Reliability Analysis of the RB-211 Jet Engines Operated by Icelandair

Harpa Rún Garðarsdóttir

Thesis of 30 ETCS credits
Master of Science in Engineering Management

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at Reykjavík University in partial fulfillment of
the requirements for the degree of
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ABSTRACT

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Jet engines are very complex systems with various interacting sub-systems and stringent reliability requirements. There has been increased interest in recent years to further develop quantitative reliability models of the jet engine in order to improve system reliability, reduce system failures and reduce maintenance costs. Existing reliability models however consider only few components of the engine or view the engine as a single component.

The main objective of this research project is to develop a quantitative method for determining the reliability of the Rolls-Royce RB-211 jet engines operated by Icelandair. A detailed reliability model of the jet engines as a whole has not been developed in the past as far as can be determined from the open literature. The reliability model of this thesis is based on the Reliability Block Diagram (RBD) modeling technique, which provides a very convenient description of how various sub-systems interact to deliver the performance of the engines as far as reliability is concerned. The commercial BlockSim 9 software is used for establishing and running the model, i.e. for accepting the models of all components and for undertaking all computations and simulations that are based on these models.

The main contribution of this thesis is the development of the initial reliability model of the RB-211 jet engines. The model is made up of sub-systems and components of the engines which take into account the lifetime distributions and maintenance properties of each component. These models are obtained by the processing of operational maintenance data that have be collected by Icelandair over a period of five years. A special software package named Weibull++ is used for this purpose. It is anticipated that the reliability model of the RB-211 jet engines will be of great value for Icelandair Technical Services (ITS) by providing a quantitative technique for evaluating reliability and different options in engine maintenance.

This research project was supported in part by a grant from Icelandair Group.

Keywords: Jet engine, Reliability, Reliability Block Diagram, Lifetime Distributions, Reliability Modeling

ÁGRIP

Áreiðanleikagreining á RB-211 þotuhreyflum Icelandair

Þotuhreyflar eru mjög flókin kerfi sem byggjast á ýmsum undirkerfum og verða að uppfylla strangar kröfur um áreiðanleika. Aukinn áhugi hefur myndast undanfarin ár á þróun megindlegra aðferða við að meta áreiðanleika og útbúa áreiðanleikalíkön af þotuhreyflum í því skyni að bæta áreiðanleika þeirra, draga úr bilanatíðni undirkerfa og minnka viðhaldskostnað. Fyrirliggjandi áreiðanleikalíkön taka þó aðeins tillit til fárra hluta hreyfilsins eða líta á hreyfilinn sem einn hlut.

Meginmarkmið þessarar rannsóknar er að þróa megindlega aðferð til að ákvarða áreiðanleika Rolls-Royce RB-211 þotuhreyfla á vegum Icelandair. Nákvæmt áreiðanleikalíkan af þotuhreyfli sem heildar kerfi hefur ekki verið þróað að svo miklu leyti sem hægt er að finna merki slíks í tækniritum sem eru aðgengileg á opnum vettvangi. Áreiðanleikalíkanið sem er þróað í þessu verkefni byggir á Áreiðanleika Blokk Rit (RBD) aðferðinni sem gefur mjög aðgengilega og einfalda lýsingu á hvernig mismunandi undirkerfi tengjast til að skila heildarlíkani af hreyflunum hvað áreiðanleika varðar. BlockSim 9 hugbúnaðurinn er notaður til að byggja og keyra áreiðanleikalíkanið, þ.e. til að setja saman líkanið byggt á líkönum af undirkerfum hreyfilsins og fyrir alla útreikninga og hermanir sem byggðar eru á þessum líkönum.

Helsta framlag þessarar ritgerðar er þróun og framsetning fyrsta áreiðanleikalíkans sem gert hefur verið af RB-211 þotuhreyflinum. Líkanið er byggt upp af undirkerfum og hlutum hreyfilsins þar sem tillit er tekið til líkindadreifinga líftíma hlutanna sem og viðhalds hvers hlutar. Þessar líkindadreifingar eru byggðar á viðhaldsgögnum yfir fimm ára tímabil úr rekstri þessara hreyfla hjá Icelandair. Í þessum tilgangi er hugbúnaðurinn Weibull++ notaður. Þess er vænst að áreiðanleikalíkanið af RB-211 þotuhreyflunum muni koma að góðum notum fyrir Tækniþjónustu Icelandair (ITS) með því að gefa kost á megindlegri aðferð við að meta áreiðanleika og áhrif mismunandi valkosta í viðhaldi hreyflanna.

Verkefnið var styrkt að hluta með sérstöku fjárframlagi frá Icelandair.

Lykilorð: Þotuhreyfill, Áreiðanleiki, Áreiðanleika Blokk Rit, Líkindadreifing líftíma, Gerð áreiðanleikalíkans

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Harpa Rún Garðarsdóttir

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1. INTRODUCTION

This chapter should provide the reader with the reason for this research project by giving a general introduction and the background of the problem being addressed in this Master's thesis.

1.1 Background

The area of reliability of complex apparatus and systems has in the past been considered to be a bit of a "black art" in the view of many technical experts. The reason is in part that the tools and methodologies for addressing the problems facing the designers and operators of complex systems have to a large extent been disparate and difficult to apply due to dimensionality. One of the problems is that large quantities of data, obtained from operations or special test programs, are typically required for developing good statistical reliability models. This situation has changed considerably in the past few years because of the emergence of new methods and new software tools that enable a more systematic approach to be taken to many of these problems. The objectives of a reliability study may for example be to understand the failure characteristics and estimation of and predicting reliability [1]. The main benefit of reliability analysis of complex systems lies not necessarily in the absolute predicted reliability, but in the ability to repeat the assessment for different component quality, expressed in terms of e.g. failure rate, different repair times and different redundancy arrangements in the design configuration [2].

One of the main driving forces with aircraft and jet engines is safety [1]. Air travel is one of the safest transportation mode with the modern commercial jet engines being very reliable [3][4]. This high reliability is required where failures of jet engines can lead to serious accidents [1]. Jet engines are an example of a very complex system with various interacting sub-systems and stringent repair requirements, thus making detailed reliability modeling of the jet engine a difficult task. Reliability assessment of jet engines using probabilistic methods has received increased interest in recent years due to greater appreciation of stochastic models and concerns about airworthiness[1] issues of aging aircrafts [6]. Furthermore the jet engine maintenance costs are the highest of airline maintenance costs and carries with it the risk of high unexpected expenditure in any single event when an engine has to be repaired on-wing or removed for a shop visit (SV) to perform a repair or full overhaul [7]. It would be beneficial for airlines to develop a quantitative reliability model to help improve forecasting and plan maintenance actions in the future, both from the point of view of reliability and cost perspectives.

[1] Airworthiness is a measure of an aircraft's condition and suitability for safe operation [5].

1.2 Problem statement

Reliability is crucial in order to ensure flight safety and efficiency in operations. The study of reliability models in order to improve system reliability, prevent system failure and reduce maintenance cost is an important area of research in the aviation industry [8]. Due to high reliability and safety requirements, good maintenance strategies for jet engines are very important. With the help of a reliability model of the jet engine, the airline can evaluate the expected impact of different decisions and maintenance strategies in terms of reliability and costs. This can be very beneficial since without such a tool the airline may have to wait several years to see the results of the different decisions on the operations and reliability of the jet engine. No such tool has however been available until now to Icelandair Technical Services (ITS) where decisions regarding engine maintenance have been made based on rules and regulations, engineering judgment and guidelines from the Rolls-Royce engine manufacturer. A reliability model of the RB-211 jet engines would be of great value for ITS by providing an up-to-date quantitative technique for evaluating reliability and different options in engine maintenance.

1.3 Aim and objectives

The main objective of this research project is to develop a quantitative method for determining the reliability of the Rolls-Royce RB-211 jet engines operated by Icelandair. This method will be based on a recognized modeling technique that provides a description of how various sub-systems interact to deliver the designed functionality and performance of the engines. The engine will be divided into sub-systems and components from a top-down point of view and their interrelationship will be established in terms of reliability. The resulting reliability model should make it possible to compute the overall reliability of the engines as well as enabling the analysis of how individual sub-systems and subassemblies affect engine reliability. Furthermore the resulting reliability model would make it feasible to evaluate maintenance strategies by simulating the performance of alternative approaches to engine maintenance. This would focus on each critical component of the engine as well as the engine as a whole. The model should provide a solid understanding of the reliability of jet engines by emphasizing transparent and accessible presentation of the results. A detailed reliability model of the system as a whole, the RB-211 jet engines, has not been developed before [9].

The following tasks will be carried out in order to achieve the aim and objectives of this research project:

- Investigation of the methods that have been used by other parties for determining the reliability of jet engines and similar systems with a view to evaluating which method would be best suited to reach the identified goals of this project.

- Initial analysis of the jet engine system leading to a model that is made up of sub-systems and modules whose reliability is known or can be determined in a straightforward manner. The interdependency of these components would also be investigated.
- Perform a simulation using these models and a suitable reliability simulation system to determine the overall reliability of the jet engines and their dependence on individual sub-systems.
- Proposal and analysis of some alternative maintenance strategies in order to investigate what possibilities exist for further increasing the reliability of the jet engines.

1.4 Research contribution

The contribution of this research project is the following:

- Formal initial analysis of the reliability of the RB-211 jet engines operated by Icelandair, including an estimate of the actual reliability of the engines in its present configuration.
- Assessment of the methods that could be employed for determining the reliability of the jet engines.
- Good understanding of the role that reliability modeling plays in ensuring the reliability of jet engines.
- A reliability model that can be used for analysis of alternative configuration and maintenance strategies.
- A reliability model that can be used for further studies including the collection of operational data to improve these models.

1.5 Research methodology

There exist various approaches for modeling system reliability. A review of the state-of-the-art in reliability analysis in the aviation industry will be performed. The methods that are found to be most promising in reaching the objectives of this research project are Reliability Block Diagram (RBD) for reliability modeling, life data analysis for analyzing operational data from Icelandair and Monte Carlo simulation for analyzing the resulting reliability model. These methods are better described in chapters 3 and 4.

A commercial software tool, BlockSim 9, developed by Reliasoft Inc. for applying the modeling RBD technique to reliability analysis will be used for reliability modeling of the jet engine. This software offers an environment for keeping track of and accounting for all the submodels of the system and providing a computation of the overall system reliability analytically or via Monte Carlo (MC) simulation. The Weibull++ software tool, also from Reliasoft Inc., will be used to process the data and generate the probability models that are used in the RBD for reliability analysis. The BlockSim software has already been used in a Master´s Thesis by Unnur

Þórleifsdottir to develop a model of the electrical power system of Isavia´s Air Traffic Control Center in Reykjavik [10]. This research project will benefit from the experienced gained in this previous project which was concluded in a successful way.

The resulting reliability model will be used to analyze the reliability of the jet engines in its present configuration and the effects of alternative maintenance strategies on the reliability.

1.6 Assumptions and limitations

The RB-211 jet engines will be modeled in its present configuration when determining the reliability. The jet engine is a very complex system with many parts and components. Following are the assumptions and limitations that have been established in the development of the reliability model.

The focus in this research project will be on the main components needed for the operation of the engine. In reality, each component can fail due to several reasons, i.e. due to several failure modes. In this research project no distinction will be made which failure modes cause component failure. Furthermore it is assumed that components fail independently of other components. When components fail they are repaired. In this model, it is assumed that the time it takes to repair each component is fixed, but the time depends on the component in question. Enough repair capacity is assumed to be available when needed. In reality however the maintenance time varies for various components and different numbers of repair crews are available depending on the location at which the repair is performed.

In the simulation of the reliability model, the hours for each operation phase[2] are assumed to be fixed, set as the average operation time for each phase from real operation data.

In addition to reliability modeling and analysis of the jet engine, the consequences of failures will also be addressed. The only costs considered in this research project are the so called disruption index (DI), which measures the disruption to the operation if failure occurs in different components, such as financial outlays and flight delays. Other maintenance costs, such as component costs, manpower costs and logistics costs are not included in this model.

1.7 Structure of the thesis

This thesis is organized into 7 chapters. Chapter 1 is intended to provide the reader with the reason for this research project. A general introduction and the background of the problem being addressed in this research project are provided. Following is the problem statement, the main objectives and the contribution of this research project. A short introduction to the methodology used in this project will be given along with

[2] Ground phase, take-off phase, in-flight phase.

the main assumptions and limitations. In chapter 2 the concepts of reliability and reliability analysis are introduced along with a review of the state-of-the-art. In chapter 3 the mathematics and theory behind reliability calculations and life data analysis are provided. In chapter 4 the RBD methodology used in this research project is explained. The case study of the development of the reliability model and reliability analysis of the RB-211 jet engines is presented in chapter 5. The results of the reliability analysis are presented and discussed in chapter 6 where the reliability model developed in this thesis is used for analysis of the jet engine in current configuration and the effects of implementing new maintenance options are evaluated. Finally chapter 7 gives a summary of this Master's thesis and the main conclusions and recommendation of future works for the reliability model developed in this research project.

2. CONCEPTUAL FRAMEWORK

In the very competitive aerospace market today, where safety, reliability and operating costs of equipment are often paramount, there are many drivers to maintain a viable and economic operation. The significance of reliability and maintainability on operations and cost has been recognized by most, if not all, airlines and engine manufacturers [11]. This chapter will provide the main concepts of reliability analysis and the methods previously used in the industry for reliability analysis of jet engines.

2.1 Concepts of reliability analysis

It is important that all concepts used in reliability analysis are defined in an unambiguous way [12]. There are different definitions of basic concepts given in different standards relating thereto. Following are the definitions used for the remainder of this research project.

Reliability cannot be specified without an associated time frame and to be more complete one should specify reliability by specifying reliability, time and confidence level [13]. Reliability is, as defined in military standard MIL-STD-721C:

> *"The probability that an item can perform its intended function for a specified interval under stated conditions"* [14].

The performance of systems not only depends on the design and operation but as well on the servicing and maintenance of the system during its operational lifetime [1]. Reliability gives the probability of no system failure for a given time period, but for repairable systems more metrics than reliability might be of interest since failures do occur and systems are repaired, for example maintainability and availability.

Maintainability is the probability that a failed system can be made operable again in a specified period of time [15]. According to military standard MIL-STD-721C, maintainability is:

> "*The measure of the ability of an item to be retained in or restored to specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair"* [14].

Availability is a performance metric for repairable systems and gives the percentage of time or the probability that a system is available when requested. Availability depends both on the reliability and maintainability of the system, i.e. in order to improve availability either an increase in reliability or an increase in maintainability (reduce downtime) is necessary. It is defined according to British Standard BS 4778 as:

> *"The ability of an item (under combined aspects of its reliability, maintainability and maintenance support) to perform its required function at a stated instant of time or over stated period of time"* [16].

Failure criteria: When analyzing system reliability, it is important to have a clear definition of what constitutes a system failure, in order to determine which failure modes, at the component level, actually cause a system failure [2]. Failure is according to IEC 50(191) the event of a termination of the ability of an item or system to perform a required function [17]. Each system function may have several failure modes, which can involve different component failure modes and even different component configurations. Having the system failures clearly defined therefore is important in order to execute the reliability analysis in a correct way [2].

Reliability analysis can be divided into qualitative and quantitative. Qualitative analysis is intended to verify the various failure modes and causes that contribute to the unreliability of a component or system. Quantitative analysis uses real failure data, which can be obtained from operation or test programs for example, together with suitable mathematical models to obtain quantitative estimates of component or system reliability and other reliability metrics [1].

2.2 Reliability analysis of jet engines

Numerous methods and models have been developed for risk and reliability assessment in safety-critical operations, such as operations in the computer, nuclear, and aviation industries [18]. In the literature, reliability analysis of jet engines has mainly been on the basis of the jet engine as a single component or made up of a few basic modules, or based on the reliability analysis of separate components without connecting them all at a system level. J. Kappas (2002) stresses the need for the development of system reliability models of the engine as a whole in the author's review of risk and reliability methods for jet engines [6]. It should be pointed out however that large amount of work that has been carried out in this field in the aviation industry is kept confidential by airlines and engine companies for competitive or commercial reasons.

The Rolls-Royce Company (RR), which manufactures the RB-211 jet engine, realizes that reliability is not an isolated or an optional part of airlines' business and aircraft components, such as the jet engine. The reliability must be addressed all the way from the start of the design through its life [19]. These methods previously used in the aviation industry range from qualitative to quantitative reliability analysis methods. Following is a short description of commonly used methods along with examples of associated literature.

2.2.1 Qualitative method

Failure modes and effects analysis (FMEA) is a technique of identifying failures and the consequences of failures within systems and are recorded in a specific worksheet relating thereto. When this is done together with a criticality analysis the combined method is then called FMECA. Performing a FMEA or FMECA is often the first step in system reliability evaluations and many companies use it for assess the failure risk during the design phase [12], [20]. Atamer (2004) shows how FMEA records can be a valuable resource for engine manufacturers and how the knowledge can be converted into useful diagnostic knowledge during engine operation, maintenance and service [21].

2.2.2 Quantitative methods

Reliability Block Diagram (RBD) provides a very convenient description of how various sub-systems interact to deliver the performance of the engines as far as reliability is concerned. RBD is a graphical representation of a system describing the function of the system and shows the logical interconnections of components needed to fulfill this function [12]. A thorough understanding of how the components function and how these functions affect the system operation is necessary before analyzing reliability of any system [22]. RBD is useful for gaining this understanding and identifying the types and levels of data and other information needed for further quantitative reliability analysis [1].

An example of an RBD can be seen in figure 2-1. The system is functioning if there is a path from the start point of the diagram to the end [10]. In this diagram components 1, 2 and 3 must function for the system to function. The other components are in a redundancy configuration, where not all of them are needed for the system to function.

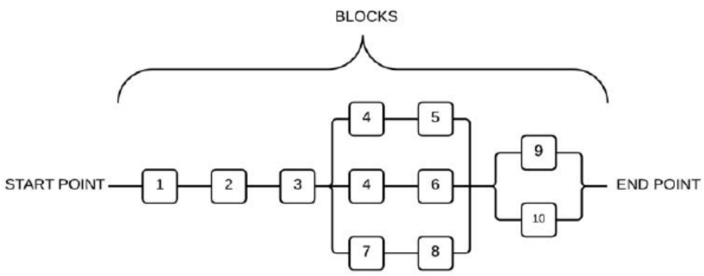

Figure 2-1 – An example of an RBD [10]

By assigning probability models to the blocks in the RBD an overall system reliability analysis can be performed. The system reliability is based on the blocks characteristics and their reliability-wise configuration. The block's configuration can be simple with a series structure or complex with for example redundancy, stand-by and k-out-of-n structures[3]. Analyzing the RBD can both be done analytically and with a simulation. For very complex systems however, with complex configuration and/or repairable components, obtaining analytical solution can be very intense or even impossible, where the simulation can be used to obtain solutions [13].

Information on the use of a detailed, complex RBD in the aviation industry cannot be found in literature. Examples are available of simple RBD's with few blocks connected in series used for reliability analysis of jet engines, such as a model of six blocks used by Baldwin (1992) when analyzing the reliability of a military aircraft engine, and a model of four blocks used by Kumar (1999) when examining reliability and maintenance measures for aircraft [23], [24].

