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Aircraft Systems Design Methodology and Dispatch Reliability Prediction

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Abstract

Aircraft dispatch reliability was the main subject of this research in the wider content of aircraft reliability. The factors effecting dispatch reliability, aircraft delay, causes of aircraft delays, and aircraft delay costs and magnitudes were examined. Delay cost elements and aircraft delay scenarios were also studied. It concluded that aircraft dispatch reliability is affected by technical and non-technical factors, and that the former are under the designer's control. It showed that the costs of aircraft delays are very significant and must be reduced.

An aircraft delay study evaluated different aircraft system contributions to the delays. It concluded that there are certain systems that cause large percentages of the delays of about 68% of the total aircraft delay. These systems are the power plant, landing gear, hydraulic, flight control and fuel systems.

The available aircraft dispatch reliability prediction methods were reviewed and the conclusion drawn was that a new prediction method was needed. A new civil aircraft dispatch reliability prediction method (DRPM) was therefore developed and validated. The outcome of this validation exercise showed the high predictability of the DRPM.

Another literature review of the available aircraft design methodologies for dispatch reliability revealed that there was a need for a methodology that can address dispatch reliability early in the aircraft design stage.

A generic aircraft systems design methodology for dispatch reliability (ASDMDR) was developed, that can be useful design tool to achieve the required aircraft dispatch reliability. The methodology main themes evolve around two component design characteristics; Reliability and Maintainability.

The methodology focused and analyses these two characteristics throughout the aircraft design hierarchy down to the component level. It can be applied at the early design stage and can be used all the way to the very advanced design phase. ASDMDR can use generic or actual failure rate and mean time to repair data.

It employs some new ideas and makes use of other common design practices to make certain that the aircraft system under design (or the aircraft in general) will achieve the desired dispatch reliability. The ASDMDR was validated and used as design improvement tool. The outcome of this showed that ASDMDR is an effective design tool for the dispatch reliability and demonstrated ways in which this might be done.
The ASDMDR can be used by a wide variety of engineers and is user-friendly.
It can be used for civil and military aircraft design projects, taking into consideration the use of appropriate input data for each aircraft type.

Keywords:
Dispatch reliability, delay rate, maintainability, aircraft availability, aircraft systems design methodology for dispatch reliability.

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Nomenclature

λ	Failure Rate
μ	Repair Rate
A/C	Aircraft
ALDT	Administrative Logistic Delay Time
A_0	Operational Availability
AIAA	American Institute of Aeronautics & Astronautics
ASDMDR	Aircraft systems design methodology for dispatch reliability
ATA	US airline Transport association
AUC	Air Transport User Council
CC	Correlation Coefficient
CCF	Common Cause Failures
COTS	Commercial Off The Shelf
DR	Delay Rate
DRPM	dispatch Reliability Prediction Method
ECP	Engineering Change Proposal
ETOPS	Extended Range Operations
EUROCONTROL	European Organisation for the Safety of Air Navigation
FADEC	Full Authority Digital Electronic Control System
FMEA	Failure Mode, Effect Analysis
FTA	Fault Tree Analysis
ISL	International Society of Logistics
ITA	Institute du Transportation Aerien.
LRU	Line Replicable Unit
MCBF	Mean Cycle Between Failures
MCBUR	Mean Cycles Between Unscheduled Removals
MCRT	Mean Corrective Repair Time
MDT	Mean Down Time
MEL	Minimum Equipment List
MFHBF	Mean Flight Hours Between Failures

MTBCM	Mean Time Between Corrective Maintenance
MTBF	Mean Time Between Failures
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
MTBPM	Mean Time Between Preventive Maintenance
MTBUR	Mean Time Between Unscheduled Removals
MTTR	Mean Time To Repair
N/A	Not Applicable
NPRD	Non-electronic Parts Reliability Data
R&M	Reliability and Maintainability
RMA	Reliability, Maintainability, Availability
SAE	Society of Automotive Engineers
SR	Scheduled Reliability

"Talking about airplanes is a very pleasant mental disease"

Sergei Sikorsky, 'AOPA Pilot' magazine February 2003

Chapter 1

Introduction

1.1 Introduction

In today's highly dynamic and competitive environment, civil aircraft operators have been under tremendous pressure to create shareholder value. One of the value drivers in the aircraft industry is the dispatch reliability of aircraft also sometimes termed operational reliability. It is the percentage of scheduled flights which depart without making a technical delay of more than 15 minutes, or cancellation. Thus, it is an aircraft delay measure.

Increased dispatch reliability reduces flight delays and cancellations resulting in greater operational efficiency, flexibility and customer satisfaction. Therefore, increased dispatch reliability results in reduced costs and increased revenues leading to a greater shareholder value.

Aircraft dispatch reliability is affected by technical and non-technical factors. The former are strongly affected by decisions made by designers, whereas the latter are governed by many aspects, which include these managed by the operators such as maintenance, logistics, operations, and management. This thesis will address only technical factors that can be influenced by aircraft designers.

1.2 Rationale

Current aircraft delay consequences are significant. It is not only the large number of delayed passengers and the inconvenience that are important, but also the associated costs which will be difficult to absorb.

Current aircraft delay costs are already very high, with some conservative estimations, as shown in Table 3.6, putting them in the region of 86 – 108.6 Euros per minute of delay and the annual delay cost is between € 6.6-11.5 billion for air transport delays in Europe [42]. Other sources such as International Society of Logistics (ISL) [105]claim that recent statistics show that the cost per minute of a late dispatch of aircraft is $1,000.

Omari [80] stated that the cost of delays and cancellations are in the region of 2% of the annual total revenue.

Another delay cost study performed by US Airline Transport Association (ATA) [5], concluded that aircraft operating delay costs amount to USD34.1 per minute while the total delay cost is more than $5 billion per year as shown in Table 3.5.

Aircraft delays are also some of the main complaints from customers [25], and they affect airline reputations.
Air Transport User Council (AUC) data base showed that 22% of the 2000/2001 total passenger's written complaints were for flight delays [2].

However, the current situation is expected to get even worse because air transport passenger numbers and cargo shipments are increasing continuously, with over a billion passengers per annum in recent years [62]. This growth is expected to continue as the world's population is increasing and more people want to travel for many reasons. This expected growth requires more flights and/or larger aircraft resulting in a very difficult challenge for the aircraft industry to produce the required number of flights at the required time. Aircraft delays will reduce the number of aircraft available at the right time and this would impair the required growth.

A study performed by Eurocontrol to analyze the average delay time in some of the European and USA airports for the year 2000 showed that around 26 % of the flights are delayed with average delay time of 44 minutes (see table 3.3) [41]. The same source also showed that around 20 % of these delays are caused by aircraft-related technical reasons.

The American Bureau of Transportation Statistics showed that flight delays are a major concern due to the fact that it is still reaching high percentages especially during the high season with flights delay percentage of up to 33% [21].

CAA data [26]shows the statistics of the average delays of all flights in the United Kingdom. These statistics showed that the percentages of delayed flights were around 30% for scheduled flights and around 35% for charter flights. The average delays of all flights are 12 & 20 minutes, for scheduled and charter flights respectively. These average delays are the delay time that occurs after the 15-minute window which means that the total delay is about 27 minutes for scheduled flights and 35 for the charter flights.

Today's cost of owning a jet transport through the life of the airplane is estimated to be two times the purchase price [11].

To help minimise this cost of ownership, high dispatch reliability must be achieved. This is accomplished through designs that hold operational complexity and in-service follow-up to a minimum.

Current evidence strongly suggest that if future aircraft do not improve on existing aircraft dispatch reliability levels, the number of delayed passengers and cargo will make it very difficult for airport facilities to operate, and air transport operations will be jeopardized.

Although aircraft operators recognize the importance and impact of dispatch reliability on their bottom line, they have not been able to address it effectively, as the above evidence has shown. The major problem facing the aircraft operators is the fact that aircraft dispatch reliability is an inherent design characteristic that is difficult and costly to improve for in-service aircraft and must be built-in the design from the outset. Design improvement actions and corrective techniques can help to improve existing aircraft dispatch reliability, but at very high cost and to a very limited level.

Taking in consideration the evidence suggesting that around 85% of the life-cycle costs of an aircraft are determined at the project stage (conceptual & preliminary) with a further 10% decided during detail design stage [54]. One of the main solutions to the aircraft delays problem is to design the desired dispatch reliability into the aircraft in the early design stage.

Past aircraft designs focused on performance aspects, and dispatch reliability suffered as a result. This is recognized widely by many users who expressed their concern that emphasizing sophisticated technologies to improve performance has degraded operational readiness [70].

The demands from customers for on-time performance and the competition to keep the operation costs down created a significant drive toward the design of aircraft with better dispatch reliability performance to meet this economic requirement. All this makes dispatch reliability a marketing figure appear in many sales brochure [6].

There has been little design effort by aircraft manufacturers toward design for dispatch reliability, because of its difficult nature and lack of suitable design methods.

Designing for aircraft dispatch reliability needs to be driven by realistic targets. Unless there are specific dispatch reliability targets that can be aimed for, there will be little improvement in aircraft dispatch reliability performance. Aircraft designers have adopted two main approaches to predict aircraft dispatch reliability – empirical prediction method and the manufacturer-specific comparison method.

In the empirical prediction method, there has been little work done recently on updating the existing standard methods. Some of these existing methods are the Transport Aircraft Dispatch Reliability Formula [45]and the development of Conceptual Navy Aircraft Reliability Prediction Models [44]. Considering the long time since this work has been performed, an up-to-date dispatch prediction method is essential [10].

The second approach to predicting dispatch reliability is the adoption of manufacturer-specific comparison prediction method to design an aircraft for dispatch reliability [86, 11,18,19].

The comparison techniques use historical dispatch reliability targets of previous aircraft as baselines against which targets for the new aircraft are set. This approach has two major shortfalls.

First, since the comparison techniques depend heavily on historical data of the previous aircraft as the basis for the design of a new aircraft, they limit creative solutions and they are more likely to introduce the same set of problems from the old aircraft into the new aircraft. This makes the technique more suitable for evolutionary rather than revolutionary designs.

Secondly, the comparison approach relies on manufacturer-specific data rendering it difficult to be use as an evaluation and benchmarking tool between different aircraft designed by different aircraft manufacturers, and the information is usually company-confidential.

Using an appropriate design methodology during the early design stage can make it possible to design an aircraft with the required dispatch reliability or military operational reliability.

The literature on aircraft system design methodologies for dispatch reliability usually use comparison techniques between previous and new aircraft designs, using the baseline aircraft as the main vehicle for addressing dispatch reliability in the design [3,11,39].

Most of these techniques rely on proprietary data that are not available in the public domain. They depend on old design data to drive the new design, can be used only for similar aircraft design, and they are applicable for advanced design stage, but not for an early design stage. This dependence on the comparison method is limiting its' use. Because of it's type-specific nature, it cannot be applied to a wide range of aircraft designs, and does not allow for technological improvements. It also has the disadvantages of limited accuracy and needs excessive analysis time.

This thesis will fill the identified gaps by (1) developing a new civil aircraft dispatch reliability prediction method that overcomes the shortcomings of the existing prediction methods; (2) developing aircraft system design methodology for dispatch reliability (ASDMDR); and (3) using the developed design methodology as a design improvement and evaluation tool of different design approaches to dispatch reliability (see below).

1.3 Aims of the Research

An initial research question was established, structured around the issue of the aircraft dispatch reliability, and the way it can be designed into aircraft from the outset. It was found that to design an aircraft for dispatch reliability, there is a need to set the dispatch reliability target in the first place. Then, an aircraft design methodology for dispatch reliability has to be created and implemented.
Thus, objectives of this PhD research were the following:

- To develop and validate an aircraft technical Dispatch Reliability Prediction Method (DRPM) that can be used during the very early design stage to predict the dispatch reliability value for the whole aircraft and for individual systems.
- To Develop and validate an Aircraft Systems Design Methodology for Dispatch Reliability (ASDMDR) by focussing on two design characteristics; reliability and maintainability.
- Use of the methodology to investigate new design approaches to improve dispatch reliability.

1.4 Structure of Thesis

The thesis comprises of five distinct sections, to suit the research objectives. These sections are described below:

Chapter 1 sets the scene and focus of the research, and contains introductory material and background material leading to the execution of this work, the research objectives, and the way that this work has been conducted.

Chapters 2 to 5 review the literature on aircraft dispatch reliability prediction methods and present the developed prediction method. It contains, in chapter 2 literature reviews of general aircraft reliability and maintainability. It also contains some aspects of systems types, reliability allocation techniques, maintenance processes and aircraft failure types and patterns. Chapter 3 reviews aircraft dispatch reliability in the literature and establishes the dispatch reliability definition, with in-depth investigation of different aspects of dispatch reliability and aircraft delays. Aircraft delays and factors affecting dispatch reliability, very detailed analysis of delay causes, magnitude and scenarios and delay studies are also presented. Chapter 4 addresses the available current general reliability prediction methods. Also, chapter 4 investigates the available aircraft dispatch reliability prediction methods for use in the conceptual design phase. Chapter 5 presents the developed new civil aircraft dispatch reliability prediction method (DRPM).

Chapters 6 to 8 review the literature on aircraft design methodologies and focuses on those for dispatch reliability. Chapter 6 discusses the aircraft design process and the way the proposed design methodology can fit on the aircraft design project.

Chapter 7 covered the available aircraft design methodologies for dispatch reliability in the literature, and focused on the demand for the ASDMDR. It also contains the development of the ASDMDR with some practical examples.
Chapter 8 validates the ASDMDR through a set of exercises, and explores the capability of the developed design methodology as a design improvement tool.

Chapters 9 and 10 discuss the findings, comparing them to the literature and consider the contribution to knowledge made by the research. It also summarises the work, and includes suggestions for further work.

Finally, appendix A contains the ADRP calculations. Appendix B calculates aircraft average delay rates. Appendix C discusses the reliability block diagram (RBD) method. Appendix D explains the mean time to repair prediction. Appendix E discusses the method of failure rate allocation. Appendix F validates the hydraulic centre sub-system. Appendix G shows some dispatch reliability reports. Appendix H introduces the RELEX reliability software.

1.5 Research Methodology

The research methodology has been constructed to answer three important questions. These are: What is the importance of aircraft dispatch reliability? Can it be predicted? And can an aircraft design methodology for dispatch reliability be developed?
For the first question, the research started with a literature review of all reliability aspects and concentrated on aircraft dispatch reliability. This was followed by collecting dispatch reliability data from different sources. It studied the different factors that affect dispatch reliability, causes of aircraft delays, and aircraft delay costs and magnitudes. It also studied delay cost elements and aircraft delay scenarios. Lastly, an aircraft delay study was produced which evaluated the aircraft system contribution to the delay.

Answering the second question involved a literature review of the available dispatch reliability prediction techniques and the development of a new aircraft dispatch reliability prediction method. The developed prediction method was explained by an example and validated using an existing aircraft data.

The final question was answered by developing the aircraft system design methodology for dispatch reliability. It involves an ASDMDR literature review, methodology construction and validation. This was followed by implementing the methodology as design improvement tool.

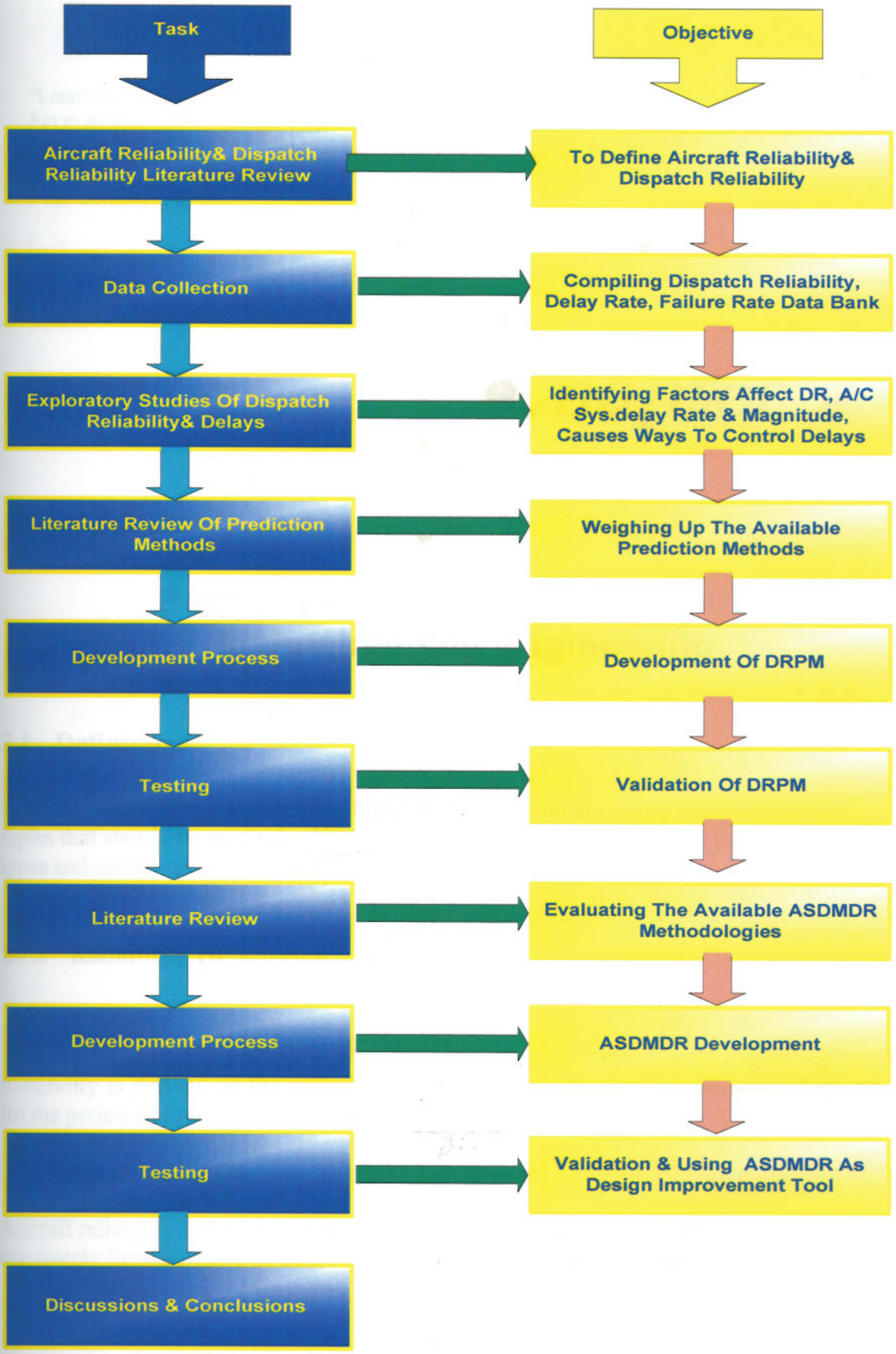


Figure 1-1: Research methodology flowchart

> "Learning should be fun. If you don't have fun in aviation then you don't learn, and when learning stops, you die."
>
> *Pete Campbell, FAA*

Chapter 2

Background to Safety, Reliability& Maintainability Engineering

2.1 Definitions

There are some useful definitions of the reliability, maintainability and other related topics that should be recognized before moving forward, these are categorised into six types and shown on the following sections.

2.1.1 Reliability Definitions

I. Reliability

Reliability is defined as the probability of a device performing its purpose adequately for the period of time required under the environment specified [86,29].

II. Aircraft Reliability

Aircraft reliability is the probability of an aircraft's systems performing its purpose adequately for the period of time required under the environment specified [23, 51,65,27].

2.1.2 Maintainability Definitions

a. Maintainability could be defined as the economy in time, manpower, equipment and necessary materials, with which potential or actual failures can be detected, diagnosed, prevented or corrected, and with which routine handling, replacement and servicing operations can be carried out [106,69].

b. It is also been defined as the probability that an item can be retained in, or restored to, a specified condition [115].

c. Maintainability can therefore be defined with respect to the probability that a device or system can be returned to a specified condition using pre-specified practices within a specified time [12].

2.1.3 Availability Definitions

I. Availability is defined as the probability that a system or component is performing its required function at a given point on time or over a stated period of time when operated and maintained in a prescribed manner[15,38, 117].

II. Inherited availability is the probability that the system will operate satisfactorily when called upon at any point in time under specified operating conditions and in an ideal logistic support environment [12]. Ideal operating conditions refer to readily available maintenance personnel, spare parts, test and support equipment, and facilities. It does not consider any logistics or administrative time delays, and it excluded preventive or scheduled maintenance tasks. Inherent availability can be calculated as in Equation 2-1[12].

$$A_{\text{inh}} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

Equation 2-1

2.1.4 Dispatch Reliability Definitions

Dispatch reliability at times called operational dependability, operational reliability or operational availability.
There are many definitions for dispatch reliability and delay rate, but in general they are very similar, and some of them are presented below:-

a) **Dispatch Reliability** is the percentage of scheduled flights, which departs without making a mechanical delay or cancellation [105].

b) **Dispatch reliability** is the probability that an airplane will not be delayed from scheduled departure due to a system malfunction [11].

c) **Dispatch Reliability** is the percentage of on-time scheduled departures, which is the complement of delay rate, and it is calculated by subtracting delay rate out of hundred.[39].

Dispatch reliability percentage can be calculated as in Equation 2-2 .

$$\textbf{Dispatch Reliability} = (100 - [\frac{\textbf{No. of Delays + Cancellations}}{\textbf{No. of Flights}}]) \times 100 \qquad \textbf{Equation 2-2}$$

d) **Mechanical Dispatch Reliability** is the percentage of on-time departures where only delays over 15 minutes or cancellations caused by equipment malfunctions are counted [39].

e) **Technical Dispatch Reliability** is the percentage of on-time departures where all delays or cancellations caused by the following are counted: All mechanical delays and cancellations reported by the airlines and all those caused by lack of spare parts, ground equipment and aircraft late out of maintenance[39].

f) **Operational Dispatch Reliability** is the probability of a transport aircraft beginning a scheduled flight within 5-15 minutes of the scheduled departure time and successfully completing the trip [86].

Aircraft manufacturers and operators usually use the following dispatch reliability definition, which will be use in this research. It is: 'The percentage of scheduled flights, which departs without making a technical delay of more than 15 minutes or cancellation.

2.1.5 Delay Definitions

I. **Delay Rate** is an indicator of the aircraft unavailability, because in general it is the complement of the dispatch reliability (i.e.100-dispatch reliability).
It is the percentage of scheduled departures which are more than xx minutes late or are cancelled [39].

$$\textbf{Delay Rate} = \frac{\textbf{No. of Delays + Cancellations}}{\textbf{No. of Flights}} \times 100 \qquad \textbf{Equation 2-3}$$

II. **Technical Delay** is defined as any failure of a scheduled revenue flight to depart as planned due to an airplane system malfunction [11].

III. **System Dispatch Delay Rate** is defined as the number of delays caused by a particular system per 1,000 departures* [11].

$$* \text{ Dispatch Delay Rate} = \frac{\text{No. of Delays}}{1{,}000 \text{ Departure}}$$ **Equation 2-4**

* Normally the number of delays is known as per 100 departures.

The delay rate definition to be used throughout this research is '<u>The percentage of scheduled departures which are more than 15 minutes late or are cancelled because of system technical failures</u>'.

2.1.6 Other Relevant Definitions

I. **Scheduled Completion Rate** is the percentage of scheduled flights completed without a mechanical cancellation [105]. It is the pre-flight probability that the equipment will perform as specified within fifteen minutes after being called upon to do so[60].

II. **Operational Reliability** is the percentage of revenue departures which do not incur a delay (technical) greater than 15 minutes, cancellation (technical), air turn back (technical) or diversion (technical).
Operational reliability is calculated as follows:

$$100 - [\frac{\text{No. of opertional interruptions}}{\text{No. of revenue departures}}] \times 100$$ **Equation 2-5**

III. **Operational availability** is the likelihood that a system will be mission operable and committable when called upon in field environment [70].

IV. **Unscheduled Removal** is when the equipment is removed due to suspected failures.

V. **The Mean Time Between Unscheduled Removal (MTBUR)** is the average time between the unscheduled removals of a component.
It is calculated by dividing the total unit flying hours (airborne) accrued in a period by the number of unscheduled unit removals that occurred during the same period.

The difference between the MTBF and MTBUR is that the former deal with confirmed failures, whereas the latter includes cases where an item has been removed but then found to be serviceable (no fault found).

$$\text{MTBUR} = \text{FTRR} * \text{MTBF}$$ **Equation 2-6**

Where, FTRR Failure to Removal Ratio

VI. **Unscheduled Removal Rate** is the unscheduled removals for the period × 1000 /components hours or cycles experienced for the Period.

VII. **Reliability Allocation** is the process of translating the overall system reliability requirements to requirements at the lower level specifically for subsystems and the configuration item level [20].

VIII. **The Minimum Equipment List (MEL)** is a list of equipment which can be inoperative and yet the aircraft can still be flown safely

2.2 Introduction to Aircraft Safety

The design of new aircraft is governed by safety requirements that are laid down by national and international bodies such as Civil Aviation Authority (CAA) and Joint Aviation Authority (JAA) to assure the safety of the aircraft[107,104,64].

The safety requirements are in the form of airworthiness design requirements which are principally aimed at the certification of new aircraft.

An airworthiness certificate is a document that grants authorization to operate a civil aircraft in flight [64].
The airworthiness of a particular operation is the status by which the aircraft is designed, maintained and operated to achieve an acceptable level of safety for passengers, crew and third parties. Within this context, design airworthiness is defined by a set of regulations and codes of practice.
The design airworthiness requirement aims to ensure that in the event of any failures on any aircraft system that would prevent the continued safe flight and landing of the aircraft is extremely improbable.
The airworthiness requirements are purposely drafted in broad terms. The designers must conduct failure analysis for each system and ensure safe operation of each aircraft function.

Safety analysis is performed using reliability techniques such as FTA, FMEA and reliability analysis results are usually the input to the safety analysis.
The safety assessment of the aircraft system involves failure mode & effect analysis (FMEA) and Zonal hazard analysis (ZHA) where previous experience on similar system is very important. Fault tree analysis (FTA) is a key technique for the evaluation of safety characteristics of an aircraft [24].

The FMEA analysis should consider the variation in the performance of the systems, awareness of the crew to the failure and their prescribed emergency actions, the probability of detecting the failure, and aircraft inspection and maintenance procedures.
Fielding [48] presented a civil aircraft system safety certification process as shown in Figure 2.1.

The system safety is defined as 'the application of engineering and management principles, criteria, and techniques to optimise all aspects of safety within the constraints of operational effectiveness, time and cost throughout all phases of the system life cycle[37].

The system safety analysis is a process whereby the designed system undergoes a hazard analysis to identify the design problem area that can affect safety. Those safety hazard aspects are assess against the airworthiness requirements such as those on ARP4761, and a safety design decision is reached [99].

If the risk is acceptable form the requirement point of view, the design process continues, if not, the system should be redesign and the whole process is repeated again as shown in Figure 2.2[48].

Hazard analysis is the main factor in any safety program, and it needs to be performed continually throughout the system design phases.

