ensuring overall minimized maintenance cost. This methodology also factors in availability of man hours, turn-around time of aircraft and slot availability [45].

Arts & Rob (2018) proposed two single-item maintenance models with minimal repair [46]. These models can be used to optimize the maintenance program of a multi-component asset and are also useful when performing an unscheduled time-consuming repair or replacement. The periodic maintenance model proposed is a generalization of the block replacement policy with least possible repair upon failure. The condition-based model proposed uses a semi-Markov model, in which a component can be in three states: good, defective, and failed. The time a component remains in the good state after replacement, known as the time-to-defect, is assumed to be exponential. Olivares et al (2018) created a methodology for the optimization of predictive line maintenance of redundant aeronautical systems subject to various wear conditions [47]. The optimization of maintenance planning is based on minimizing operational costs consisting of dispatch requirements, cancellations, delays, and equipment costs. The method proposed considers a multiple wear profile scenario to identify degradation and their future estimates and then integrates the results obtained into a maintenance planning optimization algorithm for aeronautical redundant systems. Future operational costs as well as probability distributions for other operational requirements are determined using a prognostic model. Berrade et al (2018) developed a maintenance model in which after one component has failed, the other component which may be affected by this failure is inspected, and the state of the second component determines the extent of maintenance to the system [48]. The second component is the critical component and main target of maintenance to avoid failures. The model captures the performance of interacting systems and is therefore significant.

Regattieri et al (2015) developed a three-step methodology which combines the use of mathematical models and simulation based on reparation process modelling and failure process modelling to determine optimal aircraft maintenance policies [49]. The method considers the effect of inventory management of spare parts because their impact on overall cost is significant. The authors focused on the optimization of the preventive maintenance policy of aircraft; they highlighted the feasibility of this approach in terms of aircraft availability and reduction of maintenance costs using a data analysis procedure based on reliability, availability, and maintainability principles. The results of this methodology reduced the total annual cost of A320 aircraft family to approximately 20% of the previous value and the average aircraft availability remained close to high values. Horenbeek & Pintelon (2013) presented a dynamic predictive maintenance policy that reduces long-term maintenance cost per unit time in multi-component systems while considering different component dependencies (i.e., structural, economic and stochastic dependence) [50].To determine the performance of the dynamic predictive maintenance policy, a numerical example was compared to five other traditional maintenance policies based on minimal mean maintenance costs per unit time while considering different component dependencies. The traditional maintenance policies are: continuous condition-based maintenance, age-based maintenance, age-based maintenance with grouping, block-based maintenance, and inspection condition-based maintenance [50-54].

A review of relevant literature shows a gap in research devoted to the optimization of aircraft maintenance task intervals based on reliability models that consider the time between failures.

5. Methodology for the Optimization of Aircraft Maintenance Task Interval

During the design of new or improvement of existing maintenance processes, optimization is based on results of scientific innovations and operational practices of aircraft systems. Optimization can be carried out using either a) analytical, b) analytical and computational or c) statistical simulation methods. Statistical simulation allows for the investigation of maintenance processes while considering various operational conditions.

Steps for the optimization of maintenance task intervals of aircraft systems are outlined as follows:

1. Analysis of maintenance tasks of aircraft systems to identify parameters for the models.
2. Development of basic failure models and analysis of aircraft operational data.
3. Parameterization of models, setting the tolerance values of parameters.
4. Determining efficiency indicators for the maintenance of aircraft systems.
5. Defining one or more criteria to measure efficiency of optimized maintenance task interval of aircraft systems.
6. Determining equations or algorithms for evaluating the efficiency of optimized maintenance task intervals.
7. Computing equations for the optimization of aircraft maintenance task intervals, this means designing algorithms for finding optimal values [55-58].

For this study, the key objective is the optimization of aircraft maintenance task intervals. The aircraft maintenance tasks considered are:

1. Monitoring and control of the technical condition of aircraft systems.
2. Adjusting and repair of component parts/systems to meet regulatory standards.