Fault Tree Diagram (FTD), as well as RBD, shows graphically the reliability structure of the system. The difference is that FTD shows the failure combinations of the system whereas RBD shows the success combinations. FTD is a top-down approach and illustrates all possible combinations of possible failure events within a system that can lead to failure or nonsuccess of the system function. Generally, FTD can be easily converted to RBD, but for complex configurations it is more difficult to convert RBD to FTD. Same system analysis can be done on both RBD and FTD thus erasing the distinction between those two diagrams; however it is often more natural to base system reliability evaluations on RBD where the system is represented in terms of components or functions. [13], [12]

Monte Carlo (MC) simulation is the most common method currently used in industry when analyzing reliability of complex systems [25]. MC simulation is carried out by simulating a lifetime scenario for a system by using a suitable computer package. The system is represented by a model, such as an RBD or flow diagram [12]. Random failure times are generated in the model, in accordance with the failure distributions of the components in the system. Moreover scheduled events and other conditional events, such as maintenance events initiated by component failure, are included to represent a lifetime scenario as close to real lifetime as possible [12].

When a lifetime scenario has been generated by the simulation, this scenario can be used to calculate performance metrics for the system and its components, such as reliability and expected number of failures. To obtain statistical significance, repeated simulations are needed to generate number of independent lifetime scenarios [12]. Kumamoto et al. (1977) show an example of estimating reliability of a hypothetical, large complex system represented by a reliability block diagram with the MC method [26].

Life data analysis[4] is used to make predictions about the life of all components in the population by fitting a statistical model to life data from a representative sample of

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[3] Details on component's configuration are provided in chapter 4.2.4

[4] Also commonly referred to as Weibull analysis

units. The statistical distribution for the data set is then used to estimate important life characteristics of the components such as the mean life, the failure rate, reliability or probability of failure at a specific time [27]. Bayesian statistics may be added to life data analysis, where prior information are added to the probability model along with observed data to obtain posterior probability density function [7], [12]. More details on life data distributions are found in chapter 3.1. The life data analysis has been used for reliability analysis of single components, whether a sub-component of the engine, the engine as a whole being considered as one component or for a combination of components. This method was for example used by Tyson (2011) and his team for the US Army to increase the reliability of engine fuel controllers[5] (FC) whereby the failure modes were combined and reduced with the help of life data analysis. This enabled more detailed analysis of the root cause failures of the FC [28], [29]. Weckman et al. (2001) used life data analysis to forecast engine removals on a monthly basis whereby no distinction was made between failures modes leading to engine failures causing engine removals [30]. Stranjak et al. (2008) use the Weibull lifetime distribution of engine components to obtain a reliability model for the whole engine. This model is used in a multi-agent[6] simulation model for prediction and scheduling of engine overhauls. No details are given however on which and how many components are used for this purpose and the obtained distributions [32].

Reliability centered maintenance (RCM) is a technique, originated in the aviation industry, designed to minimize the maintenance costs by balancing the costs of corrective maintenance (CM) and preventive maintenance (PM) to develop the most cost-effective PM program. It is based on the assumption that the inherent reliability of the products is a function of the design and quality and is used to ensure the inherent reliability is maintained. The RCM has been successfully applied in the industry for over 30 years [12], [33], [34]. For example, Crocker and Kumar (2000) suggest an approach using RCM and Monte Carlo simulation with soft life[7] and hard life considerations[8] for optimizing the total maintenance cost. For this the authors use one engine component for illustration [33].

Markov model is a special type of stochastic process which can be used to model systems with several states, such as operational and failed states, and the transitions between the states. Good overview of Markov modeling can be found in [12]. Markov modeling has been used in the aviation industry to determine the system reliability of large and complex systems; the following are two examples. Agte et al. (2012) propose a Markov model to evaluate the reliability and performance of a twin-engine aircraft where the engine is treated as one of the aircraft components [35]. Jackson (2009) proposes a reliability model which combines Markov analysis and the Weibull

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[5] The purpose of the fuel control is to control the fuel based on input from throttle levers in the aircraft cockpit.

[6] Information on agent-based simulation may be found in [31].

[7] Soft life is the age of component after which it will be replaced the next time the engine is repaired.

[8] Hard life is the age of component at which the component must be replaced.

distribution, which can be used to analyze for example complex systems in the aviation industry [36]. However, it is now generally acknowledged that for redundant repairable systems, like jet engines, the traditional Markov model does not correctly represent the normal repair activities [2], [37]. For situations where there are dedicated repair crews for each failure mode, the transition from failure state to operational state is independent of preceding failures and the Markov model is applicable. In real-life situations however there is limited number of repair crews so the transition to operational state depends on the progress of the repair of the last failure.

The focus of this research project is to build a model and determine the overall reliability of the RB-211 jet engines operated by Icelandair. The jet engine is a complex repairable system with redundancy configurations and maintenance activities. The main failure modes and components in this case are known[9] so that it is not necessary to use a qualitative tool to help determine the main failure causes. It was therefore determined that the methods best suited to reach the objectives of this research project are:

- **Life data analysis** to obtain lifetime distributions for each component of the jet engine that will be used in the model for the reliability analysis.
- **Reliability block diagram** to build a model of the repairable complex system that jet engines are. Even though there are no examples found in the literature of the use of complex RBD's for jet engines, the author believes there exist great opportunities in using RBD for jet engine modeling and reliability analysis.
- **Monte Carlo simulation** to help analyze the complex RBD model.

Further details on the theory behind Life data analysis is provided in chapter 3. In chapter 4 further details are provided on the RBD and MC simulation methodologies.

[9] See chapter 5.2

3. THEORETICAL FRAMEWORK

This chapter is intended to give an overview of the mathematics behind reliability theory, life data analysis, lifetime distributions and parameter estimation, focused primarily on material necessary for understanding the theory used in this research project. Extensive coverage of these subjects can be found in numerous statistical references, such as [12].

3.1 Reliability calculations

A probability distribution is fully described by its probability distribution function (*pdf*). The definition of *pdf* can be used to derive all other functions commonly used in reliability analysis [27]. Probability distributions, such as the lifetime distributions covered in chapter 3.1.1, all have their predefined form of the *pdf*. The mathematical relationship between the cumulative distribution function (*cdf*) and the *pdf* is given by [12], [13]:

$$F(t) = \int_0^t f(x)dx$$

The definition of the *cdf* can be used to derive the reliability function. The probability of a failure occurring by time t (the unreliability function) is given by [13], [27]:

$$Q(t) = F(t)$$

Reliability and unreliability are mutually exclusive so the sum of these probabilities is equal to one [16]. Then the reliability function is given by [12], [13], [27]:

$$R(t) = 1 - Q(t)$$

$$R(t) = 1 - \int_0^t f(u)du = \int_t^\infty f(u)du$$

$$R(t) = Pr(T > t), \text{ for } t > 0$$

Then the *pdf* for unreliability, i.e. the probability of instantaneous failure, is given by [13], [27]:

$$f(t) = -\frac{d(R(t))}{dt}$$

From the *pdf* the unreliability, *F(t)* = probability of failure before time a, as well as the reliability, *R(t)* = probability of no failure before time a, can be found. An example of a probability distribution function *f(t)*, the *pdf,* can be seen in figure 3-1, where the value of the *pdf* is on the y-axis and the random time variable on the x-axis.

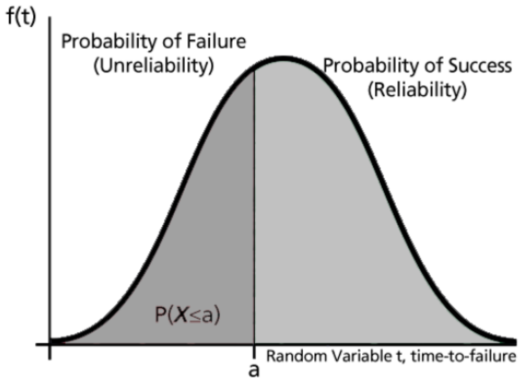


Figure 3-1 – Unreliability *pdf* [13]

The failure rate function[10], λ(t), provides the number of failures occurring per unit time, t. It is useful when characterizing the failure behavior of components and can be found by [13]:

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

Since *R(0)* = 1, so [12]:

$$\int_0^t \lambda(u)du = -\ln R(t)$$

$$R(t) = e^{-\int_0^t \lambda(u)du}$$

The reliability function *R(t)* therefore is uniquely determined by the failure rate function *λ(t)* [12].

3.1.1 Optimum reliability

The main roles of reliability analysis are to minimize the probability of failures where the impacts of failure can be costly and disturbing for operations. When adding maintenance considerations as well to the analysis, the role is to minimize the impact of failures as well. Increasing reliability or maintenance involves increased costs however, so often there is a trade-off between these costs. [1]

Figure 3-2 shows how the cost of an unreliable product decreases as the reliability increases as well as the costs of improving reliability increases with higher reliability [38].

[10] Also known as hazard function.

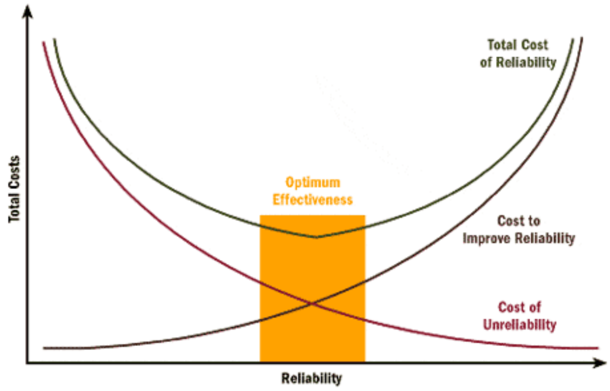


Figure 3-2 - Optimum reliability [38]

The optimum reliability should be at the point where both of these costs are minimized.

3.2 Life Data Analysis

Reliability models are used to estimate the failure rate of the product as a function of time as well as the probability of failure (or survival) of the product for a given period of time. These probabilistic reliability models are based on statistical distributions. Special subsets of probability distributions, called lifetime distributions, are most commonly used when analyzing reliability of products or components. Life Data Analysis uses statistical methods to build probabilistic models from life data which can be used to obtain reliability metrics of interest for the components.

3.2.1 Lifetime distributions

Depending on component characteristics, the failure rate as a function of time can be decreasing, constant, increasing or a combination of those. Figure 3-3 shows the so called “Bathtub” curve, which is a useful when explaining these basic concepts of reliability engineering [39]:

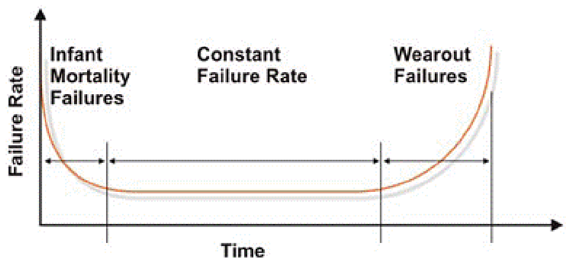


Figure 3-3 - The “Bathtub” curve showing infant, constant and wear-out failure rate vs. time. [39]

Some distributions tend to better represent life data and are most commonly called lifetime distributions. There exist a number of lifetime distributions, the following are the most widely used for this purpose [40]:

- **The exponential distribution** has been widely employed in reliability engineering due to its simplicity. It is used to describe units that have constant failure rates.
- **The Weibull distribution** is one of the most commonly used distributions in reliability engineering due to the many shapes it attains for various values of the slope parameter. The failure rate can be increasing, decreasing or constant.
- **The normal distribution** is symmetrical and is defined from negative to positive infinity with increasing failure rate.
- **The lognormal distribution** is non-negative and skewed positively which makes it more suitable for modeling life data than the normal distribution. The failure rate initially increases and then decreases.

The probability distributions in life data analysis represent the probability of component failure at each time.

The component's characteristics and failure behavior need to be considered when choosing the appropriate lifetime distribution. For example, failures of mechanical components are often modeled with Weibull distribution, whereas failures of electrical components are often modeled with exponential distribution since the failures are equally likely to occur regardless of age [41].

3.2.1.1 Exponential distribution

The exponential distribution is one of the most commonly used distributions in reliability analysis due to its simplicity [12]. The exponential distribution implies a constant failure rate λ and does not therefore capture any changes in failure rate over time. The popularity of the use of the exponential distribution has often led to misuse and erroneous results for components not having constant failure rate, where the analyst misses signals on infant mortality failures or wear-out failures mechanism [42]. The distribution however gives realistic lifetime models for certain types of components, such as electrical components, where it may be assumed that the age of the item does not change the failure behavior [12]. The probability distribution function (*pdf*) for the exponential distribution is defined as [27]:

$$f(t) = \lambda e^{-\lambda \mathrm{t}}$$

where λ is the failure rate and t is a variable representing time. In figure 3-4 the *pdf* for the exponential distribution is plotted with two different values for the failure rate λ. The x-axis represents time and the y-axis the value of the *pdf*.

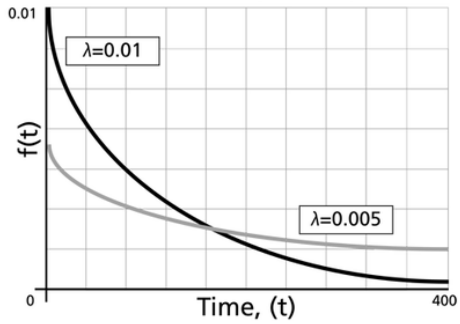


Figure 3-4 – Exponential *pdf with* two different λ values [27]

3.2.1.2 Weibull distribution

The Weibull distribution is useful in reliability calculation due to its flexibility and wide applicability and is frequently used to model time to failures of equipment [43]. By varying the parameters of the Weibull distribution, it can be used to approximate a wide range of failure characteristics, i.e. random, infant mortality or wear-out. Furthermore the analysis of the Weibull distribution provides information needed for classifying failure types, troubleshooting and scheduling inspections and preventive maintenance [44]. The *pdf* for the 2-parameter Weibull distribution is defined as [27]:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

where β is the shape parameter, η is the scale parameter and t is a variable representing time.

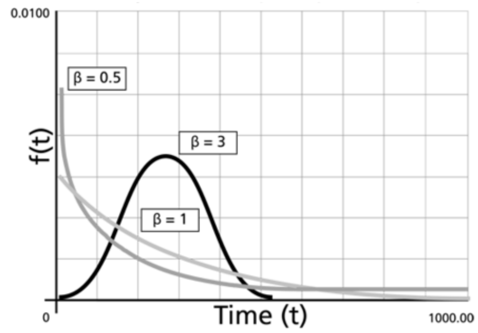


Figure 3-5 – Weibull *pdf* with three different β values [27]

In figure 3-5 the *pdf* for the Weibull distribution is plotted with three different values for the shape parameter β while the scale parameter η is fixed. The x-axis represents time and the y-axis the value of the *pdf*.

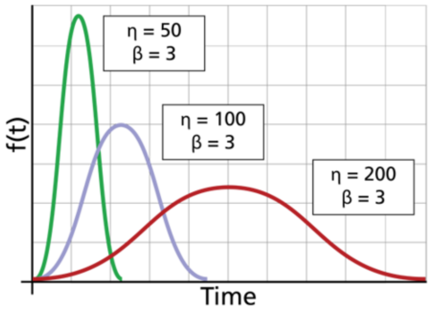


Figure 3-6 – Weibull *pdf* with three different η values [27]

The effects on the Weibull *pdf* of varying the η while keeping the β fixed can be seen in figure 3-6.

3.2.1.3 Normal distribution

The normal distribution is the most common distribution in statistics. It is sometimes used for lifetime modeling for general reliability analysis and simple electronic and mechanical components, even though it is defined from negative to positive infinity with positive probability [12]. The failure rate for the normal distribution is increasing. The *pdf* for the normal distribution is defined as [27]:

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2}$$

where μ is the mean of the times to failure, σ is the standard deviation and t is a variable representing time.

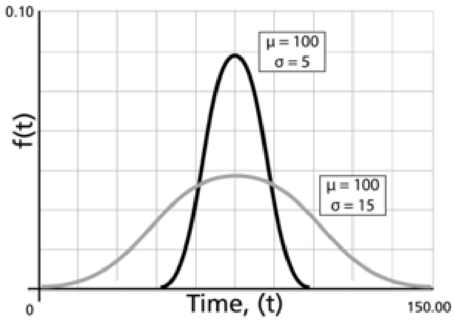


Figure 3-7 – Normal distribution, *pdf* with two different σ values [27]

The *pdf* for the normal distribution is plotted in figure 3-7, with two different values for the standard deviation σ while the mean μ is fixed. The x-axis represents time and the y-axis the value of the *pdf*.

3.2.1.4 Lognormal distribution

The lognormal distribution can have wide application and is commonly used for general reliability analysis, repair time modeling and for components with fatigue failure behavior[11], which applies for most mechanical systems [12], [27]. The lognormal distribution is non-negative and positively skewed making the distribution more suitable for lifetime modeling than the normal distribution. The failure rate is increasing, then decreasing to zero. Times to failure are lognormally distributed if the logarithm of the times to failure is normally distributed. The *pdf* for the lognormal distribution is defined as [27]:

$$f(t) = \frac{1}{t * \sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\ln(t)-\mu}{\sigma}\right)^2}$$

where μ is the mean, σ is the standard deviation and ln(t) is normally distributed time.

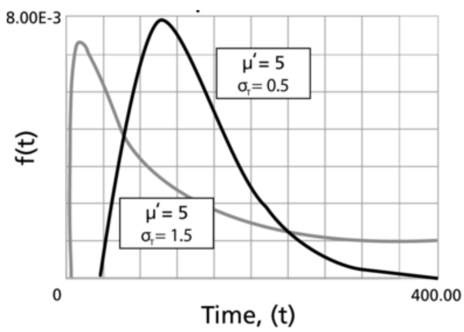


Figure 3-8 – Lognormal distribution, *pdf* with two different σ values [27]

In figure 3-8 the *pdf* for the lognormal distribution can be seen, with two different values for the standard deviation σ while the mean μ is fixed. The x-axis represents time and the y-axis the value of the *pdf*.

3.2.2 Life data classification

In life data analysis, the data needed for the lifetime distributions are the lifetime or times to failure of the components in the sample. In order to correctly estimate a lifetime distribution based on the underlying data it is important to consider what type of data it is, i.e. whether the data includes all information needed data or if there is some missing information. There are four types of data [12]:

- **Complete data:** Exact time to failure known.
- **Right censored data (Suspensions):** Component will fail sometime in the future; it has not failed yet at the time of inspection.
- **Left censored data:** Component failed sometime between time 0 and when inspected.
- **Interval data:** The time interval for when the component failed is known.

[11] Fatigue failure behavior is when the failure rate increases with more stress loads.

An illustration of a data set for five units can be seen in figure 3-9. To the left the data set is complete where all failure times are known. To the right the data set contains suspensions, where two of the units have not yet failed at time of inspection.