Aircraft conceptual design phase is the starting point for the hazard analysis where the input data are of two types, they are:

- Historical data for similar aircraft/system/component.
- The airworthiness requirements and standards which must be satisfied.

The output data from the hazard analysis are either confirms the safety validity of the design or to prove the design inadequacy.

An effective safety analysis is that considers realistic prediction of the real field data. The out put of this analysis will offer an opportunity to modify and customise the design to reduce the risks.

Dispatch reliability analysis will produce a design that possesses good reliability and maintainability characteristics. A product with high R&M features will fail less frequent and when it fails will be easy to fix. This means that the cost of ownerships will be reduced, and that the product will be much effective. Unquestionably, an increase on the product reliability and maintainability is straight increase on its safety.

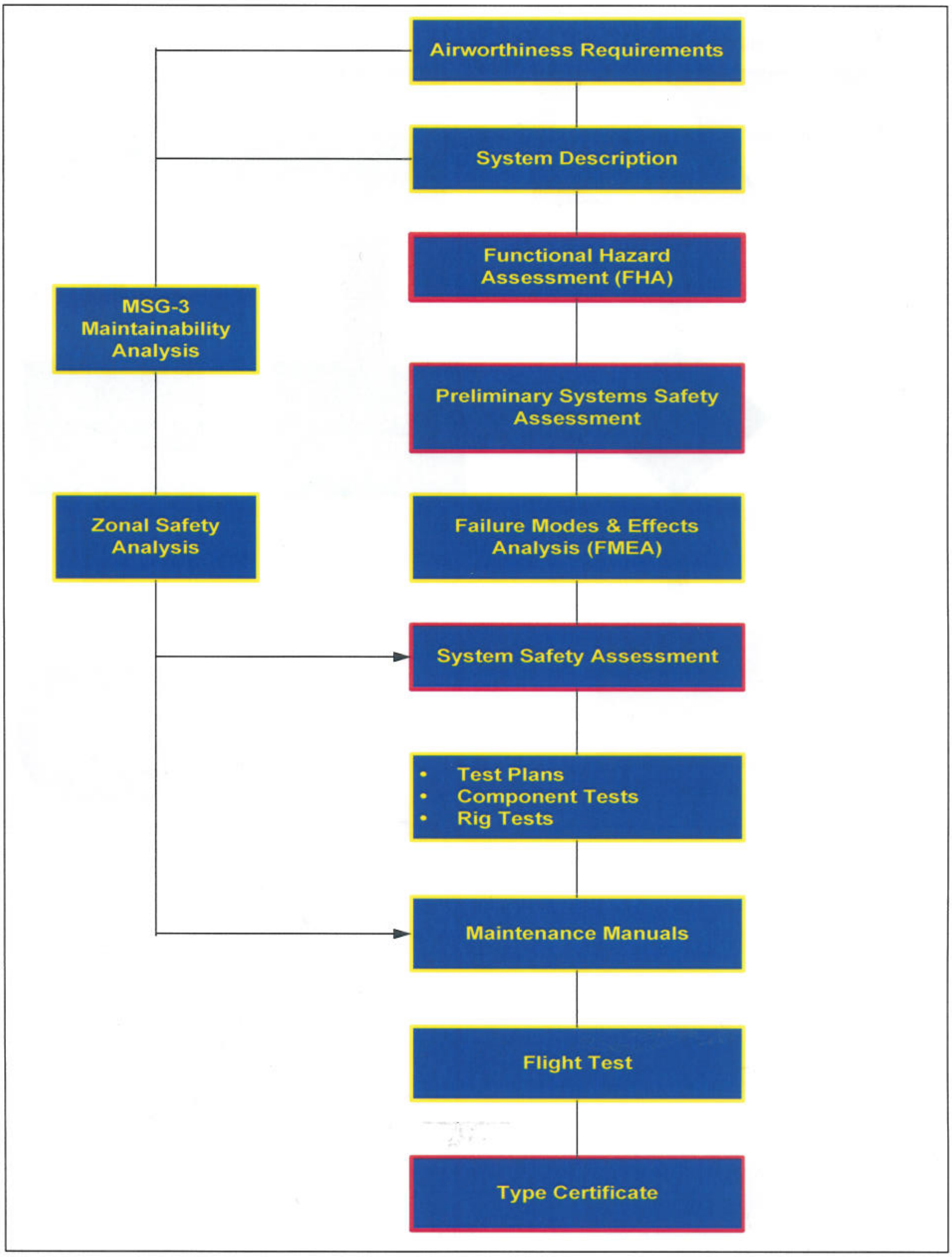


Figure 2-1: Civil aircraft system safety certification process [48]

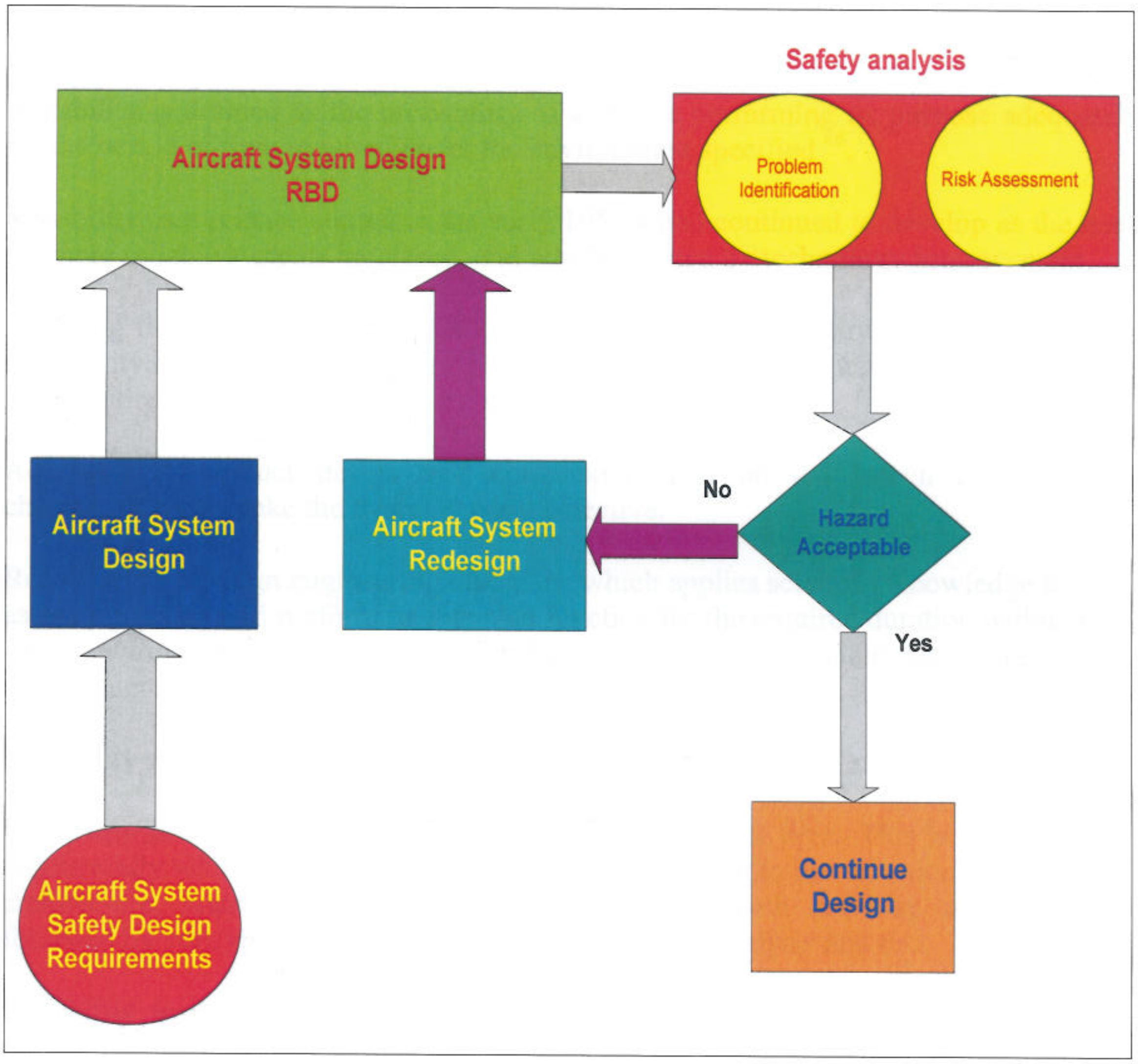


Figure 2-2: Safety analysis process

2.3 Introduction to Aircraft Reliability

Reliability is defined as the probability of a device performing its purpose adequately for the period of time required under the environment specified [86].

Reliability as a science started in the early 1950's and continued to develop as the need for more reliable systems increased, and was facilitated by technology improvement.

Applying the above reliability definition to the aircraft reliability can be read as 'the probability of an aircraft's systems performing its purpose adequately for the period of time required under the environment specified'.

Advances in product design and complexity sped up the search for reliability characteristics to make the overall system effective.

Reliability is a design engineering discipline which applies scientific knowledge to assure a product will perform its intended function for the required duration within a given environment. This includes designing in the ability to maintain, test, and support the product throughout its total life cycle.

Reliability analysis is of primary importance during the design of an aircraft [24].

Reliability is best described as product performance over time. This is accomplished concurrently with other design disciplines by contributing to the selection of the system architecture, materials, processes, and components, both software and hardware; followed by verifying the selections made by thorough analysis and test.

Reliability is a product design attribute that cannot be ignored. Every design has reliability characteristics - it is a critical ingredient of all designs created within all industries. It is far better to explicitly consider reliability than to ignore it and hope for the best.

A superficial thoughts on the reliability would suggest that the reliability might decrease as the number of components increases; this is because the number of items which might go wrong increases, this point is addressed by[78].

Nevertheless a scientific investigation of the supposed correlation between reliability and number of components has been carried out, studying a number of weapons for which accurate date exist. It concluded there is no such correlation [23] .

System complexity will have an affect on its' reliability performance. A reduction in the quantity of parts or in the number of different parts used is a standard approach in trying to improve the inherent reliability of an electronic design [57].

There are suggestions that there is a consistent relationship between complexity and observed mean time between failures (MTBF).

Stovall [101] produced a part count chart to be used to predict transport aircraft electronic equipment reliability. This method showed that the equipment reliability (MTBF) decreases as the degree of complexity increase.

Aggressive design improvement by means of engineering change proposal (ECP) can be correlated to the improvement of reliability, although this would be at more cost[50].

The truth is that success is achieved when the weakest or least adequate individual component of a system is capable of coping with the most severe loading or environment to be encountered, that is "the strength of the chain is that of its weakest link". This has been emphasised by [77] who at the same time "recognise the fact of variability, or scatter, both in the capability or strength of product, and in the duty it will have to face". That is the load which will be imposed on it.

Achieving close to 100% reliability will need a very high safety margin and hence a heavier and probably more expensive item, which make it not practical.

There are some skills and knowledge required to achieve reliable products, they include:

- **Statistical Analysis**

  This is requires statistical study knowledge and skills to be able to extracts the required information out of the product reliability data which can help to design a reliable product.

- **Product Reliability Modeling**

  This is a reliability modeling of the system using various techniques such as fault tree analysis (FTA) and reliability block diagram (RBD) which can help to decide on the suitable reliability solution that utilize redundancy or rely on the product reliability[38,47,110].

- **Trade Study Analysis**

  Trade-off technique is a very useful and effective method that can help to choose the appropriate solution among many alternatives.

- **Reliability Predictions**

  The reliability prediction technique is to predict the reliability behavior of the system and components. The prediction outcome helps to assess the system against the requirement and weather it can meet these requirements or design modification is required. Reliability predictions are useful in the early design stages of a product to help assess the expected performance compared to other products

- **Worst Case Analysis (WCA)**

It is a specific analysis of a device or system that assures that the device will meets its performance specifications. There are typically accountings for tolerances that are due to initial component tolerance, temperature tolerance, age tolerance and environmental exposures (such as radiation for a space device). The beginning of life analysis comprises the initial tolerance and provides the datasheet limits for the manufacturing test cycle. The end of life analysis provides the additional degradation resulting from the aging and temperature effects on the elements within the device or system.

- **Failure Modes, Effects, Criticality Analysis (FMECA) & Failure Mode and Effects Analysis (FMEA)**

Failure Mode and Effects Analysis (FMEA) and Failure Modes, Effects and Criticality Analysis (FMECA) are methodologies designed to identify potential failure modes for a product or process [47,57,84,110]. This is to assess the risk associated with those failure modes, to rank the issues in terms of importance and to identify and carry out corrective actions to address the most serious concerns

- **Maintenance Concept Definition**

It defines the level-of-effort necessary to maintain system availability, reliability, and the functionality necessary to fulfil the operational concept.

- **Supportability Analyses**

They are a set of analytical tools to use within the context of an overall systems engineering process, with an objective of determining how to assure system reliability in a cost effective manner throughout the life cycle. The results of the supportability analyses significantly influence the design requirements outlined in the Capabilities Documents and system performance specifications.

- **Derating Analysis**

It is defined as the method of assuring that stresses, either environmental or operational, are applied below rated values. This analysis is to enhance reliability by decreasing failure rates. The purpose of derating analysis is to protect against inherent variability in an operating environment and part operating characteristics.

- **Human Engineering Analysis**

It is information analysis about human requirements and capabilities, and applies it to the design and acquisition of complex systems. Human factors engineering provides the opportunity to develop or improve all human interfaces with the system, optimize human / product performance during system operation, maintenance, and support; and make economical decisions on personnel resources, skills, training, and costs.

2.4 Importance of Reliability in Overall Design and Operation

The importance of the reliability in general on the aircraft industry has increased very rapidly, and the pressure that has been imposed on the aircraft manufacturer toward better reliability is very strong.

There are a number of reasons why reliability in general is an important product attribute, including:

- **Reputation.** A company's reputation is very closely related to the reliability of their products. The more reliable a product is, the more likely the company is to have a favorable reputation.
- **Customer Satisfaction.** While a reliable product may not dramatically affect customer satisfaction in a positive manner, an unreliable product will negatively affect customer satisfaction severely. Thus high reliability is a mandatory requirement for customer satisfaction.
- **Warranty Costs.** If a product fails to perform its function within the warranty period, the replacement and repair costs will negatively affect profits, as well as gain unwanted negative attention. Introducing reliability analyses is an important step in taking corrective action, ultimately leading to a product that is more reliable.
- **Repeat Business.** A concentrated effort towards improved reliability shows existing customers that a manufacturer is serious about their product, and committed to customer satisfaction. This type of attitude has a positive impact on future business.
- **Cost Analysis.** Manufacturers may take reliability data and combine it with other cost information to illustrate the cost-effectiveness of their products. This life cycle cost analysis can prove that although the initial cost of their product might be higher, the overall lifetime cost is lower than a competitor's because their product requires fewer repairs or less maintenance.
- **Customer Requirements.** Many customers in today's market demand that their suppliers have an effective reliability program. These customers have learned the benefits of reliability analysis from experience.
- **Competitive Advantage.** Many companies will publish their predicted reliability numbers to help gain an advantage over their competitors who either does not publish their numbers, or has lower numbers.

Obviously all the above mention reasons are applicable to aircraft, however aircraft reliability is prevailing in three particular areas throughout the whole aircraft life, they are:

a) Life-cycle cost

Reliability of a product has a major effect on its life-cycle cost. It is well known on the industry that about 66% of the product life-cycle cost (LCC) is determined by the end of the conceptual design phase [43, 12].

Thus, a very good design practice is to make sure that the reliability is designed into a product and not added to it. This is because the cost of correction or modification of the product to rectify or enhance its reliability is much more when the product is in-service, than if it is still on the drawing board.

Less than 3% of the total aircraft pre-production cost is attributed to the conceptual and preliminary design phases [62]but decisions made at this very early design phase are very crucial for the aircraft ownership cost.

Figure 2-3[62]shows how the design and manufacturing activities are scheduled and it shows the cost trend throughout the aircraft project process (the curved black arrow).

The experience of manufacturers in many industries has shown that 85~90 % of the total time and cost of product development are committed in the early stages of product development, when only 5~10 % of project time and cost have been expended [91]. This is because in the early design stages, fundamental decisions are made regarding basic geometry, materials, system configuration, and manufacturing processes.
Hence, the importance of getting reliability right on the very early design stage.

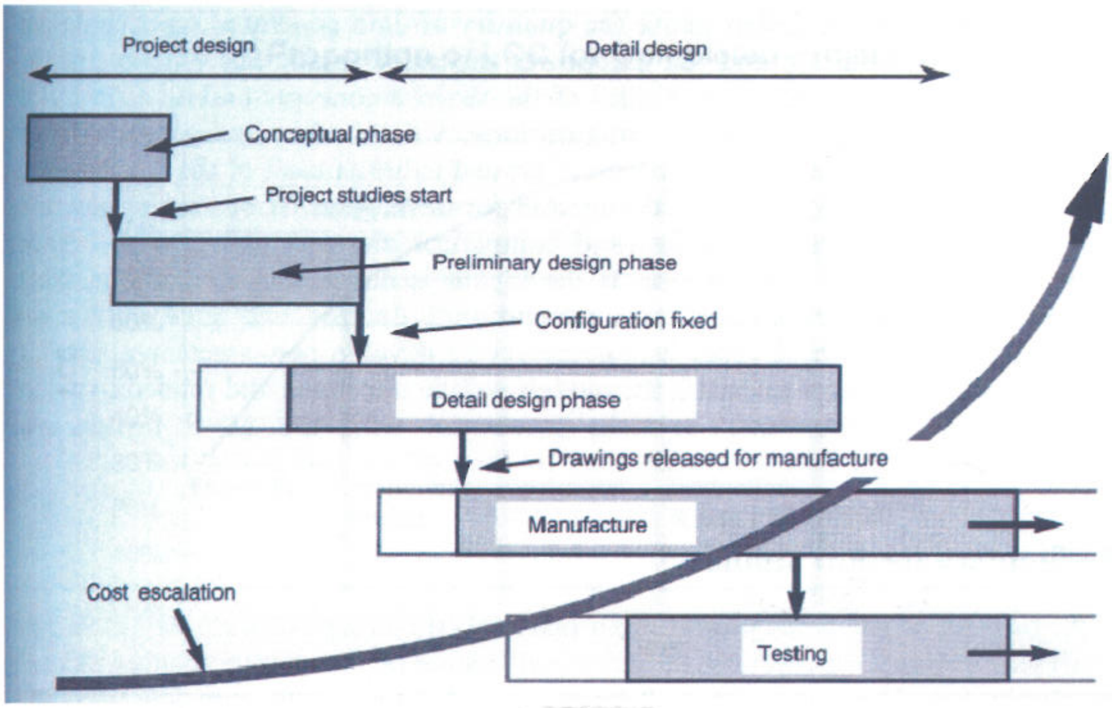


Figure 2-3: The aircraft design process

Cost of aircraft ownership is very important factor on the customer decision to choose a particular aircraft type. Aircraft that demonstrate high reliability will be less expensive to operate, and thus be more appealing to customers.

Figure 2.4 shows the proportion of life cycle cost (LCC) for an aircraft project.

It revealed that there is a large commitment to life-cycle cost in the early phases of the system /product development.

Although the actual expenditures on a given project will accumulate slowly at first, mounting during the latter phases of design and through production and manufacturing, the commitment to life cycle cost will be larger during the early design stage and as can be seen it in Figure 2-4 [116], more than 80 % of the product estimated life-cycle cost is locked in by the end of the preliminary design phase. That means support cost which includes maintenance cost for a system/product, which often make up a large percentage of the system total cost, can be highly influenced by early design decisions. Productivity of a system/product can be highly degraded by inappropriate considerations of the reliability and maintainability aspects early on the design stage.

Reliability in general is a very important design feature which can reduce the cost of ownership and enhance the productivity of a product, reference [28] indicate that the cost of rectifying a fault is cheapest at the earliest possible stage in an aircraft's life because it can increase 1000 time between the initial design prototype and when the aircraft in service.

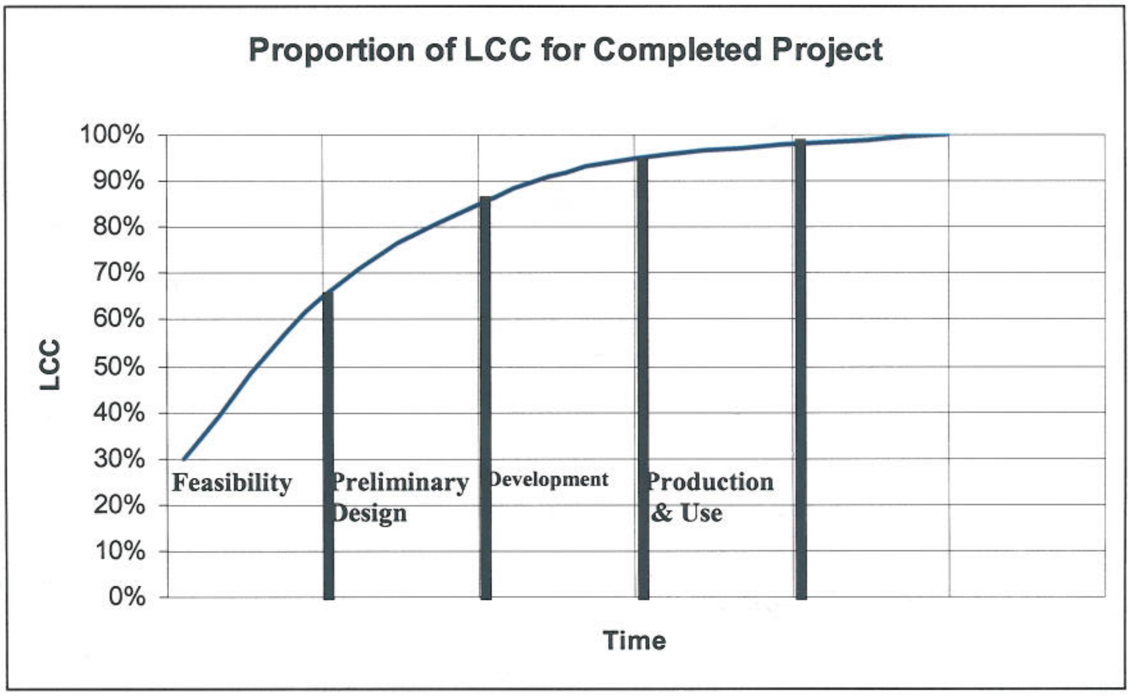


Figure 2-4: Life Cycle cost

b) Direct maintenance cost (DMC)

Aircraft direct maintenance cost is comprised of the following three components; manpower (labour), material, and depreciation. Normally, maintenance material cost is strongly correlated with the total cost of the aircraft, and the depreciation is strongly influenced by the unit cost.

It is not hard to notice that DMC are affected by the aircraft reliability. This is because two of the above DMC components are influenced by the aircraft components reliability. Less reliable aircraft components mean more maintenance time and spares.
Direct maintenance costs can be very expensive and some sources expected it to be around 9% of the total airline costs [97,96,85,113].

c) Safety

The aircraft safety requirements initiated and maintained the hard work for better reliability performance.
Aircraft regulators imposed ambitious reliability requirements on the aircraft manufactures to improve the air travel safety. These reliability requirements help to improve the air travel safety over the years, and analysing the aircraft accidents data showed steady reduction of the accidents.

2.5 Reliability Design Responsibility

There are two schools of thoughts regarding the reliability design responsibility.
One side believes that reliability engineers should work closer with the designer in a team environment. The team environment is supposed to facilitate directing the embodiment of reliability features during appropriate windows of opportunity in the design process.

The other school believes that ''the basic responsibility for design reliability rests solely on each engineering designer and can not be delegated to any other staff, group, or individual''[86].
The designer should be provided with computerised tools and knowledge to replace much of the support conventionally provided by the reliability engineer. The computerised tools should avoid the lag in feedback which occurs when design assessments are performed by someone other than the designer [61].

As an example of the latter school is the procedure adapted by Boeing Company in the seventies, of allocating the responsibility on the design engineer on the design of the B737aircraft.

This research locates itself in the latter philosophy and thinks it is more appropriate for the aircraft design and should be adopted for different reasons, some of these are:

a) Special systems designers are the most knowledgeable about their design characteristics and would be able to make better decisions.

b) It speeds up the design process by eliminating the interaction between designers and reliability specialists.

c) Reliability skills are very accessible and can be acquire by the aid of computerized software.

2.6 Measures to Achieve High Reliability in Design

Considering reliability in the design process is proving to be very important in order to achieve a product that satisfies customer requirements. Conceptual and preliminary design phases are the areas where a lot of design ideas are formulated and it is therefore important during these design phases to place high attention to reliability.
General design guidelines that can be of great help to the designer are stated in many references such as [71], they include:

- **Modular Design**

This is to design an item using different modules, that modules can be used on other item and so on. By using this concept, the effort to maximize the reliability of these modules is duplicated across all of the uses of these modules. It also enhances maintainability since only the defective module needs to be repair or replaced to have the item up and running again.

- **Design Simplification**

Despite the scientific investigation that was carried out to investigate the supposed correlation between reliability and number of components mentioned above, which revealed that there was no correlation [23], it is generally accepted that components reliability is inversely related to the number of constituent parts, interfaces and fixings, i.e. its complexity.

So lowering the number of component, parts etc when designing a system can be an effective means of enhancing its reliability.
In general, the simpler the design, the higher the inherent reliability should be.

- **Derating**

Derating in design means designing the item to be used at a stress levels below a specific value (rated stress value). This technique will ensure that item will always work at a stress level below the sustainable level.
An item that been designed to operate below the sustainable stress level means increasing the safety margin, hence improving reliability. This type of reliability improvement technique is very effective but it can increase the cost. A trade-off analysis should be applied between the reliability gain and the extra costs.

- **Quality Control**

The selection of the manufacturer of an item or part should be restricted to the one with proven reliability history for comparable components. An alternative method is to increase the quality control activities during manufacturing.

- **Sensitivity Analysis**

All designs should be subjected to a sensitivity analysis covering the extreme range of tolerance, transient loading effects and other environmental factors, to ensure that the design is robust and can tolerate all of these likely variations.

- **Environment Control**

Design should take account of the outside factors which may affect the reliability of the product in terms of temperature, humidity, pressure, voltage frequency, electromagnetic interference shock, vibration, sand and dust. As an example, engine designer should provide some protection measures to prevent the affect of sand and dust on the engine reliability.

- **Failure Tolerant**

Design should be fault tolerant where it is possible. Single failures should not cause complete loss of the item's function except in non-safety related areas.

- **Use of Redundancy**

Redundancy is a very effective way of increasing reliability and availability, but it has its own draw backs, which are increases of cost, weight and degradation of maintainability. A very accurate trade-off exercise will help to improve reliability. Redundancy has some very definite limitations and can not be considered as cure-all. Here are some of those limitations:

a) Size and weight limitation may result on a redundant system being less reliable than for a single system design.
b) Common cause failure would effects redundancy and hence the reliability will not be better. The common cause failure (CCF) is failure phenomena that caused by one single root which affects more than one item.
c) What appears to be redundant may not really be so. For example, a twin-engine aeroplane which will not maintain altitude and flying speed on one engine is theoretically less reliable on a long over water flight than a single-engine aeroplane. This is because a twin-engine plane has twice the probability of engine failure that a single-engine plane has.