We defined the efficiency indicators of aircraft components and systems as:

1. Costs incurred by airlines due to failures of aircraft components and systems.
2. Steady state availability of aircraft systems.
3. Overall operational costs.
4. Probability of failure-free operation of aircraft systems [59].

There are two types of probability distribution: probability density function (PDF) and cumulative distribution function (CDF) [60]. PDF is widely used for maintenance optimization, and in our study, selecting the PDF of the time between failure is the initial step for the mathematical modelling. Based on the PDF, the efficiency of the maintenance processes is calculated; the average operational cost per unit time is chosen as the efficiency indicator and it is calculated using the equation

$$E(C/T_{\mathrm{M}}) = \frac{E(n/T_{\mathrm{M}})C_{\mathrm{R}} + C_{\mathrm{M}}}{T_{\mathrm{M}}}, \tag{1}$$

where $E(n/T_{\mathrm{M}})$ is expected value of number of failures, C_{R} is repair cost, C_{M} is maintenance cost, T_{M} is the maintenance interval based on flight hours/cycles.

We further consider the exponential and Erlang mathematical models of time between failures.

Exponential model of time between failures

The probability density function for this model is defined by

$$f(t) = \lambda e^{-\lambda t}, \ \lambda > 0, \ t > 0,$$

where λ is the failure rate.

For the exponential model of time between failures, the number of failures is determined using a Poisson distribution

$$P(n/t) = \frac{(\lambda t)^n}{n!} e^{-\lambda t}.$$

The expected number of failures for the observed time interval T_{M} of the aircraft systems is defined by

$$E(n/T_{\mathrm{M}}) = \lambda T_{\mathrm{M}}.$$

Equation (1) can be presented as

$$E(C/T_{\mathrm{M}}) = \lambda C_{\mathrm{R}} + \frac{C_{\mathrm{M}}}{T_{\mathrm{M}}}. \tag{2}$$

The dependence of equation (2) on T_{M} does not contain minimum values because

$$\frac{\partial E(C/T_{\mathrm{M}})}{\partial T_{\mathrm{M}}} = -\frac{C_{\mathrm{M}}}{{T_{\mathrm{M}}}^2} \neq 0.$$

Therefore, for the exponential model of time between failures, an optimized maintenance task interval is not feasible and optimal maintenance task interval tends to infinity.

Erlang model of time between failures

The probability density function for this model is defined by

$$f(t) = \lambda^2 t e^{-\lambda t}, \ \lambda > 0, \ t > 0.$$

The probability density function for the duration of *n*-th failure

$$f_n(t) = \int_{-i\infty}^{i\infty} \left(\int_0^{\infty} \lambda^2 t e^{-\lambda t} e^{iwt} dt \right)^n dw. \tag{3}$$

Mathematical transformation of equation (3) gives the following result

$$f_n(t) = \frac{t^{2n-1}}{(2n-1)!} \lambda^{2n} e^{-\lambda t}.$$

The probability of occurrence of *n* failures during the observed time interval is defined by CDF

$$F_n(t) = \int_0^t f_n(t) dt. \tag{4}$$

The distribution of number of failures can be calculated as

$$P(n/t) = F_n(t) - F_{n+1}(t) = \int_0^t f_n(t) dt - \int_0^t f_{n+1}(t) dt = \frac{(\lambda t)^{2n+1}}{(2n+1)!} e^{-\lambda t} + \frac{(\lambda t)^{2n}}{(2n)!} e^{-\lambda t}.$$

Therefore, the expected number of failures during the observed time interval T_{M} is expressed by

$$E(n/T_{\mathrm{M}})=\sum_{n=1}^{\infty} nP(n/T_{\mathrm{M}})=\sum_{n=1}^{\infty}\left(n\frac{(\lambda T_{\mathrm{M}})^{2n+1}}{(2n+1)!}+\frac{(\lambda T_{\mathrm{M}})^{2n}}{(2n)!}\right)e^{-\lambda T_{\mathrm{M}}}=\frac{\lambda T_{\mathrm{M}}}{2}+\frac{e^{-2\lambda T_{\mathrm{M}}}}{4}-\frac{1}{4}.$$