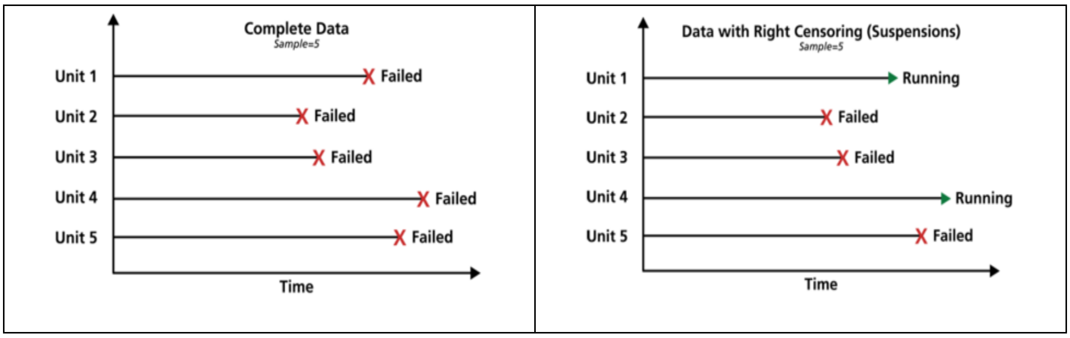


Figure 3-9 – Example of complete data set and data set with suspensions [27]

Censored data do not add as much information as complete data. It is important however not to ignore the missing information on times to failure when estimating the underlying lifetime distribution, the number of components suspended for example must be taken into account. [45] [46]

3.2.3 Parameter estimation

The parameters of the chosen model are estimated to fit a model to the data set. There are several parameter estimation methods available. For life data analysis, the parameter estimation methods most commonly used for life data analysis are; probability plotting, least squares (linear regression), maximum likelihood and Bayesian methods. [27]

In probability plotting the data is plotted on a specially constructed probability plotting paper. An attempt is made to linearize the *cdf* of the distribution by employing this plotting paper. This method was mainly used before the widespread use of computers that can easily perform the calculations for more complicated methods, such as least squares and maximum likelihood. This method however is good to help assess how well the probability distribution fits the data. [27], [47]

The least squares parameter estimation mathematically estimates the parameters that result in a straight line best fitting the data. The straight line is fitted to the data points such that the sum of the squares of the vertical deviations from the points to the line is minimized [48].

The maximum likelihood estimation (MLE) is a statistical approach where the parameters are estimated such that the probability that the data set belongs to that distribution is maximized. MLE has good statistical properties when the sample size is large but can be biased for small sample sizes [27].

In Bayesian statistics a prior knowledge is incorporated into the life data analysis along with a given set of current observations. This prior information could come from previous comparable experiments, from engineering knowledge or from operational or observational data. Bayesian statistics can be particularly useful when there is limited data for given failure mode or design but there is a strong prior understanding of the failure rate behavior [12], [27].

As a rule of thumb, least squares parameter estimation should be preferred for small sample sizes (less than 30) and for complete data. MLE should be used when sample size is sufficiently large and/or censored data is present [27]. In this research no other data than the failure data, i.e. no prior knowledge, will be incorporated into the model and censored data is present so the MLE method will be used.

3.2.3.1 Confidence bounds

There is always uncertainty involved in life data analysis, since the estimates are based on the observed lifetimes of sample components. Confidence bounds are used to quantify this uncertainty and give an estimated range of plausible values that for the parameter being estimated. Confidence bounds are generally thought of as one-sided or two-sided. For example when using 90% two-sided confidence bounds in parameter estimation, it means that the true value of the parameter should lie within the bounds with 90% certainty, i.e. 90% of the time the true value lies within the bounds and below or above in 10% of the time. Figure 3-10 shows graphically an example of a two-sided 90% confidence bound [49].

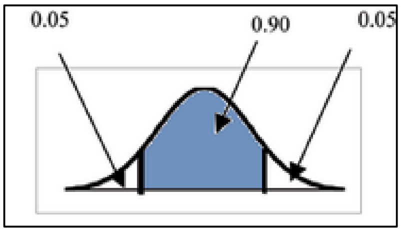


Figure 3-10 - Two-sided 90% confidence bounds.

4. METHODOLOGY

The reliability analysis of the jet engines operated by Icelandair will be performed by building a reliability block diagram (RBD) model of the engines. The reliability model will be analyzed by simulating the diagram.

4.1 Reliability Block Diagram (RBD)

RBD is a success-oriented network describing reliability structure or the functioning of the system, using blocks to represent the components of the system and lines for success paths. The way the components are interconnected for the system to be operational may be illustrated by a RBD. An example of a RBD can be seen in figure 4-1. For the system to be operational, a functioning path has to exist from the start of the diagram to the end [12].

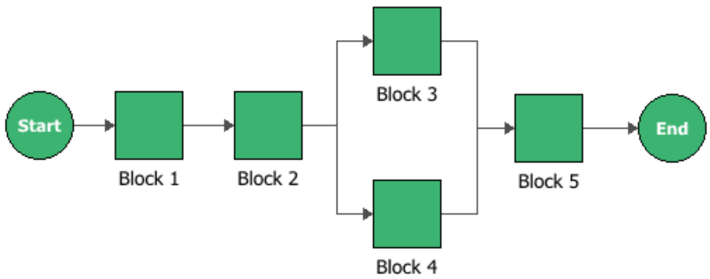


Figure 4-1 – An example of RBD. The system is operational if a path exists from the start to the end.

The system level RBD model is established as a function of the components (the blocks in the diagram). Having the life distributions for the components, i.e. the individual reliabilities, reliability metrics of interest can be obtained for the whole system based on the reliabilities of the components. [22]

The commercial BlockSim 9 software is used in this research project for establishing and running the RBD model, i.e. for accepting the models of all components and for undertaking all computations and simulations that are based on these models.

4.2.4 RBD configurations

The RBD shows the reliability-wise connections of components needed to fulfill a specific function. The system is only operational when a path exists from the start point of the system to the end point. There are different reliability-wise configurations possible and the RBD may be constructed from one configuration or a combination, depending on the system [12], [13], [22].

4.2.4.1 Series configuration

The simplest form of a system is where all blocks are connected reliability-wise in series. In this configuration, if one block fails than the system fails, i.e. all blocks must be operational for the system to be operational [22]. An example of a system in a series configuration can be seen in figure 4-2:

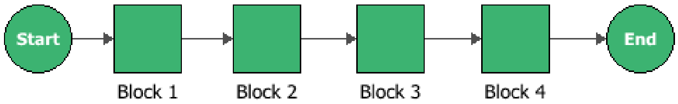


Figure 4-2 – RBD in series configuration

The reliability function (R_S) for a system with n components in series configuration is [13]:

$$R_S = R_1 * R_2 * \dots * R_n = \prod_{i=1}^{n} R_i$$

4.2.4.2 Parallel configuration

If a system is operational if at least one of its components is operational, it is in a parallel configuration. This is also called redundancy, since there is not a need for all components to be operational for the system to be operational [22]. Redundancy is often designed into systems in order to prevent or mitigate the risk of system failure where the reliability increases with more components in parallel [50]. An example of a system in a parallel configuration can be seen in figure 4-3:

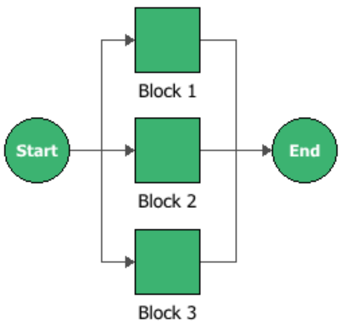


Figure 4-3 - RBD in parallel configuration

The reliability function (R_S) for a system with n components in parallel configuration is [13]:

$$R_S = 1 - (1 - R_1)(1 - R_2) \dots (1 - R_n) = \prod_{i=1}^{n} 1 - (1 - R_i)$$

4.2.4.3 k-out-of-n configuration

When system is in a k-out-of-n configuration, at least k out of total n components must be operational for the system to be operational. Series configuration is therefore an n-out-of-n configuration and parallel configuration is a 1-out-of-n configuration [12]. A node block is used to specify the number of components needed for the system to be operational, i.e. the node can have *n* paths leading into it (*n* blocks in parallel) and requires that *k* out of those *n* paths must be operational for the system to be operational [51]. An example of a system in 2-out-of-3 configuration can be seen in figure 4-4, where at least two components must function for the system to function:

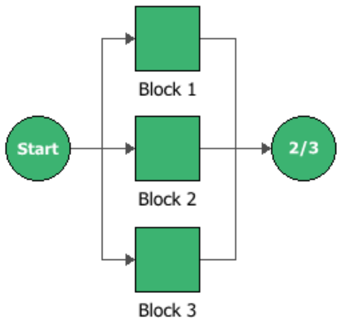


Figure 4-4 - RBD in k-out-of-n configuration

The reliability function (R_S) for a system with *n* components in *k*-out-of-*n* configuration is [13]:

$$R_S = \sum_{i=k}^{n} \binom{n}{i} R^i (1-R)^{n-1}$$

Where R is the reliability for each component and *k* is the number of paths required.

4.2.4.4 Other configurations

Load sharing configuration is when two or more components share the responsibility of the system being operational. If one component fails, the other(s) compensate for that failure and take on increased load so the system can continue to operate [51]. Now the failures of the components are dependent[12], so the failure of one component usually decreases the reliability of the other(s) under increased load [52].

Standby configuration is when *k* out of *n* redundant components are required to be in an active state and the remaining components are in a standby state, where both states have a defined failure distribution. After a failure in an active component, the component in a standby state is activated to keep the system operational [22], [51].

These configurations are not used in this research project and will not be discussed further.

4.2.3 Block properties

A block in a RBD can be a component, a system, a sub-system or a failure mode. Each block has its own lifetime distribution and other properties, such as cost and maintenance properties. In each block in the BlockSim 9 software, a universal

[12] Failures of components are assumed to be independent in previously defined configurations.

reliability definition (URD) is defined, which are the resources that are used to represent the properties that are applied to the blocks and include the failure behavior and maintenance tasks [13], [51].

4.2.3.1 Failure model

A failure model, which describes the failure behavior, of each component is defined for each block, within the block's URD. This failure model may be estimation, based on engineering judgment or an obtained lifetime distribution through life data analysis[13].

4.2.3.2 Maintenance definition

The performance of a repairable components and systems not only depends on its design and operation, but also on the servicing and maintenance of the components during the operational lifetime [1]. Maintenance is defined in general as any action that restores failed items to an operational state or retain non-failed items in operational state [13]. There are two primary categories of maintenance actions, preventive maintenance and corrective maintenance [1].

Preventive maintenance comprises actions taken before the component or the system fails, intended to increase the reliability and/or the lifetime of systems. These actions involve minor servicing up to major overhauls [1]. Cost is always important when scheduling preventive maintenance. In some circumstances the cost of a failure does not outweigh the cost of preventive maintenance, in other circumstances however it may be more sensible to replace components that have not failed at a predefined interval rather than waiting for a failure which may cause costly disruption for the operation [13].

Corrective maintenance consists of the actions taken to restore a failed component or system to an operational state. These actions include repair or replacement of failed components that are necessary for the system to be successfully operational again [1], [13]. If a component in the jet engine is replaced during corrective maintenance, the failed component is removed from the engine and replaced by another component previously repaired. The removed component is repaired to operational state and is used as a replacement when the next component of the same type fails [9].

[13] See chapter 3.2 for information on life data analysis

4.3 RBD model analysis

The RBD model can be analyzed analytically to obtain for example a reliability function for the system and other reliability metrics of interest. When the system is repairable, other analyzing methods are necessary to count for repair and restoration actions, where the operating time of the system is no longer continuous and the age of the system components is no longer uniform. To obtain information on reliability and availability for repairable systems, analysis through simulation, such as the Monte Carlo simulation becomes necessary. [51], [53]

The use of software for analyzing RBDs has become popular for reliability analysts and engineers, especially for complex redundancy systems [54].

4.3.1 Analytical analysis

Analytical system analysis involves the determination of a mathematical expression describing the reliability of the system in terms of the reliabilities of the components. That is, the system's *pdf* is obtained, using probability theory, from each component's lifetime distribution. From the *pdf*, various reliability metrics can be obtained, such as the reliability as a function of time and the mean-time-to-failure (MTTF) of the system. [53]

In this research project however, the system is repairable, so analytical analysis will not be performed.

4.3.2 Repairable systems analysis

For repairable systems, information on the repair and maintenance characteristics of the components are included in the components characteristics. When analyzing repairable and/or complex redundant systems, simulation is required since the analytical solutions are very difficult or even impossible to obtain. [54]

4.3.2.1 Monte Carlo simulation

Monte Carlo simulation is the most flexible approach when analyzing availability of repairable systems [12]. Typical lifetime scenarios for the system are simulated by generating random failure times for the components in the system, based on each component's lifetime distribution. Moreover scheduled maintenance events and other conditional events, such as corrective maintenance initiated by component failure, are included to represent a lifetime scenario as close to real lifetime as possible.

The overall system behavior is then determined by combining the failure times and maintenance events of the components in accordance with their reliability-wise connection. The lifetime scenarios generated in the simulation are then used to calculate performance metrics for the system and its components. [12], [53]

4.3.2.2 Reliability metrics

When lifetime scenarios have been simulated, these scenarios are used to calculate performance metrics for the system [12]. There are different metrics possible when analyzing reliability, what metric one chooses to use depends the objective of the analysis and on the underlying reliability model. For repairable system analysis the reliability alone does not give enough information, since it is the probability of no system failure for a given time period. Maintainability and availability of the system must be taken into account, i.e. the system fails and is repaired so the system uptime and downtime are considered. [12], [13]

M(t) is the maintainability at time t, i.e. the probability that after a failure, the item will be operational again after time t. The time it takes to repair the item is treated as a random variable and is given a probability distribution. For example, for an exponential repair distribution with repair rate μ, the maintainability would be defined as:

$$M(t) = 1 - e^{-\mu t}$$

The performance criterion for repairable systems is availability, i.e. the probability that the system is operational when it is needed. *A(t)* is the point availability at time t, i.e. that an item is operational at time t. The availability can also be measured as an average availability over specified period, including or excluding preventive and corrective maintenance events. The availability depends on the reliability until time t and the maintainability, i.e. repair actions on the item are completed and it has not failed since. The mean availability, including all maintenance events is defined as [13]:

$$\bar{A}_{All} = \frac{Uptime}{Total\ operating\ time}$$

The Failure Criticality Index (FCI) is a relative index representing the percentage of times that a component failure caused a system failure. For each component, the FCI is defined as [55]:

$$FCI_i = \frac{Number\ of\ system\ failures\ caused\ by\ component\ i}{Total\ number\ of\ system\ failures}$$

Other metrics of interest when analyzing repairable systems might be the following [13], [22]:

- Expected number of failures, $\mathbf{N_f}$, which is the average number of failures over all simulation runs.
- System uptime, $\mathbf{T_{UP}}$, is the average time the system was operating and is found by summing up the uptimes for each simulation and dividing by the number of simulations.

- System downtime, $\mathbf{T_{Down}}$, is the average downtime of the system due to all downing events and is found by summing up the downtimes for each simulation and dividing by the number of simulations.
- Mean-time-to-first-failure **(MTTFF)** is the mean time to first system failure and is found as the average of first system failure over all simulation runs.
- Mean-time-between-failures **(MTBF)** is the mean time between system failures and is found as the average over all simulation runs. This metric however does not tell the whole story about reliability of systems, since the same MTBF for different components does not result necessarily in the same reliability at any given times. Reliability metrics may be therefore more descriptive of the expected life of components rather than MTBF [42].
- Mean-time-to-repair **(MTTR)** is the mean time of repair times and is found as the average of repair times over all simulation runs.

4.4 Reliability phase diagram (RPD)

Reliability phase diagrams (RPDs) are extensions of RBDs, where they are used to represent and analyze systems whose reliability-wise configuration and/or other properties of the system or components change over time, with the system going through different operational and maintenance phases. Each stage during operation can be represented by a phase with properties inherited from an RBD corresponding to the reliability configuration in that phase. RPD is the series of these phases connected in chronological order and provide a great flexibility and ability to simulate such complex scenarios more realistically. [13], [56]

Two types of phases are used in the RPDs in the BlockSim software, operational phases and maintenance phases. The operational phases are used to represent the stages of the system operation that are not exclusively dedicated to the execution of maintenance tasks and are always linked to an RBD. The maintenance phases are used to represent the portion of a system's operation time where maintenance tasks are performed and the system is down [13], [56].

For the maintenance phase, there is a possibility to define an interval maintenance threshold, a number from 0 to 1 (let's call it X), which adds some flexibility to the timing of scheduled maintenance tasks. Then the scheduled tasks will be performed if the component's age has reached X% of its scheduled maintenance task when the maintenance phase starts. If the threshold is 0,9 for example and a failure occurs after 10.000 hours in a component which scheduled for a preventive maintenance after operating for 11.000 hours, then this preventive maintenance task will also be performed during the maintenance phase, since the component's age has reached more than 90% of the scheduled time, 10.000/11.000 = 0,91. [13]

The RPD is then analyzed through simulation, where the execution from the first phase to the last phase is referred to as one cycle [13]. After a successful execution of an operational phase the simulation goes to the next phase, either being another operational phase or a maintenance phase. If a system fails in an operational phase, the system is either sent to a maintenance phase or the simulation stops for that cycle.

Following is an example of an RPD for a hypothetical system, with two operational phases and a maintenance phase, see figure 4-5, with different RBDs for both phases, see figure 4-6 [13]:

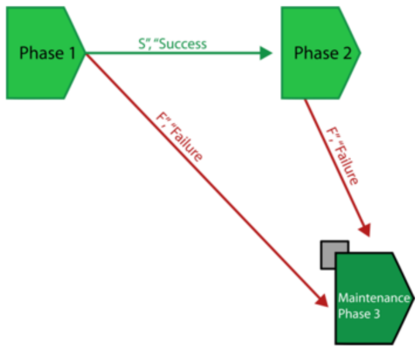


Figure 4-5 – An RPD with two operational phases and one maintenance phase [13]

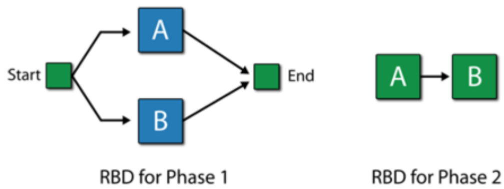


Figure 4-6 – Two different RBD's for the two phases in the RPD above [13]

4.5 Assumptions

The main focus of this research project is to build a quantitative reliability model of the RB-211 jet engines operated by Icelandair, in their present configuration. The main components of the jet engine are considered when building the model. Each component in reality is however made up of many smaller parts and therefore several possible failure modes. No distinction is made in this reliability model as to which parts or failure modes cause component failure. Furthermore, it is assumed that each component failure is independent of other component failures.

The failure behavior is determined by applying life data analysis for the components based on available failure data over the period 01.01.2009 to 21.04.2014, obtained from Icelandair's operation and maintenance registration system. For some components there was no failure data available during this period however, for those components the failure behavior was based on engineering judgment in cooperation with Kristján O. Magnússon, an engineer at ITS. With more data available, the failure behavior of the components can easily be updated and/or changed.

In this model, the duration of repair and maintenance actions is assumed to be fixed whereas in reality it can vary. These fixed durations can easily be changed to dynamic distributions when a thorough analysis of maintenance times has been made. Moreover the number of repair crews available for each component can be specified, whereas in this model it is assumed that enough repair crews are ready for all components failures. The maintenance events considered in this model are corrective maintenance events due to component failures and the preventive maintenance events when components are restored at predefined intervals. Other service checks and in-shop repairs are not defined.

The cost considered in this model is a Disruption Index (DI)[14], which measures the disruption to the operation such as financial outlays and flight delays, if failure occurs in different components. Other maintenance costs, such as component costs, manpower costs and logistics costs are not incorporated in this model.