- **Material Compatibility**

Consideration of the material compatibility early on the design stage will help to improve reliability, like limiting the possibility of corrosion or thermal stresses.

2.7 Reliability Allocation

Reliability allocation which sometimes called reliability apportionment is a procedure to allocate the entire target reliability of a product into its subsystem, and again, allocating the sub-target reliability of each subsystem into component level.

The purpose of reliability allocation is to establish target reliability for each level in a product structure so that designers and management have a clear goal to aim for.

Reliability allocation process has different definitions, but they are very similar. They include [60]:

- The assignment of performance requirement to a function.
- The assignment of a requirement to a system element
- The breakdowns of a top-level requirement into its subordinate components, for example, dispatch reliability.

2.7.1 The Necessity for Reliability Allocation

Designers should have a clear system target that could be aimed for; otherwise the design output will have no bearing to the customer requirements. Customer requirements are translated to design goals that should be achieved. The form of these design goals can be reliability, performance, cost maintainability, dispatch reliability, availability or any other specific parameters.

The reliability allocation process is the distribution of the system's specific reliability or dispatch reliability target or value to the next lower level and so on until the lowest possible level.

Reliability allocation is a necessary action at the early design stage because of the following reasons:

1. The first and foremost reason is it provides the designer with a clear reliability objective.
2. It provides a reliability target for the system, subsystem and components which can be used to predict the overall product reliability figure.
3. It provides a target figure for the systems that can be used by several sub-contractors involved in a project.

2.7.2 Reliability Allocation Methods

Reliability allocation is usually achieved via the reliability block diagram and the product rule. Ebeling [38] says that reliability block diagrams are useful tools in accomplishing the reliability allocation.
In general it is required that the following inequality to hold:

$$h(R_1(t), R_2(t)...., R_n(t)) \geq R^*(t) \qquad \textbf{Equation 2-7}$$

Where $R_i(t)$ is the reliability at time *t* of the *i*th component.
$R^*(t)$ is the system reliability goal at time ***t***, and ***h*** is a function that relates component reliabilities to system reliability.

For example, if all the components are in series and their failures are independent of one another, then

$$\prod_{i=1}^{n} R_i(t) \geq R^*(t) \qquad \textbf{Equation 2-8}$$

When all components are exhibiting constant failure rates, then

$$\prod_{i=1}^{n} e^{-\lambda_i t} \geq R^*(t) \qquad \textbf{Equation 2-9}$$

Or

$$\sum_{i=1}^{n} \lambda_i \leq \lambda_s \qquad \textbf{Equation 2-10}$$

There are different reliability allocation methods that are available; all of them are designed to break down the required reliability target to the next lower level.

Some methods are very simple and use a very straight forward approach, whereby the overall system reliability target is divided evenly between the subsystems.

Other methods utilize more sophisticated techniques to offset the difference in system's complexity, operation environment and design characteristics.

The requirements allocation occurs from the aircraft level to the subsystem level or from the subsystem level to the component level. The allocation can starts only when

there is enough information about the aircraft under design, i.e. during the conceptual and preliminary design phase.
This principle is well explained on many references, such as Jachson [60, 17].

Other methods for reliability allocation such as these on Fuqua, [49] and DoD [33]define six approaches to reliability allocation.
These are: 'the Equal, AGREE, ARINC, Feasibility-of- objectives, Minimization-of-Effort, and Dynamic Programming.

Three are used most among these methods, they are EQUAL, AGREE and ARINC allocations.

Also, Boyd[20] develops a formula which combined the Equal method with the ARINC method that can be used easily and it take care of the complexity of the system. The following are explanations of some allocation methods.

a) EQUAL Allocation Method

This is the simplest way of reliability allocation but its drawback is that it lacks the ability to accommodate system complexity.
This method assumes the reliability model of the system (product) is in series and it allocates the same reliability value for each item on the lower level. The mathematical model is presented below in Equation 2-11.

$$R_S = \prod_{i=1}^{n} R_i \qquad , \quad i=1, 2, \ldots, n \qquad \textbf{Equation 2-11}$$

On the above equation, the system overall reliability is equal to the multiplication of its sub-system reliability values.
The allocation of the sub-system reliability is obtained by divide the overall system reliability target amongst the sub-systems as shown on the below in Equation 2-12.

$$R_i = (R_S)^{\frac{1}{n}} \qquad \textbf{Equation 2-12}$$

The *EQUAL* allocation method is suitable for very simple and similar units that are consist of likewise components and are subjected to working conditions of the same kind. However, on the aircraft case, this is not usually the case which makes this method not suitable for the failure rate allocation of the aircraft system.

b) AGREE Allocation Method

This method was developed by the Advisory Group on Reliability of Electronic Equipment in 1950 [79].

It assumes that the reliability model of a product is in a series and subjected to the exponential failure distribution. It is based on unit complexity rather than unit failure rate. The allocation formula is used to determine a minimum acceptable mean life (failure rate) for each unit to satisfy minimum acceptable system reliability. The unit importance factor is defined in terms of the probability of system failure if that particular unit fails, with one is the highest value for the importance factor and zero is the lowest. When the unit importance factor is one, this means that this particular unit must operate satisfactory for the system to be continuing operating. On the other hand, zero units' importance factor means this unit has no affect whatsoever on the system satisfactory operation.

The allocated failure rate for the *j*th unit is calculated using Equation 2-13.

$$\lambda_j^* = \frac{n_j[-\log R^*(T)]}{E_j t_j N}$$ **Equation 2-13**

Where

n_j	The number of modules in the *j*th unit (or it can be taken as the number of LRU in sub-system).
E_j	The importance factor of the *j*th unit.
t_j	The number of hours the *j*th unit will be required to operate in *T* system hours ($0 < t_j <= T$)
N	Total number of modules in the system.
$R^*(T)$	The reliability requirement.

The *AGREE* allocation method is very effective and it take into account many considerations like the unit's importance, complexity and operating hours. This makes it much suitable for the later design phase when more information about the LRU and components are available. However, for the early design phases, this method needs a lot of detailed information that would not be available which makes it inappropriate at this stage.

c) ARINC Allocation Method

This method produced by the Aeronautical Radio, Incorporated (ARINC). It assumes that the components are in series, independent and possess a constant failure rates.
This method is based on the failure rate and uses the system failure rate requirement and the predicted unit failure rate as the basis for the allocation. Therefore, unit's allocated failure rates are proportional to their predicted failure rates.

Given a series system consists of n units, the ARINC allocation method steps are:

1. Obtain the system failure rate requirement (λ^*).
2. Estimate unit failure rates (λ_i).
3. Relative unit weights are computed from Equation below:

$$W_i \frac{\lambda_i}{\sum_{i=1}^{n} \lambda_i}$$

Equation 2-14

4. Unit's allocated failure rate (λ') is calculated by the Equation 2-15.

$$\lambda' = W_i \lambda^*$$

Equation 2-15

d) Equal & ARINC Combined Method [20]

Boyd produced a new allocation formula which combined the Equal method with the ARINC method. This can be used easily and makes some allowance for the complexity of the system. The unit's failure rate allocation can be performed by using Equation 2-16.

$$\lambda_{ia} = \lambda_{sr} (K/N + (1-K)\lambda_{ip} / \lambda_{sp})$$

Equation 2-16

The equal method is the simplest way to allocate reliability and it has many benefits, such as simplicity and the low cost of application. However, it lacks the ability to accommodate system complexity.

Combining the Equal and ARINC methods should overcome some of the first method's downsides, and maintain its simplicity. This combined method was applied to different cases and proved to be a reasonable means of allocation.
The K symbol above is a constant value that can be 0, 1, or 0.5.
Taking K equal to 1 is in fact going back to the Equal method. On the other hand, using K=0 means the ARINC method is being used. When K=0.5, the combination exists.

2.8 Failures

Reliability of any item is affected largely by the failure frequency. Failure is defined as the inability of an item to do what it is required. Failures could be functional or total complete failure.

A single failure of an item can affect one or more of its functions depend on the number of functions this item may have. In this case, the failure called functional failure. In other situation, the complete failure of an item which affects all of its functions is called a complete failure.

2.8.1 Failures Types

There are different types of failures that can happen to aircraft/system/components, they include:-

- Single active failures.
- Passive and undetected failures.
- Combinations of independent failures.
- Common-mode failures.
- Cascade failures.
- Failures produced by the environment.

Single Active Failures

This is the type of failure which produces deterioration in the performance of the system or the aircraft, an example is the failure of engine to produce power.

Passive and Undetected Failures (dormant)

In some systems there can be a fault in one channel which leaves the system operating, and it only revealed when another channel fails. The presence of the fault is undetected by the pilot and such faults are called 'dormant faults'. As an example is the failure of one hydraulic channel on multi- channel system.

In case of this type of failure, a good solution is the provisioning of inherently higher channel reliability and /or reduced periods between checks. Multiplexing is of no great help in this case.

High levels of safety needed for essential systems are usually achieved by some form of 'fail safe 'design, mainly by redundancy, but there are various threats to the independence of the channels of redundant systems. These may lead to multiple failures at higher rates than would be forecast by calculating the multiple failure rates from the failure rates of the components channels.

The cause of this is that, for various reasons, the channel failures are not always independent. It is only by eliminating or reducing the effect of this lack of independence that proper advantage can be gained from the redundancy provided.

Combinations of Independent Failures

It is a multiple failure of more than one system, as an example, two engines failure to produce power.

Common-mode failures (Common-cause failures)

It is possible for the same root cause to affect each part of a system, as an example is that each channel of an electronic system may be affected by electromagnetic interference produced by failures in another system or by atmospheric electrical disturbance.

Cascade Failures

A cascade failure is a particular type of common-mode failure where a single failure, which in itself may not be hazardous, can be part of a series of other failures. An example is a tire burst followed by a piece of it going to an engine causing engine fire, leading to inability to control the aircraft which results in a catastrophic accident.

Failures Produced by the Environment

It is important to consider whether the systems are especially vulnerable to some environmental conditions particularly if they can cause common-mode failures. An example would be the strike of lightening that might cause a very serious failure on the aircraft systems and components.

2.8.2 Failure Patterns

The traditional view of failure is that most items operate reliably for a period of time, and then they reach the wear out phase. This view is reflected in Figure 2-5 below [73].

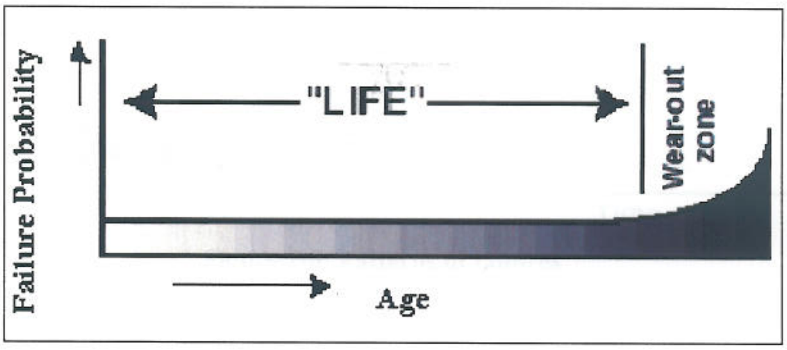


Figure 2-5: Traditional failure pattern [73]

This concept relates the component failure probability to the working life. A result of this view is the idea that the more often an item is overhauled, the less likely it is to fail. This concept is true for certain types of simple equipment, and for some complex items with dominant failure modes.

If the failure pattern of an item does, in fact, fit this curve, we are justified in concluding that the overall failure rate will be reduced if some action is taken just before this item enters the wear out zone. In these cases, allowing the item to age well into the wear out region would cause a substantial increase in the failure rate. Note, however, that such action will not have much effect on the overall rate unless there is a high probability that the item will survive to the age at which wear out appears.
Age-related failures are also often associated with fatigue, corrosion, abrasion and evaporation.

In real life, many failures occur at times during the component life before it reaches the expected life. This led to many studies that investigate component failure patterns. However, it was found that the conditional-probability curves fell into the six basic patterns shown in Figure 2-6.
Pattern A is often referred to in reliability literature as the bathtub curve [73].

Follow-on studies in Sweden in 1973, and by the U.S. Navy in 1983, [75] produced similar results. In these three studies, random failures accounted for 77-92% of the total failures while age related failure characteristics for the remaining 8-23%.

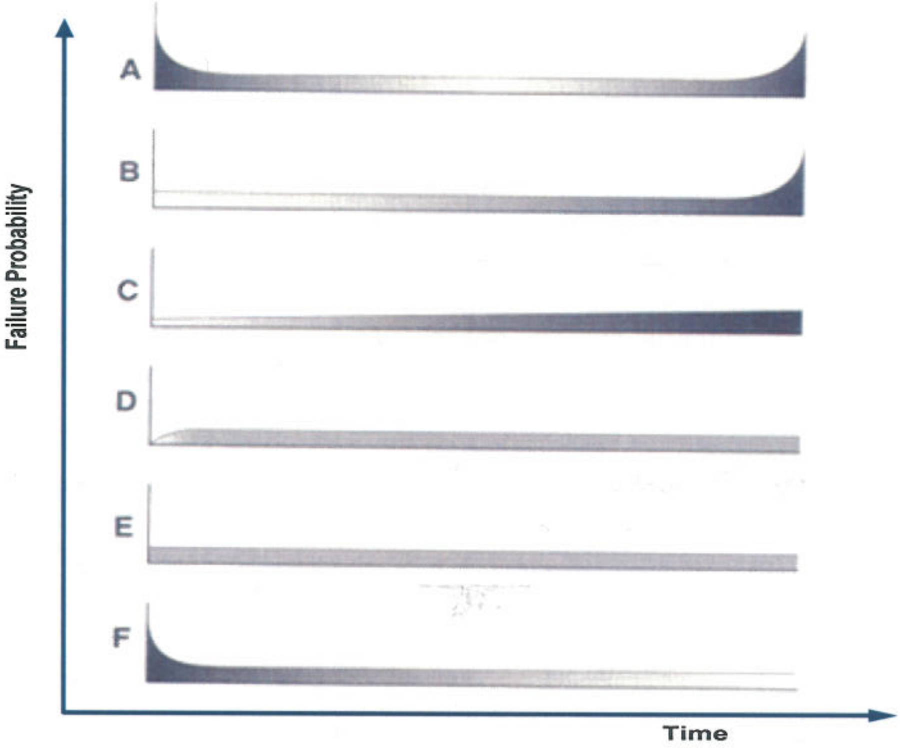


Figure 2-6: Patterns of failures [73]

In Figure 2-6, the vertical axis represents the conditional probability of failure and the horizontal axis represents operating age since manufacture, overhaul, or repair. These six curves are derived from reliability analyses conducted over a number of years, during which all the items analyzed were found to be characterized by one or another of the age-reliability relationships shown.

Pattern A represent the bathtub curve. It begins with a high rate of failure (infant mortality) followed by a constant or gradually increasing conditional probability of failure, then by a wear-out zone. An age limit may be desirable, provided a large number of units survive to the age at which wear out begins.

Pattern B shows constant probability of failure, finishing in a wear-out zone (the same as Figure 2.5). Once again, an age limit may be desirable (this curve is characteristic of aircraft reciprocating engines).

Pattern C shows slowly increasing probability of failure, but there is no identifiable wear-out age. It is usually not desirable to impose an age limit in such cases (this curve is characteristic of aircraft turbine engines).

Pattern D shows low probability of failure when the item is new, or just out of the shop following overhaul or repair then a rapid increase to a constant level.

Pattern E shows a constant probability of failure at all ages (random failure).
Pattern F starts with high infant mortality, which drops eventually to a constant probability of failure (particularly applicable to electronic equipment).
These findings contradict the traditional view that there is always a relation between reliability and component/item working age.

The presence of a well defined wear out region is far from universal. In fact, of the six curves in Figure 2-6, only A and B show wear out characteristics. It happens, however, that these curves are associated with a great many single-celled or simple items. In the case of aircraft, such items as tires, reciprocating-engine cylinders, brake pads, turbine-engine compressor blades, and all parts of the airplane structure. Most complex items had conditional-probability curves represented by curves C to F—that is, they showed no concentration of failures directly related to operating age.

Studies done on civil aircraft showed that 4% of the items conformed to pattern A, 2% to B, 5% to C, 7% to D, 14% to E and no fewer than 68% to pattern F[73].

These finding prove that aircraft components tend to have a random failure. Failures which are not age-related (random failures) have been discovered to form the majority of failures with a few percentages for the age-related failures.

This is due primarily to a combination of variations in applied stress and increasing complexity. These two factors are very dominant for aircraft.

Aircraft components are subjected to very variable stresses during daily operations. This is might be because of external or internal factors.

Lightning and bird strike are external factors that might happen during any period of aircraft component life, and they could cause a failure, regardless of the component age.

On the other hand, poor maintenance practice could be the reason for a change of component stress resistance. Damaging a component during installation will change its design stress resistance and cause it to fail randomly.

Aircraft high performance and greater safety are achieved at the cost of greater complexity.
Grater complexity means balancing the size and weight needed for durability with lightness and compactness needed for high performance.

These complexity and weight trade-offs mean there are usually more components which can fail and more connections and interfaces between them, hence more failures.
It also means the reduction of the safety margin which reduces the warning time before failure.

2.9 System Types

There are different sort of functional relationships or arrangement between aircraft system, subsystem or between components on the same subsystem.
Evaluating system reliability is depends on the system architecture. There are two fundamental types of arrangements and others that are derivative. These two are series and parallel systems.

a) **Series system**

A series system is when the items are connected functionally in series like Figure 2-7 below, where the all item in the system have to operate in order to the system to be functional. An item failure mean complete system failure.

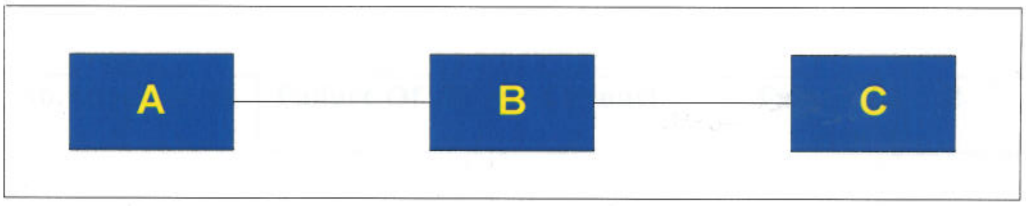


Figure 2-7: Series System Configuration

Consider a system consist of three items connected in series as shown below in Figure 2-7.
The probability of the system failure is the summation of the failure probability of the sub-system, i.e.
$P = P_A + P_B + P_C$
One failure on any sub-system will cause a complete failure to the main system.

b) Parallel System

Parallel system is when the items are connected functionally in parallel configuration like Figure 2.6. In this type of arrangement, not all items in the system have to operate in order to the system to be functional.
The system success path is multiple, and the system can be operative if there is only one successful path.

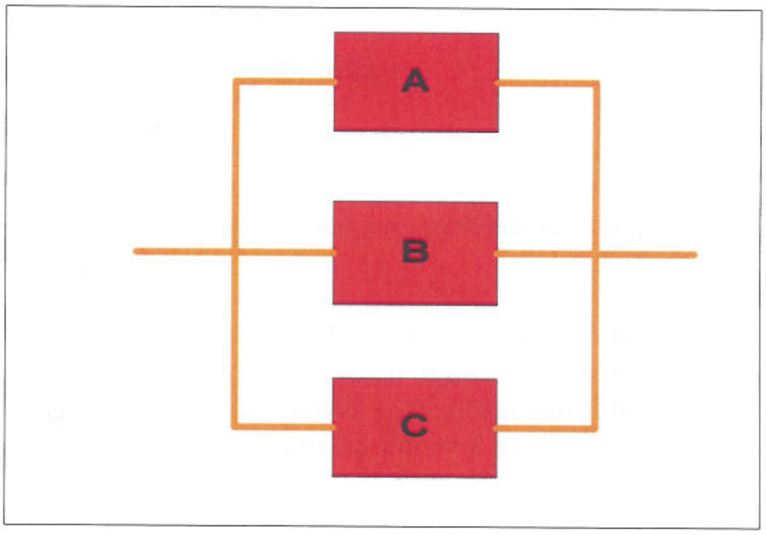


Figure 2-8: Parallel System Configurations

Consider a system consisting of three items connected in parallel as shown in Figure 2-8.

With this arrangement, all three sub-systems would have to fail to cause the complete system failure. Hence the probability of total failure is the product of the failure probability for the three sub-systems, i.e. $P = P_A \times P_B \times P_C$

Suppose that a system was made up of identical channel in parallel, each with a failure probability $P=10^{-3.}$ The failure probability is shown in Table 2-1.

No. of channels	Failure Of Single Channel	Failure Of All Channels
1	$P=10^{-3}$	$P=10^{-3}$
2	$2P=2\times10^{-3}$	$P2=10^{-6}$
3	$3P=3\times10^{-3}$	$P3=10^{-9}$
4	$4P=4\times10^{-3}$	$P4=10^{-12}$

Table 2-1: Failure probability

Probability of failure per hour, (p), is the inverse of the mean time between failure, as shown in Equation 2-17.

$$p = \frac{1}{T_m}$$ **Equation 2-17**

where $T_m = \text{MTBF} = \frac{1}{\lambda}$

Probability of failure before reaching, t, hour is $1 - e^{pt}$

2.10 Introduction to Maintainability

Maintainability is defined as the economy in time, manpower, equipment and necessary materials, with which potential or actual failures can be detected, diagnosed, prevented or corrected, and with which routine handling, replacement and servicing operations can be carried out.

It may be measured as the ability of an item under stated conditions of use to be retained in or restored to a specific condition when maintenance is performed by personnel having specified skill levels under stated conditions and using prescribed procedures and resources. Maintenance could also be defined as the act of repairing or servicing equipment.

Maintainability could be attributed to the ease of repairing/replacing a failed item.
In this context, it is a design parameter intended to minimize repair time [35].

Maintainability is an inherent characteristic of system or product design. In other words, it can be viewed as the relative ease and economy of time and resources with which an item can be retained in, or restored to, a 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 [12,74].

Thompson [106]stated that design for maintainability is concerned with achieving good designs that consider the general care and maintenance of equipment and the repair actions that follow a failure.
Maintainability can therefore be defined with respect to the probability that a device or system can be returned to a specified condition using pre-specified practices within a specified time.

Maintainability is associated with the measures taken during the design, development and installation of a manufactured product that reduce the required maintenance actions, man-hours, tools and logistic costs, skill levels and facilities to ensure that the product meets the requirements for its intended use. It does so by providing built-in design features that ensure accessibility, serviceability, parts interchangeability and first and foremost, reliability.

Maintainability as one characteristic of military aircraft mission reliability contributes very greatly on aircraft availability and sortie generation capability.

Past experience showed that any improvement in the inherent reliability and maintainability are translated to a high level of aircraft availability and better achievement on sortie generation capability. This is can be seen on the design of the F-15 aircraft [66].

Maintainability is influenced by the level of reliability and availability that needs to be achieved.
If the equipment reliability is too low, more emphasis has to be placed on maintainability issues to enable a restoration of availability and dispatch reliability.

Military aircraft readiness is very similar to civil aircraft dispatch reliability in essence that it is a function of reliability and maintainability, and the sortie rates and full mission capability are affected by the maintainability characteristics[66].

The concept of maintainability includes both the constraints of the item to be maintained (the aircraft in the case of this research) and the requirements for maintenance equipment (ground support equipment).

Rectifying failed item to a working condition entail fault finding, access to the faulty item, repair or replacement of the faulty item, and managing manpower and spares.
The required time for this activity includes logistical times that are not considered by the designers.
This is because the equipment maintainability design features influences only faultfinding, dismantling and reassembly, and adjustments. Other activities such as spares handling and manpower management are logistics related, therefore, they are out of control of the designers.

As a result, designers usually concern themselves with the mean corrective repair time (MCRT)[106].

Maintainability analysis programme can be used to enhance item/system availability by reducing the down time, providing efficient restoration of the equipment to an operating condition, and maximizing operation readiness.

Design for maintainability should include the implementation of such programme which has many advantages, some of which are listed below:

- To make an early assessment of whether the predicted downtime, quality and quantity of personnel, tools and test equipment are adequate and consistent with the needs of system availability.
- To verify that the design complies with maintainability requirements.
- To highlight for the designer, those areas of poor maintainability which justify product improvement, modification or a change of design.
- To allow for design decisions to be made through the evolution of alternatives and through the use of trade-off studies.
- To contribute towards determining maintenance, repair, servicing policies and critical support factors via logistic support analysis.

The consequences of ruling out maintainability in the design of an aircraft from the start are very series and costly, some of these penalties are:

- Inability to perform maintenance efficiently.
- Excessive remove and replace times.
- Inadequate spares holding.
- Excessive spares costs.
- Low aircraft availability.

Aircraft manufacturing companies usually apply a maintainability programme that can help to design and develop a maintainable aircraft that can meet all the specific maintainability requirements.

Most of these programmes are based on the military standard handbook MIL-472, which contains maintainability prediction techniques.
Although this maintainability prediction procedure was designed a long time ago and was for ground electronic systems, it has been much used by the aircraft industries and proved to offer rational results. One of the main criticisms of this procedure, however, is that it is not up to date, but since the procedure is based on human ability and performance which almost remains constant, this is make it insensitive to time and is valid for today applications.

The maintainability programme forms only one element of an aircraft design project but it is an input to other design work analysis and system effectiveness, such as aircraft reliability, testability, availability and life cycle cost.

Early and effective planning and implementation of a maintainability program can significantly lower the risk of reduced aircraft system operational effectiveness resulting from maintainability design shortfalls. This reduces maintenance time and support, which directly relates to reduced operating costs and increased system operational time.

There was a lack of emphasis on maintainability on many aircraft design projects, and in some cases, maintainability program was cancelled early on as a cost saving [30, 52].

Maintainability in design has traditionally not been thought of as a measurable concept and often regarded as a qualitative parameter. As result of this, many products suffered from the poor maintainability features.

2.11 Aircraft Maintenance Process

There are generally a number of aircraft maintenance processes that are used either together or separately. These processes are aimed to prevent aircraft or components failing in service and they can be:

- Airworthiness Limitations
- Hard-time maintenance

- On-condition maintenance
- Condition monitoring

The primary maintenance processes referred to above do not have an implied order of preference. Each process has its place in an effective maintenance program. The application of a given process should be determined primarily by the design of the component or equipment and secondarily by the operator's economic requirements.

a) Airworthiness Limitations

Airworthiness Limitations are periods at which specific components must be removed from service. These periods are set by the manufacturer of the aircraft or component.

Confidence in continued airworthiness has traditionally been based on maintaining safety margins by the prescription of fixed component lives and aircraft and component overhaul periods. Fixed lives have been applied to items that are safety critical or where fatigue is known to be limiting factor. Overhaul lives have been applied where deterioration occurs which may not be discovered during routine inspection
Airworthiness Limitations take into consideration such things as:

- The Criticality of the Functions Performed
- The In-Service Loading of Parts
- The Exposure of Parts to Fatigue or Wear

These airworthiness limitations are required to be published in the Airworthiness Limitations section of the aircraft maintenance manual and are considered to be mandatory. They may also be published as Inspections for Continued Airworthiness. Airworthiness Authorities may also set component life limitations, in the form of Airworthiness Directives, where such limits are not prescribed by the manufacturer.

b) Hard-Time Maintenance

Hard time maintenance requires the periodic overhaul, restoration or replacement of the affected equipment or part. In the early years of commercial transport aviation, hard time was generally considered to be the most effective maintenance program and was applied with the objective of ensuring operating safely when aircraft systems redundancy was limited.