The efficiency (1) can be presented as

$$E(C/T_{\mathrm{M}})=\frac{(2\lambda T_{\mathrm{M}}+e^{-2\lambda T_{\mathrm{M}}}-1)C_{\mathrm{R}}+4C_{\mathrm{M}}}{4T_{\mathrm{M}}}. \tag{5}$$

We analyzed equation (5) to find the minimum value. To do this, we calculated the derivative.

$$\frac{dE(n/T_{\mathrm{M}})}{dt}=\frac{-2\lambda C_{\mathrm{R}}T_{\mathrm{M}}e^{-2\lambda T_{\mathrm{M}}}-C_{\mathrm{R}}e^{-2\lambda T_{\mathrm{M}}}+C_{\mathrm{R}}-4C_{\mathrm{M}}}{{T_{\mathrm{M}}}^{2}}.$$

The optimal aircraft maintenance task interval can be found by solving the equation

$$-2\lambda C_{\mathrm{R}}T_{\mathrm{M}}e^{-2\lambda T_{\mathrm{M}}}-C_{\mathrm{R}}e^{-2\lambda T_{\mathrm{M}}}+C_{\mathrm{R}}-4C_{\mathrm{M}}=0. \tag{6}$$

In this case the approximate equation can be used

$$e^{-2\lambda T_{\mathrm{M}}}\approx 1-2\lambda T_{\mathrm{M}},$$

where

$$-2\lambda C_{\mathrm{R}}T_{\mathrm{M}}+4\lambda^{2}C_{\mathrm{R}}{T_{\mathrm{M}}}^{2}-C_{\mathrm{R}}+2\lambda C_{\mathrm{R}}T_{\mathrm{M}}+C_{\mathrm{R}}-4C_{\mathrm{M}}=0.$$

Therefore

$$\lambda^{2}C_{\mathrm{R}}{T_{\mathrm{M}}}^{2}-C_{\mathrm{M}}=0.$$

The optimal maintenance task interval is defined by

$$T_{\mathrm{M\,opt}}=\sqrt{\frac{C_{\mathrm{M}}}{\lambda^{2}C_{\mathrm{R}}}}. \tag{7}$$

Equation (7) is an approximate value. The exact equation for optimal maintenance interval can be obtained by solving equation (6) based on Lambert function $W(x)$

$$T_{\mathrm{M\,opt}}=\frac{-1-W\left(\dfrac{4C_{\mathrm{M}}}{C_{\mathrm{R}}}-1\right)}{2\lambda}. \tag{8}$$

Based on analysis of the exponential and Erlang model of time between failures, the step-by-step procedure for optimizing maintenance task interval for any arbitrary model of time between failures is given below:

– calculation of the probability density function for duration of *n*-th failure for any given probability density function $f(t)$ for time between failures using the theory of functional transformation of random variables

$$f_{n}(t)=\int_{-i\infty}^{i\infty}\left(\int_{0}^{\infty}f(t)e^{iwt}dt\right)^{n}dw;$$

– calculation of the probability $F_{n}(t)$ of *n* failures which occurred during the observed time interval using (4);

– determining the distribution of number of failures during the observed time interval

$$P(n/t) = F_n(t) - F_{n+1}(t);$$

– calculating the expected value of number of failures during observed time interval T_M

$$E(n/T_\mathrm{M}) = \sum_{n=1}^{\infty} nP(n/T_\mathrm{M});$$

– analyzing the obtained equation for efficiency according to (1) for optimality i.e. finding the value of the optimal maintenance task interval.

Model development flowchart is presented in Fig. 3.

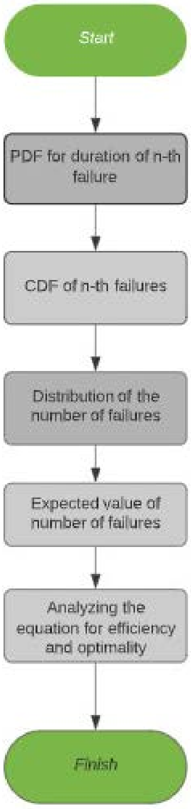

Fig.3. Model development flowchart

6. Analysis of Simulation Results

This section analyses the simulation results for calculating optimal maintenance task interval for aircraft systems using different models of time between failures. The simulation was based on the Monte Carlo method and was implemented in MathCAD software.