The resulting reliability model is analyzed by simulation to create typical lifetime scenarios of the jet engine. The duration defined for each operation phase is assumed to be fixed, set as the average duration for each phase from real operation data. These durations can be changed to represent different operational conditions.

This chapter should have provided the reader with an understanding of the basic methodology which will be used in the case study of reliability analysis of the jet engines operated by Icelandair, which will be presented in next chapter.

[14] Discussed in section 5.4.5.3

5. THE CASE STUDY

This chapter begins with providing an overview of the RB-211 jet engines operated by Icelandair. Following is a description of how the methodology presented in chapter 4 is used to build a reliability model of the jet engines.

5.1 Overview of a turbofan jet engine

The jet engine is one of the most complex mechanical systems of our times, as can be seen in figure 5-1 [57],[58]:

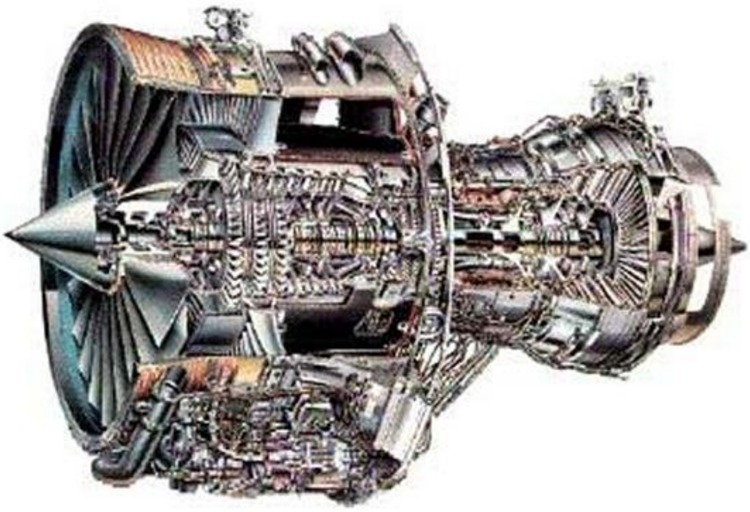


Figure 5-1 – Cut-away of the Rolls Royce RB211-535 turbofan jet engine

Most large commercial airlines use turbofan jet engines with a gas turbine at the core which turns a large fan assembly and compressors. Air enters the engine through the fan; part of this air is compressed and mixed with fuel before being ignited resulting in a burning process. The exhaust from the combustion chamber drives the turbines and provides a part of the force that propels the plane forward. The remaining thrust is generated by the by-pass air which is accelerated rearwards from the fan but does not go through the core. Figure 5-2 illustrates the path of the air as briefly described above as well as showing the RB-211 jet engine's main modules [57].

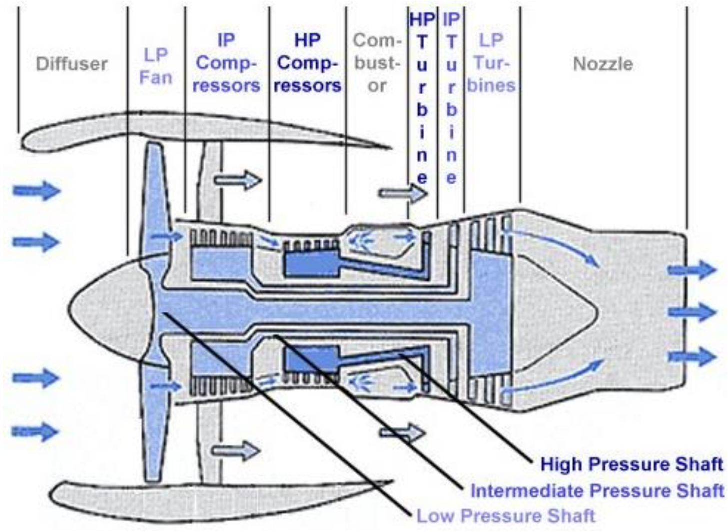


Figure 5-2 – Rolls Royce RB-211 Turbofan [57]

Jet engines deteriorate with time due to wear, fatigue, erosion, distortion and other forms of stress, thus requiring continuous maintenance actions [59]. The intense pressure and high temperature experienced during operation take a heavy toll on the engine's components, and maintenance and repair can be costly [60]. Cost associated with engine's maintenance is the highest maintenance cost item for airlines making it critical for airlines to develop efficient maintenance strategies [7],[61]. The decision to remove an engine for overhaul depends on the airline's maintenance program and operating limitations. Information on some critical parameters, such as oil pressure which is readily observable from the cockpit and recoded automatically, and from data collected by ground crew, such as from bore-scope readings and other inspections [60].

The components that are critical for normal operation of the jet engine are modeled in this research project. Next chapter discusses how and which components were chosen to be modeled.

5.2 Functional diagram of the jet engine

A functional diagram of the jet engine was developed by Kristján O. Magnússon, an ITS engineer, in order to identify the components needed for normal operation of the jet engines. The functional diagram shows how the main components of the engine are interconnected. These components were then chosen to be the failure modes for further analysis and RBD modeling. [62]

Figure 5.3 provides the overall functional diagram which shows the main components and systems of the RB-211 jet engines:

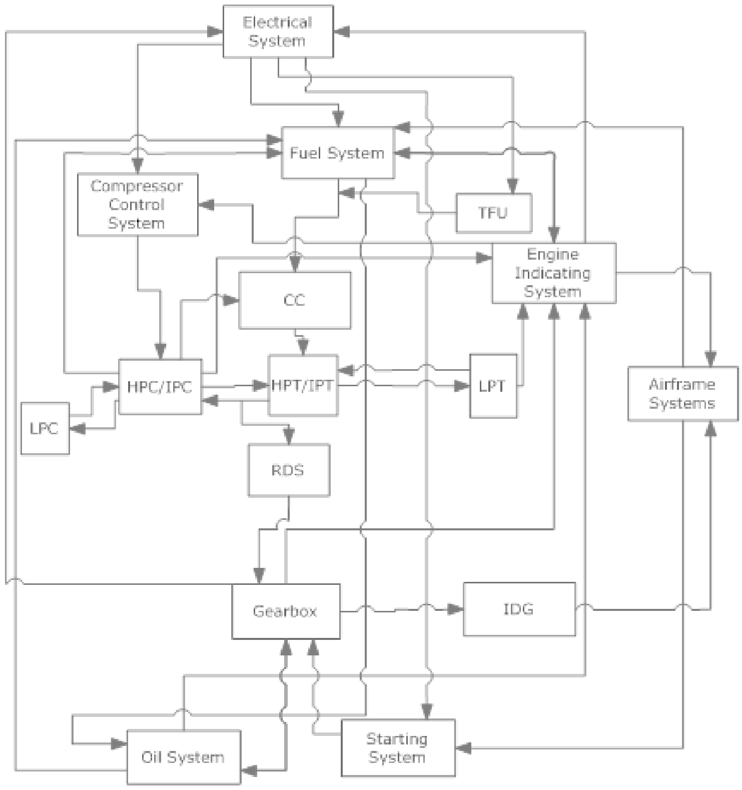


Figure 5-3 – Functional Diagram – Engine overview [62]

The following sub-systems possess their own functional diagrams, each including components used in this reliability model. In appendix A the functional diagrams of the sub-systems are provided.

- Engine Indication System
- Oil System
- Compressor Control System
- Starting System
- Electrical System
- Fuel System

A list of all the components that will be used for reliability modeling of the RB-211 jet engines, with and without abbreviation, are found in appendix B.

5.3 Data

The data used to obtain lifetime distributions for all the components that will be used in the RBD, are failure data over the period 01.01.2009 to 21.04.2014 which is a little over five years. This data is obtained from Icelandair's operation and maintenance registration system. The events that are considered as failures are those resulting in the component being removed from the engine as well as an estimate of the number of additional in-shop repairs, i.e. repairs on the component still on the engine [63]. For confidential reasons, the data will not be displayed in this report.

Over this period, the total flight hours for the Icelandair fleet were 328.034. Each aircraft has two engines; hence this results in 656.068 total engine flight hours.

On the average, each engine undergoes overhaul after 21.287 flight hours. At that time, the engine is removed from the aircraft and most components are restored to as-good-as-new condition. Other components have their own hard time maintenance interval, which implies that after operating for certain flight hours, the component is restored. This interval may be shorter or longer than the average interval between engine overhauls. Finally there are some components that are neither restored during engine overhaul nor do they have a hard time maintenance interval; they are allowed to operate until failure occurs.

5.3.1 The lifetime distributions

To obtain the lifetime distributions, the Weibull++ software from Reliasoft is used. In this case the failure times for each component are listed, along with the number that did not fail during this period, i.e. the number of suspensions for each component. The times at which suspensions occur are at either at the time interval of an engine overhaul or at the hard time maintenance interval (for the components that have hard time intervals)

As the data sets contain suspensions, the maximum likelihood estimation (MLE) method is used for the parameter estimation. The software suggests the probability distribution that best fits the data set for each component being analyzed along with the estimated parameters. For some components, no failures did occur during this period. For these, engineering judgment[15] along with experience from Icelandair operations was used to estimate which lifetime distribution was suitable along with the parameters [63].

The lifetime distributions and the parameters for each component are provided in section 5.4.5.1, which discusses the block properties.

5.4 The reliability model of the jet engines

The reliability-wise configuration of the components comprising a system has to be determined in order to construct an RBD of the system, i.e. how the components are connected reliability-wise in order to fulfill the system function [53]. The reliability-wise configuration of the components is not always as the physical and functional configuration.

[15] In cooperation with Kristján O. Magnússon, ITS engineer

The components chosen for reliability modeling in this research project, and the most critical components of the jet engine, are the components in the functional diagram of the jet engine introduced in figure 5-3. In the following sections, the RBDs for the jet engine are presented.

5.4.1 Jet engine RBD

The RBD for the jet engine can be seen in figure 5-4. The blocks in the engine RBD are the blocks from the functional diagram previously provided, since they were considered to represent the main components or failure modes of the engine.

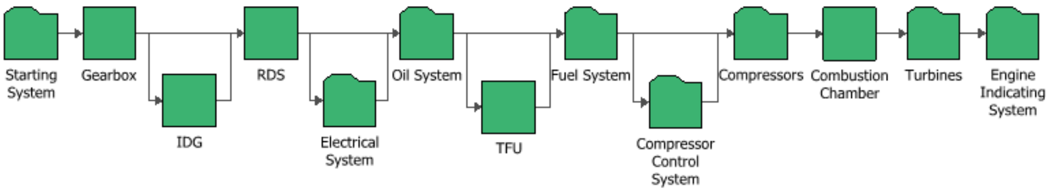


Figure 5-4 – RBD for the jet engine

Most of the blocks in this diagram are connected in series, since they all must function for the engine to operate. If a failure occurs in any one of them, the engine must be shut down. There are four blocks however connected in a parallel way (IDG, Electrical System, TFU and Compressor Control System) in the series. This means that even though these components fail during flight, the engine will still operate [64]. They must however be repaired before the next flight and therefore are required in the model to account for the operational disruptions and maintenance burden resulting from failure.

When blocks in the RBD have a "folder" shape it means that this block represents a sub-system, where the sub-system represents its own RBD. In the RBD depicted in figure 5-4, these are:

- Starter System
- Electrical System
- Oil System
- Fuel System
- Compressor Control System
- Compressors
- Turbines
- Engine Indication System

These were chosen as sub-systems, instead of including all the blocks in the main diagram for easier visualization of the system. Having blocks represent a sub-system engenders all the same reliability results as if the blocks of the sub-systems were in the main diagram. In the next section, the RBD's for the sub-systems are presented.

5.4.2 Sub-systems RBDs

Blocks in an RBD can represent components and parts of a system. They can also be used to represent another RBD, this RBD is then a sub-system used in the main system. A sub-system can also contain another sub-system and so forth. In the main jet engine RBD there are eight sub-systems.

5.4.2.1 Starter System

The RBD for the Starter System, see figure 5-5, is simple and consists of two components;

- Starter Valve,
- and Starter.

The two blocks are connected in series and must both function for the Starter System to function.

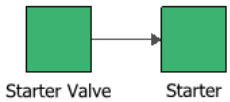


Figure 5-5 – Sub-system RBD for the Starter System

5.4.2.2 Electrical System

The Electrical System consists of six components:

- Dedicated Generator,
- Upper Dedicated Generator (DG) Control Unit,
- Lower Dedicated Generator (DG) Control Unit,
- Electronic Engine Control (EEC),
- Electronic Transient Pressure Unit (ETPU),
- and Bleed Valve Control Unit (BVCU).

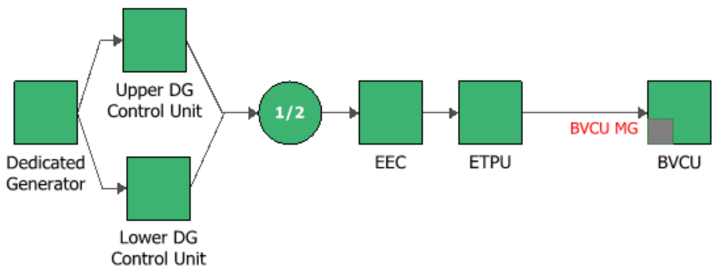


Figure 5-6 – Sub-system RBD for the Electrical System

The RBD for the Electrical System can be seen in figure 5-6. In this diagram a 1-out-of-2 redundancy is present, where there are two DG Control Units and one of them is sufficient for the electrical system to continue to function[16]. The BVCU is both present in this diagram as well is in the Compressor Control System (see 5.4.2.5). This is the same component and therefore is represented in both diagrams as a "mirrored block" (marked with a grey box in the lower left corner). Mirrored blocks are used to represent the same component with more than one block placed in multiple locations, if a failure occurs for a mirrored block in one diagram, it also fails in the other diagram [53].

5.4.2.3 Oil System

The Oil System consists of six components;

- Oil Tank,
- Oil Pumps Pack,
- Fuel Cooled Oil Cooler (FCOC),
- Oil Temperature Transmitter,
- Oil Pressure Transmitter,
- and Chip Detector.

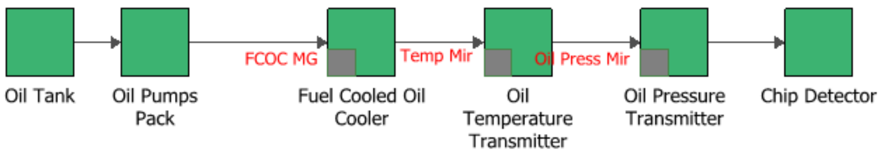


Figure 5-7 – Sub-system RBD for the Oil System

In figure 5-7 the RBD for the Oil System can be seen. The blocks are connected in series since all components must function for the oil system to function. As was the case with the BVCU in the Electrical System, the blocks marked with a grey box are mirrored blocks and are present in other systems as well. The FCOC is also present in the Fuel System (see 5.4.2.4) and both the Oil Temperature and Oil Pressure Transmitters are also present in the Engine Indicating System (see 5.4.2.8).

5.4.2.4 Fuel System

The RBD for Fuel System can be seen in figure 5-8 and consists of five components;

- Low Pressure (LP) Fuel Pump,
- FCOC,
- High Pressure (HP) Fuel Pump,
- Fuel Flow Governor (FFG),
- and Fuel Flow Transmitter.

[16] This is represented by the node marked with 1/2

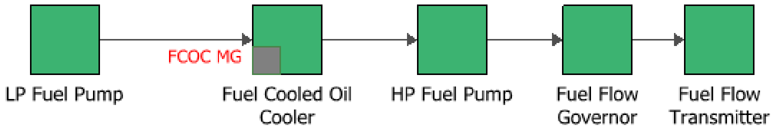


Figure 5-8 – Sub-system RBD for the Fuel System

The components are all connected in series and must all function for the Fuel System to function. The FCOC is a mirrored block and is also present in the Oil System (see 5.4.2.3).

5.4.2.5 Compressor Control System

The RBD for the Compressor Control System, see figure 5-9, is simple with only two components in a series configuration;

- BVCU,
- and High-Pressure-Compressor/Intermediate-Pressure-Compressor (IPC/HPC) Control Solenoids.

The two components must both function for the Compressor Control System to function. The BVCU is a mirrored block and is also present in the Electrical System (see 5.4.2.2).

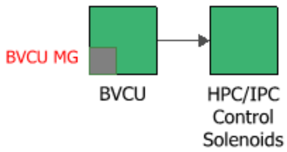


Figure 5-9 – Sub-system RBD for the Compressor Control System

5.4.2.6 Compressors

The RBD for the Compressors, see figure 5-10, consists of three blocks;

- Low Pressure Compressor (LPC)
- Intermediate Pressure Compressor (IPC),
- and High Pressure Compressors (HPC).

The three compressors are connected reliability-wise in series and must all function for the Compressors to function.

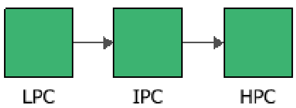


Figure 5-10 – Sub-system RBD for the Compressors

5.4.2.7 Turbines

There are two components in the Turbines RBD, see figure 5-11. These are;

- Intermediate-Pressure-Turbine/High-Pressure-Turbine (IPT/HPT)
- and Low-Pressure-Turbine.

They are connected reliability-wise in series and must both function for the Turbines to function.

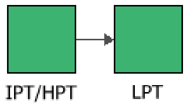


Figure 5-11 – Sub-system RBD for the Turbines

5.4.2.8 Engine Indication System

The most complex RBD configuration of the sub-systems is for the Engine Indicating System, see figure 5-12. The system consists of twelve components as well as three Dummy blocks;

- N3 Tacho Generator,
- N1 Probe 1 and 2,
- N2 Probe 1, 2 and 3,
- P1 Probe,
- Pf Rakes,
- Engine Pressure Ratio (EPR) Transmitter,
- Oil Temperature Transmitter,
- Exhaust Gas Temperature (EGT) Thermocouples,
- Oil Pressure Transmitter.

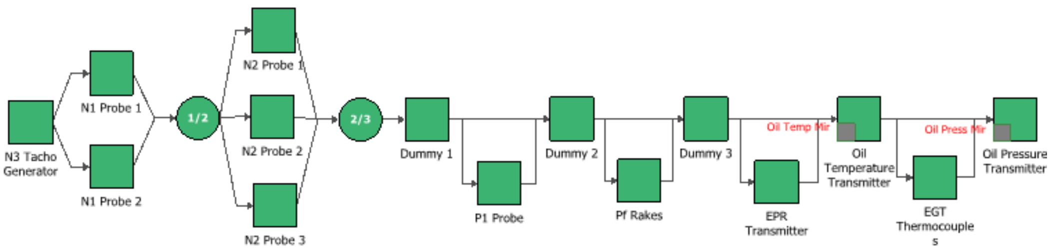


Figure 5-12 - Sub-system RBD for the Engine Indication System

The blocks presented in figure 5-12 called "Dummy" are blocks that cannot fail and have no influence on the failure behavior of the system. They are used in this diagram to make a parallel way for the P1 Probe, Pf Rakes and EPR Transmitter, which can fail during flight without the Engine Indicating System failing, but must though be repaired before next flight.

There are two redundancy configurations in this RBD. First are the two N1 Probes, where either one is sufficient for the Engine Indicating System to function. Second are the three N2 Probes, where two of them suffice for system operation.

Two mirrored blocks are present in this diagram, the Oil Temperature and Oil Pressure Transmitters. They are also present in the Oil System.