It is a process where the known deterioration of an item is limited to an acceptable level by maintenance actions at given periods of time. These periods are usually set in relation to:

- Calendar time
- Number of cycles
- Number of landings
- Aircraft hours in service

The maintenance actions would include overhaul, partial overhaul, and parts replacement in accordance with the relevant manuals. These actions allow the aircraft or component to be released to service for a further specified period.
Examples of this type of action could include removal of radio or navigation equipment for bench calibration at prescribed periods or removal of an engine for overhaul and testing to specification.

c) On-Condition Maintenance Concept

In recent years aircraft maintenance practices have been influenced by changes in aircraft design philosophy and improvements in engineering technology.
Advances in manufacturing techniques and material specifications have made it less necessary to carry out frequent disassembly of aircraft and components to establish confidence.

Many reliability studies such as the one mention on section 2.7.2 prove that the aircraft component failure pattern is not age-related.
Except there is a very clear age-related failure mode, imposing component life-time (live) might not improve the reliability of complex items.

In fact, scheduled overhauls can actually increase overall failure rates by introducing infant mortality into otherwise stable systems [73].

Also, it was recognized that for some types of equipment, checking to a physical standard at periodic intervals is an effective maintenance process. The standard is designed to provide a basis for the removal of the given part before failure during normal operations.

An awareness of these facts has led the aircraft industry to introduce the on-condition maintenance concept.

The on-condition concept depends on the possibility of checking an items performance/condition at prescribed intervals, to an appropriate standard in order to determine whether it can continue in service. However, this concept is not intended to provide a freedom to run until failure [83].

The validity of the on-condition concept relies on effective inspections that provide warning of impending failure.

There are some items on some aircraft systems that cannot be adequately inspected other than by stripping, and the action of stripping provides an opportunity to overhaul the product.

In general, on-condition maintenance can be the correct thing to do for failures that do not jeopardize safety or has minor consequences. But when the failure consequences affect safety and cause significant effects, some methods of preventive maintenance, periodic checks or component living must be introduce to reduce the failure effect.

On-condition maintenance is a preventative process in which an item is monitored either continuously or at specified periods. The item's performance is compared to an appropriate standard in order to determine if it can continue in service.
The standard may be:

- An upper or lower limit of an indicated parameter such as a fluid-pressure instrument reading.
- A simple go or no go indicator such as a fuel-filter pressure-drop warning light.

On-condition maintenance should include the assessment of pilot monitoring performance, functional checks, scheduled maintenance, and the use of incidental servicing to carry out opportunity assessments of components. Also, the use of indirect assessments results from other component failures, routine component replacement due to life limitations, and from accidents.

The continued satisfactory operation of the structure or component may be determined by inspection, operation, or examination without detailed dismantling. The necessity to service, recondition, overhaul, or repair is made dependent on the condition.

Failure of the item to continue to meet the documented standard will indicate that further maintenance actions are necessary. The fundamental purpose of on-condition maintenance is to remove an item before it fails in service. It is not a philosophy of fit until failure or fit and forgets.

The failure pattern studies showed that about 89 % of aircraft component are from patterns D, E and F with the majority (68 %) of the later pattern (see section 2.7.2). These patterns shared one most important attribute which is that no relationship between component failure and age.

Although failure is not age-related on most aircraft components, the majority of these components show some indication or warning of failure development or they are approaching failure. These condition symptoms are called a potential failure.

The on-condition maintenance tasks involve checking for potential failures, where maintenance actions can be planned on the right time to prevent failures.

d) Condition Monitoring

This type of maintenance is not preventive process, but one in which information on item gained from operational experience is collected, analysed, and interpreted on a continuing basis as a means of implementing corrective procedures [25].

In the space age, man will be able to go around the world in two hours -- one hour for flying and one hour to get to the airport.

Neil McElroy, 'Look,' 1958

Chapter 3

Aircraft Dispatch Reliability and Delay Considerations

3.1 Introduction

Dispatch reliability is one aspect of aircraft reliability which has increasing importance. It is commonly known in the commercial transport field 'as the probability of a transport aircraft beginning a scheduled flight within 15 minutes of the scheduled departure time and successfully completing the trip'[86]. It is sometimes called scheduled reliability, and other dispatch reliability definitions are given in section 2.1.4.

Aircraft inherent design availability is synonymous with "scheduled reliability" and used both by manufacturers and operators [80].
Aircraft dispatch reliability is, in fact the availability of an aircraft of meeting a schedule for revenue services.

Dispatch reliability is a punctuality indicator of the aircraft performance hence, it is a delay gauge. Air transport delays are a major concern for the industry and a relentless source of complaints from the passengers, as often verified in the media.
It is a major indicator of the airline performance and may felt and experienced by users themselves.

Dispatch reliability in general is a function of not only the design of the aircraft but also of the surroundings (environment) in which the aircraft operates. This environment includes many aspects, such as the operator management, competence of the technical staff, operator financial stability, and even the political situation where the aircraft is operated.

Recent passengers surveys shows that on-time performance, which is dispatch reliability contributes most to the satisfaction with a flight [9,67,58].

Dispatch reliability without a doubt is the most discussed operational topic and needs to meet stringent targets.

With the tendency of the press to report bad news stories, the dispatch reliability of an airline comes under pressure and, improvements must be made.

High dispatch reliability means more flights on time; more customer satisfaction resulting in more profit. Of course the opposite is not desired by both parties.

Aircraft dispatch reliability becomes very important figure on the aircraft industry and it is very often used as selling figure for the aircraft. As an example, the new Canadian Bombardier C-series brochure claimed that the aircraft will have 99% entry into service dispatch reliability [16].

Dispatch reliability and scheduled completion rate are two methods operators can use as a gauge to determine how its fleet is performing, and there is a difference between them. An easy comparison is that dispatch reliability looks at both delays and cancellations (initial only). These two factors together are called Mechanical Interruptions (M.I.).
Scheduled completion rate looks at cancellations taken for maintenance only. This shows how many flights did not depart due to maintenance.

Aircraft operator management also uses dispatch reliability to evaluate the work of different organizations. As an example, management can use dispatch reliability report to assess the work of the supply department and how it is affecting dispatch reliability.

Apart from passenger's perception, there are other economic advantages linked to good dispatch reliability performance: high service availability of aircraft, low number of aircraft substitutions, and less passenger-related expenses and thus reducing the operating cost. It also reflects a reliable and safe aircraft operation.

Direct operating cost (DOC) is comprised of many factors including maintenance cost, aircraft departure slot cost, and airport barking cost. Dispatch reliability has a clear influence on direct operating cost (DOC) because it affects all the above factors.

Dispatch reliability is one of the major contributors of airline indirect operating costs [60]. For example, the airline will incur direct costs in terms of lost ticket sales and indirect costs such as ferry flights for repair and replacement and direct passengers costs for missed connections. Dispatch reliability data is the core of reliability and performance reports produced monthly by aircraft operators, and it is used to monitor the aircraft/operator performance. For an example of these reports see appendix G.

Dispatch reliability is not purely a reliability parameter, but an integrated factor affected by both reliability and maintainability considerations [39].

Meth [70]analysed the factors effecting operational availability and conclude that enhancement to the operational availability could be achieved on the design by making the mean time to repair (MTTR) shorter.

Reliability design analysis and optimisation of the aircraft design for reliability are very important during the early conceptual design phases and been asserted in many references such as [119, 47, 24].

Traditional design methods, which exclude the reliability until a very late design stage should be replaced by a new design method that can 'make the designer more productive, thereby providing him the time to analyse and optimise the early design'[119]. This means early in the design, the dispatch reliability target should be established, and then the allocation of the delay rates should follow. These should then be used during the choice of system architectures and components.

Scholz [93] says that the aircraft price is driven by aircraft systems. Aircraft systems account roughly for one third of the direct operating cost (DOC) and direct maintenance cost (DMC).

Aircraft dispatch reliability can also translated to punctuality, i.e. adherence to published times. Punctuality is measured by on-time performance and departure and/or arrival delay with respect to the flight schedule.

Most airlines preserve punctuality by using buffers to counter predictable delays on a statistical basis. Buffers are an expensive way of ensuring a good quality service to passengers.

Since the scope of this research was to focus on aircraft design aspects, only technical dispatch reliability will be considered. This means that technically-related factors are considered, other factors listed above are outside the control of the designer.

3.2 Factors Affecting Aircraft Dispatch Reliability

The starting point was the assumption that technical dispatch reliability is equal to inherent availability. More discussions are presented in section 7.4.1.

The factors affecting civil or military aircraft dispatch reliability are numerous and are shown in Figure 3.1.

These factors include system reliability and maintainability design, the characteristics and performance of the logistics support systems, the quantity and location of the logistics resources and the working condition.
They are interrelated, but design factors have the strongest influence.
Mean time between failures (MTBF) is mainly a function of the reliability design of the system and component.

Although MTBF is predominantly a measure of the system design; other factors, such as inadequate training leading to errors or abuse during operations and maintenance, can effectively decrease it.

Mean time to repair (MTTR) is a measure of the maintainability design of the system and component, and affected by the physical maintainability aspects of the design such as accessibility and packaging of the black boxes, the design and external diagnostics capabilities including built-in-test equipment (BITE), test equipment effectiveness, troubleshooting manuals, and the quality, availability and training of the maintainer.

The mean logistic downtime (MLDT) is primarily driven by management factors involving the operation of the logistics system and the resources that are allocated for system supply and maintenance. However, reduction on the estimated MTBF can put a strain on the logistics resources which would increase the MLDT.
MLDT depends on many aspects that include the level of spares stocked, the lead times which are the required time to receive a spare part, and the location and capability of repairing facilities.

These factors can be rearranged according to their direct cause into three categories, they are:

I. Aircraft Design Factors
II. Operator-Related Factors
III. Working Condition Factors

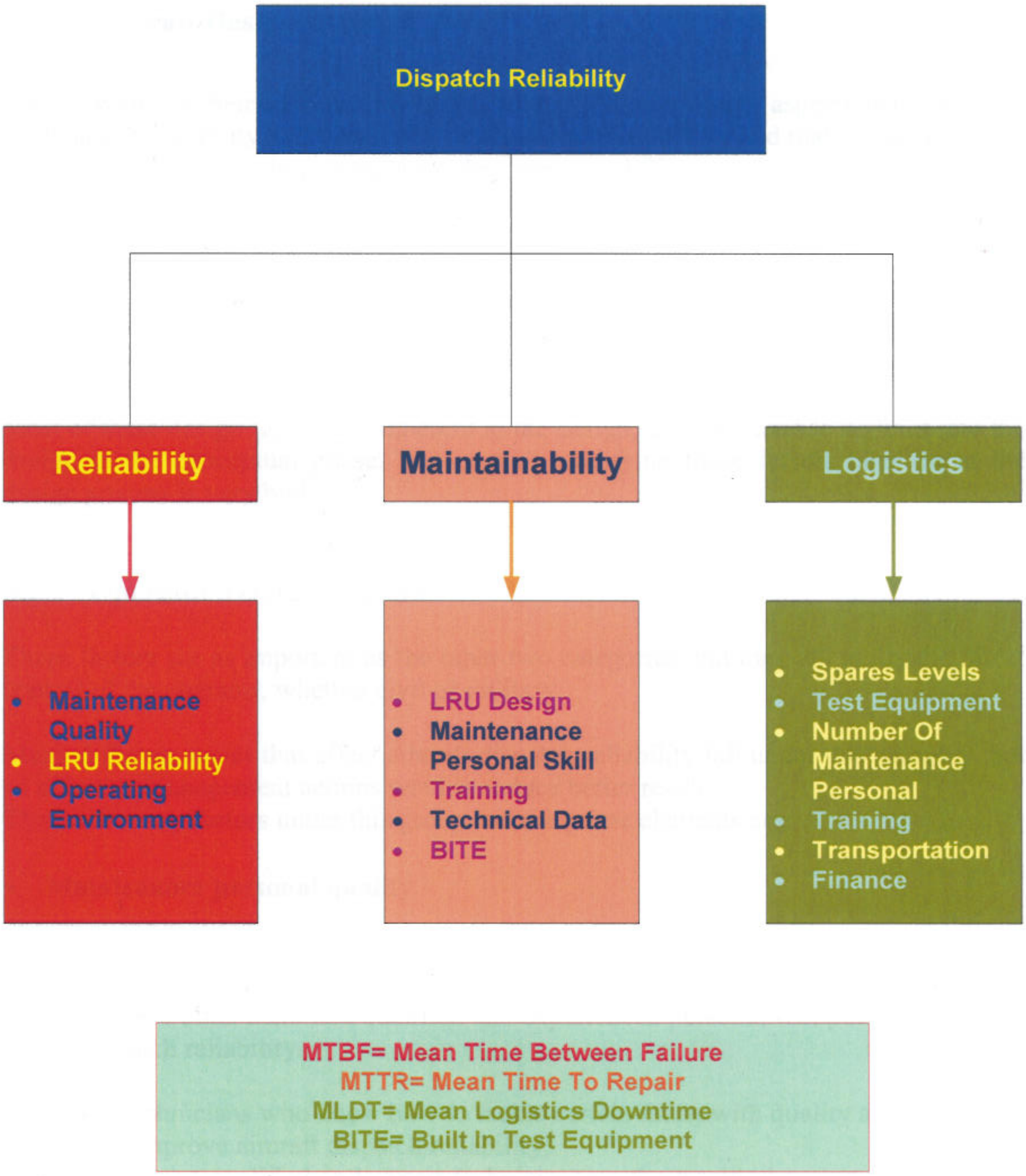


Figure 3-1 : Factors affecting aircraft dispatch reliability

3.2.1 Aircraft Design Factors

These factors as their name indicates are related with the design aspects that influence the dispatch reliability and they mainly evolve out of reliability and maintainability.
These factors are very important since they are very difficult to amend once the aircraft is in service. No matter how much resources are available for the other categories, this would not influence these design factors.

Component reliability, interchangeability and accessibility are among the very wide range of design features that affect very critically the aircraft operational availability or dispatch reliability, which is the prime interest of this research.

Most of these design factors are inherent in the design, and they tend to be built into the design in the conceptual phase. The cost of modifying these factors later on in the design process is very high.

3.2.2 Operator-related Factors

These factors are as important as the other two categories, but they are under the direct control of the operator, whether civil or military.

Many different issues that affect aircraft dispatch reliability fall under this category, but an effective management actions would produce better result.
There are many factors under this group and the prime elements are:

- **Maintenance personal quality**

This is the experience and quality of the technicians who do the maintenance tasks. Whereas more qualified maintenance personal will improve the dispatch reliability of an aircraft, on the other hand less qualified and experienced personal will put a lot of strain on the dispatch reliability.

Specialist technicians who know how to tackle certain faults with quality and speed will very much improve aircraft dispatch reliability.
Placing the most qualified and expert technicians on the troubleshooting and diagnosis tasks will help to improve the dispatch reliability.

- **Engineering Management effectiveness**

The management effectiveness would help to improve dispatch reliability by many means, such as being proactive in dealing with operational matters, and adapting the right method of personal training.
Many management activities drive departure performance well before departure day. Developing a suitable maintenance schedule is one of the most important factors that affect the dispatch reliability, which is under the management's direct control.

Adequate maintenance planning should help improve dispatch reliability. As an example, bringing forward or delaying some scheduled maintenance to a suitable time will help the availability of aircraft.

- **Operator financial capability**

Airline financial capacity plays an essential role on aircraft dispatch reliability. The availability of adequate spares, maintenance equipment and the necessary infrastructure are very important factors that could affect the availability.

Attaining high aircraft operational availability is feasible when the operator has a healthy financial condition.

- **Operator work culture**

Discipline and work quality are part of the organizational working culture. In some areas of the world, the worker may be treated unfairly, worker discipline is not monitored and customer satisfaction is not looked after, which all contribute to more delays.

- **Destination airport (facilities, maintenance level available …etc.)**

Upon arrival at certain destinations, and prior to departing to another, an aircraft needs some servicing and preparation (turn around) which could be anything between one to two hours

The turnaround time is very important factor on aircraft dispatch. It is influenced by many things; among them are the available facilities on the destination airport, the technical support, and the turnaround model adapted by the operator.

Turnaround activities must be considered by the designers, who can determine optimum provision of LRU maintainability aspects such as access, locations, weight, etc.

Better airport facilities and adequate technical support will improve the turnaround time, which means fewer delays.

Tailored and flexible turnaround models that cater for the aircraft type will improve the aircraft availability.

Airports with fast and less bureaucratic immigration and customs procedure will help on reducing aircraft delays.

The availability of adequate test equipment, aircraft ground equipment and power units in the airport are very important and do effects the dispatch reliability very much.

3.2.3 Working Condition Factors

These factors are largely out of the control of the operator, and are result of many different elements that combine together.
Such factors are very different in nature and need highly skilled management and large amounts of resources to overcome them.

These factors are non-aircraft-related but include flight timing, crew, airport, Air traffic control (ATC), flight type, weather and other factors.

The following is an explanation of some of these working condition factors:-

a) Flight Timing Factors

These are factors that connected with the allocation of the desired departure and arrival times that are convenient for passengers. Those desired times are market and peak demand-driven in airlines.

They cause a huge demand on the maintenance and resources which in turn affect dispatch reliability. As an example, ten departures occur in a single five-minute period at 1900 on Fridays from London Heathrow airport.

b) Airport Factors

Airport factors that have an effect on dispatch reliability include airport night curfews which exist in many airports. This results in a very high demand for arrival slots after the curfew ends, and this has very similar effects on the maintenance and resources and thus, on the dispatch reliability.

c) Crew Factors

It includes crew availability and working hours. While the crew availability has very direct effect on the dispatch reliability, the crew working hours can force the operator to reduce the turn around time. Turnaround time between two flights may be made shorter to satisfy the crew working time. This results in shorter turnaround times available to do the turnaround tasks, thus a higher delay probability.

d) Air Traffic Control Factors

These factors have a considerable effect on aircraft delays. Table 3-1[26]shows the results of a study which compared the actual push-back times and the scheduled departure times. The analyses include about 12,940 BA movements, August to September 2001. There was a very wide variation, with 35 per cent of BA aircraft pushing-back more than ten minutes after scheduled time of departure.

Time	–9 to –1 minutes	On time	1–10 minutes	10–20 minutes	20–30 minutes	30–60 minutes	Over 60 minutes
Percentage of aircraft	16	21	28	17.3	6.2	7.4	4.1

Table 3-1: Push-back to scheduled departure time [26]

By comparison, Table 3-2 [26]shows another analysis of the time between the push-back request and the actual time of push-back. This showed a much smaller variation. This study showed that the delay in result of late authorization of the ATC is about 8%.

Time	No delay	0—1 minutes	1–2 minutes	2–3 minutes	3–4 minutes	4–5 minutes	Over 5 minutes
Percentage of aircraft	92.1	3.2	1.0	1.0	0.6	0.9	1.2

Table 3-2: Delay caused by response to push-back request [26]

e) Flight Type Factors

Flight types, such as short or long haul flights can affect dispatch reliability in different aspects. Long haul flights normally have a variation in the flight time caused by things such as weather conditions. Wind direction and speed can alter the expected flight time which, if combined with a very busy arrival destination, could result on a very late arrival time. This delay on the arrival time, when associated with short transit time, would make the time allowable to rectify faults very short and hence cause an aircraft delay.

Long haul operations which, most of the time means international flight brings with them some unavoidable inefficiency that effects dispatch reliability.

Long haul international flights need longer turnarounds because more time is needed for cleaning, catering and flight preparation. Also, having to put the embarking passengers through tight security checks and extensive immigration and customs processes, will sometimes cause aircraft delays.

Twin-engined aircraft, which fly extended range (ETOPS) need longer turnaround time because more strict maintenance checks need to be done. This will influence dispatch reliability if the allocated turnaround time do not account for this special needs.

f) Passenger Factors

These factors are among the crucial factors which cannot be controlled by the operator. Late boarding, security, and high no turn-up rates are factors that contribute to the flight delays.

g) Miscellaneous Factors

These are very different and it could be any things from custom or immigration performance, industrial actions to politically related matters.

On the military arena, these factors are different and more numerous. Military aircraft that are required for special missions like nuclear or biochemical mission will need unusual preparations that might induce delay.

Aircraft operated in a war environment will be subject to very different factors which sometimes cause delays.

3.3 Aircraft Delay Magnitude and Cost

There are many different standards that an operator can use to judge how reliable an aircraft are, in regard to scheduled departures. An operator can choose to record delay times at different thresholds, or to use a lower threshold if it wishes, but nowadays, it has become standard to use delays at or above 15 minutes.

Aircraft delays occur when the pre-planned turnaround activities take longer than expected, or when previous flight arrived late.

Table 3-3 shows the result of a recent study done by Eurocontrol [40]to analyze the punctuality and the average delay time on some of the European and USA airports for the year 2000.

The study finding showed very alarming figures, with more than a quarter of the scheduled flights being delayed.

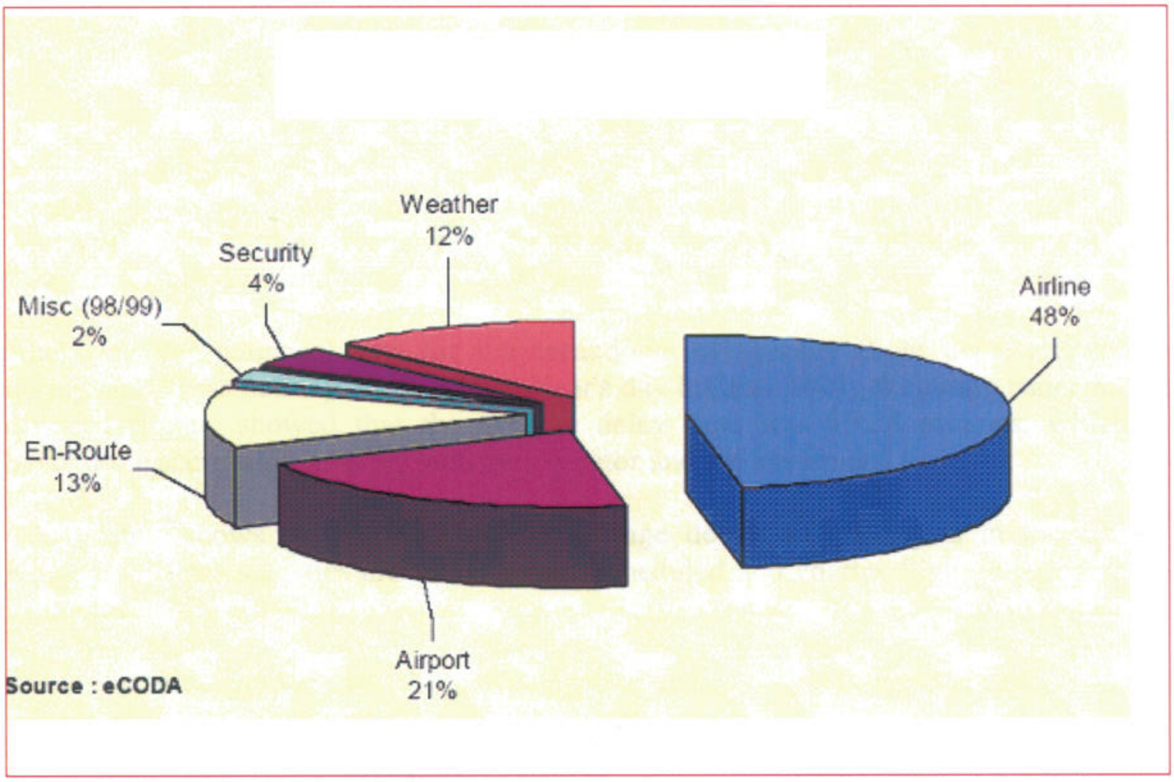
	Eurocontrol Area	USA
Departure punctuality	74%	74%
Average delay time (>15 minutes)	39 minutes	44 minutes
Arrival punctuality	73%	77%
Average delay time (>15 minutes)	43 minutes	53 minutes

Table 3-3: Average Punctuality & Delay Time [40]

Another source showed that charter airline average delay time for summer 2000 was 40 minutes [2].

Delay causes are different and can be airlines, weather, security, airport and other causes, and airline related causes can reach about 48% as in the data provided by

Eurocontrol as shown in Figure 3-2 [41]. The aircraft-related technical causes amount to nearly 20 % of all delays causes.



Source : eCODA

Figure 3-2: Aircraft delays causes [41]

The cost of aircraft delays that comes as a result of inadequate dispatch reliability is very high and is very crucial since delays are some of the main complaints from customers[25], and they do have a negative affect the airline reputations.

Air Transport User Council (AUC) data base showed that the 22% of the 2000/2001 total passenger's written complaints were for flight delays [2].

The American Bureau of Transportation Statistics showed that flight delays are a major concern due to the fact that it is still reaching high percentage especially during the high season [21], see Table 3-4.

Period	Percent of Flights Delayed Over 15 Minutes Excludes Cancelled & Diverted Flights (%)
Memorial Day Holiday 2001,	13.50
Presidents' Day Holiday 2001	20.25
Christmas Holiday 2000 &New Year's Day Holiday 2001,	33.60

Table 3-4: Flight delay percentage

As shown above, the percentage of flight delay is very high, although some of the delays are caused by non-technical reasons.

Analysing the statistical data for the breakdown of average flight departure delays during Christmas holiday 2000 & New Year's day holiday 2001, excluding cancelled & diverted flights, showed that the average delay time was 19.54 minutes, which is beyond the acceptable level by both the operator and the customers.

CAA data [26]shows the statistics of the average delays of all flights in the United Kingdom. These statistics are tabulated for scheduled and charter flights that operated from eleven UK airports.

These statistics showed that the percentages of delayed flights were around 30% for scheduled flights and around 35% for the charter flights.

The average delays of all flights are 12 & 20 minutes for scheduled and charter flights respectively.

These average delays are the delay time calculated after the 15 minutes window, which means that the total delay is about 27 minutes for scheduled flights and 35 for the charter flights.

3.3.1 Aircraft Delay Costs

Delays are not only painful inconveniences for the passengers and airlines, but they also induce large costs, for the airlines, their customers and the community as a whole[55]. Reasons for air transport delays are very complex and need investigations for a better appraisal of the various costs involved, as well as the information needed to analyze and evaluate them.

The airlines bear additional costs on fleet, as well as flying and ground personnel, since delays prevent them from operating in optimum conditions. They also must compensate

passengers for their discomfort and prejudices. Also, according to their type of operations, airlines might experience specific costs (i.e. linked to hub operations).
Additional long-term costs might also be observed such as a loss of competitiveness and the consequences of a degraded social climate, which follows degraded working conditions.

The delay-related costs for users are mostly airline passenger's opportunity cost, measured by their value of time.
The delay-related costs for the community involve environmental costs as well as costs incurred by other players involved in the air transport business such as hotels, travel agents, tour-operators, airports, etc.