Fig. 4 compares dependence of efficiency on maintenance task interval obtained according to equation (2) and that obtained from simulations using the model developed in this paper. The statistical simulation for the initial data (time between failures) set is exponentially distributed with failure rate $\lambda = 0.001$ and sample size $n = 1000$, costs for maintenance $C_\mathrm{M} = 100$ and repair $C_\mathrm{R} = 1000$, number of repetitions $N = 10000$.

Simulation results shown in Fig. 4 prove that for the exponential model of time between failures models, an optimal maintenance task interval which corresponds to a local minimum point on the graph of Average operational cost per unit time vs Maintenance task interval as shown in Fig. 4, does not exist. And so, $T_{\mathrm{M\,opt}} \to \infty$. It can also be seen that the model simulation results compare favorably with analytical results gotten from equation (2).

Fig. 5 shows the results of time between failures calculated using equation (5) and the model simulation, for the Erlang model. The initial data set for Erlang model $\lambda = 0.0005$, sample size $n = 1000$, costs for maintenance $C_\mathrm{M} = 200$ and repair $C_\mathrm{R} = 1000$, number of repetitions $N = 10000$. The simulation results in Fig. 5 prove the existence of a "minimum". The values of the optimal maintenance task interval obtained according to equation (5) correspond with simulation results.

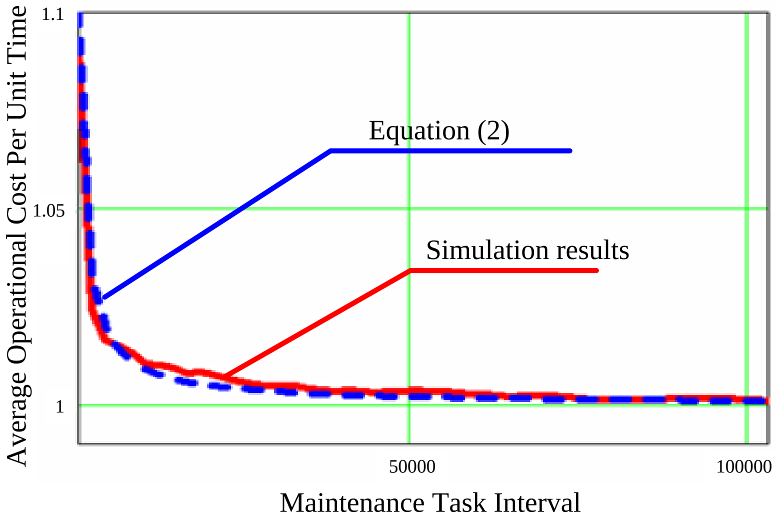

Fig.4. The dependence of efficiency on maintenance task interval obtained based on analytical equation (blue line) and statistical simulation (red line) for exponential time between failures.

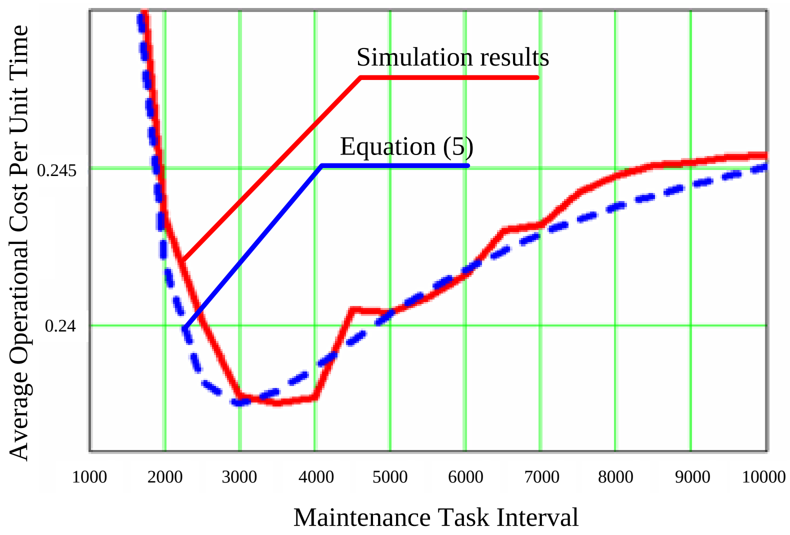

Fig.5. The dependence of efficiency on maintenance task interval obtained based on analytical equation (blue line) and statistical simulation (red line) for Erlang distribution of time between failures.