5.4.4 The Reliability Phase Diagram (RPD)

A typical commercial aircraft and hence the jet engines go through different phases during operation. These are most commonly the ground phase, take-off phase, climb phase, cruise phase, descent phase and landing phase. Furthermore the aircraft go through a maintenance phase where failed components are repaired and regular and preventive maintenance is performed.

In this reliability model of the RB-211 jet engines these different phases will be implemented in the model. In addition to reliability analysis, the results from the different phases will be used to evaluate the consequences of failure.

For the jet engines there is no significant operational difference in stress during the climb phase, cruise phase, descent phase and landing phase. Hence the four phases will be considered as an in-flight phase. The reliability-wise configuration of the components does not differ between the operational phases whereas the failure consequences however are different depending on which phase the engine is operating in. For example, an engine failure during take-off is much more severe than failure during ground phase.

The duration of each operational phase has to be set as constant in the BlockSim software. The durations for the operational phases used in this model are based on average duration of these operational phases for the Icelandair fleet. The duration of the maintenance phase depends on the components maintenance properties and the failed components in each instance. The stress load (phase duty cycle) on the system can be different between operational phases. The in-flight phase is considered as a normal operational condition whereas the ground phase has a lower stress load and the take-off phase has higher stress load on the system. The phases considered in this model along with their estimated average durations and stress loads are:

- Ground phase - Duration: 20 minutes – Stress load: 0,1
- Take-off phase – Duration: 5 minutes – Stress load: 12
- In-flight phase – Duration: 3,5 hours – Stress load: 1
- Maintenance phase – Duration: Depends on component failures and maintenance properties – Stress load: Not applicable

The different stress loads during the different phases are estimates based on operational information from Heimir Ö. Hólmarsson and Kristján O. Magnússon, ITS engineers [9]. These durations and stress loads can easily be changed within the software for different operational conditions.

5.4.4.1 The RPD model

The resulting RPD which is used for simulating a typical lifetime scenario of the jet engine is illustrated in figure 5-13.

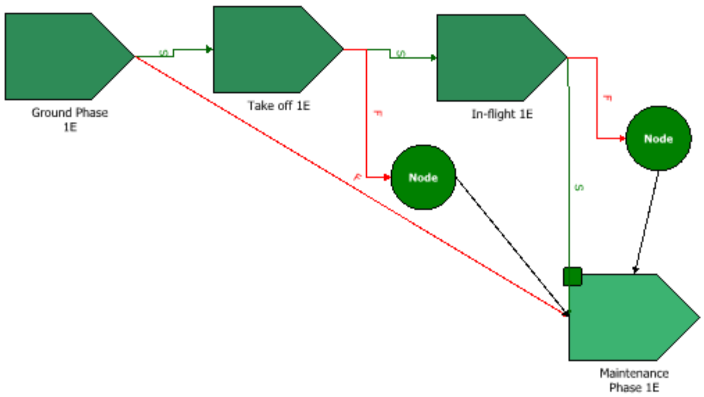


Figure 5-13 – RPD used for simulation with one engine

The three operational phases are based on the jet engine RBD (see figure 5.4). After a successful operation in each phase the simulation moves to the next operational phase and finally to the maintenance phase. The green lines represent the success path whereas the red lines represent the failure paths. The nodes are used for the cases when both the success path and the failure path lead to the same next phase. The interval maintenance threshold is set to be 0,95, which implies that scheduled preventive maintenance will be performed during the maintenance phase if the component's age has reached 95% of the scheduled time. After a completion of one simulation run, the next simulation run starts again in the ground phase etc. If an engine failure occurs during one of the operational phases, the simulation moves to the maintenance phase.

5.4.5 Component properties

The analysis of the system reliability, availability and other reliability metrics are based on the failure behavior of the components of the jet engine. For each component, a specific lifetime (failure) distribution is defined. These distributions are either found by mathematical approaches or by engineering judgment[17]. In addition to the failure behavior of components, their maintenance properties are important for the availability calculations. In the case of airlines operation, an engine failure can have severe consequences from both safety and cost perspectives.

[17] Discussed in section 5.3.1

5.4.5.1 Failure behavior

The lifetime distributions for the components were found by failure data analysis, using the maximum likelihood parameter estimation, in the Weibull++ software. Due to confidential reasons, the procedures in obtaining the lifetime distributions will not be displayed in this thesis.

The analysis resulted in the Weibull distribution for fifteen of the components, the lognormal distribution for one component and an exponential distribution for three components. For some components however, due to difficulties in obtaining failure data, a normal distribution was assumed, and for three of them, which very rarely fail, it was assumed in this model that they cannot fail (CNF) [63]. In table 5-1, the lifetime (failure) distributions with all relevant parameters are provided.

	Failure distributions			Failure distributions	
Component	**Distribution**	**Parameters**	**Component**	**Distribution**	**Parameters**
TFU	Weibull	β=1,63 ,η=32.000	FCOC	Exponential	λ=32.803
IDG	Weibull	β=0,42 ,η=17.147	HP Fuel pump	Weibull	β=0,82 ,η=29.555
CC	Normal	μ=21.287, σ=6.445	FFG	Weibull	β=0,70 ,η=12.949
LPC	Normal	μ=21.287, σ=6.445	FF transmitter	Weibull	β=2,08 ,η=29.705
IP/HPC	Normal	μ=21.287, σ=6.445	N3 Tach gen	Weibull	β=1,05 ,η=37.423
IP/HPT	Normal	μ=21.287, σ=6.445	N1 probe	Exponential	λ=65.607
LPT	Normal	μ=21.287, σ=6.445	P1 probe	Weibull	β=1,42 ,η=32.280
RDS	CNF	-	Pf rakes	Normal	μ=15.000, σ=7.500
BVCU	Weibull	β=0,70 ,η=21.967	EPR transmitter	Weibull	β=1,62 ,η=32.985
HPC/IPC Solenoids	Normal	μ=15.000, σ=7.500	N2 probe	Normal	μ=50.000, σ=20.000
Starter Valve	Weibull	β=0,58 ,η=17.229	EGT thermoc.	Normal	μ=15.000, σ=7.500
Starter	Lognormal	μ=10,33, σ=3,30	Oil temp transm.	Exponential	λ=31.241
Dedicated Gen.	Weibull	β=2,20 ,η=27.595	Oil press transm.	Exponential	λ=32.803
DGCU	Weibull	β=0,57 ,η=24.050	Oil tank	CNF	-
EEC	Weibull	β=0,55 ,η=24.640	Oil pump pack	CNF	-
ETPU	Weibull	β=1,04 ,η=32.328	Chip detectors	Normal	μ=21.287, σ=6.445
LP fuel pump	Weibull	β=0,73 ,η=30.064	Gearbox	Normal	μ=21.287, σ=6.445

Table 5-1 - Lifetime distributions and parameters of the components

5.4.5.2 Maintenance properties

No attempt was made to go into deep analysis of maintenance times for each component in this research project. The estimated corrective maintenance (CM) duration for each component as well as, if applicable, the scheduled preventive maintenance (hard time) are listed in table 5-2. The CM durations are an estimation based on normal operation; in reality however the CM duration can vary and often depend on the location at which the repair is performed. The hard times are the actual scheduled preventive maintenance times at which components must be overhauled, in the current operation at Icelandair.

	Maintenance properties			Maintenance properties	
Component	CM time	Hard time	Component	CM time	Hard time
TFU	6 hours	no	FCOC	15 hours	no
IDG	6 hours	no	HP Fuel pump	6 hours	20000 hours
CC	24 hours	no	FFG	6 hours	15000 hours
LPC	24 hours	no	FF transmitter	2 hours	no
IP/HPC	24 hours	no	N3 Tach gen	6 hours	no
IP/HPT	24 hours	no	N1 probe	0,5 hours	no
LPT	24 hours	no	P1 probe	6 hours	no
RDS	24 hours	no	Pf rakes	6 hours	no
BVCU	6 hours	no	EPR transmitter	6 hours	no
HPC/IPC Solenoids	6 hours	no	N2 probe	0,5 hours	no
Starter Valve	2 hours	no	EGT thermoc.	6 hours	no
Starter	2 hours	no	Oil temp transm.	2 hours	no
Dedicated Gen.	6 hours	no	Oil press transm.	2 hours	no
DGCU	2 hours	no	Oil tank	24 hours	no
EEC	6 hours	no	Oil pump pack	12 hours	no
ETPU	6 hours	no	Chip detectors	24 hours	no
LP fuel pump	6 hours	25000 hours	Gearbox	48 hours	no

Table 5-2 – Maintenance properties

5.4.5.3 Failure consequences

Rolls-Royce, the manufacturer of the RB-211 jet engines operated by Icelandair, has since 2005 been running an improvement process called "Project Zero", aimed at increasing reliability and reducing operational disruptions [65]. Fundamental to the application of this process is the scoring system called "Disruption Index" (DI), which gives weights to operational disruptions. Most severe events are those that occur in-flight, such as in-flight shutdown, next are the events occurring while the aircraft is on the ground, such as delays, and finally are maintenance events, such as some unplanned maintenance activity.

The consequences of failures in this research project are based on this DI scoring system, where the failure of component is different depending in which phase failure occurs, and a failure in one component may have different consequences than failure in another component. The higher the DI is, the more severe consequences are of the failure. The DI for each component in each phase were obtained in cooperation with ITS engineer Kristján O. Magnússon [63], and are listed in table 5-3. Further details on how the disruption indexes were found are provided in appendix C.

	Disruption index per phase				Disruption index per phase		
Component	Ground	Take-off	In-flight	Component	Ground	Take-off	In-flight
TFU	0,1	0,35	1,6	FCOC	0,4	2	2,4
IDG	0,1	0,3	0,2	HP Fuel pump	0,1	2	2,4
CC	0,7	2,3	2,4	FFG	0,1	2,3	2,4
LPC	0,7	2,3	2,4	FF transmitter	0,05	0,35	0,1
IP/HPC	0,7	2,3	2,4	N3 Tach gen	0,1	0,9	1,5
IP/HPT	0,7	2,3	2,4	N1 probe	0,02	0,3	0,25
LPT	0,7	2,3	2,4	P1 probe	0,1	1,7	0,4
RDS	0,5	2,3	2,4	Pf rakes	0,1	1,7	0,4
BVCU	0,1	0,5	1,4	EPR transmitter	0,1	1,7	0,4
HPC/IPC Solenoids	0,1	0,5	0,5	N2 probe	0,02	0,3	0,25
Starter Valve	0,05	0,8	0,5	EGT thermoc.	0,1	0,5	1,2
Starter	0,05	0,8	0,5	Oil temp transm.	0,05	0,25	1,9
Dedicated Gen.	0,1	0,8	1,4	Oil press transm.	0,05	0,25	1,9
DGCU	0,05	0,65	0,4	Oil tank	0,6	2	2,4
EEC	0,1	0,7	1	Oil pump pack	0,2	2	2,4
ETPU	0,1	0,3	1,3	Chip detectors	0,7	0	0
LP fuel pump	0,1	2	2,4	Gearbox	0,7	2,3	2,4

Table 5-3 – Disruption index per phase

The average number of failures for each component in each phase is found as the average after simulating the RPD. Then DI is summed up for each component, for example if one failure occurs on average in each phase for the TFU, the resulting DI for that component is 0,1+0,35+1,6=2,05. The DIs for all components are summed up resulting in the system DI.

5.6 Summary

This section is to make a more clear understanding of the structure and the steps taken to build the reliability model. The process is illustrated in figure 5-14 and explained below:

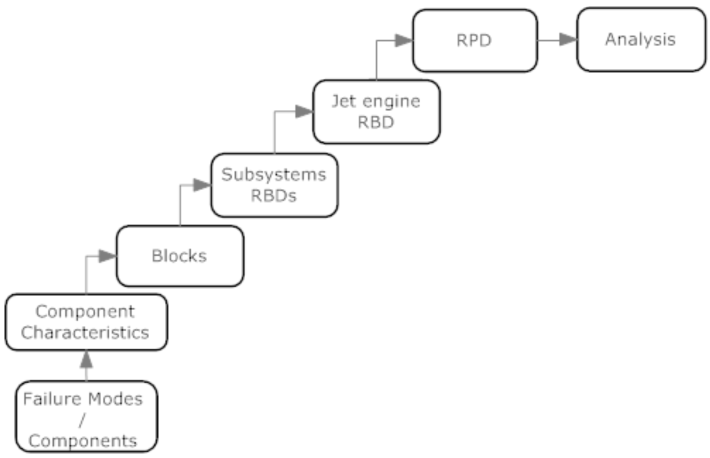


Figure 5-14 – Structure of the reliability model

- To begin with, the failure modes and/or components to be analyzed in the reliability model were chosen from a functional diagram of the jet engine.
- The lifetime distributions and other component characteristics were then estimated, both by life data analysis and engineering judgment.
- These components with their characteristics are the reliability blocks used for the RBDs.
- These blocks are in RBDs for sub-systems, which then are in the RBD of the jet engine along with more blocks, where the reliability-wise configuration of the blocks is determined.
- The RBD of the jet engine is the basis for the RPD, which represents typical jet engine cycle with operational phases and maintenance phase.
- The RPD model will be used for reliability analysis, where the model is simulated by generating random numbers to represent typical lifetime scenarios.
- Finally the results from simulating the reliability model will be analyzed with regard to reliability metrics and the Disruption Index.

In chapter 6 the resulting reliability model will be used for reliability analysis of the jet engines.

6. RESULTS – RELIABILITY MODEL ANALYSIS

In this chapter the reliability model developed in the previous chapter will be used to calculate the reliability, or more suitably, since the jet engine is a repairable system, the availability and other reliability metrics. Furthermore the model will be used to illustrate how it can be used to evaluate the effects of alternative maintenance strategies.

When components fail, corrective maintenance is performed whereby they are repaired or replaced. Three components have a hard time scheduled preventive maintenance, whereby the components are restored to as good as new condition, at predefined intervals. These are the FFG at 15.000 hours of operation, the HP Fuel Pump at 20.000 hours and the LP Fuel Pump at 25.000 hours[18].

The Reliability Phase Diagram (RPD), which is built up of the Reliability Block Diagram (RBD) of the jet engine, is used for simulation purposes. Each simulation is set to represent 22.000 hours of the lifetime of jet engines. This time interval was chosen since on the average, based on data from 01.01.2009 to 21.04.2014, the jet engines are sent for overhaul after approximately 21.000 flight hours. During overhaul most of the components are restored to as good as new condition. The 22.000 hours then account for the flying hours as well as when maintenance actions are being performed. 500 simulations[19] were performed each time, i.e. for current procedure and the two maintenance options.

The reliability metrics of interest that will be obtained from analyzing this reliability model are the following[20]:

- Mean availability of the system over the interval of 22.000 hours
- Point reliability at 22.000 hours (representing the probability of no system failure has occurred at 22.000 hours)
- MTTFF – The mean time to first system failure
- MTBF – The mean time between system failures
- Expected number of failures
- System uptime
- System downtime
- Number of maintenance actions
- Disruption index
- FCI – Failure criticality index

[18] The LP Fuel Pump has a scheduled preventive maintenance after the 22.000 hours of each simulation run, hence this maintenance action is not performed in this time setup.
[19] The simulation results reached a steady state after around 200 runs
[20] See chapter 4.3.2.2 for information on reliability metrics for repairable systems

If to change or not the hard time interval for the FFG is a typical consideration the engineers at ITS are facing. The industry recommendation today for the FFG in the RB-211 jet engines is to set the hard time interval for the FFG at 12.000 hours, instead of 15.000 hours. These recommendation are based on data from many airline operators; many of them might operate in a different operational environment than Icelandair [9]. Shortening the hard time interval would entail a higher component cost. If this resulted in increased reliability and lower DI, it might pay off. It might be interesting as well to see the effects if further increasing the hard time interval. This will be done to see the results by setting the hard time interval at 18.000 hours as well. The reliability model can potentially be used to evaluate such decisions of changing maintenance strategies.

6.1 Overall system reliability results

Successful operation of the system is achieved when the engine goes through the three operational phases without failure; the ground phase, the take-off phase and the in-flight phase. When the engine is in an operational state, this counts as up-time of the system. A system failure is declared when the engine fails during operation. After a system failure the engine is brought to the operational state again by carrying out a repair action (corrective maintenance). The corrective maintenance and the preventive maintenance are performed in the maintenance phase and count as system down-time.

By performing the simulations, for both the current procedures and the two new maintenance options, i.e. decreasing the hard time interval for the FFG from 15.000 hours to 12.000 hours and increasing the interval to 18.000 hours, where each simulation represents 22.000 hours, the following results were obtained. In table 6-1, the overall system results are presented for current maintenance procedures and for the two new maintenance options.

System results	Hard time interval for the FFG		
	Current: 15.000 Hr	Change to: 12.000 Hr	Change to: 18.000 Hr
Mean Availability (All Events):	98,74%	98,71%	98,73%
Std Deviation (Mean Availability):	0,20%	0,20%	0,20%
Reliability at 22000 (prob of no failure):	0	0	0
Expected Number of Failures:	15,6	16,1	15,3
Std Deviation (Number of Failures):	3,9	3,8	3,9
MTTFF (Hr):	1.384	1.458	1.365
MTBF (Total Time) (Hr):	1.412	1.365	1.439
Uptime (Hr):	21.724	21.717	21.722
CM Downtime (Hr):	266	271	269
PM Downtime (Hr):	10	12	9
Total Downtime (Hr):	276	283	278
Number of CMs:	30,3	30,7	30,4
Number of PMs:	1,7	2,0	1,6

Table 6-1 – Overall system reliability results for current procedures and new maintenance options

The results in table 6-1 are obtained as the average of the results from all the 500 simulations. For the current configuration the mean availability is 98,74% with a standard deviation of 0,20%. The reliability at 22.000 is 0, since a system failure in the jet engine has always occurred before that time[21]. The expected number of failures is 15,6, with a standard deviation of 3,9. The MTTFF is 1.384 hours and the MTBF is 1.412 hours. The total up-time of the system is 21.724 hours and the total downtime is 276 hours, which consists of 266 hours for corrective maintenance and 10 for preventive maintenance. The number of corrective maintenance events is 30,3; this is higher than the expected number of failures since some components are allowed to fail even though the engine can still operate. The number of preventive maintenance actions is 1,7.

For the first new maintenance option, where the hard time interval for the FFG is 12.000 hours instead of 15.000, it is interesting to see that reducing the interval does not result in higher availability. In fact no considerable changes in other performance metrics are expected. The expected number of failures, the MTBF, the system up-time, the system down-time and the number of maintenance events do all result in a little worse outcome for the new maintenance option as well. The only improvement is in the MTTFF which is expected to increase by 74 hours.

For the second new maintenance option, where the hard time interval for the FFG is increased to 18.000 hours, it is also interesting to see that increasing the interval does not result in considerable changes in availability or other performance metrics.

6.2 The mean availability

In figure 6-1, the mean availability of the system for the time period of 22.000 hours is plotted for the current procedure. The x-axis represents the timeline from 0 – 22.000 hours. The y-axis represents the mean availability during this period on the scale from 0 to 1, i.e. from 0% to 100%. The mean availability is represented by the blue line near the top of the figure, i.e. near 1.

[21] A system failure occurs when any of the components needed for the operation of the jet engine fail.