Aircraft delay cost forms a substantial figure that is different between aircraft operators, where it is non-linearly related to duration. For example, a thirty minutes delay is likely to be more costly than 30 times one minute of delay. The thirty minutes delay is more likely to disrupt ground operations, gate allocation, crew schedules, and passenger itineraries.

It is also possible that the unit cost of delay decreases beyond a certain duration because airlines take different measures in order to minimize the overall impact of delay (e.g. cancel the flight).

The cause of delay can play an important part on the cost of the delay. Flight that delayed due to the lack of take-off slots will be different than flights that are delayed because of the late arrival of the aircraft.

The cost of delay also depends on the nature of the airline (short-haul vs. long-haul, schedule vs. charter) and on its reaction activities. Operators may take different types of actions to make their operations less sensitive to delays. They usually include a buffer into their schedule; they plan for extra flight crew, ground personnel and additional aircraft.
Although these actions decrease the cost of delays when they occur, they also increase costs of the normal operations.

Delay costs are also subject to combinatorial effects [42]. The severity of the impacts is likely to depend not only on the duration of delay to a specific flight but also on the interaction of delays for many flights. This is particularly relevant in the era of extensive hubbing.

Some sources claim that recent statistics show that the cost per minute of a late dispatch of aircraft is $1,000 and the cost per one day out of service per aircraft is estimated around $900,000[105].
Omari [80] stated that the cost of delays and cancellations are in the region of 2% of the annual total revenue.

In the military environment, unavailability of aircraft when required in peacetime and wartime can have extremely serious consequences for the defence capability.

Today's cost of owning a jet transport through the life of the airplane is estimated to be two times the purchase price [11].

To help minimise this cost of ownership, adequate dispatch reliability must be achieved. This is accomplished through design that keeps operational complexity and in-service follow-up to a minimum.

Demands from customers for on-time performance, and of the competition to keep costs down create a significant thrust toward better design to meet this economic requirement.

The aircraft delays cost which result from poor dispatch reliability is very high and has direct and indirect effect.

The direct costs include some obvious elements that range from lost tickets sales, passengers cost for lost connection flight, maintenance costs, providing meals for the passengers during the delay right to the airport fees.

The less obvious are the indirect costs which sometimes has very great effects. It includes the ferry flight for repair or replacement cost and most importantly is the airline loses of reputation. The last is very hard to put right if damaged and can affect very seriously the airline future.

Maintenance costs as result of delays is one of the delay costs elements, a recent study puts maintenance costs at $200,000 per year per aircraft due to unnecessary delays, cancellations, unnecessary repairs and excessive spares [87].

A delay cost study performed by US Airline Transport Association (ATA) [5], concluded that aircraft operating delay costs amounts to USD34.1 per minute with the total delay cost is more than $5 billion per year as shown in Table 3-5 [5].

1997 (US dollars)	**Aircraft Operating cost per minute($)**	**Delay minutes (millions)**	**Delays costs ($ millions)**
Gate	24.30	5.16	125.3
Taxi out	30.47	34.65	1055.7
Airborne	47.64	16.12	767.7
Taxi in	29.81	9.64	287.4
Total aircraft operating	34.11	65.56	2236.1
Added ground costs (guess)			850.0
Value of passenger time			2100.0
Total costs			5186.1

Table 3-5: Calculated delay cost [5]

Another research performed by Institute du Transport Aérien studied air traffic in European countries in 1999. It includes only the scheduled traffic which forms about 65% of the total European traffic.

The study shows that the annual overall costs for airlines and passengers could be estimated between EUR6.6 and EUR11.5 billion with a corresponding average unit cost per minute of delay ranging from EUR39.4 - EUR48.6 for the airlines, and EUR 46.6 - EUR60 incurred by passengers, with the total cost per minute of delay is EUR 86 – EUR 108 [42]see Table 3-6.

	Delay cost per minute (EUR/min)	Annual delay cost (€billion)
For airlines	39.4 - 48.6	3.0 - 5.1
For passengers	46.6 – 60.0	3.6 - 6.4
Total	86 – 108.6	6.6 – 11.5

Table 3-6: Aircraft delay cost

3.3.2 Delay Cost Elements

Aircraft delays costs can be divided into many elements, which are shown in Table 3-7 below[42].

Aircraft operating costs
• Fuel • Air bridges • Aircraft parking • Maintenance
Operating staff costs
• Flying personnel - Spare crews - Scheduled crew • Ground personnel
Structural costs • Fleet size -Spare aircraft -scheduled aircraft • Ground equipment
Passengers associated costs • Food and drink expenditure • Miscellaneous expenditure • Passengers rerouting (Loss of revenue) • (cancellation by passengers) • Commercial compensation
Connection costs • Reduction of flight connection efficiency • Flight cancellations
Long term costs • Loss of market share to other airlines • Loss of corporate image • Social consequences • Subcontractors • Average passenger revenue
Costs for passengers • Value of time lost • Cost of automobile parking • Cost of transportations • Prejudice compensation
Cost for the community • Environment • Others (travel agents, tour operators, hotels …etc.)

Table 3-7: Aircraft delay cost elements

3.3.3 Aircraft Delay Scenario

When aircraft lands and is placed at the departure gate, it has to go through a set of activities in preparation for the next flight.
These activities can be divided into two groups, aircraft-related activities and non-aircraft-related activities.

The aircraft-related activities are mainly concentrated on the turnaround tasks. Upon successively passing both types of activities within the allocated time, the aircraft will depart without incurring a delay.

Delays occurs when the aircraft spends more time on the turnaround than the allocated time, or the when non-aircraft-related activities take more time than the allowable time, or when flight has to be cancelled due to other reasons, be they technical or other.

A flowchart representing the delay generation sequences is shown in Figure 3-3, the main topics of which are:

i. Write-Ups and Scheduled Maintenance Tasks
ii. Turnaround
iii. Delays

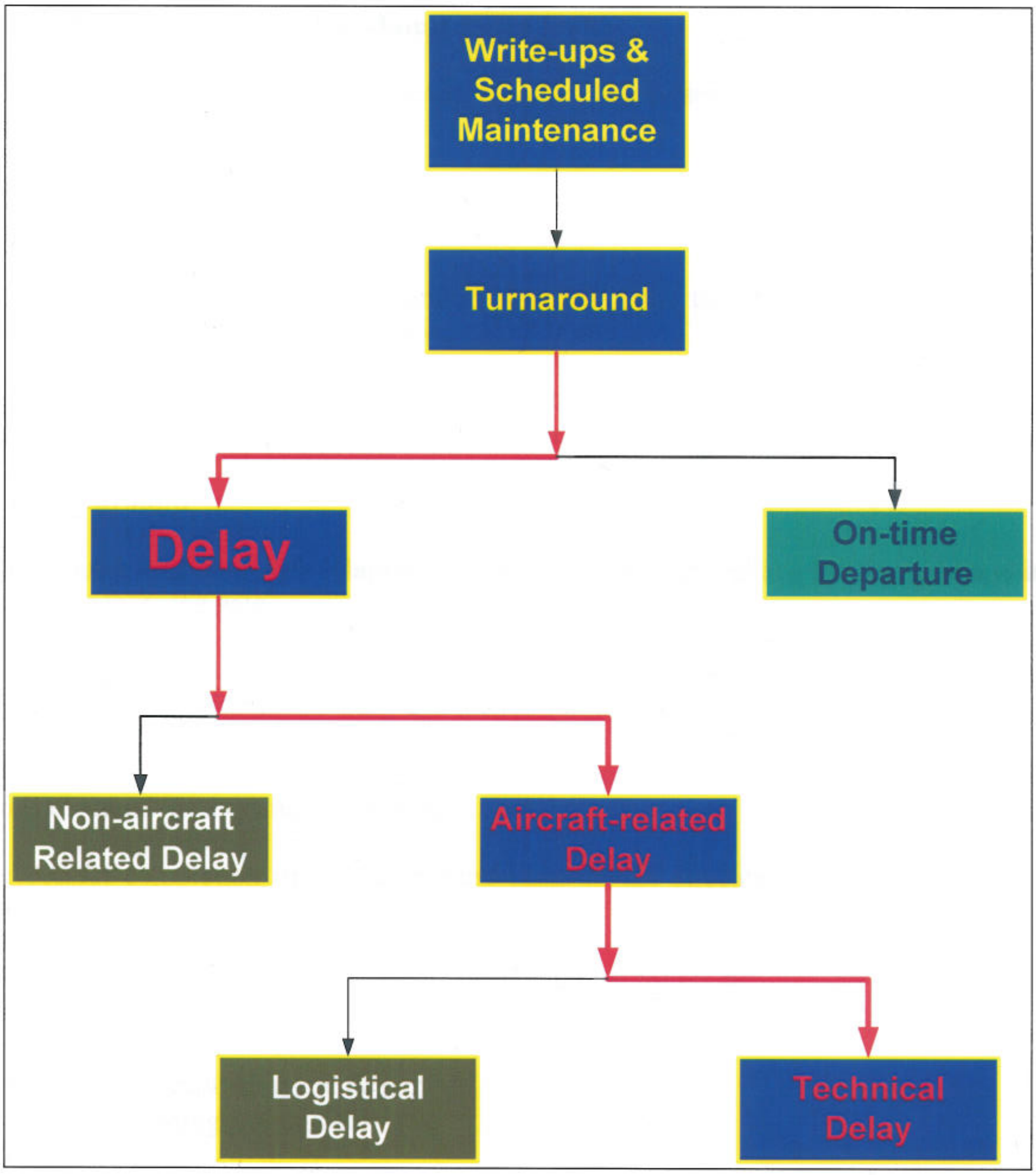


Figure 3-3 : Delays generation sequence

i.) Write-Ups and Scheduled Maintenance Tasks

This includes any malfunction record reported before-arrival or on-arrival, and any required scheduled maintenance.

The before-arrival malfunction reports are generated by the aircrew or flight crew onboard the aircraft or data received from the previous station.

On-arrival malfunction information is obtained from the pilot report (PIREP) or received verbally from the flight crew.

Scheduled maintenance tasks are set of maintenance tasks that need to be performed before the next flight and are defined by the aircraft maintenance manual.

ii.) Turnaround

Turnaround time is the time elapsed between an aircraft arrival at a loading gate and it's departure from the gate.

It is also an airplane's unloading time following arrival at a gate plus the time required to ensure that the airplane is ready and loaded for its next departure

Maintenance actions plus the normal turn around activities will be performed during the time allocated for the aircraft turnaround.

Successful completion of the turnaround tasks in the allocated time is a major step toward on-time departure.

The most significant turnaround elements include the following:

- Pre-flight check
- Passengers enplaning and deplaning
- Cargo's loading and unloading
- Refuelling
- Servicing
- Cleaning
- Catering
- Clearing the write-ups and performing scheduled maintenance
- De-icing

Military turnaround activities are different than the civil turnaround activities. There are some obvious elements that are essential for civil aircraft and are not for military aircraft such as catering, passenger-related activities, cargo activities and cleaning.

On the other hand, some turnaround activities are exclusively for military purposes such as armament loading, target programming and sortie-dependent requirements.
Typical turnaround schedules for civil and military aircraft are shown in Figure 3-4 and Figure 3-5 respectively.

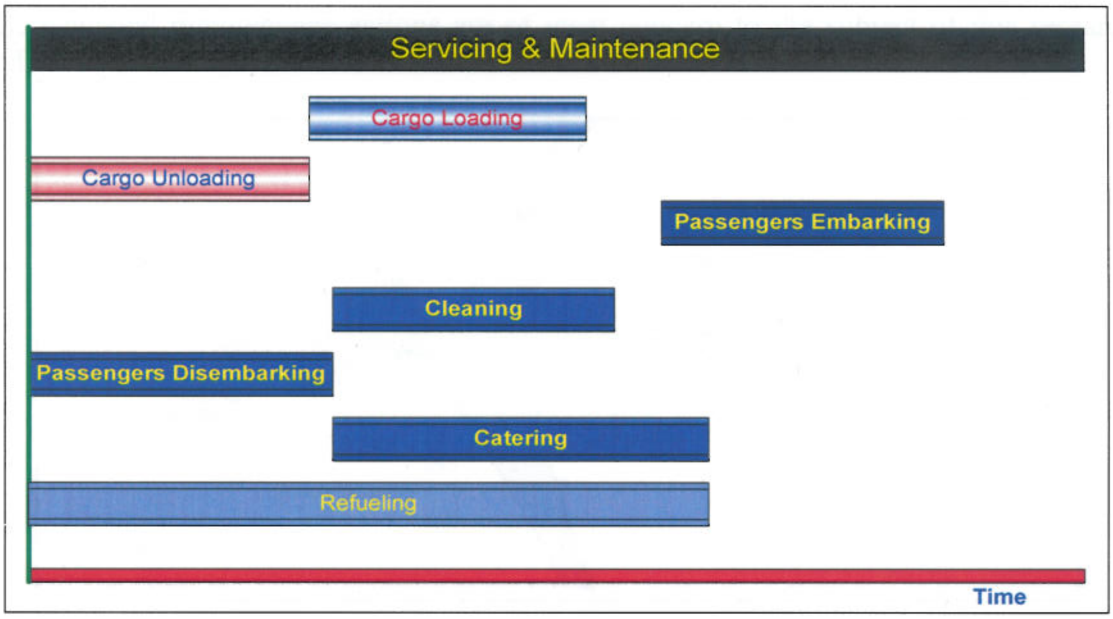


Figure 3-4: Civil aircraft turnaround activities scheduled

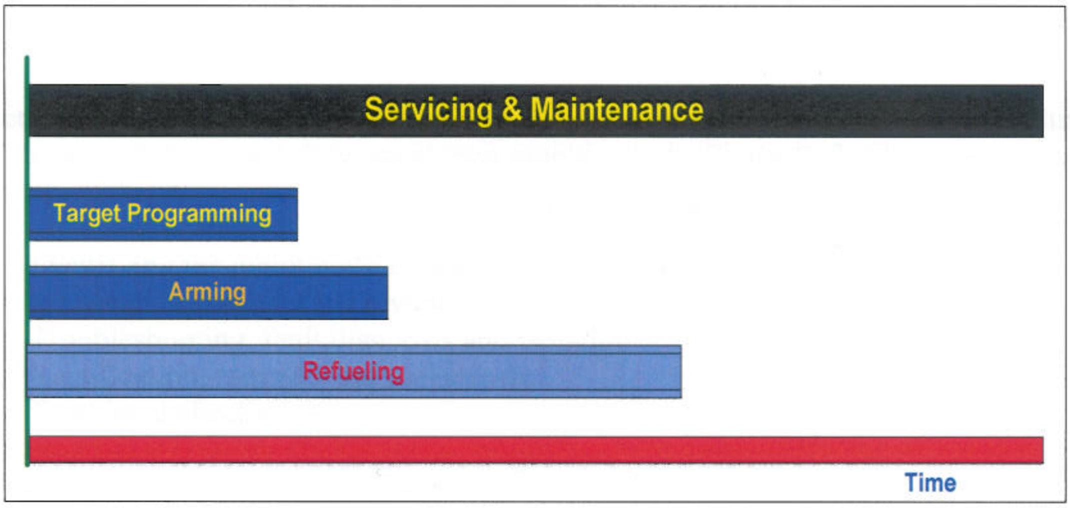


Figure 3-5: Military aircraft turnaround activities scheduled

Turnaround times vary widely across aircraft industry, but most civil aircraft are between half and two hours.

In the United States, a typical narrow body turnaround time is from 25 to 40 minutes. A wide body turnaround is from 45 to 75 minutes, the longer being for international flights [22].

Figure 3-6 shows an aircraft during the turnaround and typical activities and where they are performed[13].

The technical maintenance actions are of most concern to the subject of this research and will be examined in more detail.

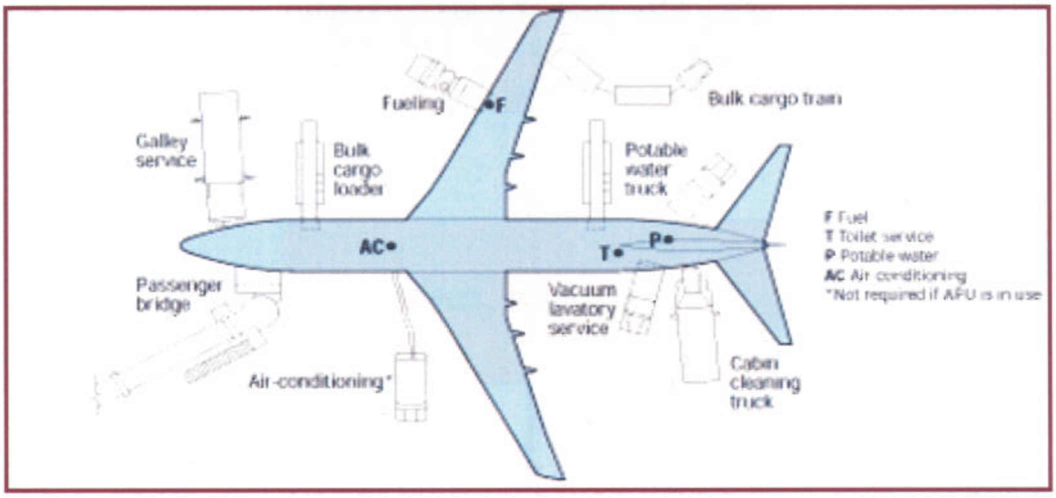


Figure 3-6: Aircraft at Turnaround [13]

There are set of tasks that take place at the turnaround time which are divided into two groups, technical turnaround tasks and non-technical turnaround tasks. At this stage, only technical turnaround tasks will be discussed because the non-technical turnaround tasks are beyond the scope of the current study.

A set of technical turnaround tasks comprise the maintenance actions performed during the turnaround time, and they are shown graphically in Figure 3-7. They are discussed later and include:-

a. Identifying the maintenance work that needs action
b. Minimum equipment list review
c. Troubleshooting, fault diagnosis and isolation
d. Rectification, removal and replacement
e. Functional checks

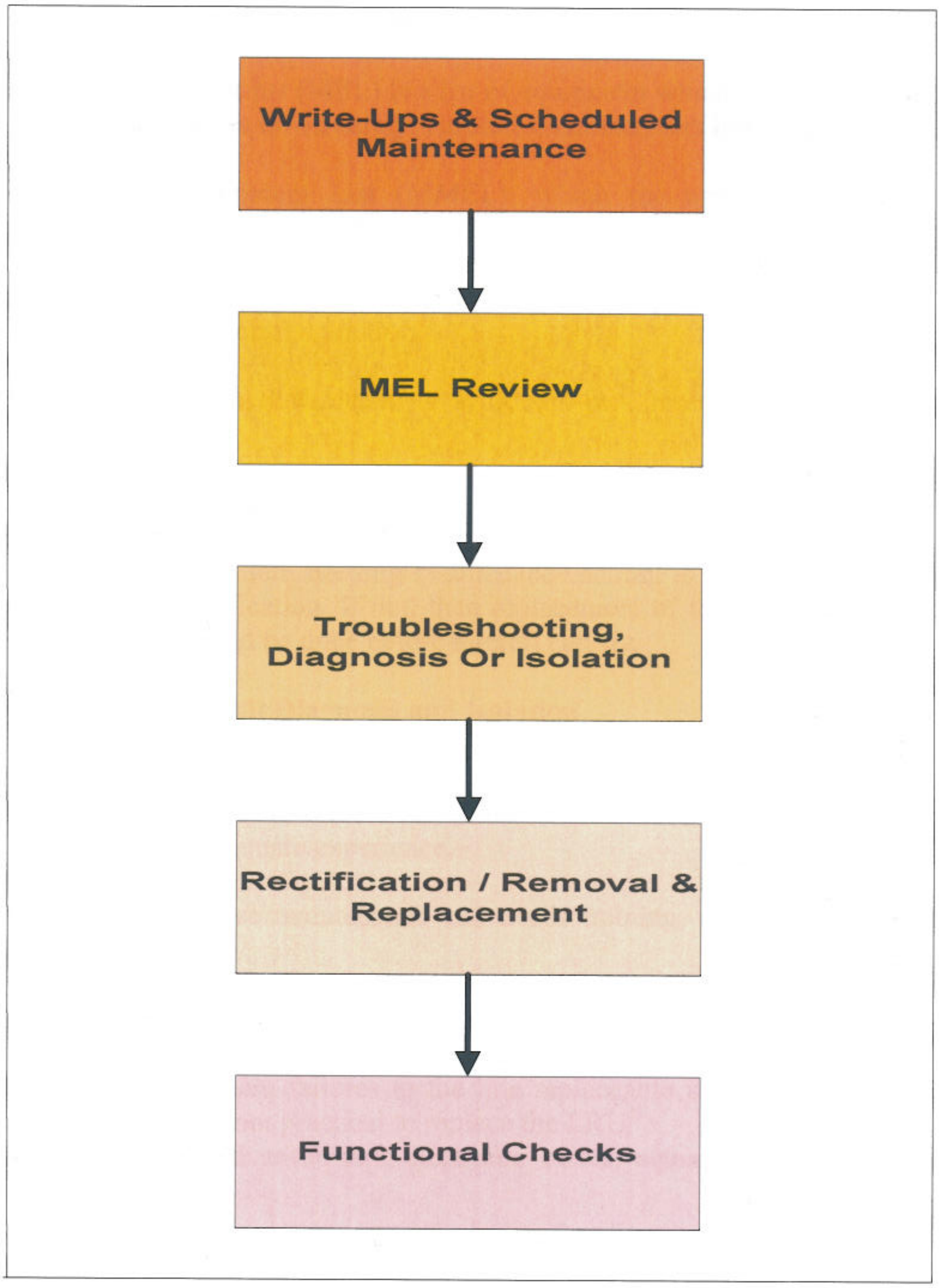


Figure 3-7: Turnaround maintenance tasks

a) Identifying the Required Maintenance Tasks

Maintenance tasks include the before-arrival malfunction report, on-arrival malfunction information and scheduled maintenance. This is the first turnaround task, and it is performed by the exact identification of the required maintenance actions, and the allocation of the manpower and equipment to perform these tasks.

b) Minimum Equipment List Review

The minimum equipment list (MEL) is a list of equipment which can be inoperative and yet the aircraft can still be flown safely. Aircraft manufacturers have established a

Master Minimum Equipment List (MMEL), which the appropriate civil aviation authority reviews and approves. However, the airline may choose to delay a departure on criteria more severe than those of the aviation authority which led to the creation of the minimum equipment list (MEL), since the airline's list is customized to that airline's style of operation and aircraft operation.

The minimum equipment list review is a process performed to define any required maintenance work.

The maintenance work (fault) is checked against the MEL to determine the aircraft ability to depart with the fault or not.
If the faulty item, or an item needing maintenance action, is on the MEL, the aircraft can depart without rectification. If not, then replacement of the faulty item or suitable maintenance action should be done before aircraft can fly.

c) Troubleshooting, Fault Diagnosis and Isolation

This task is to establish the nature of the fault and to identify the deficient component. This is a most important task, since it can consume much time if the technician does not have the right skill or adequate experience.

It is the key to corrective maintenance and needs training, experience, intuition and built-in-test capability.

Fault isolation falls into two categories; on-board diagnosis and on-the-bench diagnosis. On-board diagnosis uses built-in-test-equipment (BITE) to help the line maintenance technician to isolate system failures to the line replaceable unit (LRU), or to the line repairable item, if it was not practical to replace the LRU.
LRU's can be described as aircraft electronic boxes, actuators, instruments or any distinctive equipment.

Built-in test equipment and advanced-technology diagnostic systems can help to reduce the time consumed by this task.
There are many types of diagnosis system onboard today aircraft. Some are very sophisticated and others utilize the technicians experience and knowledge.

Another way to improve fault isolation is by using a concept termed the prognostic method.
This technique forecasts the failure before it happens, which allow the necessary maintenance actions to be planned in advance. Planning these actions helps to minimize the aircraft down time and delays.
An example of this is the use of engine chip dedicators to forecast the incoming failure, and then attribute it to a specific engine component. This allows correction of the

coming fault at a convenient time. Thus does not affect the dispatch reliability by causing delays.

An example of on-the bench diagnosis is automatic test equipment (ATE). This is a very useful means to help the line maintenance technician to check an LRU or in-depth troubleshooting of an entire aircraft system.

d) Rectification, Removals and Replacement

When the fault is isolated and proper action is known, corrective action may be performed. This may be some adjustment or removing the faulty item and replacing it with serviceable item.

The time consumed on performing these corrective actions depends on their nature. Some major corrective actions need considerable amounts of time and flights may have to be delayed or sometimes cancelled. Other types of corrective actions need less time and they do not cause delays.

e) Functional Checks

This is a check to make sure that the system or sub-system is working adequately after fault rectification.

Sometimes it is necessary to strip down the system and remove some parts in order to get access to the faulty component.
After bringing the system or sub-system together, a functional check sometimes is needed to check satisfactory operation.
This task sometimes needs external test equipment and may take a long time.

iii) Delays

When aircraft completes the turnaround activities within the turnaround time, it should depart on-time, provided there are no non-aircraft related delays.

Delays are divided into two different groups, according to their origin; aircraft-related delays and non-aircraft related delays.

a) Aircraft-Related Delays

These are the delays which occur because the aircraft itself is not ready for departure. Aircraft -related delays can be divided into two types, technical and logistic delays:-

- **Technical delays**

  These are delays that make the aircraft technically unable to depart due to the failure to correct technical malfunctions on one or more of the aircraft systems during the allocated turnaround time. These delays are attributed to the design features of the aircraft' systems and components.

The main two design features of these types of delay are the aircraft component reliability and maintainability.

Component failure frequency, accessibility, interchangeability, and simplicity are the most important factors that affect this type of delay.

These types of delays are the subject of this study, which concentrates on the inherent reliability and maintainability that are designed into a system.

- **Logistics delays**

These are the delays that make the aircraft technically not ready for departure for logistical reasons. These are all related to the maintenance and supply effectiveness of the operator. Logistic effectiveness includes spare parts availability, maintenance personal quality, maintenance facilities and the logistics management effectiveness.

The deficiency in any one of these elements will degrade the turnaround performance and may cause delays.

These delays are not considered in this study because they are mainly management, rather than design-dependent.

b) Non-Aircraft-Related Delays

These are caused by reasons other than the aircraft itself. The aircraft in this case is ready for departure but may have been held up as result of one of several different reasons. These vary widely according to their source and they can be due to one or more of the following:-

- Passengers disembarking or boarding.
- Customs and immigration.
- Airport authority such as air traffic and other service providers.
- Operator planning such as slot reservation, aircrew time table etc.
- Aircrew and flight crew
- Weather
- Ground servicing
- Industrial actions

These types of delays are not considered in this research since they are not aircraft-design related.

3.3.4 Aircraft Delay Studies

The aim of these studies is to identify the most troublesome aircraft systems that affect dispatch reliability. Aircraft operators usually report reliability data in many forms. The most important of these are the delay rate per ATA chapters and pilot reports (PIREPS).

The aircraft systems delay rates offer a percentage indication of every aircrafts' system contribution to total aircraft delays.