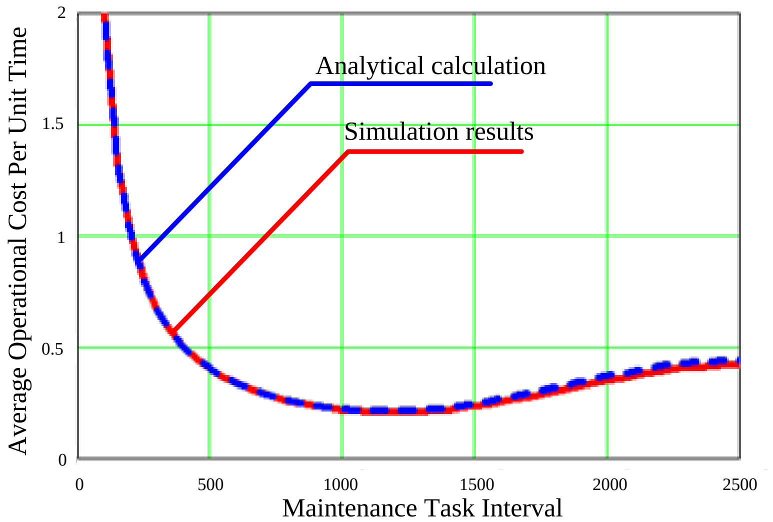

Fig.6. The dependence of efficiency on maintenance task intervals obtained based on the analytical equation (blue line) and statistical simulation (red line) for normal distribution of time between failures.

Any arbitrary model can either be a normal, Weibull, Poisson, Birnbaum-Saunders, or Inverse Gaussian distribution. For this analysis, we considered only the normal distribution. Fig. 6 shows the dependency of efficiency on maintenance task interval for the normal model of time between failures. The initial data set for this model is a normal distribution with mean $m = 2000$ and standard deviation $\sigma = 500$, sample size $n = 1000$, costs for maintenance $C_{\mathrm{M}} = 200$ and repair $C_{\mathrm{R}} = 1000$, number of repetitions $N = 10000$.

For the normal distribution, there is an optimal maintenance interval, and the value of this interval can be calculated analytically or based on statistical simulation.

7. Conclusion and Future Scope

This paper explored the optimization of aircraft maintenance using synthesis of algorithms for calculating optimal maintenance interval. Initial data for algorithm synthesis are models for time between failures. The paper considered the exponential and Erlang models. For the exponential model of time between failures, the analytical calculations showed that the possibility of optimizing maintenance task interval does not exist. This was also demonstrated using the simulation results based on the model developed in this paper. For the Erlang model, the approximate and exact equations for optimal maintenance task intervals were obtained. For any given arbitrary model, the step-by-step procedure for performing the optimal maintenance interval calculation was presented.

To check the correctness of the analytical equation, statistical simulation using Monte Carlo method was carried out in MATHCAD software. The results of the simulation compared favorably with results obtained using equations; this proves the correctness of obtained results.

The findings presented in this paper can potentially be used for determining and optimizing costs during the first three phases of aircraft life cycle. An advantage of the proposed method is its simplicity, making it easy to use by airline personnel for planning maintenance tasks.

Future scope of this research are as follows:

– analysis of deteriorating aircraft systems;
– development of more mathematical models using aircraft operational data;
– improvement of aircraft maintenance policies;
– heteroscedasticity analysis for data of time between failures;
– development of artificial intelligence-based data processing during operations of aircraft.

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