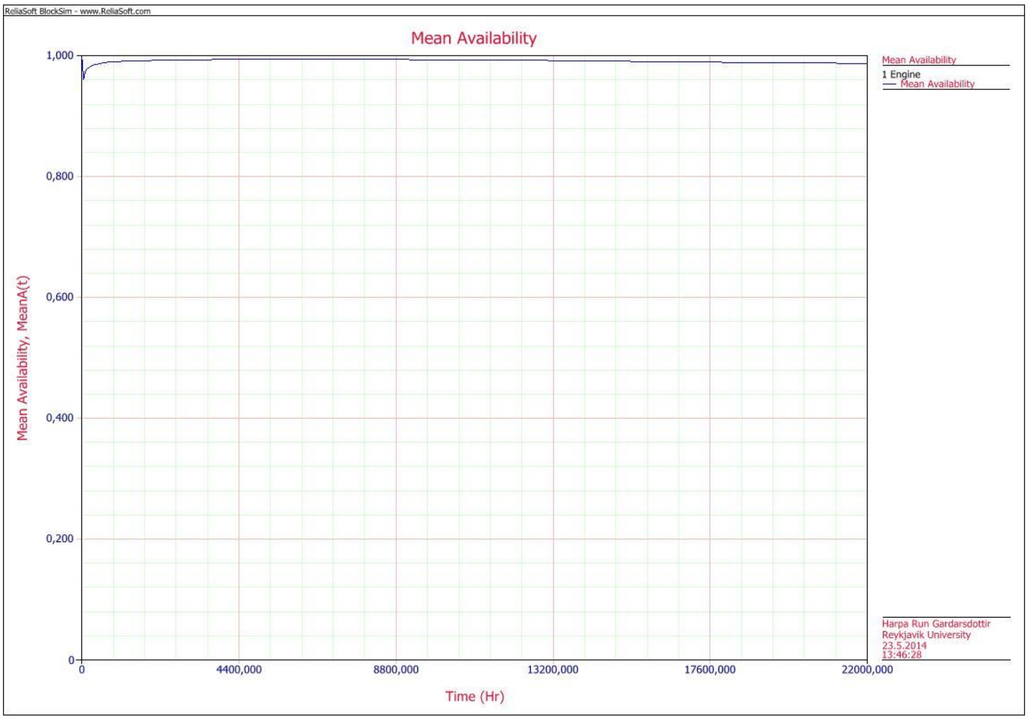


Figure 6-1 - The mean system availability, current procedures

The mean availability of the system is close to 100% for most of the time. It can be seen that the availability decreases in the beginning, which indicates that failures are more likely to occur at the beginning of the typical operational life-time after an overhaul rather than in the latter part of this time period. This might be the result of imperfect restoration during the overhaul of the engine. The mean availability increases again to an almost steady state value before it starts decreasing again towards the end of the period.

The mean availability behaved very similarly for the current procedure and the new maintenance options, hence only one figure is shown here which is applicable to all three cases for visualization purposes.

6.3 The Disruption Index

The disruption index (DI) was calculated for all components, where the expected number of failures for each component in each phase was multiplied by the DI for that component in that phase, resulting in total DI for each component. To obtain the system DI, the DI for all components was summed up. Table 6-2 provides the DI for the system and the current procedures and for both new hard time intervals for the FFG. Details on the DI for all components in all phases can be seen in appendix D.

Disruption Index	Hard time interval for the FFG		
	Current: 15.000 Hr	Change to: 12.000 Hr	Change to: 18.000 Hr
System total:	37,59	38,11	37,19
Fuel Flow Governor:	5,16	5,36	5,04

Table 6-2 – Disruption index for the system and the FFG for current procedures and new maintenance options

Decreasing the hard time interval for the FFG resulted in a higher DI, both for the system and for the FFG. Increasing the hard time interval for the FFG resulted in a lower DI for both the system and the FFG. As before the difference is not large. For the current procedures the DI is 37,59 for the system and 5,16 for the FFG. The DI increases to 38,11 for the system and 5,36 for the FFG if the hard time interval is set at 12.000 hours. The DI decreases to 37,19 for the system and 5,04 for the FFG if the hard time interval is set at 18.000 hours.

6.4 Expected FFG failures

The expected number of failures of the FFG in each phase, for the current procedures and for the new maintenance options, can be seen in table 6-3.

Expected number of FFG failures	Hard time interval for the FFG		
	Current: 15.000 Hr	Change to: 12.000 Hr	Change to: 18.000 Hr
Ground Phase	0,02	0,04	0,02
Take-off Phase	0,49	0,53	0,49
In-flight Phase	1,68	1,72	1,63
Total	**2,19**	**2,29**	**2,14**

Table 6-3 – Expected number of FFG failures per phase for current procedures and new maintenance options

It can be seen that the expected number of FFG failures is slightly higher for the first new maintenance strategy; 2,29 versus 2,19 for the current procedures. The expected number of FFG failures is expected to decrease for the second maintenance option; 2,14 versus 2,19 for the current procedures. These results are in line with the results for the DI, where the DI is higher if the hard time interval is set at 12.000 hours and lower if the hard time interval is set at 18.000 hours.

These results are also illustrated in figure 6-2 where it can be seen that decreasing the hard time interval for the FFG down to 12.000 hours would increase the expected number of FFG failures in all phases. Furthermore it can be seen that increasing the hard time interval to 18.000 hours would result in the same expected number of failures in the first two phases and even decrease in the in-flight phase, hence decrease the expected total number of FFG failures.

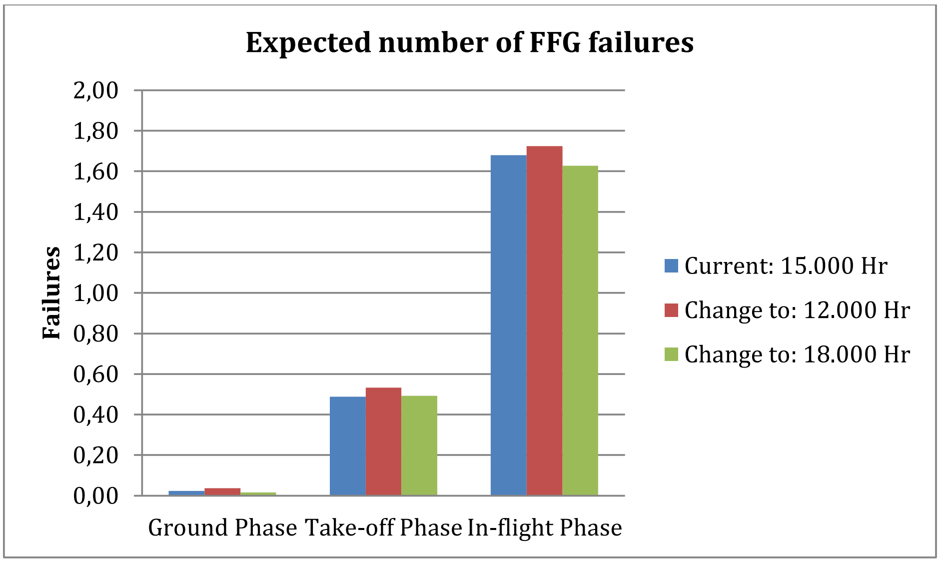


Figure 6-2 – Expected number of FFG failures per phase, for current procedures and new maintenance options

6.5 Failure Criticality Index (FCI)

The FCI expresses the percentage of time that a failure event of a component causes a system failure. This index is useful in identifying the components that cause the most failures and disruptions to the operations.

In figure 6-3, the FCI of the FFG can be seen for the current operational procedures and for the two new maintenance options.

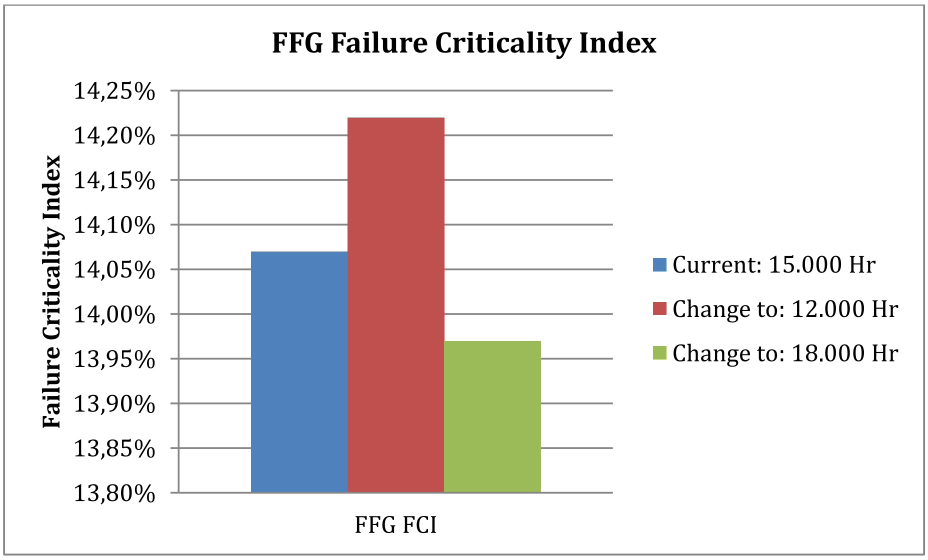


Figure 6-3 – FFG Failure Criticality Index, for current procedures and new maintenance options

For current procedures, the FCI for the FFG is 14,07%, meaning that in 14,07% of the time when system failure occurs, it was caused by the FFG. If the hard time interval for the FFG is decreased to 12.000 hours, the FCI of the FFG would increase to 14,22%, i.e. more system failures would be caused by the FFG. If the hard time interval is increased to 18.000 hours, the FCI would decrease to 13,97%.

According to ITS staff[22] the FFG is the component causing most system failures. This is also the case for the airline industry in general [63]. These results are in accordance with that where FFG failures are the reason for most of the system failures in current procedures. The FCI results for other components are at the highest 11% for the current procedures and the new maintenance options.

6.6 Decision evaluation

The decision to increase or decrease hard time service limits is one of many decisions that airlines must take. The decision depends on mostly on the question of reliability vs. cost. The decision to decrease a hard time interval would entail an increased component cost due to shorter service time, i.e. time in operation. It might however lead to lower maintenance costs and operational disruptions if the component fails often with high associated costs. When preventive maintenance is performed on components, the objective is to increase reliability and hence lower the operational disruptions resulting from failures. If the failure behavior of the component in question is such that failures are more likely to occur early, preventive maintenance might not result in higher reliability.

For the evaluation of the decision as to whether or not to decrease the hard time interval for the FFG down to 12.000 hours, the results from this reliability model indicate that decreasing the hard time interval for the FFG would neither result in higher system availability nor lower expected number of failures and DI. The results from the FCI indicate that the FFG would still cause the most system failures.

For the evaluation of the decision as to whether or not to increase the hard time interval for the FFG up to 18.000 hours, the results from this reliability model indicate that increasing the hard time interval for the FFG would neither result in lower system availability nor lower expected number of failures and DI. The results from the FCI indicate that the FFG would not cause more system failures.

The main reason for the little difference of the results between the current procedures and the new maintenance options evaluated in this chapter may be due to imperfections in the overhaul of the FFG. That results in failure of components rather at the beginning of the component life-time. If imperfect overhaul takes place, these failures have occurred well before 12.000 hours.

[22] Heimir Ö. Hólmarsson and Kristján O. Magnússon

The results from the reliability analysis of the jet engine performed in this research project indicate that it would not pay off to overhaul the FFG sooner than at 15.000 hours as no availability improvements are expected. Moreover additional operating hours are valuable. As the availability is not expected to decline with additional hours, it might pay off to increase the hard time interval to 18.000 hours. Inspections and analysis of the condition of the FFG removed after 15.000 hours should be undertaken however to find out if this was warranted.

It is important to bear in mind when using the reliability model developed in this thesis, that the model is based on many assumptions. The model is useful to give indication on the expected results; however engineering judgment should also be included.

6.7 The value of this model for Icelandair and ITS

Until now, a reliability model of the jet engine, where the engine is represented by a system level model built up of components of the engine, has not been available to ITS and Icelandair. This model would make it possible to analyze different decisions and the effects on the system reliability. Furthermore it would make it possible to better analyze and visualize the bottlenecks in the system, which components are causing the most failures or disruptions to the operation. [66]

Today the ITS engineers are, amongst other projects, concentrating on optimizing their maintenance program for both the aircrafts and the engines. The objective of their maintenance program is to increase the reliability and lower maintenance costs. The main steps of this maintenance optimization program are to examine failure reports of the components that fail most frequently or cause most disturbances to the operation and suggest other arrangements of the current maintenance strategies of those components. A change in maintenance strategy is for example to change a preventive maintenance interval and add or remove preventive maintenance for some components. These new maintenance strategies can both lead to worse and improved outcomes. The results of implementing new maintenance strategies however are not visible to the engineers until after some amount of flight hours. Being able to predict the outcomes of changing the maintenance strategies would therefore be of a great value to Icelandair, leading to improved decision making. [66]

Icelandair is following a maintenance program called MSG-3 (Maintenance Steering Group), which was first introduced in 1980 around the time when the first Boeing 757 aircrafts came to the market. This is a methodology used for scheduling maintenance tasks in efficient way. The reliability model developed in this research project is in line with this methodology and current practices in the industry, where the focus in on a system analysis from a top-down view, where aircraft systems are analyzed on an aggregated level and worked from there down to component level. [66]

The reliability model of the jet engines could also be of a great value for the purchasing department, where results from the model can be used to better forecast spare parts requirements etc.

7. Summary and Conclusions

In this thesis a quantitative reliability model is developed and applied to determining the reliability of the RB-211 jet engines. This is done for current operational procedures used by Icelandair as well as for evaluating a decision whether or not to implement a new maintenance procedure.

A summary of this research project, conclusions and possible future development and work is provided in the following sections.

7.1 Summary

The jet engine is an example of a very complex system with various interacting sub-systems and stringent maintenance requirements. Very high reliability is required as jet engine failures can have serious consequences for airlines and flight safety. This has resulted in increased interest in recent years for quantitative reliability assessment of the jet engine in order to improve system reliability, reduce system failure and reduce maintenance costs.

A review of the state-of-the-art revealed that there is a need is for developing a detailed reliability model of the jet engines. Existing models only consider very few components of the engine or view the engine as a single component. A system level reliability model, including the sub-systems and components, would therefore be of a great value for the aviation industry by providing a quantitative technique for determining reliability and for the evaluation of different options in engine maintenance.

The main objective of this research project was to develop a quantitative reliability model of the Rolls-Royce RB-211 jet engines operated by Icelandair. This model should make it possible to compute the overall reliability of the engines as well as allowing the analysis of how individual sub-systems affect the engine reliability. Furthermore the model should make it possible to evaluate different maintenance strategies in terms of reliability and costs.

This was accomplished by developing a detailed reliability model of the RB-211 jet engines as described in chapter 5. The Reliability Block Diagram (RBD) modeling technique was chosen for that purpose. The RBD model was developed by use of the commercial BlockSim software tool, developed by Reliasoft Inc. The software offers an environment for building up system reliability models by accounting for all the sub-models and components of the system and provides computation of the overall system reliability both analytically and by performing simulation based on the reliability models of individual components and maintenance actions.

The blocks in the RBD were chosen to represent the main components needed for normal operation of the jet engine. The failure behavior of these components was analyzed from operational data obtained from Icelandair Technical Services (ITS) by using the Weibull++ commercial software from Reliasoft. This data analysis resulted in lifetime probability distributions for all components assigned to the blocks, i.e. the blocks reliabilities. The maintenance properties, i.e. scheduled maintenance and corrective maintenance actions, was estimated for each block and implemented in the model.

The reliability model was analyzed by simulating typical lifetime scenarios of the jet engine as it went through operational and maintenance phases, by generating random failure times for each block according to their respective lifetime probability distribution. The failed blocks were repaired each time in accordance with their assigned maintenance properties. The results from simulating the reliability model were used for calculations of various reliability metrics, both on a system level and on a component level. Furthermore the model was used for analysis of alternative maintenance options.

In addition to using the model for reliability analysis, the failure consequences, measured in terms of the Disruption Index (DI), were estimated for the current and alternative options in maintenance. The decision evaluation which airlines often face in this area, i.e. whether or not to implement different maintenance strategies or procedures, can therefore be based on quantitative reliability results as well as estimates on the impact of disruptions on the operation, i.e. by determining the associated D.I.

7.2 Conclusions

The main results and benefits of this research project are the following:

- Initial quantitative reliability model of the RB-211 jet engines made up of sub-systems and components of the engine, where the effects of each component on the system reliability can be determined.
- The reliability model takes into account the lifetime distributions and maintenance properties of each component.
- For more realistic reliability analysis, the model takes into account the different operational and maintenance phases the jet engine goes through during normal operation.
- The reliability model can be used as a tool in decision making by evaluating the expected effects of alternative configurations and maintenance procedures.
- The reliability model is flexible and can easily be modified to account for different operational conditions.
- An initial reliability model of the RB-211 jet engine that can be used for further studies and improvements.

The first quantitative reliability model of the RB-211 jet engines was developed in this research project. The reliability model is made up of sub-systems and components of the engine, where the system reliability is dependent on the components reliability and their reliability-wise configuration. The model describes the various sub-systems and components interconnections and interdependencies needed to deliver the designed functionality of the jet engine.

The jet engine is a repairable system making the system reliability determined by the components reliability and their maintenance properties. The reliability of each component is determined by lifetime probability distributions obtained from operational data. Components are assigned with the repair and maintenance properties for corrective maintenance as well as for preventive maintenance events.

Some systems are in continuous operation. The typical operation of a jet engine however includes several phases; ground phases, flight phases and maintenance phases. The operational stress on the components of the engine between phases is different and is implement in the model. If failure occurs during operation, the failed components cannot be repaired until in the maintenance phase, where corrective and preventive maintenance actions are performed. The reliability model developed in this thesis takes these different phases into account in order to represent more realistic lifetime scenario for the jet engine.

The reliability model developed in this thesis provides a quantitative tool for decision evaluation regarding alternative configurations and maintenance options for airlines. With the help of the reliability model of the jet engine, ITS now can evaluate the expected results of different decisions and maintenance strategies in terms of reliability and costs. Until now decisions regarding maintenance have been made based on industry guidelines, rules and regulations and engineering judgment. Having this reliability model is very valuable since without such a tool ITS may have to wait several years to see the results of the different decisions on the operations and reliability of the jet engine.

The use of this model in reliability analysis and decision making was demonstrated in chapter 6. Reliability analysis of the RB-211 jet engine in its current configuration was performed as well as evaluation of the expected effects of changing the hard time preventive maintenance time for the Fuel Flow Governor. The current scheduled overhaul for the FFG is at 15.000 hours for the Icelandair jet engines. The industry recommendation is currently at 12.000 hours. However ITS experts[23] believe based on their experience, that in the case of the jet engines operated by Icelandair, this would not result in higher availability of the system or the FFG [9]. It was therefore decided to use the reliability model to evaluate whether shortening the operation time for the FFG, as recommended, would result in improvements of availability or other

[23] Kristján O. Magnússon and Heimir Ö. Hólmarsson

reliability metrics. Furthermore the model was used to evaluate the results of extending the operation time even further to 18.000 hours.