Pilot reports (PIREPS) provide a percentage indication of the system contribution to the total pilot reports.

The available reliability data were categorized into two types, one for short-haul and other for long-haul aircraft. The short-haul aircraft are those operating for 3 hours or less while the long-haul is those operating for more than 3 hours.

Large amounts of data were to be acquired from UK and overseas operators.
Aircraft reliability data within the same category will be different, due to different operator's maintenance practices and operating environments.

For this reason, a large and widespread data sources will be more convincing and should give a realistic outcome to analysis.

Studying aircraft reliability data showed that there were some aircraft systems causing more delays than others.

Two studies were performed to identify the systems that causing the most delays. The first concentrated on the delay rates and the second by examining pilot reports.

3.3.4.1 Delay Rate Study Results

Large amount of aircraft reliability information were obtained for this research from different aircraft operators. For more information see Appendix G.

The total number of short-haul aircrafts in this study was 160 distributed over 8 types, while the number of long-haul aircrafts in this study was 120 distributed over 8 types.

The delay rates were grouped by ATA chapter (see table 3-8) and the average delay rates were calculated. Average delay rates were more realistic since they averaged data from more than ten operators' data for every ATA system.

The aircraft analysed were divided into two group, long-haul and short-haul depending on their flying time.

Calculating the ATA average delay rate for all the aircraft revealed many interesting points:

- The ATA chapter 71-80 (power plant) has the highest delay rate for both short and long-haul aircraft. This can be seen graphically in Figure 3-8& Figure 3-9. This is probably due to the complexity, hard operating environment; high stress levels and continuous demand for this system.

- The system which shows the next highest delay rate was the ATA 32 (landing gear) for the short-haul aircraft. This is probably due to the high number of landings over period of time performed by short-haul aircraft.

- Flight control and hydraulic systems for Short-haul aircraft shared the third highest delay rate percentage. This would be due to the characteristics of short-haul flights, which impose more work load on the flight controls per flying hour. The same can be said about the hydraulic system, which provide the power needed by the flight controls.

- For long-haul aircraft the second highest delay rate was shared by more than one system. They were the same systems as for short-haul (landing gear & hydraulic systems) plus fuel system, which is to be expected for long-haul airplanes, because of the size and complexity of the fuel system.

ATA	**System**
21	Air conditioning
22	Auto pilot
23	Communications
24	Electric power
25	Equipments
26	Fire protection
27	Flight control
28	Fuel
29	Hydraulic power
30	Ice protection
31	Instrument
32	Landing gear
33	Light
34	Navigation
35	Oxygen
36	Pneumatic
38	Water waste
49	APU
51	Structure
52	Doors
71-80	Power plant

Table 3-8: ATA Chapter Number

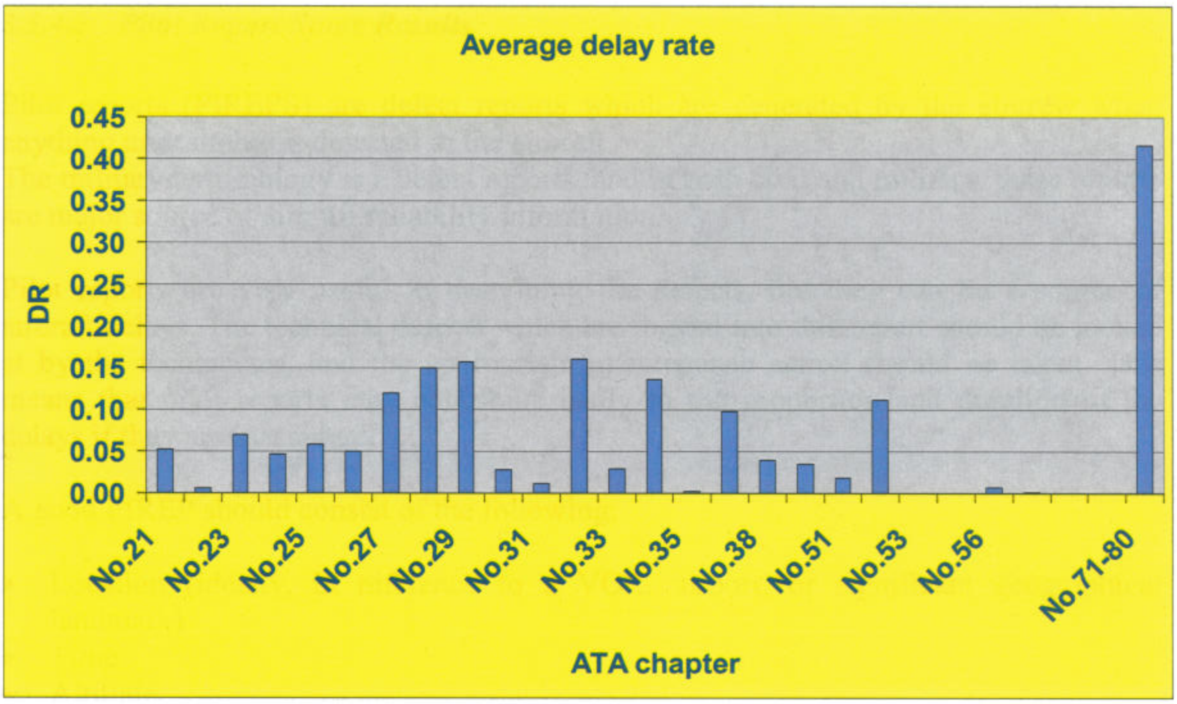


Figure 3-8: Average delay rates for long-haul aircraft

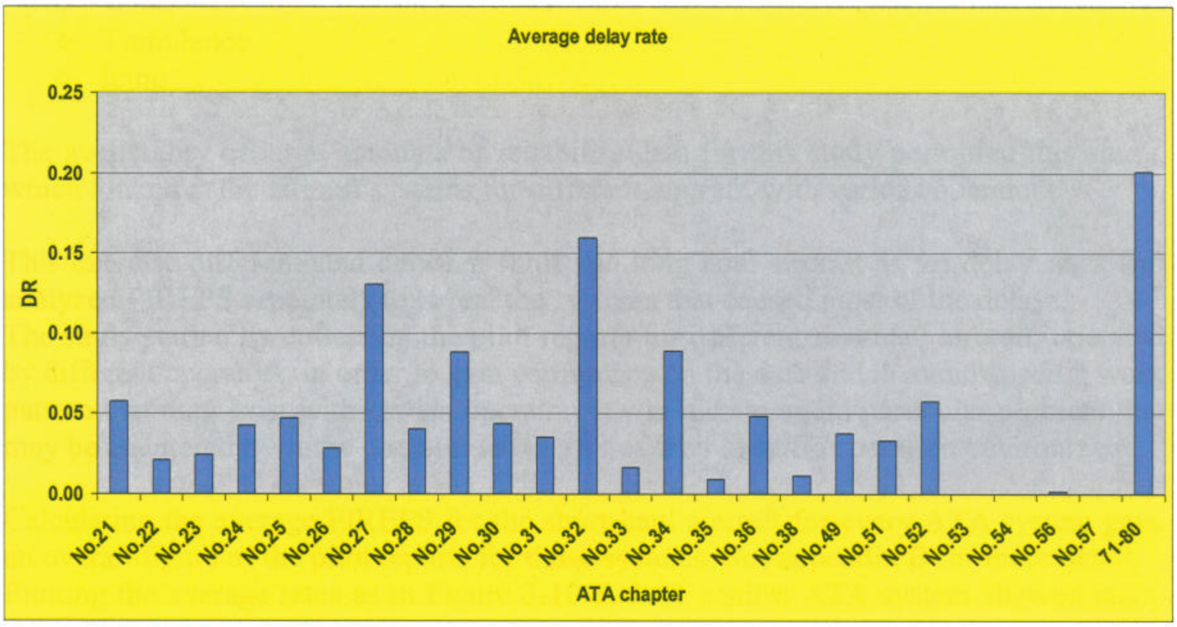


Figure 3-9: Average delay rates for short-haul aircraft

3.3.4.2 Pilot Report Study Results

Pilot reports (PIREPS) are defect reports which are generated by the aircrew when anything undesirable is detected in the aircraft.
The military terminology is a defect reports, and in both civil and military, these reports are major source of aircraft reliability information.

Pilot reports are very useful in describing the defects, but they can be a source of aircraft delays. The technical defects which are logged into this report should be looked at by the technicians, and the appropriate maintenance action should be taken. This means that pilot reports may contribute badly to the proportion and duration of the delays if they are inaccurate.

A good PIREP should consist of the following:

- Location (ideally, in reference to a VOR, airport, or significant geographical landmark)
- Time
- Altitude
- Aircraft Type
- Remarks or other significant weather data.
- Condition being reported, which should include all or most of the following items.
    - Sky Cover, including base and top reports
    - Flight Visibility and Weather
    - Temperature (especially when reporting icing)
    - Wind
    - Turbulence
    - Icing

The availability of large amounts of reliability data for this study permitted this study, which looked at the aircraft systems for different aircraft, with various operators.

This exercise differentiated between short and long haul aircraft as for delay rates and analyzed PIREPS separately to reveal the systems that caused most of the delays.
The study started by collecting the pilot reports for different sort-haul aircraft, operated by different operators, in order to gain confidence on the data and to avoid specific work pattern that may exist with certain operator. It was also to avoid particular problem that may be countered by some operator as a result of their specific operation environment.

Calculating the average PIREPS for the short-haul aircraft for every ATA system gave an overall figure of the pilot reports for those systems. See appendix B for more detail.
Plotting the average rates as in Figure 3-10 & 3-11 against ATA system showed many interesting points, among them are:

- ATA chapter 25, which is the equipment and furnishing system, was at the top of list of the pilot-reported systems in both short and long haul aircraft. This could be attributed to the fact that this system is the system most subject to direct passenger's usage. Seats, equipments and carpets are all affected by the non-stop contact and use by customers and are vulnerable to the continuous handling.

This study finding coincided with other work completed in 1979 [80]. The current study showed that technology improvement has done very littlie to alleviate this problem being at the top of the PIREP list, although there is very obvious reduction on the number of these pilot reports against this system for new aircraft. This may confirm that the reason for the high percentage of PIREP for this system is due to the fact that it is subject to passenger handling.

- The lights and communication system were the next on the pilot report list. The considerable increase in passenger entertainment facilities has increased the incidence of failures of these systems.
- An interesting observation about the pilot reports is that it has a corresponding relationship with the increase in individual aircraft age. The more the aircraft age, the more pilot reports are generated. As an example, more pilot reports are generated for the equipment system on aircraft that been on service for 10 years than on the same type of aircraft when it has been in service for 3 years.
- A comparison between the delay rates and PIREP was then performed. This was to observe what the relationship between them (if any) was? This is important as they all affect the dispatch reliability.

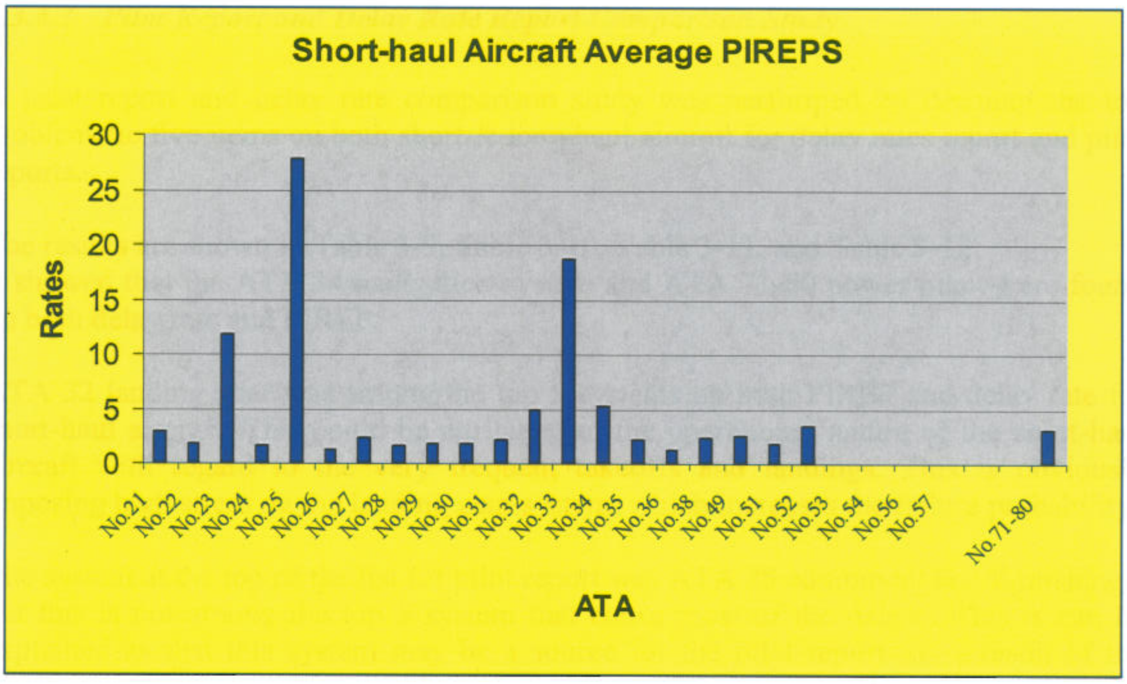


Figure 3-10: Average pilot reports for short-haul aircraft

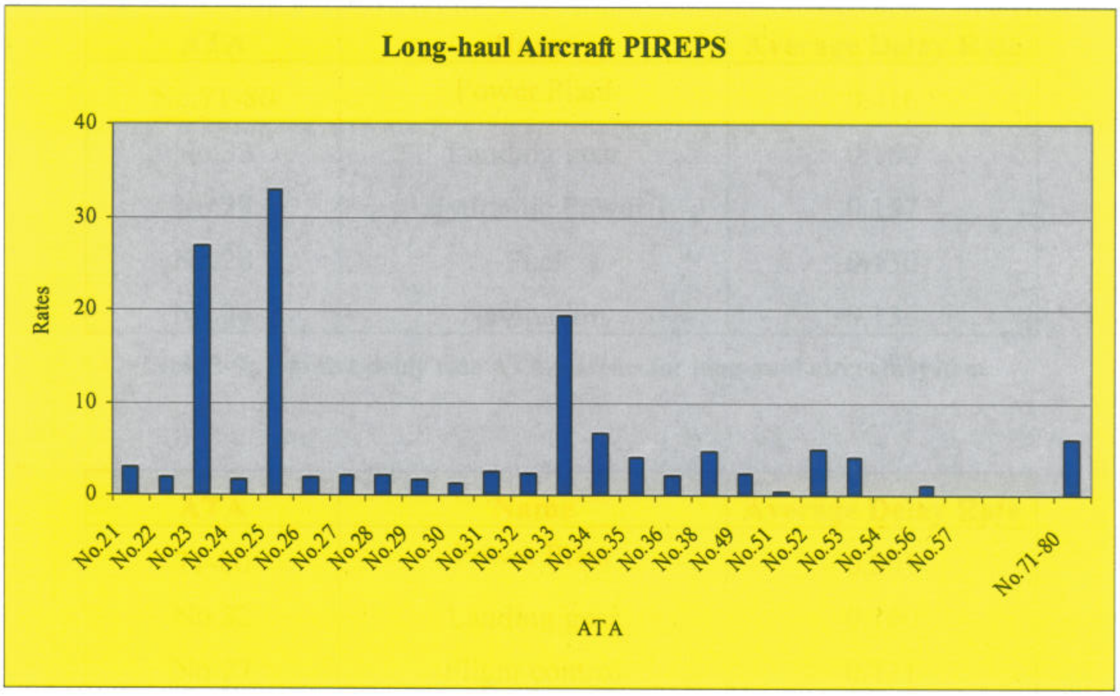


Figure 3-11: Average pilot reports for long-haul aircraft

3.3.4.3 Pilot Report and Delay Rate Report Comparison Study

A pilot report and delay rate comparison study was performed by defining the top problematic five items on both short & long haul aircraft for delay rates report and pilot reports.

The results are shown in Table 3-9, Table 3-10, Table 3-11, and Table 3-12.
It showed that the ATA 34 navigation system and ATA 71-80 power plant were found on both delay rate and PIREP.

ATA 32 landing gear was among the top 5 systems on both PIREP and delay rate for short-haul aircraft. This could be attributed to the operational nature of the short-haul aircraft with regard to the very frequent takeoffs and landings. This is obviously imposing high stress on the landing gear system, which increases the failure probability.

The system at the top of the list for pilot report was ATA 25 equipment and furnishings, but this is not among the top 5 system that cause most of the delays. This is can be explained as that this system may be a source for the pilot reports as a result of the direct customer handling, but this system snags are easy to rectify, and this consume little time, and does not significantly effect the aircraft dispatch. Also it might be because some of equipment and furnishing write-up are on the minimum equipment list (MEL) which means that aircraft can depart without rectifying them and corrective action may be postponed to later convenient period. This means they do not contribute to the aircraft delay.

ATA	Name	Average Delay Rate
No.71-80	Power Plant	0.416
No.32	Landing gear	0.160
No.29	Hydraulic Power	0.157
No.28	Fuel	0.150
No.34	Navigation	0.136

Table 3-9: Top five delay rate ATA systems for long-haul aircraft system

ATA	Name	Average Delay Rate
71-80	Power Plant	0.201
No.32	Landing gear	0.160
No.27	Flight control	0.131
No.34	Navigation	0.089
No.29	Hydraulic Power	0.088

Table 3-10: Top five delay rate ATA systems for short-haul aircraft system

ATA	Name	Average Pilot Reports
No.25	Equipments/furnishings	32.81
No.23	communications	26.83
No.33	Light	19.36
No.34	Navigation	6.77
No.71-80	Power plant	5.96

Table 3-11: Top 5 pilot reports for long-haul aircraft system

ATA	Name	Average Pilot Reports
No.25	Equipments/furnishings	27.79
No.33	Light	18.81
No.23	communications	11.80
No.34	Navigation	5.21
No.32	Landing gear	4.97

Table 3-12: Top 5 pilot reports for short-haul aircraft system

3.3.4.4 Pilot Report and Delay Rate Studies Discussions

These two studies show a consistency in the sense that most of the top five problematic systems were exist on both studies results. The outcomes of these results can help aircraft systems designers by drawing their attention to place more efforts in design toward these problematic systems. It also can be useful finding for aircraft operators to concentrate on these systems to help reducing delays.

Finally, as a result of these studies, future scientific work can be directed towards these systems to help minimizing their downside effect on aircraft dispatch reliability performance.

"One of the most critical problem areas is that of poor quality reliability information for reliability control in operations, and for design purposes"
Professor J. P. Fielding, Cranfield University, College of Aeronautics

Chapter 4

Reliability and Aircraft Dispatch Reliability Prediction

4.1 Introduction

Accurate predictions are very useful in different aspects of our everyday activity. Predicting our future income would help us to make the correct decisions, whether buying a house, making an investment, or simply going in a holiday. Forecasting in the business world is therefore all the more important since the businesses involve more people and can affect wider sectors of society.

The aircraft business is currently one of the leading businesses in the world, and people everywhere are becoming more dependent on it day by day. More people are using air transport and the trend is increasing, with more than one billion passengers per year today [56].

Therefore, being able to predict the potential number of passengers would help an airline to select the most appropriate planes for its fleet in future.

In the aircraft industry, improvements in product design have been accomplished via reliability prediction for several decades. This allows economic provisioning for repair costs, the required technical support, spare parts inventories, system availability, operational effectiveness and other issues.

Reliability prediction has traditionally focused on the detailed design phase. This is to make use of the prototype testing capability and the field data available at that stage to forecast the reliability performance.

However, it would be much more cost effective to undertake the reliability prediction at a very early stage in the design, because the outcome of the prediction can be used early on the design phase to make corrections and to tailor design features towards the required targets. Furthermore, undertaking reliability predictions early in the design process can identify potential failures and weaknesses in the design; hence, the rectification would be easier and cheaper. Therefore, the earlier the deficiencies are identified and corrected, the more capable and inexpensive the end product will be.

The estimation of product reliability is a process which requires judgement about its future, but this kind of prediction depends on modelling past experience and data.
The purposes of reliability prediction are many and they can be summarised as the following [72,90,63]:

- Feasibility Evaluation

This involves evaluating the compatibility of a proposed design concept with the design reliability requirements.

- Comparison of Competing Designs

This is undertaken to use the predicted reliability in making broader system level design trade-off decisions, involving factors such as cost, weight, performance, etc.

- Identification of Potential Reliability Problems

A high-quality prediction will provide a systematic method of checking all components for potential reliability problems.

- Provision of Reliability Inputs to Other R/M Tasks

Reliability prediction outputs are essential data for reliability and maintainability targets.

4.2 Reliability Prediction Techniques

There are in the literature many methods to predict failure rate and component reliability, and they can be divided into two main types, empirically-Based and Science-Based reliability prediction models.

4.2.1 Empirically-Based Reliability Prediction Models

The most frequently used model is the US MIL-HDBK-217 Reliability Prediction of Electronic Equipment, which has been produced by the US Department of Defence [109].

It is used mainly to predict the reliability for electronic equipment and depends on generic failure rates [72]. However, many other models like British Telecom, Siemens, Nippon, and Eriksson are empirical models, similar to MIL-HDBK-217.

All of these procedures support their empirical models by failure data from the field, by component reliability life test results provided by manufacturers, and by the data that they copy from each other [102].

These models have similar parameters, but the failure rates they produce for the same components are different [19,100].
The main reason for these variation are differences in failure rate data sources for each procedure, and the facilities available for updating the models with the evolution of technology [102].

Most of these empirically-based models are used to predict the reliability for electrical products such as OREDA [98].

A number of trials have been undertaken to produce reliability prediction models for mechanical components, such as that by Vannoy[111], who produced an improved mechanical reliability prediction model which is a combination of MIL-HDBK 217 type and Weibull distribution techniques, and account for the fact the failure rates vary with time.

Nelson[76] developed a reliability prediction model for mechanical equipment that consists of several steps, namely:

- Categorising mechanical components into functional classes (parts).
- Establishing primary and secondary failure mechanism by performing failure mode, effect analysis (FMEA).
- Derivation of the base failure rate for the parts.
- Formulation of the component failure rate by summing the constituent failure rates.

This method provides a good procedure, but it consumes considerable amounts of time and requires a very thorough understanding of the system under consideration.

The Reliability Analysis Centre (RAC), which is a Department of Defence information analysis centre in the USA sponsored by the Defence Technical Information Centre, produced a document which contains field failure rate data for a variety of mechanical, electrical, electromechanical, and mechanical parts/assemblies. The last version of which is dated 1995 [90].

This document contains failure rates data which represents a cumulative compilation of data collected from the early 1970s through to May 1994.
The RAC made a concerted effort to make sure that the data collected was screened and verified in order to publish only the most accurate data. This source provides designers and reliability engineers with failure rate data that is very valuable and which is essential to reliability engineering work.

Many sources for the failure rate data in this document were from the aircraft industry, and as such, this document is a good source of aircraft component failure rate data, with the assumption that most aircraft systems, sub-systems and components exhibit a constant failure rate. Another reason for its applicability for aircraft work is that aircraft systems are highly complex, and this is where empirical models can be very effective. The failure rate data in this document could be used for aircraft design reliability analysis, provided that sound engineering judgment and a thorough knowledge of the failure physics of the item under analysis are applied. There are needs to an effective consideration of the system or sub-system modelling that could simulate the system under analysis.

The main advantage of the empirical models in general, is that they are simple to use, but their main drawback is the lack of accuracy.

A comparison of commercial reliability prediction programs was undertaken, and it was concluded that as systems continue to become more and more complex, reliability prediction methods can supply a good foundation for incorporating reliability studies into the design process [18].

4.2.2 Science- Based Reliability Prediction Models

An alternative to the empirically-based reliability prediction models is a new deterministic reliability prediction method that has been introduced, which analyses each individual failure mechanism separately, in order to estimate component life.

It emphasises the engineering aspects involved with failure mode and mechanisms [84]. With this method, all potential failure mechanisms need to be analysed, which requires the component manufacturers to submit large amounts of data, and to perform expensive activities which may limit its usability.

This type of prediction technique is explained thoroughly by Pecht [84]but it is not suitable for an early dispatch reliability prediction work.

4.3 Examples of Reliability Prediction Models

Many reliability prediction models are discussed in the literature, only some of which methods are suitable for aircraft applications. These are discussed below.

a) Ormon [81]produced a simulation model for predicting system reliability without knowing the exact failure rate for the components in the system. The model can be used as a design tool to predict system reliability performance early in the design process. The simulation model estimates mission reliability, average time to failure for the system, and average mission cost.
   This type of reliability prediction lacks accuracy, because it uses assumed components failure rates.

b) Vogas [112]suggests that sneak analysis, as a complement to simulation and testing, can uncover problems that may not be otherwise detected. Sneak analysis can reduce scheduled risks and costs by detecting errors before fabrication and can detect potential operational problems, including those which might appear as intermittent failures. Vogas defines sneak conditions as the modes of operations which were not anticipated during design, whereas component failures do not exist until some particular point in time. The sneak analysis is an unexpected path or logic flow within a system which, under certain conditions, can initiate an undesired function or inhibit a desired function. The principle governing sneak analysis is that the design is systemically reduced to its simplest elements, which are then presented in such a way that past experience can be used to direct analysis of each element's functionality. This is an effective method to find the unexpected system behaviour but it does not pay enough attention to the normal system failure pattern.

c) Sharma [95] formulates a methodology to determine the probability of system failure when it contains components that can fail latently, so that the failures are detectable either with the occurrence of a subsequent failure or during the performance of the next scheduled inspection. Again this is a methodology that might be good when product in service but not for an early design stage.

d) Yang [118]developed a simulation model to calculate dispatch reliability (DR) and scheduled reliability (SR) among other output. The developed model used Monte-Carlo simulation technique to study the relevant effects of reliability and maintainability (R&M), fleet size, repair method, spare parts, supply, scheduled flight, and weather conditions on the dispatch reliability and scheduled reliability. Although this method is good at predicting dispatch reliability, it is more suitable for in-service applications. This is because it needs a lot of information that will be available on advance design phase.

e) Aggarwal [1]defines the criticality of a component as the probability of system failure if that particular component fails. He states that a value of 1 (or 100%) for the criticality implies certainty of the system failure consequent upon the failure of the component. He concludes that there is no need to worry about the allocation of reliability value for the components which do not have high criticality values. This is may be correct for simple systems, but for a complex system such as aircraft systems, this is too risky a step to take. This is because aircraft systems are comprised of large numbers of components that interconnect, and some components might not appear critical in themselves, but when looked at with regard to their relation to other components, they could play a highly critical part.

f) Serghides[94]developed a reliability and maintainability(R&M) predication methodology for combat aircraft conceptual design process. This consists of 13 Equations, each of which consists of two parts; the basic Equation and the technology improvement factor. The system delay rate is expressed as a function of one or two selected aircraft design parameters, and the total number of used parameters is 11. It provides two R&M prediction methodologies for combat aircraft and jet airliners. This prediction formula gives a high predictability for the combat aircraft, although a less accurate result is obtained for the jet airliners. However, this prediction formula is now outdated and needs to be updated.

4.4 Aircraft Dispatch Reliability Prediction for Conceptual Design Phase

4.4.1 Introduction

The importance of aircraft dispatch reliability continues to increase, and there is a pressing need for a prediction method that can be used in the very early stages of design. However, there are few dispatch reliability prediction methods available which can be used during the conceptual design phase, and those that are available are outdated. The available methods are:

- Comparison Procedure.
- Transport Aircraft Dispatch Reliability Formula [45, 36]
- Development of Conceptual Navy Aircraft Reliability Prediction Models [44].

Below is brief description of these methods.

4.4.2 Comparison Procedure

This method was used in different versions by aircraft manufacturers to predict reliability and maintainability, and hence the direct maintenance cost, at the conceptual design stage of a new aircraft programme. The main concept of this procedure is that it relies on an existing aircraft as a baseline from which to derive the dispatch reliability for the new aircraft. The two aircraft must share a high commonality and usually they are from the same manufacturer and of the same aircraft family.

Knowing the whole aircraft dispatch reliability target, the individual systems can be assigned quantitative reliability targets, on the basis of old aircraft experience.
The application of this method requires many assumptions to be made about the design of the aircraft systems, and entails the use of subjective judgement.

Examples of this approach are the design of the B727 airplane by the Boeing Company, McDonnell Douglas design for the MD-80 aircraft design, and Airbus for the A310. Allocation of the dispatch reliability targets for the MD-80 was based on the DC-9 aircraft as a baseline; a top-down allocation method was used to establish the individual system goals.

In the Boeing Company case, the dispatch reliability design target was set by a simple arithmetic comparison of the flight time for the old aircraft and the new one, and the dispatch reliability target for the new aircraft was set to achieve the same target as the old aircraft [86].

Airbus Industries applied the comparison procedure to the design of A310-200 aircraft where the baseline aircraft was A300B4 [3].

High similarity is always assumed between the two aircrafts and their systems, which is not always the case, unless the new aircraft is a derivative of the baseline aircraft. This makes it unsuitable for general use.

4.4.3 Transport Aircraft Dispatch Reliability Formula

This formula [45]was based on historical aircraft delay rate data, which had been collected and analysed, and a dispatch reliability prediction formula was developed. The formula can give a reasonably accurate prediction of total aircraft delay rate and hence the dispatch reliability, using only a few simple parameters. The delay rate is predicted using two formulae, one for short-haul and the other for long-haul aircraft.

The improvement in technology is catered for by multiplying the resulting delay rate by a correction factor.

The formula has a high accuracy for whole aircraft prediction, and the parameters used are available during the conceptual design phase.

This method is very effective and could be applied at very early design stages when little is known about the proposed aircraft. However, this method was developed a long time ago and needs to be updated with more recent data.

4.4.4 Conceptual Navy Aircraft Reliability Prediction Models

This reliability prediction model [44] was developed by the Vought Corporation for the US Navy in 1980.

The two models are for the navy fixed wing and rotary wing aircraft. Each model consists of a set of Equations which relate the reliability of each major aircraft subsystem, expressed as the Mean Flight Hours Between Failures (MFHBF), to aircraft design/performance parameters. The Equations of each model were statistically derived from historical data for 32 fixed wing and 11 rotary wing Navy/ Marine Corps aircraft.

The aircraft design/performance parameters included about 101 parameters for each of the 32 fixed wing aircraft and 89 parameters for each of the 11 rotary wing aircraft.

The model includes jet and turboprop aircraft from different naval roles, as data from fighters, tankers, and transport aircraft, all incorporated together and used to develop the model. This means that the aircraft in the sample were different in both size and role.

Major design differences between the aircraft exist, which would in turn have a significant effect on their delay rate, and this introduces inaccuracy in the reliability prediction model.

This prediction model is suitable for use with Navy aircraft only, but since it was developed long time ago, future work would be needed to develop an updated model for general aircraft.

"A good scientist is a person with original ideas.
A good engineer is a person who makes a design
that works with as few original ideas as possible"
Freeman Dyson

Chapter 5

Development of (DRPM) Method

5.1 Introduction

This chapter contains a detailed description of the development of a commercial airplane dispatch reliability prediction method (DRPM). Additional calculations information is presented in appendix A.

To design an airplane with the right dispatch reliability, reasonable dispatch reliability targets have to be set, and a design methodology to reach these targets should be followed.

There are many reasons for developing the aircraft dispatch reliability prediction method, the most important is the need for an objective means to:

- Establish realistic baseline reliability requirements for the proposed aircraft.
- Evaluate aircraft (systems) reliability characteristics during the conceptual phase, which allow for design optimization.
- Evaluate other reliability predictions methods.
- Provide dispatch reliability data for cost, reliability and maintainability analysis.

The developed method provides a mathematical expression to predict the delay rate for every aircraft system in accordance to the ATA chapter, which will in turn predict the dispatch reliability for the whole aircraft during the conceptual design phase.

The developed method was to be able to:

- Perform the reliability assessment of a wide spectrum of aircraft design concepts.
- Be responsive to variations in aircraft design features.
- Be capable of providing representative reliability values based on historical data.

5.2 The Developed Prediction Method

Aircraft dispatch reliability is calculated by subtracting total aircraft systems delay rates from one hundred percent. This means that the dispatch reliability prediction will be based on the prediction of an aircraft system's delay rates.

The delay rate prediction model was based on the investigation of the relationships between aircraft delay rates (i.e. reliability design parameter), and aircraft design or performance parameters. Parameters calculated for new aircraft are also used when appropriate. All of the prediction equations use parameters that are available during the conceptual design stage.

The development of the prediction model involved two major tasks:

1. Database development.
2. Derivation of the prediction Equations.

Figure 5-1 provides a flowchart of the model development process.

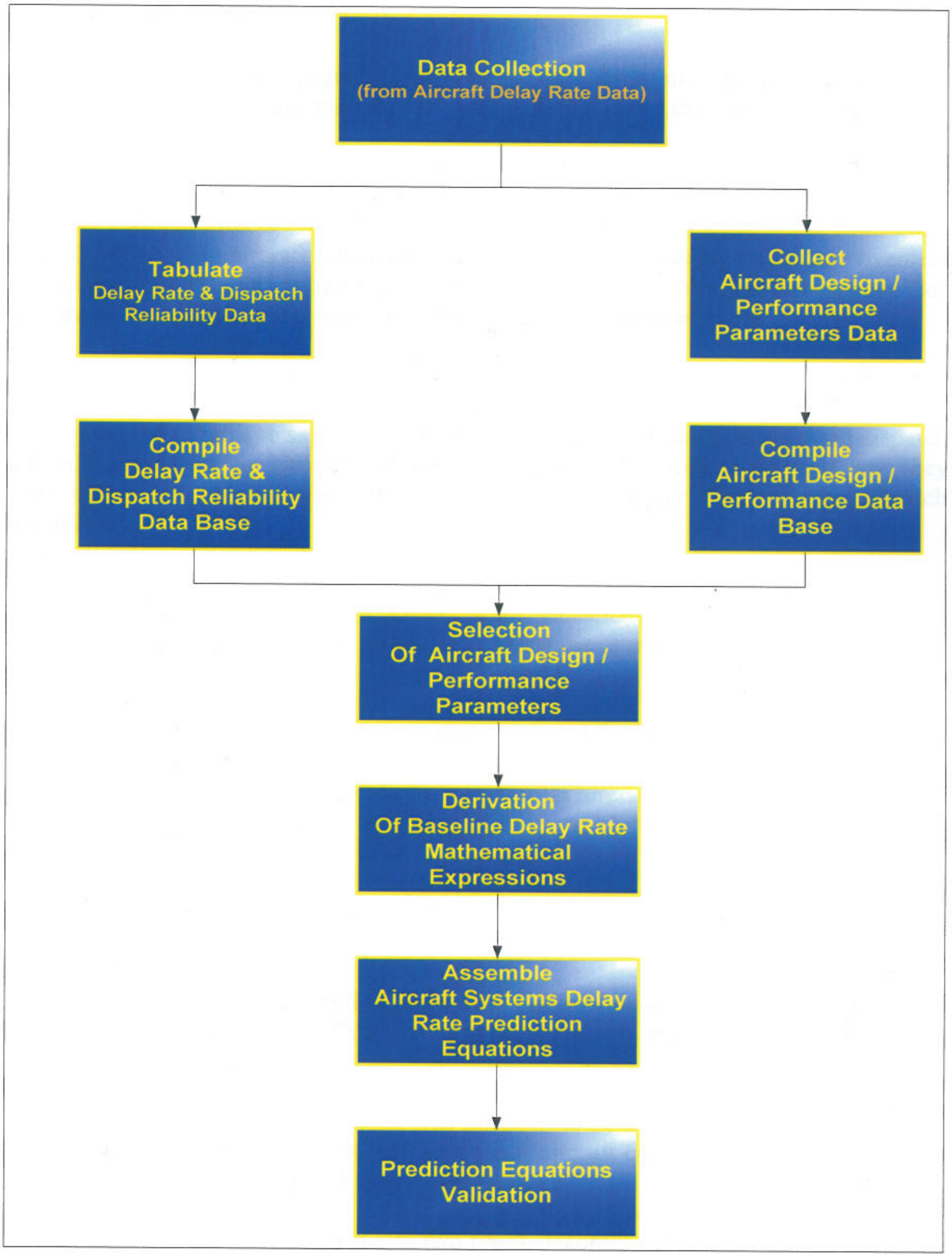


Figure 5-1: Dispatch reliability prediction model flowchart

5.2.1 Data Collection

The development of a passengers aircraft dispatch reliability method requires the use of accurate and up-to-date information; therefore it should come from reliable sources.

Development of such a prediction method requires large amounts of information for different aircraft types over a long period of time in order to give a reasonable result and to avoid seasonal effects. The delay rate data collected for this work came from more than 25 airlines and aircraft manufacturers, some are UK based and other are overseas based operators. It is for aircraft that had been in service for more than three years. This is to avoid the aircraft infant mortality which can take up to three years.

The data collection was a very difficult and time-consuming task and needed large efforts. All the aircraft used in the derivation of this method were in service for more than three years, that is to say, they had reached maturity. Some of the obtained dispatch reliability data were for aircraft that been in service for less than three years, and they were eliminated because they show inconstancy and lower than average dispatch reliability.

Aircraft operator's record delay rate data differently, and thus some of the obtained delay rate data was ready to use. Others were subjected to data processing, such as calculating average annual delay rate or calculating the average monthly delay rate from graph.

Data concerning the aircraft delay rates that were used for the production of the method in this research were the average for one year's operation; this was to overcome seasonal effects. The delay rate data for a particular aircraft type were calculated from different operators' data, where possible, in order to eliminate the effect of different styles of operation.

The collected delay rates were per ATA system which attribute delay rate to a specific system independently of other aircraft systems.

The aircraft selected for this method were from different manufacturers and intended for different types of operations. This was to make it generic and not subject to particular sizes, roles or technology.

The number of aircraft in the method was intended to be as large as possible because it offers mature aircraft delay rates, 160 short-haul aircraft consisting of 8 types and 120 long-haul aircraft consisting of 8 types were studied

The selected aircraft were divided into two types, according to flight times. Three hours or less was considered short-haul, while the rest were long-haul. Some of these aircraft can be used for long and short-haul flights depend on the airliner type of operation. However, most of the selected aircraft followed the adopted criterion.

The delay rate database was established using an Excel spreadsheet, and the subsequent processing was performed using Microsoft Excel.

5.2.2 Aircraft Design /Performance Parameters Database

The developed prediction method was intended to be used during the conceptual design phase; therefore the design / performance parameters that were to be used should be available during that phase. To reflect this principle, the design /performance data base includes five basic parameters for each aircraft in the model, which are normally available at the conceptual design phase.

These five parameters were collected from different sources such as:

- Aircraft and engine company data.
- Aircraft manufacturer's internet site.
- Jane's All the world's aircraft [59].
- Flight International magazine.
- Aircraft design books.

The design /performance parameters are presented in Table 5-1.

No.	Design parameter	Notation	Units
1	Maximum Aircraft Takeoff Weight	MTW	Kg
2	Total Number of Passengers	NP	-
3	Maximum Aircraft Thrust	Thr	kN
4	Flight Length	FL	hr
5	Cruise Speed	CS	Kts

Table 5-1: Design /performance parameters

Derivative Parameters

For the purpose of obtaining the most suitable relationship, derivative parameters were calculated; these are shown in Table 5.2.

No.	New Calculated Parameters	Notation	Units
1	Maximum Aircraft Weight/Flight Length	MTW/FL	Kg/hr
2	Total Number of Passengers/Flight Length	NP/FL	hr^{-1}

Table 5-2: Derivative parameters

The design/performance parameters and delay rate data were put into the main database in an Excel spread sheet, and as an example, the ATA 22 (auto pilot system) is shown in Table 5-3.

ATA 22	auto pilot	No. of passengers /flight time	Max.takeoff weight(kg)/flight time	No. of passengers	Average Flight length (hr)	Max. takeoff weight (kg)	Cruise Speed (kts)	Max. A/C Thrust (kN)	Delay Rate %
	aircraft 1	81.44	37876.29	79	0.97	36740	462	123.2	0.017
	aircraft 2	150.00	61250.00	180	1.20	73500	448	235.8	0.030
	aircraft 3	55.68	23409.09	49	0.88	20600	450	62.6	0.030
	aircraft 4	62.31	21719.23	162	2.60	56470	530	215.2	0.013
	aircraft 5	69.23	36553.85	189	2.73	99792	459	332.8	0.017
	aircraft 6	65.56	28977.78	177	2.70	78240	530	220	0.020
	aircraft 7	61.11	21111.11	165	2.70	57000	530	220	0.000
	aircraft 8	81.00	41200.00	243	3.00	123600	458	387	0.010

Table 5-3: Auto pilot system (ATA22) database

5.2.3 Analysis Process

The mathematical relationships between the seven design/performance parameters and the delay rate for each aircraft ATA system was investigated to find out which parameter had the strongest relationship. This process is called correlation analysis, and was carried out on a spreadsheet designed specifically for this work, to calculate the correlation coefficient(r) between each of the seven parameters and the delay rate values.

Correlation coefficients measure the degree to which two things (variables) vary together[92].

If the parameter variable under study varies positively and perfectly with the delay rate variable, then the correlation coefficient will be (1.00).

On the other hand, if the two things vary negatively and perfectly, then the correlation coefficient will be (-1.00).

When the two data vary separately, which means there is no correlation between them, the correlation coefficient will be zero.

Equation A.1 was used to calculate the correlation coefficient and it is shown in Appendix A, page 240.

The confidence of the correlation coefficient can be obtained by measuring the probability of the correlation coefficient (PCC) between two uncorrelated variables. This concept is well explained in many statistics books.

It is also called the quantitative significance of the correlation coefficient, and is measured by using the probabilities for correlation coefficient shown in Taylor Table C [103].

The same reference suggests that correlation can be regarded as 'significant' if the probability of obtaining a correlation coefficient from uncorrelated variables is less than 5%. A correlation is 'highly significant' if the probability is less than 1 %.

A system delay rate prediction Equation can be obtained when the correlation coefficient is sufficiently high and the probability for correlation coefficient is significant or highly significant.

Trendline are used to graphically display trends in data and to analyze problems of prediction. As an example, a trendline is shown in Figure 5-2 for ATA 23. Such analysis is also called regression analysis. By using regression analysis, the trendline can be extended in a chart beyond the actual data to predict future values.

The degree of the trendline accuracy is measured by a parameter called R-squared value (R^2), which is an indicator from 0 to 1 that shows how closely the estimated values for the

trendline correspond to the actual data. A trendline is most reliable when its R-squared value is at or near 1.
The least squares fit for a line represented by Equation 5-1.

$$Y=mX+b \qquad \textbf{Equation 5-1}$$

Where m is the slope, b is the intercept, y is the delay rate, and x is the specific parameter's value.

Correlation coefficients for all the parameters, with the delay rates were calculated and the parameter which had the highest correlation coefficient was selected. More information about how to calculate the correlation coefficient and the formula used for this are presented in Appendix A page 240.

In cases when the correlation coefficient was low, i.e. the correlation between the delay rate and the selected parameters was weak, the natural log or exponential of the delay rate was used and the correlation coefficient was then calculated.

The correlation analysis was performed for each aircraft system and the resulting correlation coefficients are shown under every parameter. As an example, the correlation coefficient calculations for the ATA 23 (communications system) are shown in Table 5-4.

The different values of the parameter that had the highest correlation coefficient are plotted against the corresponding delay rate values, and a trendline is drawn, and the linear equation which represents this relationship was obtained.

For each ATA chapter, a linear Equation was derived which represent the delay rate as a function of a parameter.

A total of 500 correlations between delay rate data and aircraft performance/design parameters were performed, and more than 350 graphs were plotted.

ATA 23		No. of passengers / flight time	Max.takeoff weight(kg) / flight time	No. of passengers	Average Flight length (hr)	Max.takeoff weight(kg)	cruise speed (kts)	Max. A/C Thrust (kN)		
	N	8	8	8	8	8	8	8	0.174	Σ y
	Σ x	625.22	272097.35	1241.00	16.78	545942.00	3867.00	1796.60	0.00432	Σ y^2
	Σ x^2	55367.15	10524900550.96	219629.00	40.95	44971199364.00	1879793.00	478334.52		
	Σ x^2- ((Σ x)^2) /N)	6504.784	1270279881	27118.875	5.752	7714615944	10581.875	74863.075		
	Σxy	13.371	5839.89	23.73	0.319	10481.94	82.64	34.35		
	Σ xy- Σ x Σ y/N	-0.208	-69.88	-3.226	-0.045	-1375.54	-1.347	-4.67		
	Σ y^2- ((Σ y)^2) /N)	0.00054	0.00054	0.000541	0.00054	0.00054	0.00054	0.00054		
	Correlation Cofficient (r)	-0.111	-0.084	-0.842	-0.811	-0.673	-0.563	-0.733		

Table 5-4: Correlation coefficient calculations for communication system ATA 23

5.2.4 Result

The developed delay rate prediction equations are shown in Table 5.5 and 5.6, for short-haul and long-haul aircraft respectively.

The correlation coefficients (r) and the R-squared value (R^2) for most of the systems were high, except in ATA 28 (Fuel system), where it was low.

The delay rate equation for every system was derived, and the prediction equations for all the ATA systems were produced for short-haul and long-haul aircraft.
The parameters used in the equations are shown in Table 5-7.

Dispatch reliability for the whole aircraft can be calculated as shown in Equation 5-2, by substituting the total delay rates of 100.

$$\text{Dispatch reliability} = 100 - \text{delay rate} \qquad \textbf{Equation 5-2}$$

Where the delay rate is the total aircraft delay rate, which can be calculated by summation of the predicted delay rate for all the aircraft systems.

Another approach was taken to calculate the dispatch reliability for the whole aircraft by using one equation only.

This was performed by collecting much aircraft dispatch reliability data and analysing the relationships between dispatch reliability and the seven aircraft design /performance parameters. Correlation coefficients for all the seven parameters, with the total dispatch reliability were calculated and the parameter which had the highest correlation coefficient was selected.

A graph that represents the relationships between the selected parameter and the total dispatch reliability was plotted, a trendline is drawn, and the linear equation which represents this relationship was obtained

The result is Equation 5-3 for short-haul aircraft and Equation 5-4 for long-haul aircraft. These two equations can be used to predict whole aircraft dispatch reliability without using the delay rate for individual aircraft systems.

These two equations provide simplified predictions of dispatch reliability, but did not take into account detailed engineering links to the variables used. However, it provides a first-order prediction that is appropriate at the very beginning of the aircraft design process.

$$\text{Dispatch reliability} = 1.8893 \,\text{Ln}\,(\text{Thr}) + 87.954 \qquad \text{Short-haul} \qquad \textbf{Equation 5-3}$$

$$\text{Dispatch reliability} = -0.0066\,(\text{NP}) + 100.18 \qquad \text{Long-haul} \qquad \textbf{Equation 5-4}$$

ATA	System	Delay rate prediction Equation	r	R^2	PCC %
21	Air conditioning	DR= 0.0006(CS) - 0.2132	0.72	0.52	95.42
22	Auto pilot	DR = -0.0063(FL) + 0.0318	0.70	0.50	94.70
23	Communications	DR= -0.00018(NP) + 0.0449	0.84	0.88	98.90
24	Electric power	DR = -7E-07(MTW/FL)+ 0.0707	0.86	0.73	99.20
25	Equipments	DR= 0.0005(CS) - 0.1904	0.87	0.75	99.35
26	Fire protection	DR= -0.0001(Thr) + 0.0528	0.79	0.63	97.94
27	Flight control	DR= -0.0007(NP/FL) + 0.1879	0.76	0.57	96.86
28	Fuel	LnDR= -0.0166(NP/FL) - 2.1379	0.70	0.49	94.70
29	Hydraulic power	DR = -5E-07(MTW) + 0.1428	0.50	0.23	79.00
30	Ice protection	DR = 0.0007(CS)- 0.2627	0.78	0.60	97.58
31	Instrument	DR= -1E-06(MTW/FL) + 0.0696	0.62	0.38	89.34
32	Landing gear	DR = -0.0008(NP) + 0.2704	0.89	0.80	99.65
33	Light	DR = 0.0074(FL) + 0.0039	0.80	0.65	98.30
34	Navigation	DR= -0.0003(Thr) + 0.1419	0.74	0.55	96.14
35	Oxygen	DR = -0.000094(NP) + 0.0234	0.64	0.40	90.68
36	Pneumatic	DR= -0.0006(CS) + 0.323	0.87	0.76	99.35
38	Water waste	DR = 3E-07(MTW) - 0.0088	0.80	0.64	98.30
49	APU	DR = -0.014(FL) + 0.061	0.71	0.50	95.06
51	Structure	DR = -6E-07(MTW) + 0.0777	0.71	0.50	95.06
52	Doors	DR = -0.0005(NP) + 0.1239	0.82	0.68	98.60
71-80	Powerplant	DR = 0.0014(CS) - 0.4259	0.67	0.45	92.69

Table 5-5: Short-haul delay rate prediction equations

ATA	System	Delay rate prediction Equation	r	R^2	PCC %
21	Air conditioning	DR= 0.0009(CS) - 0.4041 ✗	0.80	0.63	98.30
22	Auto pilot	DR= 0.0004NP/FT - 0.0127 ✓	0.85	0.72	99.05
23	Communications	DR= 5E-07MTW - 0.065 ✗	0.80	0.64	98.30
24	Electric power	DR= 1E-06MTW/FT + 0.0323 ✓	0.89	0.78	99.65
25	Equipments	DR= 0.0016NP/FT - 0.0475 ✓	0.91	0.82	99.82
26	Fire protection	DR=0.0003NP - 0.0379 ✓	0.57	0.32	85.30
27	Flight control	DR= 0.0029NP/FT - 0.0772 ✓	0.81	0.67	98.45
28	Fuel	DR=0.0005NP - 0.0549 ✓	0.68	0.46	93.36
29	Hydraulic power	DR=0.0004NP - 0.0107	0.45	0.20	73.00
30	Ice protection	DR=2E-06MTW/FT - 0.0306	0.69	0.47	94.03
31	Instrument	DR=2E-07MTW/FT+ 0.0095	0.95	0.007	99.90
32	Landing gear	DR=0.0007NP - 0.0291	0.42	0.23	69.40
33	Light	DR= 1E-06MTW/FT - 0.0144	0.89	0.18	99.65
34	Navigation	DR= 0.0033CS - 1.4863 ✗	0.76	0.58	96.86
35	Oxygen	DR= 9E-05NP/FT - 0.0027	0.77	0.60	97.22
36	Pneumatic	DR= -0.0108FT + 0.1855	0.85	0.72	99.05
38	Water waste	DR= 0.0011CS - 0.5014 ✗	0.57	0.32	85.30
49	APU	DR= 0.0009NP/FT- 0.0028	0.80	0.63	98.30
51	Structure	DR= 0.0015CS - 0.6801	0.87	0.75	99.35
52	Doors	DR= 0.0005NP - 0.0878	0.71	0.50	95.06
71-80	Powerplant	DR= -0.0003Thr + 0.4981	0.79	0.62	97.94

Table 5-6: Long-haul delay rate prediction equations

CS (Kts)	Cruise Speed
MTW (Kg)	Maximum Take Off Weight
MTW/FL (Kg/hr)	Maximum Take Off Weight / Flight Length
NP/FL (hr^{-1})	Number Of Passengers / Flight Length
NP	Number Of Passengers
FL (hr)	Flight Length
Thr (kN)	Aircraft Thrust

Table 5-7: Aircraft parameters

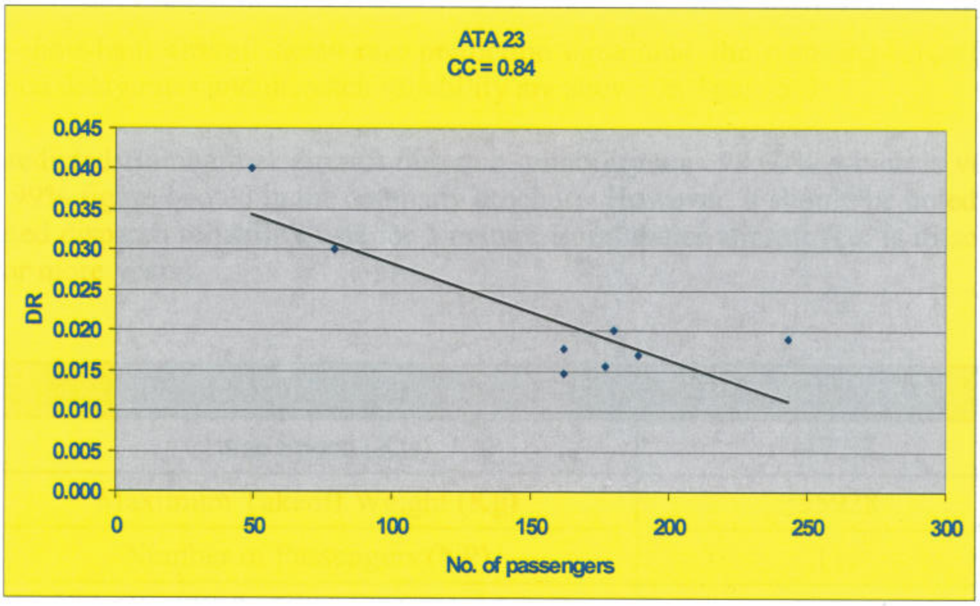


Figure 5-2: Delay rate V No. of passenger for the communication system (ATA23)

The DRPM equations provide simplified predictions of dispatch reliability, but do not take into account detailed engineering links to the variables used. However, they provide a first-order prediction that is appropriate at the very beginning of the aircraft design process.

5.3 Dispatch Reliability Prediction Method Example

The developed prediction method was applied to an aircraft that is under development as an example for illustration purpose.

The aircraft is the Bombardier C series 110 STD, which is short-haul aircraft to be designed and manufactured by Bombardier Aerospace, Canada. The aircraft is expected to enter service in 2010, and the company brochure claims that it can achieve 99% entry into service reliability.

Dispatch reliability prediction method was applied to this aircraft using published data[16].

The basic aircraft data was obtained from the Bombardier Aerospace brochure and is presented in Table 5-8.