It was found that no considerable changes in availability or DI are expected if the maximum operation time for the FFG is decreased to 12.000 hours. The main reason for this may be due to imperfections in the overhaul of the FFG which result in failure of components at the beginning of the component life-time. If imperfect overhaul takes place, these failures have occurred well before 12.000 hours. Furthermore it was found that extending the operation time to 18.000 hours would even bring about very similar availability and DI results. These results indicate that it would not pay off to overhaul the FFG sooner than at 15.000 hours as no availability improvements are expected. Moreover additional operating hours are valuable. As the availability is not expected to decline with additional hours, it might pay off to extend the operation time to 18.000 hours. However inspection and analysis of the condition of the FFG removed after 15.000 hours should be undertaken to find out if this was warranted.

It is important to bear in mind however when evaluating such decisions that the model developed in this thesis is based on many assumptions and engineering judgment must be included. The model is useful to give indication on the expected results.

One important property of the reliability model developed in this thesis is that it can easily be modified to account for different operational conditions, different components reliabilities and different maintenance strategies.

The reliability model of the RB-211 jet engines developed in this research project can be used for further studies and improvements as will be explained in the next section.

7.3 Future works

The reliability model developed in this research project provides an initial quantitative reliability analysis of the RB-211 jet engines which can furthermore be used to evaluate alternative configurations and maintenance strategies. The model can be extended and improved by further studies:

- Obtain more accurate lifetime distribution for all components based on operational data.
- Include dynamic maintenance models.
- Expand the model by including lower level parts of the engine.
- Expand the model by including more parts of an aircraft where the engine is a sub-system of a larger system.
- Further validation of the model.

The individual component reliabilities determined in this thesis, i.e. the lifetime distributions, are based on 5-years-period failure data. However failure times could not be obtained for all the components during that period. For those components, the lifetime distributions were based on ITS staff engineering judgment. In order to obtain more accurate system reliability estimations, lifetime distributions should be based on real data for all components.

With this reliability model of the jet engine in hand, the model could be expanded to account for more realistic and dynamic maintenance models where repair crews, component spares and logistic delays are included. For this to be done a detailed analysis of the maintenance processes must be made.

Moreover the model can be expanded by including lower level parts of the jet engine and/or including more parts of an aircraft, where the engine is a sub-system of a larger system.

Further validation of the reliability model should be performed by analyzing the results from the model and compare them with more operational data.

REFERENCES

[1] W. R. Blischke and D. N. P. Murthy, *Case Studies in Reliability and Maintenance*. John Wiley & Sons, 2003.

[2] D. J. Smith, *Reliability, Maintainability and Risk 8e: Practical Methods for Engineers including Reliability Centred Maintenance and Safety-Related Systems*. Elsevier, 2011.

[3] “12 Reasons Why Flying Is The Safest Way To Travel,” *Business Insider*. [Online]. Available: http://www.businessinsider.com/flying-is-still-the-safest-way-to-travel-2013-7. [Accessed: 26-Apr-2014].

[4] M. L. Wald, “A Cleaner, Leaner Jet Age Has Arrived,” *The New York Times*, 09-Apr-2008.

[5] “Airworthiness Directives.” [Online]. Available: http://easa.europa.eu/airworthiness-directives-ad. [Accessed: 25-May-2014].

[6] J. Kappas, “Review of Risk and Reliability Methods for Aircraft Gas Turbine Engines,” May 2002.

[7] E. da C. P. Batalha, “Aircraft Engines Maintenance Costs and Reliability: An Appraisal of the Decision Process to Remove an Engine for a Shop Visit Aiming at Minimum Maintenance Unit Cost,” May 2012.

[8] H. Wang and H. Pham, *Reliability and Optimal Maintenance*. Springer, 2006.

[9] K. O. Magnússon and H. Ö. Hólmarsson, “Various considerations regarding jet engine operation,” 16-Apr-2014.

[10] U. Þórleifsdóttir, “Reliability Analysis of the Reykjavik Area Control Center Air Traffic Management System,” 2013.

[11] R. G. Jackson, “Reliability and Maintainability -A Look at the Rolls-Royce RB.211,” SAE International, Warrendale, PA, SAE Technical Paper 851829, Oct. 1985.

[12] M. Rausand and A. Høyland, *System reliability theory: models, statistical methods, and applications*, 2nd ed. Hoboken, NJ: Wiley-Interscience, 2004.

[13] ReliaSoft, *System Analysis Reference - Reliability, Availability & Optimization*. Tucson, USA: Reliasoft Corporation, 2014.

[14] MIL-STD-721C, “Definitions of terms for reliability and maintainability.” Department Of Defence, Washington, DC, 1981.

[15] K. C. Kapur and L. R. Lamberson, *Reliability in engineering design*. Wiley, 1977.

[16] BS 4778, “Glossary of Terms Used in Quality Assurance Including Reliability and Maintanability Terms.” British Standards Institution, London, 1991.

[17] IEC 50(191), “International Electrotechnical Vocabulary (IEV) - Chapter 191 - Dependability and Quality of Service.” International Electrotechnical Commission, Geneva, 1990.

[18] M. H. . Everdij, H. A. . Blom, and B. Kirwan, “Development of a Structured Database of Safety Methods,” presented at the 8th International Conference on

Probabilistic Safety Assessment and Management, New Orleans, Louisiana, USA, 2006.

[19] P. Hopper, “Designing for Reliability - the Rolls-Royce Approach,” presented at the RTO AVT Symposium on “Design Principles and Methods for Aircraft Gas Turbine Engines,” Toulouse, France, 1998.

[20] R. W. Walker, “Assessment of technical risks,” in *Proceedings of the 2000 IEEE International Conference on Management of Innovation and Technology, 2000. ICMIT 2000*, 2000, vol. 1, pp. 402–406 vol.1.

[21] A. Atamer, “Comparison of FMEA and field-experience for a turbofan engine with application to case based reasoning,” in *2004 IEEE Aerospace Conference, 2004. Proceedings*, 2004, vol. 5, pp. 3354–3360 Vol.5.

[22] J. Blow, “Applied R&M Manual for Defence Systems Part C - R&M Related Techniques - Reliability Block Diagrams.” Ministry of Defense, 2011.

[23] R. P. Baldwin, “Aircraft engine reliability analysis using lower confidence limit estimate procedures,” Naval Postgraduate school, Montery, California, 1992.

[24] U. D. Kumar, “New trends in aircraft reliability and maintenance measures,” *J. Qual. Maint. Eng.*, vol. 5, no. 4, pp. 287–295, Dec. 1999.

[25] A. Jackson, “Reliability modeling that combines Markov analysis and Weibull distributions,” in *Reliability and Maintainability Symposium (RAMS), 2013 Proceedings - Annual*, 2013, pp. 1–6.

[26] H. Kumamoto, K. Tanaka, and K. Inoue, “Efficient Evaluation of System Reliability by Monte Carlo Method,” *IEEE Trans. Reliab.*, vol. R-26, no. 5, pp. 311–315, Dec. 1977.

[27] ReliaSoft, *Life Data Analysis Reference*. Tucson, USA: Reliasoft Corporation, 2014.

[28] L. Tyson, “Improving the Reliability of a Turbofan Jet Engine,” *Uptime Magazine*, pp. 48–51, Jul-2011.

[29] L. Tyson, “Improving the Reliability of a Turbofan Jet Engine - Part 2,” *Uptime Magazine*, pp. 40–41, Nov-2012.

[30] G. R. Weckman, R. L. Shell, and J. H. Marvel, “Modeling the reliability of repairable systems in the aviation industry,” *Comput. Ind. Eng.*, vol. 40, no. 1–2, pp. 51–63, Jun. 2001.

[31] S. M. and G. V. Stefania Bandini, “Agent Based Modeling and Simulation: An Informatics Perspective,” 31-Oct-2009. [Online]. Available: http://jasss.soc.surrey.ac.uk/12/4/4.html. [Accessed: 10-May-2014].

[32] A. Stranjak, P. S. Dutta, M. Ebden, P. Vytelingum, and A. Rogers, “A Multi-Agent Simulation System for Prediction and Scheduling of Aero Engine Overhaul,” presented at the Seventh International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS-08), 2008, pp. 81–88.

[33] J. Crocker and U. D. Kumar, “Age-related maintenance versus reliability centred maintenance: a case study on aero-engines,” *Reliab. Eng. Syst. Saf.*, vol. 67, no. 2, pp. 113–118, Feb. 2000.

[34] M. Rausand, “Reliability centered maintenance,” *Reliab. Eng. Syst. Saf.*, vol. 60, no. 2, pp. 121–132, May 1998.

[35] J. S. Agte, N. K. Borer, and O. D. Weck, “Multistate Design Approach to Analysis of Twin-Engine Aircraft Performance Robustness,” *J. Aircr.*, vol. 49, no. 3, pp. 781–793, 2012.

[36] A. Jackson, “Markov analysis with non-constant hazard rates,” M.S., California State University, Long Beach, United States -- California, 2009.

[37] D. J. Smith and K. G. L. Simpson, *Safety Critical Systems Handbook: A STRAIGHTFOWARD GUIDE TO FUNCTIONAL SAFETY, IEC 61508 (2010 EDITION) AND RELATED STANDARDS, INCLUDING PROCESS IEC 61511 AND MACHINERY IEC 62061 AND ISO 13849*. Elsevier, 2010.

[38] R. Wurzbach, “Benchmarking Oil Analysis,” *Practicing Oil Analysis*, Nov-2002.

[39] D. Troyer, “Reliability engineering principles for the plant engineer,” *Reliable Plant*. [Online]. Available: http://www.reliableplant.com/Read/18693/reliability-engineering-plant. [Accessed: 09-May-2014].

[40] T. R. Chandrupatla, *Quality and reliability in engineering*. New York: Cambridge University Press, 2009.

[41] R. Apthorpe, “A Probabilistic Approach to Estimating Computer System Reliability,” pp. 31–46, 2001.

[42] G. Sarakakis, A. Gerokostopoulos, and A. Mettas, “Special topics for consideration in a design for reliability process,” in *Reliability and Maintainability Symposium (RAMS), 2011 Proceedings - Annual*, 2011, pp. 1–6.

[43] A. K. S. Jardine, P. M. Anderson, and D. S. Mann, “Application of the weibull proportional hazards model to aircraft and marine engine failure data,” *Qual. Reliab. Eng. Int.*, vol. 3, no. 2, pp. 77–82, Apr. 1987.

[44] B. Dodson, *The Weibull Analysis Handbook*. ASQ Quality Press, 2006.

[45] ReliaSoft, “Life Data Classifications,” *Reliability EDGE*, no. 1, p. 4, Q2-2000.

[46] M. S. Hamada, A. Wilson, C. S. Reese, and H. Martz, *Bayesian Reliability*. Springer, 2008.

[47] W. B. Nelson, *Applied Life Data Analysis*. John Wiley & Sons, 2005.

[48] V. Strejc, “Least squares parameter estimation,” *Automatica*, vol. 16, no. 5, pp. 535–550, Sep. 1980.

[49] S. Dean, “Confidence Intervals: Confidence Interval, Single Population Mean, Population Standard Deviation Known, Normal,” *OpenStax CNX*. [Online]. Available: http://cnx.org/content/m16962/latest/?collection=col10522. [Accessed: 06-May-2014].

[50] B. Subotic, “Framework for the Analysis of Controller Recovery from Equipment Failures in Air Traffic Control,” Phd, Imperial College London, London UK, 2007.

[51] ReliaSoft, *BlockSim 9 - Quick Start Guide*. Tucson, USA: Reliasoft Corporation, 2013.

[52] D. Kececioglu, *Reliability Engineering Handbook*. DEStech Publications, Inc, 2002.

[53] ReliaSoft, *System Analysis Reference - Reliability, Availability & Optimization*. Tucson, USA: ReliaSoft Publishing, 2007.

[54] A. Brall, W. Hagen, and H. Tran, “Reliability Block Diagram Modeling - Comparisons of Three Software Packages,” in *Reliability and Maintainability Symposium, 2007. RAMS ’07. Annual*, 2007, pp. 119–124.

[55] ReliaSoft, “Reliability Importance Measures of Components in a Complex System - Identifying the 20% in the 80/20 rule,” *Reliability HotWire*, no. Issue 66, Jul-2006.

[56] ReliaSoft, “Reliability Phase Diagram Analysis,” *Reliability EDGE*, no. 1, p. 4, Q1-2007.

[57] J. Scott, “Aerospaceweb.org | Ask Us - Pentagon & Boeing 757 Engine Investigation,” *Aerospace Web*, 06-May-2006. [Online]. Available: http://www.aerospaceweb.org/question/conspiracy/q0265.shtml. [Accessed: 04-May-2014].

[58] Rolls-Royce Ltd, *The jet engine*, 6th edition. London: Rolls-Royce, 2005.

[59] E. E. Lewis, *Introduction to reliability engineering*, 2nd ed. New York: J. Wiley, 1996.

[60] D. M. Kennet, “Did Deregulation Affect Aircraft Engine Maintenance? An Empirical Policy Analysis,” *RAND J. Econ.*, vol. 24, no. 4, pp. 542–558, 1993.

[61] D. M. Kennet, “A Structural Model of Aircraft Engine Maintenance,” *J. Appl. Econom.*, vol. 9, no. 4, pp. 351–68, 1994.

[62] K. O. Magnússon, “Icelandair jet engines - Functional Diagrams.” 15-Feb-2014.

[63] K. O. Magnússon, “Engine statistics,” 23-Apr-2014.

[64] K. Kusy, “RBD configuration,” 14-Apr-2014.

[65] C. Alcock, “R-R pulling out stops to mature Trent XWB,” *Aviation International News*, 15-Jul-2010. [Online]. Available: http://www.ainonline.com/aviation-news/farnborough-air-show/2010-07-15/r-r-pulling-out-stops-mature-trent-xwb. [Accessed: 21-May-2014].

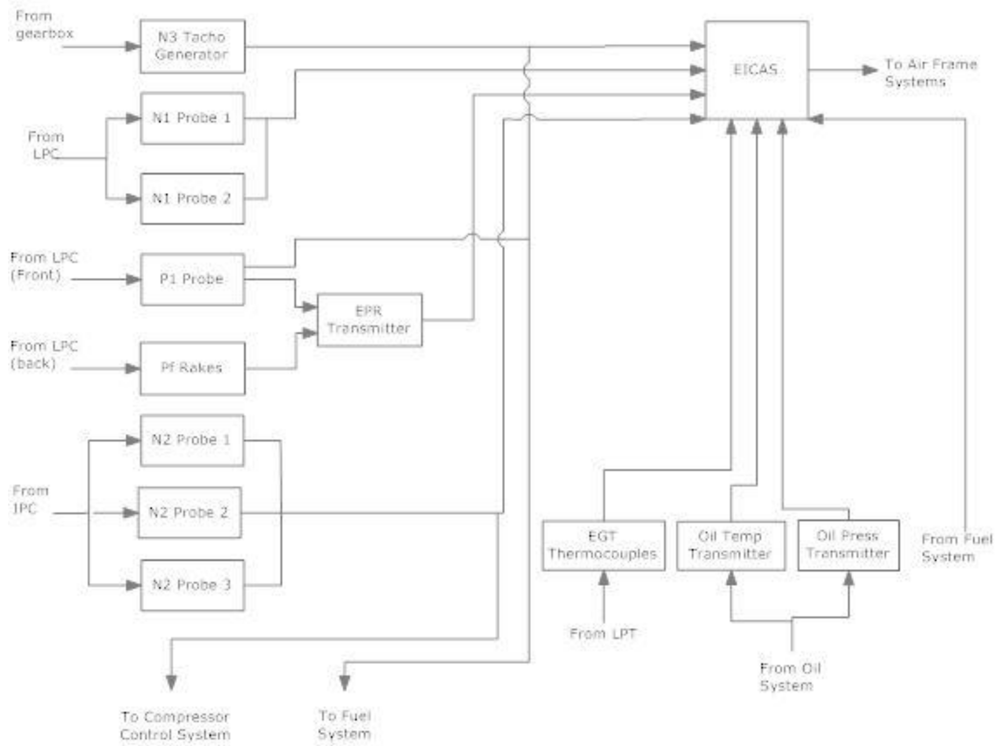
[66] H. Ö. Hólmarsson and E. D. Haraldsdóttir, “The use of this model for Icelandair,” 14-May-2014.

APPENDICES

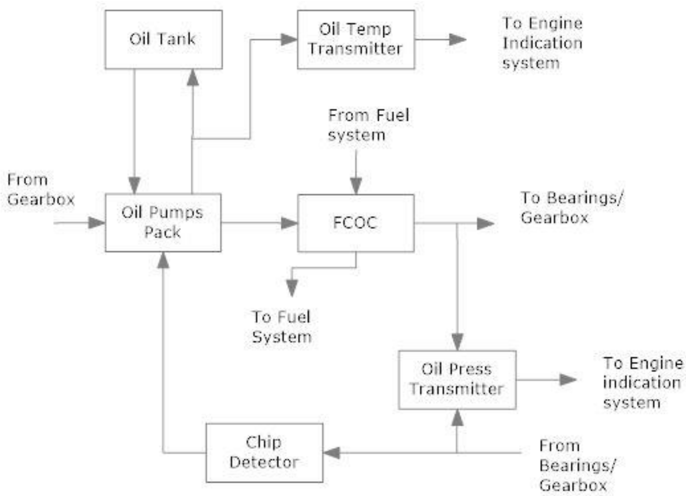
A. Functional diagrams

Following are the functional diagrams of the sub-systems of the RB-211 jet engine presented in chapter 5.2:

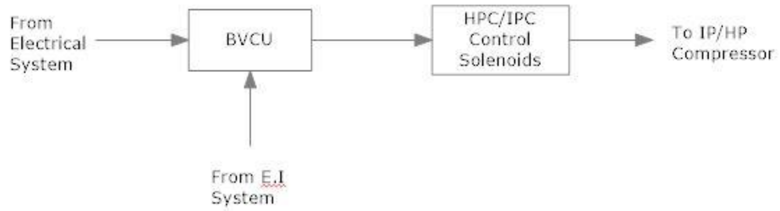
Engine Indication System:



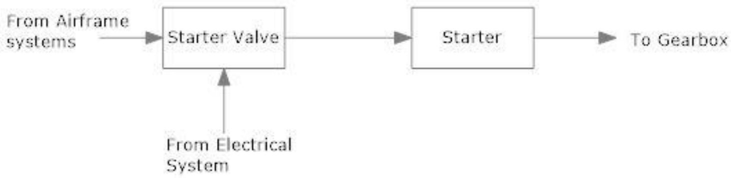
Oil System:



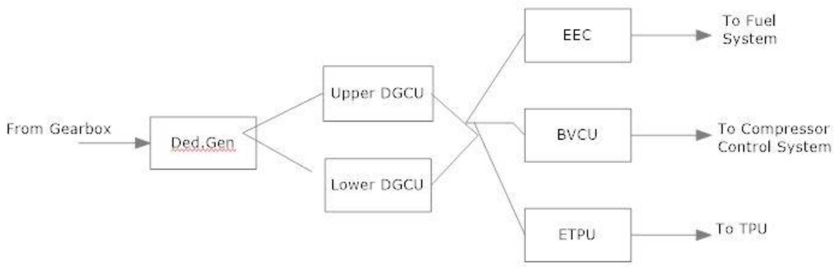
Compressor Control System:



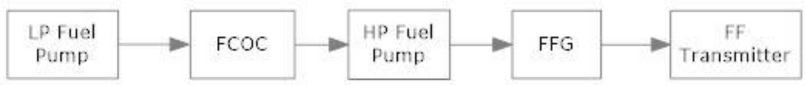
Starter System:



Electrical System:



Fuel System:



B. RB-211 Jet Engine Component list

The components used for the reliability modeling of the RB-211 jet engines are the following, in alphabetical order:

- Bleed Valve Control Unit (BVCU)
- Chip Detectors
- Combustion Chamber (CC)
- Dedicated Generator (Ded Gen)
- Dedicated Generator Control Unit (DGCU)
- Electronic Engine Control (EEC)
- Electronic Transient Pressure Unit (ETPU)
- Engine Pressure Ration Transmitter (EPR Transmitter)
- Exhaust Gas Temperature Thermocouples (EGT Thermocouples)
- Fuel Cooled Oil Cooler (FCOC)
- Fuel Flow Governor (FFG)
- Fuel Flow Transmitter (FF Transmitter)
- Gearbox
- High-Pressure Compressor/Intermediate-Pressure Compressor Solenoids (HPC/IPC Solenoids)
- High-Pressure Fuel Pump (HP Fuel Pump)
- Integrated Drive Generator (IDG)
- Intermediate-Pressure/High-Pressure Compressors (IP/HPC)
- Intermediate-Pressure/High-Pressure Turbines (IP/HPT)
- Low-Pressure Compressor (LPC)
- Low-Pressure Fuel Pump (LP Fuel Pump)
- Low-Pressure Turbine
- N1 Probe
- N2 Probe
- N3 Tacho Generator (N3 Tacho Gen)
- Oil Pressure Transmitter (Oil Press Transmitter)
- Oil Pump Pack
- Oil Tank
- Oil Temperature Transmitter (Oil Temp Transmitter)
- P1 Probe
- Pf Rakes
- Radial Drive Shaft (RDS)
- Starter
- Starter Valve
- Transient Fuel Unit (TFU)

C. Disruption Index

The Disruption Index (DI) is found for each component by weighting their possible impact on the operations. At the top line the impact of each event is given a number. The second line represents the possible impact events. These are:

- Aborted Take-Off – above 80 kts (ABTO)
- Diversion (DIV)
- Air Turnback (ATB)
- In-flight Shutdown (IFSD)
- Aborted Take-Off – below 80 kts (ABTO)
- Surge, fuel leak, other (No IFE)
- Remote Site Resque (RSR)
- Unplanned Engine Removal (UER)
- Delay 15 – 30 mins (D30)
- Delay 30 mins – 2 hours (D120)
- Delay 2 – 6 hours (D360)
- Delay 6 – 12 hours (D720)
- Delay more than 12 hours (D720+)
- Cancellation (CAN)

Disruption index for the Ground Phase:

DI	1,0	0,8	0,8	0,6	0,2	0,3	0,3	0,2	0,0	0,1	0,1	0,2	0,4	0,5	
Component	ABTO1	DIV	ATB	IFSD	ABTO2	No IFE	RSR	UER	D30	D120	D360	D720	D720+	CAN	TOTAL DI
TFU											1				0,1
IDG											1				0,1
CC								1						1	0,7
LPC								1						1	0,7
IP/HPC								1						1	0,7
IP/HPT								1						1	0,7
LPT								1						1	0,7
RDS														1	0,5
BVCU											1				0,1
HPC/IPC Solenoids											1				0,1
Starter Valve										1					0,05
Starter										1					0,05
Dedicated Generator											1				0,1
DGCU										1					0,05
EEC											1				0,1
ETPU											1				0,1
LP fuel pump											1				0,1
F.C.O.C													1		0,4
HP Fuel pump											1				0,1
FFG											1				0,1
FF transmitter										1					0,05
N3 Tach gen											1				0,1
N1 probe									1						0,02
P1 probe											1				0,1
Pf rakes											1				0,1
EPR transmitter											1				0,1
N2 probe									1						0,02
EGT thermocouples											1				0,1
Oil temp transmitter										1					0,05
Oil press transmitter										1					0,05
Oil tank								1					1		0,6
Oil pump pack												1			0,2
Chip detectors								1						1	0,7
Gearbox		1		1			1	1						1	2,4

Disruption Index for the Take-Off Phase:

DI	1,0	0,8	0,8	0,6	0,2	0,3	0,3	0,2	0,0	0,05	0,1	0,2	0,4	0,5	
Component	ABTO1	DIV	ATB	IFSD	ABTO2	No IFE	RSR	UER	D30	D120	D360	D720	D720+	CAN	TOTAL DI
TFU						1				1					0,35
IDG					1						1				0,3
CC	1					1	1	1						1	2,3
LPC	1					1	1	1						1	2,3
IP/HPC	1					1	1	1						1	2,3
IP/HPT	1					1	1	1						1	2,3
LPT	1					1	1	1						1	2,3
RDS	1					1	1	1						1	2,3
BVCU						1						1			0,5
HPC/IPC Solenoids						1						1			0,5
Starter Valve						1	1					1			0,8
Starter						1	1					1			0,8
Dedicated Generator						1	1					1			0,8
DGCU						1	1			1					0,65
EEC						1	1				1				0,7
ETPU					1						1				0,3
LP fuel pump	1						1	1						1	2
F.C.O.C	1						1	1						1	2
HP Fuel pump	1						1	1						1	2
FFG	1					1	1	1						1	2,3
FF transmitter						1				1					0,35
N3 Tach gen					1		1						1		0,9
N1 probe						1									0,3
P1 probe	1						1						1		1,7
Pf rakes	1						1						1		1,7
EPR transmitter	1						1						1		1,7
N2 probe						1									0,3
EGT thermocouples							1					1			0,5
Oil temp transmitter					1					1					0,25
Oil press transmitter					1					1					0,25
Oil tank	1						1	1						1	2
Oil pump pack	1						1	1						1	2
Chip detectors															0
Gearbox		1		1			1	1						1	2,4

Disruption Index for In-Flight Phase:

DI	1,0	0,8	0,8	0,6	0,2	0,3	0,3	0,2	0,0	0,1	0,1	0,2	0,4	0,5	
Component	ABTO1	DIV	ATB	IFSD	ABTO2	No IFE	RSR	UER	D30	D120	D360	D720	D720+	CAN	TOTAL DI
TFU				1		1		1						1	1,6
IDG												1			0,2
CC		1		1			1	1						1	2,4
LPC		1		1			1	1						1	2,4
IP/HPC		1		1			1	1						1	2,4
IP/HPT		1		1			1	1						1	2,4
LPT		1		1			1	1						1	2,4
RDS		1		1			1	1						1	2,4
BVCU				1		1	1					1			1,4
HPC/IPC Solenoids						1						1			0,5
Starter Valve						1						1			0,5
Starter						1						1			0,5
Dedicated Generator				1		1								1	1,4
DGCU						1					1				0,4
EEC						1	1						1		1
ETPU						1	1	1						1	1,3
LP fuel pump		1		1			1	1						1	2,4
F.C.O.C		1		1			1	1						1	2,4
HP Fuel pump		1		1			1	1						1	2,4
FFG		1		1			1	1						1	2,4
FF transmitter											1				0,1
N3 Tach gen		1		1							1				1,5
N1 probe								1		1					0,25
P1 probe													1		0,4
Pf rakes													1		0,4
EPR transmitter													1		0,4
N2 probe								1		1					0,25
EGT thermocouples		1											1		1,2
Oil temp transmitter		1		1			1					1			1,9
Oil press transmitter		1		1			1					1			1,9
Oil tank		1		1			1	1						1	2,4
Oil pump pack		1		1			1	1						1	2,4
Chip detectors															0
Gearbox		1		1			1	1						1	2,4

D. Disruption Index results

Disruption Index for current procedures:

Disruption Index (DI): Current procedures								
Block Name	Failures in ground phase	DI Ground	Failures in Take-off	DI Take-off	Failures In-flight	DI In-flight	Total failures	Total DI
Combustion Chamber	0	0,7	0,172	2,3	0,584	2,4	0,756	1,7972
IDG	0,024	0,1	0,384	0,3	1,212	0,2	1,62	0,36
TFU	0	0,1	0,128	0,35	0,476	1,6	0,604	0,8064
RDS	0	0,5	0	2,3	0	2,4	0	0
Gearbox	0,008	0,7	0,164	2,3	0,584	2,4	0,756	1,7844
LP Fuel Pump	0,008	0,1	0,232	2	0,816	2,4	1,056	2,4232
Fuel Cooled Oil Cooler	0	0,4	0,144	2	0,58	2,4	0,724	1,68
HP Fuel Pump	0,004	0,4	0,268	2	0,744	2,4	1,016	2,3232
Fuel Flow Governor	0,024	0,1	0,488	2,3	1,68	2,4	2,192	5,1568
Fuel Flow Transmitter	0,004	0,05	0,112	0,35	0,456	0,1	0,572	0,085
N3 Tacho Generator	0,008	0,1	0,156	0,9	0,432	1,5	0,596	0,7892
N1 Probe 1	0,004	0,02	0,088	0,3	0,276	0,25	0,368	0,09548
N1 Probe 2	0,004	0,02	0,092	0,3	0,308	0,25	0,404	0,10468
N2 Probe 1	0,004	0,02	0,024	0,3	0,072	0,25	0,1	0,02528
N2 Probe 2	0,008	0,02	0,036	0,3	0,092	0,25	0,136	0,03396
N2 Probe 3	0,008	0,02	0,028	0,3	0,092	0,25	0,128	0,03156
P1 Probe	0,004	0,1	0,12	1,7	0,472	0,4	0,596	0,3932
EPR Transmitter	0	0,1	0,12	1,7	0,464	0,4	0,584	0,3896
EGT Thermocouples	0,072	0,1	0,28	0,5	0,956	1,2	1,308	1,2944
Pf Rakes	0,04	0,1	0,32	1,7	0,956	0,4	1,316	0,9304
Oil Temperature Transmitter	0,008	0,05	0,164	0,25	0,696	1,9	0,868	1,3638
Oil Pressure Transmitter	0,016	0,05	0,16	0,25	0,592	1,9	0,768	1,1656
Dedicated Generator	0,008	0,1	0,148	0,8	0,428	1,4	0,584	0,7184
Upper DG Control Unit	0,012	0,05	0,284	0,65	1,012	0,4	1,308	0,59
Lower DG Control Unit	0,012	0,05	0,292	0,65	0,896	0,4	1,2	0,5488
EEC	0,004	0,1	0,196	0,7	0,896	1	1,096	1,0336
ETPU	0,036	0,1	0,152	0,3	0,608	1,3	0,796	0,8396
HPC/IPC Control Solenoids	0,048	0,1	0,3	0,5	1,028	0,5	1,376	0,6688
BVCU	0,056	0,1	0,24	0,5	0,992	1,4	1,288	1,5144
Starter Valve	0,04	0,05	0,432	0,8	1,228	0,5	1,7	0,9616
Starter	0,004	0,05	0,184	0,8	0,628	0,5	0,816	0,4614
Oil Tank	0	0,6	0	2	0	2,4	0	0
Oil Pumps Pack	0	0,2	0	2	0	2,4	0	0
Chip Detector	0	0,7	0,148	0	0,552	0	0,7	0
LPC	0,016	0,7	0,164	2,3	0,596	2,4	0,776	1,8188
IPC/HPC	0,008	0,7	0,16	2,3	0,56	2,4	0,728	1,7176
LPT	0,004	0,7	0,136	2,3	0,624	2,4	0,764	1,8132
IPT/HPT	0,012	0,7	0,144	2,3	0,636	2,4	0,792	1,866

Disruption Index results for new maintenance option, hard time interval for FFG at 12.000 hours:

Disruption Index (DI): New maintenance option - FFG hard time 12.000 hours								
Block Name	Failures in ground phase	DI Ground	Failures in Take-off	DI Take-off	Failures In-flight	DI In-flight	Total failures	Total DI
Combustion Chamber	0,008	0,7	0,168	2,3	0,608	2,4	0,784	1,8512
IDG	0,02	0,1	0,408	0,3	1,176	0,2	1,604	0,3596
TFU	0	0,1	0,116	0,35	0,464	1,6	0,58	0,783
RDS	0	0,5	0	2,3	0	2,4	0	0
Gearbox	0,004	0,7	0,184	2,3	0,596	2,4	0,784	1,8564
LP Fuel Pump	0,016	0,1	0,284	2	0,792	2,4	1,092	2,4704
Fuel Cooled Oil Cooler	0,004	0,4	0,112	2	0,564	2,4	0,68	1,5792
HP Fuel Pump	0,004	0,4	0,252	2	0,748	2,4	1,004	2,3008
Fuel Flow Governor	0,036	0,1	0,532	2,3	1,724	2,4	2,292	5,3648
Fuel Flow Transmitter	0,004	0,05	0,124	0,35	0,408	0,1	0,536	0,0844
N3 Tacho Generator	0	0,1	0,156	0,9	0,508	1,5	0,664	0,9024
N1 Probe 1	0,004	0,02	0,088	0,3	0,32	0,25	0,412	0,10648
N1 Probe 2	0	0,02	0,116	0,3	0,34	0,25	0,456	0,1198
N2 Probe 1	0,004	0,02	0,036	0,3	0,068	0,25	0,108	0,02788
N2 Probe 2	0,004	0,02	0,036	0,3	0,1	0,25	0,14	0,03588
N2 Probe 3	0	0,02	0,012	0,3	0,076	0,25	0,088	0,0226
P1 Probe	0,004	0,1	0,144	1,7	0,536	0,4	0,684	0,4596
EPR Transmitter	0,004	0,1	0,112	1,7	0,44	0,4	0,556	0,3668
EGT Thermocouples	0,056	0,1	0,32	0,5	0,884	1,2	1,26	1,2264
Pf Rakes	0,064	0,1	0,276	1,7	0,988	0,4	1,328	0,8708
Oil Temperature Transmitter	0,012	0,05	0,168	0,25	0,632	1,9	0,812	1,2434
Oil Pressure Transmitter	0,004	0,05	0,204	0,25	0,728	1,9	0,936	1,4344
Dedicated Generator	0,004	0,1	0,116	0,8	0,496	1,4	0,616	0,7876
Upper DG Control Unit	0,02	0,05	0,276	0,65	0,916	0,4	1,212	0,5468
Lower DG Control Unit	0,016	0,05	0,288	0,65	0,896	0,4	1,2	0,5464
EEC	0,012	0,1	0,268	0,7	0,904	1	1,184	1,0928
ETPU	0,028	0,1	0,164	0,3	0,576	1,3	0,768	0,8008
HPC/IPC Control Solenoids	0,072	0,1	0,292	0,5	0,948	0,5	1,312	0,6272
BVCU	0,064	0,1	0,212	0,5	0,956	1,4	1,232	1,4508
Starter Valve	0,064	0,05	0,432	0,8	1,236	0,5	1,732	0,9668
Starter	0,004	0,05	0,208	0,8	0,728	0,5	0,94	0,5306
Oil Tank	0	0,6	0	2	0	2,4	0	0
Oil Pumps Pack	0	0,2	0	2	0	2,4	0	0
Chip Detector	0,008	0,7	0,172	0	0,588	0	0,768	0,0056
LPC	0,008	0,7	0,156	2,3	0,576	2,4	0,74	1,7468
IPC/HPC	0,012	0,7	0,172	2,3	0,616	2,4	0,8	1,8824
LPT	0,008	0,7	0,144	2,3	0,616	2,4	0,768	1,8152
IPT/HPT	0,012	0,7	0,2	2,3	0,572	2,4	0,784	1,8412

Disruption Index results for new maintenance option, hard time interval for FFG at 18.000 hours:

Disruption Index (DI): New maintenance option - FFG hard time 18.000 hours								
Block Name	Failures in ground phase	DI Ground	Failures in Take-off	DI Take-off	Failures In-flight	DI In-flight	Total failures	Total DI
Combustion Chamber	0,004	0,7	0,14	2,3	0,628	2,4	0,772	1,832
IDG	0,02	0,1	0,36	0,3	1,328	0,2	1,708	0,3756
TFU	0,004	0,1	0,132	0,35	0,464	1,6	0,6	0,789
RDS	0	0,5	0	2,3	0	2,4	0	0
Gearbox	0	0,7	0,164	2,3	0,604	2,4	0,768	1,8268
LP Fuel Pump	0,016	0,1	0,212	2	0,7	2,4	0,928	2,1056
Fuel Cooled Oil Cooler	0	0,4	0,148	2	0,488	2,4	0,636	1,4672
HP Fuel Pump	0,004	0,4	0,228	2	0,812	2,4	1,044	2,4064
Fuel Flow Governor	0,016	0,1	0,492	2,3	1,628	2,4	2,136	5,0404
Fuel Flow Transmitter	0	0,05	0,144	0,35	0,488	0,1	0,632	0,0992
N3 Tacho Generator	0	0,1	0,14	0,9	0,492	1,5	0,632	0,864
N1 Probe 1	0	0,02	0,092	0,3	0,324	0,25	0,416	0,1086
N1 Probe 2	0,004	0,02	0,088	0,3	0,344	0,25	0,436	0,11248
N2 Probe 1	0,008	0,02	0,028	0,3	0,084	0,25	0,12	0,02956
N2 Probe 2	0,016	0,02	0,04	0,3	0,084	0,25	0,14	0,03332
N2 Probe 3	0,008	0,02	0,016	0,3	0,084	0,25	0,108	0,02596
P1 Probe	0,004	0,1	0,112	1,7	0,484	0,4	0,6	0,3844
EPR Transmitter	0	0,1	0,084	1,7	0,444	0,4	0,528	0,3204
EGT Thermocouples	0,088	0,1	0,248	0,5	1,012	1,2	1,348	1,3472
Pf Rakes	0,072	0,1	0,352	1,7	0,9	0,4	1,324	0,9656
Oil Temperature Transmitter	0,008	0,05	0,172	0,25	0,604	1,9	0,784	1,191
Oil Pressure Transmitter	0,004	0,05	0,132	0,25	0,54	1,9	0,676	1,0592
Dedicated Generator	0,004	0,1	0,156	0,8	0,504	1,4	0,664	0,8308
Upper DG Control Unit	0,012	0,05	0,328	0,65	0,968	0,4	1,308	0,601
Lower DG Control Unit	0,012	0,05	0,212	0,65	0,824	0,4	1,048	0,468
EEC	0,012	0,1	0,24	0,7	0,992	1	1,244	1,1612
ETPU	0,028	0,1	0,188	0,3	0,636	1,3	0,852	0,886
HPC/IPC Control Solenoids	0,068	0,1	0,28	0,5	1,084	0,5	1,432	0,6888
BVCU	0,064	0,1	0,304	0,5	0,94	1,4	1,308	1,4744
Starter Valve	0,048	0,05	0,388	0,8	1,208	0,5	1,644	0,9168
Starter	0,004	0,05	0,188	0,8	0,612	0,5	0,804	0,4566
Oil Tank	0	0,6	0	2	0	2,4	0	0
Oil Pumps Pack	0	0,2	0	2	0	2,4	0	0
Chip Detector	0,004	0,7	0,192	0	0,54	0	0,736	0,0028
LPC	0,008	0,7	0,136	2,3	0,612	2,4	0,756	1,7872
IPC/HPC	0,004	0,7	0,172	2,3	0,648	2,4	0,824	1,9536
LPT	0,016	0,7	0,168	2,3	0,564	2,4	0,748	1,7512
IPT/HPT	0,004	0,7	0,208	2,3	0,56	2,4	0,772	1,8252

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