This Bombardier aircraft falls into the short-haul category; hence, the short-haul delay rate prediction equations were to be used to predict the individual systems delay rates.

Using short-haul aircraft delay rate prediction equations, the resulting aircraft system predicted delay rates and dispatch reliability are shown in Table 5-9.

The predicted Bombardier aircraft dispatch reliability was 98.60% which is very close to the 99% figure quoted in the company brochure. However, it should be noted that this predicted dispatch reliability was for a mature Bombardier aircraft (i.e. is in-service for three or more years).

Bombardier C series 110 STD Aircraft Basic Data	
Cruise Speed (Kts)	477.3
Maximum Takeoff Weight (Kg)	55928
Number of Passengers (NP)	110
Flight Length (Hr)	3
Aircraft Thrust (kN) (Thr)	284.9
MTW/FL	18643
NP/FL	36.67

Table 5-8: Bombardier aircraft basic data

ATA	System	Predicted Delay Rate
21	Air conditioning	0.073
22	Auto pilot	0.013
23	Communications	0.023
24	Electric power	0.058
25	Equipments	0.048
26	Fire protection	0.024
27	Flight control	0.162
28	Fuel	0.065
29	Hydraulic power	0.115
30	Ice protection	0.071
31	Instrument	0.051
32	Landing gear	0.182
33	Light	0.026
34	Navigation	0.056
35	Oxygen	0.012
36	Pneumatic	0.037
38	Water waste	0.008
49	APU	0.019
51	Structure	0.044
52	Doors	0.069
71-80	Power plant	0.242
Total Delay Rate		**1.40**
Total Dispatch Reliability %		**98.60**

Table 5-9: Bombardier 110 STD aircraft systems delay rate and dispatch reliability results

5.4 Validation

Validation process of the developed dispatch reliability prediction method was performed using in-service aircraft that fulfil the following requirements:

- Aircraft must be in-service for more than three years (have reached maturity).
- Actual dispatch reliability data is available.
- The dispatch reliability data should not have been used in the development of the prediction method.

The validation was performed by comparing the output of the prediction method, which was the delay rates and dispatch reliability values, with the actual corresponding values for the same aircraft, and the accuracy of the prediction was calculated.

The validation process was performed for the two types of prediction models; i.e. those for short-haul and long-haul aircraft.

5.4.1 Short-haul Aircraft Prediction Method Validation

The platforms for this process were two short-haul aircraft that had been in service for more than three years to avoid early age troubles.

The dispatch reliability data were extracted from an operator's fleet reliability report, and the basic data were subjected to the prediction equations.

The first aircraft underwent the validation process was the BAe Avro RJ100 aircraft, which is a regional jet, and its basic data presented in Table 5-10.

The resulting predicted delay rates, with the actual delay rates data is shown in Table 5-11.
The result showed that the error percentage for predicting the aircraft's dispatch reliability was very small at 0.14%, which shows a very high degree of accuracy.

Using the whole aircraft dispatch reliability prediction equation (Equation 5-3), the predicted RJ100 aircraft dispatch reliability was 97.08%, with an error percentage of 1.51%.

The second aircraft was Boeing 757-300, which was twin-engine, short-to-medium-range jetliner. Its basic data are shown in Table 5-12.
The resulting predicted delay rates, with the actual delay rates data are shown in Table 5-13.

The result shows that the prediction accuracy is very high with a very small error percentage for predicting the aircraft dispatch reliability at 0.04%.

Using the whole aircraft dispatch reliability prediction equation (Equation 5-3), the predicted Boeing 757-300 aircraft dispatch reliability was 99.18%, which when compare to the actual dispatch reliability value produce an error percentage of about 0.17%.

Short-haul Aircraft (BAe Avro RJ100) Basic Data	
Cruise Speed (Kts)	430
Maximum Takeoff Weight (Kg)	44426
Number of Passengers (NP)	110
Flight Length (Hr)	1.5
Aircraft Thrust (kN)	125
MTW/FL	29617.33
NP/FL	73.33

Table 5-10: Short-haul aircraft basic data

ATA	System	Predicted Delay Rate	Actual Delay Rate
21	Air conditioning	0.045	0.0350
22	Auto pilot	0.022	0.0080
23	Communications	0.025	0.0050
24	Electric power	0.050	0.0900
25	Equipments	0.025	0.0300
26	Fire protection	0.040	0.0008
27	Flight control	0.137	0.1100
28	Fuel	0.036	0.0305
29	Hydraulic power	0.121	0.0890
30	Ice protection	0.038	0.0280
31	Instrument	0.040	0.0200
32	Landing gear	0.182	0.2000
33	Light	0.015	0.0112
34	Navigation	0.104	0.0740
35	Oxygen	0.013	0.0330
36	Pneumatic	0.065	0.1060
38	Water waste	0.005	0.1600
49	APU	0.040	0.1080
51	Structure	0.051	0.0006
52	Doors	0.069	0.1000
71-80	Power plant	0.176	0.2000
Total Delay Rate		**1.30**	**1.44**
Total Dispatch Reliability %		**98.70**	**98.56**
Error %		**0.14**	

Table 5-11: Predicted & actual delay rates for RJ100 short-haul aircraft

Short-haul Aircraft (B757-300) Basic Data	
Cruise Speed (Kts)	460
Maximum Takeoff Weight (Kg)	123600
Number of Passengers (NP)	243
Flight Length (Hr)	3
Aircraft Thrust (kN)	380
MTW/FL	41200
NP/FL	81

Table 5-12: B757-300 short-haul aircraft basic data

ATA	System	Predicted Delay Rate	Actual Delay Rate
21	Air conditioning	0.063	0.040
22	Auto pilot	0.013	0.010
23	Communications	0.001	0.000
24	Electric power	0.042	0.040
25	Equipments	0.040	0.030
26	Fire protection	0.015	0.000
27	Flight control	0.131	0.090
28	Fuel	0.032	0.030
29	Hydraulic power	0.081	0.090
30	Ice protection	0.059	0.040
31	Instrument	0.028	0.020
32	Landing gear	0.076	0.130
33	Light	0.026	0.010
34	Navigation	0.028	0.060
35	Oxygen	0.001	0.000
36	Pneumatic	0.047	0.090
38	Water waste	0.028	0.020
49	APU	0.019	0.030
51	Structure	0.004	0.000
52	Doors	0.002	0.020
71-80	Powerplant	0.218	0.240
Total Delay Rate		**0.95**	**0.99**
Total Dispatch Reliability %		**99.05**	**99.01**
Error %		**0.04**	

Table 5-13: Predicted & actual delay rates for B757 short-haul aircraft

5.4.2 Long-haul Aircraft Prediction Method Validation

Boeing 747-400 and Boeing 777-268ER long-haul aircraft were underwent the validation exercise.

The basic data for the first aircraft is presented in Table 5-14. The resulting predicted delay rates, with the actual delay rates data is shown in Table 5-15.

The result shows high prediction accuracy with very small error percentage for predicting the aircraft dispatch reliability at 0.29%.

Using the whole long-haul aircraft dispatch reliability prediction equation (Equation 5-4), the predicted Boeing 747-400 aircraft dispatch reliability is 97.43%, which when compared to the actual dispatch reliability value produces an error percentage of about 0.58%

The second aircraft underwent the validation process was Boeing 777-268ER, and its basic data presented in Table 5-16. The resulting predicted delay rates, with the actual delay rates data is shown in Table 5-17.

The result shows that the prediction accuracy is very high with a very small error percentage for predicting the aircraft dispatch reliability at 0.17%.

Using the whole long-haul aircraft dispatch reliability prediction equation (Equation 5-4), the predicted Boeing 777-268 aircraft dispatch reliability is 98.17%, which when compared to the actual dispatch reliability value produces an error percentage of about 0.30%.

Long-haul Aircraft (B747-400) Basic Data	
Cruise Speed (Kts)	567
Maximum Takeoff Weight (Kg)	396,900
Number of Passengers (NP)	416
Flight Length (Hr)	10
Aircraft Thrust (kN)	1060
MTW/FL	39690
NP/FL	41.6

Table 5-14:B747-400 long-haul aircraft basic data

ATA	System	Predicted Delay Rate	Actual Delay Rate
21	Air conditioning	0.0880	0.090
22	Auto pilot	0.0039	0.070
23	Communications	0.1335	0.019
24	Electric power	0.0720	0.076
25	Equipments	0.0191	0.070
26	Fire protection	0.1627	0.089
27	Flight control	0.0434	0.110
28	Fuel	0.1531	0.250
29	Hydraulic power	0.1557	0.064
30	Ice protection	0.0488	0.026
31	Instrument	0.0016	0.020
32	Landing gear	0.2621	0.220
33	Light	0.0541	0.035
34	Navigation	0.3848	0.161
35	Oxygen	0.0010	0.003
36	Pneumatic	0.0775	0.142
38	Water waste	0.1223	0.091
49	APU	0.0346	0.061
51	Structure	0.1704	0.110
52	Doors	0.1202	0.026
71-80	Powerplant	0.1801	0.268
Total Delay Rate		**2.29**	**2.00**
Total Dispatch Reliability %		**97.71**	**98.00**
Error %		**0.29**	

Table 5-15: Predicted & actual delay rates for B747-400 long-haul aircraft

Long-haul Aircraft (B777-268 ER) Basic Data	
Cruise Speed (Kts)	541
Maximum Takeoff Weight (Kg)	299370
Number of Passengers (NP)	287
Flight Length (Hr)	9
Aircraft Thrust (kN)	684
MTW/FL	33263.3
NP/FL	31.9

Table 5-16: B777-268ER long-haul aircraft basic data

ATA	System	Predicted Delay Rate	Actual Delay Rate
21	Air conditioning	0.0881	0.106
22	Auto pilot	0.0047	0.016
23	Communications	0.0780	0.077
24	Electric power	0.0732	0.120
25	Equipments	0.0222	0.060
26	Fire protection	0.1294	0.098
27	Flight control	0.0492	0.034
28	Fuel	0.0976	0.098
29	Hydraulic power	0.1113	0.019
30	Ice protection	0.0511	0.085
31	Instrument	0.0013	0.012
32	Landing gear	0.1844	0.205
33	Light	0.0553	0.099
34	Navigation	0.2990	0.196
35	Oxygen	0.0012	0.076
36	Pneumatic	0.1099	0.201
38	Water waste	0.0937	0.170
49	APU	0.0364	0.027
51	Structure	0.1314	0.003
52	Doors	0.0647	0.104
71-80	Powerplant	0.2761	0.320
Total Delay Rate		**1.96**	**2.13**
Total Dispatch Reliability %		**98.04**	**97.87**
Error %		**0.17**	

Table 5-17: Predicted & actual delay rates for B777-268 ER long-haul aircraft

"Simplicate and Add Lightness"

Design philosophy of Ed Heinemann,
Douglas Aircraft.

Chapter 6

The Aircraft Design Process Incorporating a System Design Methodology for Dispatch Reliability

6.1 Aircraft Design Process

6.1.1 Introduction

Aircraft design is a complex process that involves many disciplines and requires large resources. It entails many compromises between different competing factors and constraints.
Past experience plays a major role in the initial synthesis of the aircraft design concept[54].

Design data for an existing aircraft is a very valuable asset for the design of the future aircraft. This is because in practice the most successful aircraft designs are those developed by teams that have considerable experience with similar classes of aircraft [54].
There are different phases in the aircraft design process, but the main phases are three, conceptual, preliminary and detail design [88,108, 60].

The three design phases can be seen in an aircraft life cycle context as shown in Figure 6-1[60].

6.1.2 Aircraft Conventional Design Process

The conventional design process is consists of three primary phases preceded by the definition of the requirements and followed by the manufacturing, testing and certification. These processes are shown graphically in Figure 6-2 [62].

Many design analyses are required during different design phases, and these analyses are iterative. Computerize design tool are used throughout the design phases and advances on the computer sciences allowed more efficient design to be achieved.

Access to historical aircraft design data is very important during design phases and it has a large affect on the design quality[7,8,18].

On the past conventional design, very little emphasis is placed on the dispatch reliability, because the design objective was to produce a design that can fulfil all functional requirements, and dispatch reliability was not amongst them. As a result many aircraft suffer from poor dispatch reliability performance at the beginning of their service and large resources has to be utilized to improve dispatch reliability.

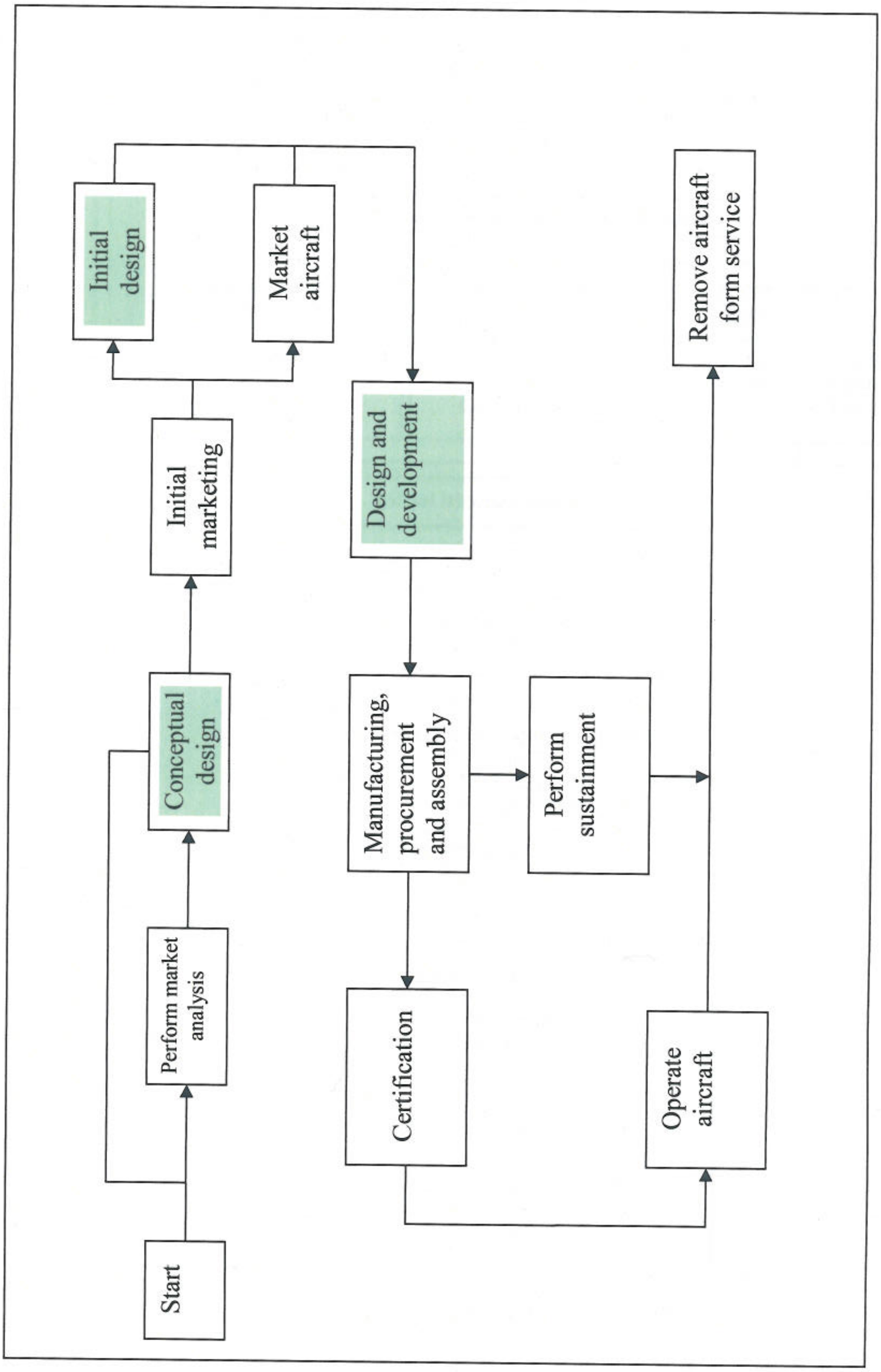


Figure 6-1: Life-cycle functional flow for an aircraft

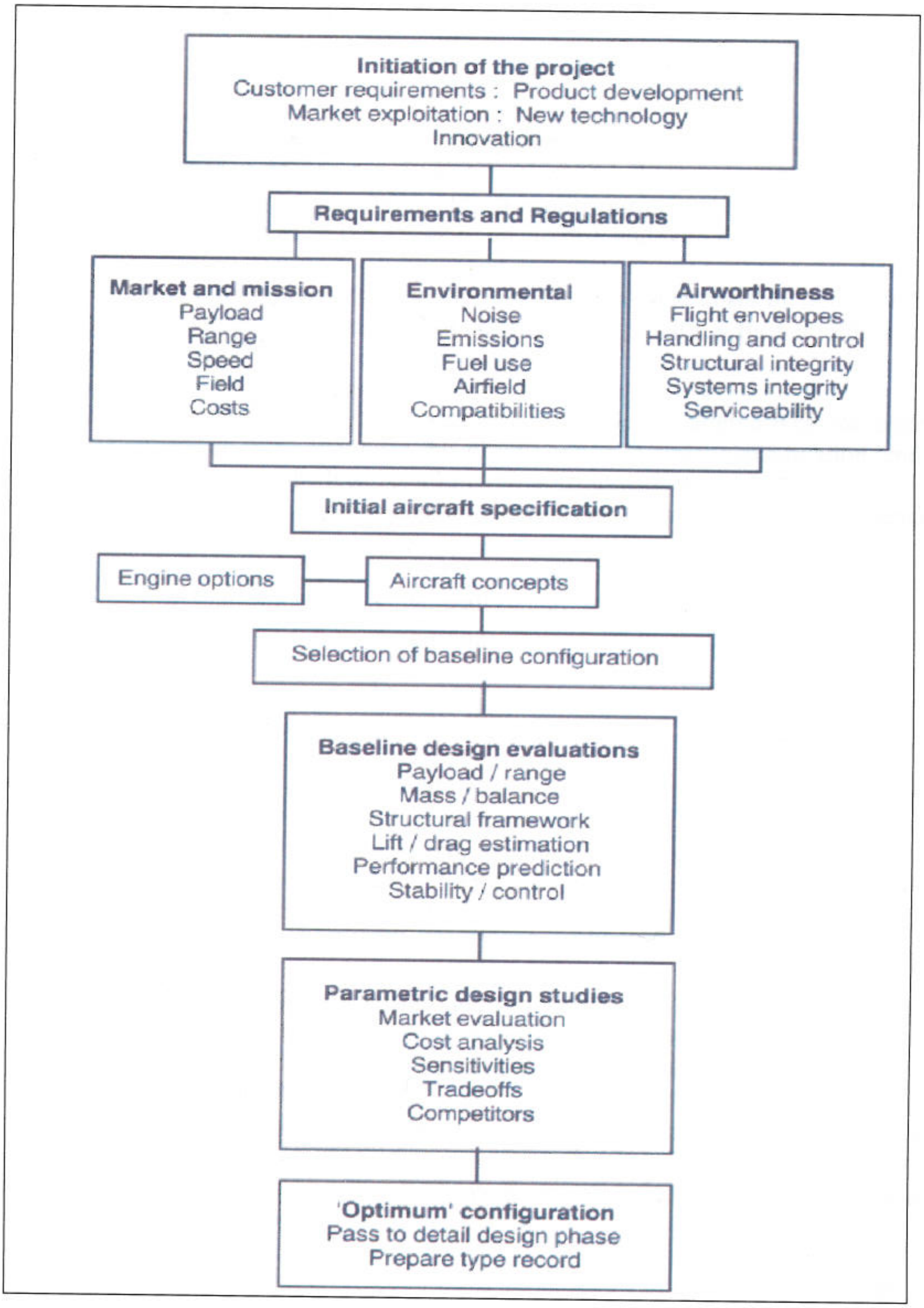


Figure 6-2: Aircraft design process [62]

6.2 The ASDMDR throughout Design Phases

6.2.1 Introduction

Aircraft inherent product reliability and maintainability can be achieved through good design. Post production modifications and improvement can do very little on improving inherent reliability (R) and maintainability (M). It is only during the early design phase that the required R&M can be built on the design of an aircraft, and with much lower cost.

It has been suggested that something like 85% of the life-cycle costs of an aircraft are determined at the project stage (conceptual & preliminary) with a further 10% decided during detail design stage [54].

Conceptual design is characterized by a large number of design alternatives and trade-off studies, continues evolutionary change to the aircraft concepts under consideration, and it is on the conceptual design that the basic configurations arrangements are made[47].
Systems, subsystems and components general locations and general features are generally defined on the conceptual phase.

The design activities that influence maintainability and reliability range from the definition of initial requirements in a specification, through concept design, to detail design[106].

Design requirements that refer to R&M should be explicit and not implicit and they should be stated independently of other requirements [106].

Defining quantified R&M requirements will help the designer to work toward unambiguous target. It is of no use to the designer that R&M requirement are specified in vague statement which could means many things. As an example, stating that fuel pump should be very reliable is by no means a definite target that can be aimed for. This reliability requirement should be quantified in term of failure rate or mean time between failures (MTBF).

An effective aircraft design practise would define the top-level R&M requirement for the whole aircraft. The top-level target is then divided amongst aircraft's systems with the aid of suitable allocation method, via experience or by comparison with similar systems.

Design decisions made during the conceptual phase will, by definition, shape the overall design and in doing so will constrain the scope of any detailed design activity. This would result in only minor improvement to the R&M performance being possible during the detail design phase and at higher cost.

The iterative nature of the design project creates good opportunity to modify the design to suit the needs.

Some resources thinks that all the three design phases formed an opportunities to consider reliability and maintainability (R&M) [106].

This is might be possible in the case of small size design, one could iterate back from detail design activity to a higher level of detail design, it is even possible that one could go back to change the concept design if it seem to be inapplicable.

However on large design scale like aircraft, the iteration process becomes very limited. It could be perform within a particular design phase, but not back to a different design phase. This is because once a particular design phase completed, there are very large resources already committed and the iteration back to alter the design would be very costly. Therefore, iterations back to the concept are only possible for small projects and not for the big one.

This is demonstrating the importance of the considering (R&M) early on the design stage. Reliability analyses should be performed at the conceptual design phase. Performing the analysis at the detail design phase where often at a time close to the end of that phase will make the outcome of this analysis with little benefit to the R&M design [106].

There are some who think that R&M quantitative assessment during the conceptual design phase is not practical and should be delayed until more information are available [106].

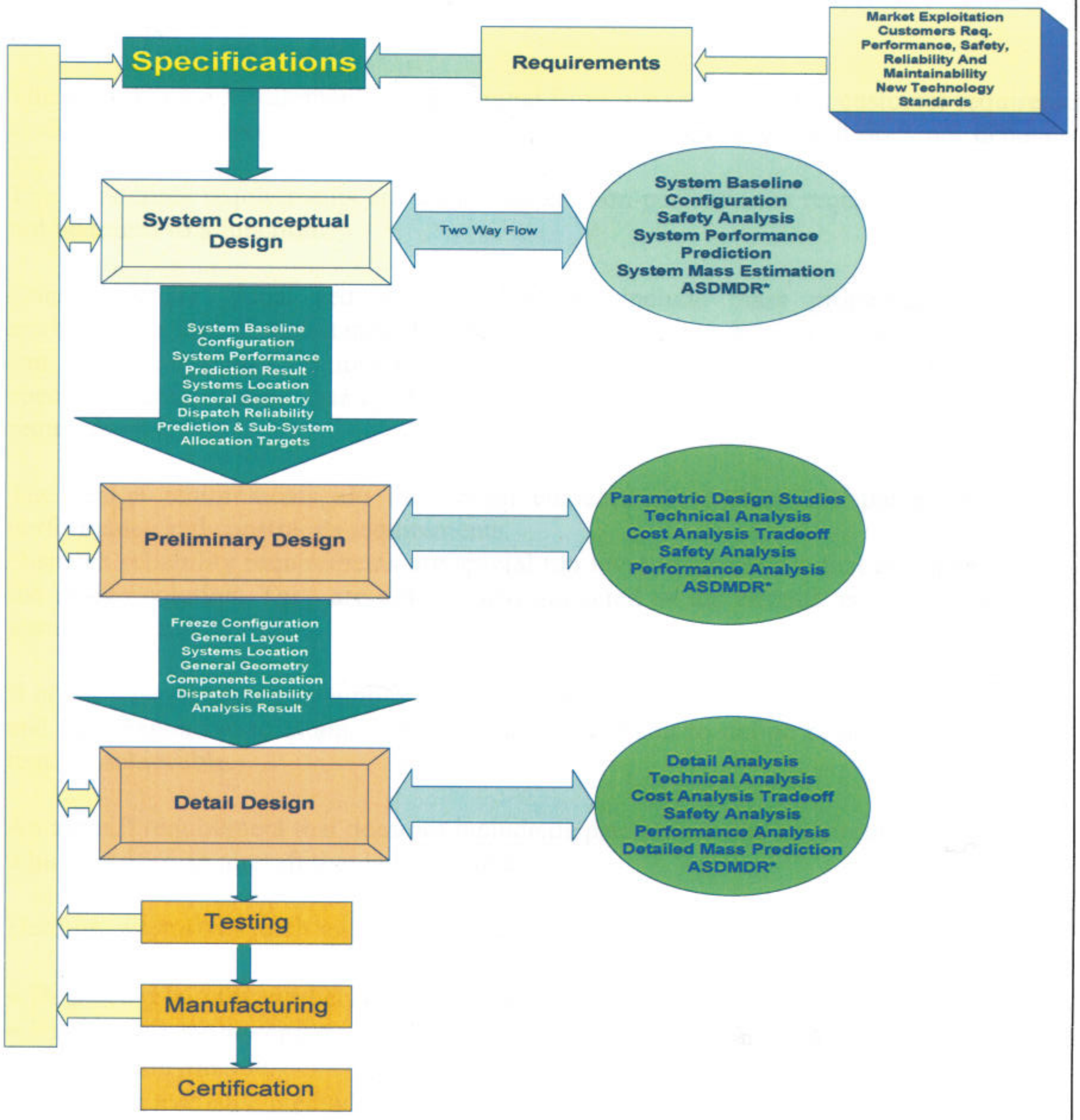
This practice on the aircraft project can not be afford, because waiting for more detail data about aircraft systems and components to be available, mean changing things to suit the dispatch reliability will be difficult and costly.

Although, design changes are continue throughout the three design phases, but the major ones are over by the end of the conceptual phase.
This is make the conceptual phase a very suitable to satisfy the reliability and maintainability requirements with the minimum possible cost.

On the past, dispatch reliability aspects would not be given much attention during the conceptual design phase, since the main emphasis at this stage of the design will be focused on producing a design that can fulfil all functional requirements, reliability and maintainability will typically be an output from this process, rather than a deriving force.

On some cases, an assessment of reliability performance will generally be based upon the reliability performance of the predecessor equipment.

A modified aircraft systems design process was developed in this research and presented in Figure 6-3, where the aircraft systems design methodology for dispatch reliability (ASDMDR) is employed throughout the design process.



* Aircraft Systems Design Methodology for Dispatch Reliability (ASDMDR)

Figure 6-3: Modified aircraft design process

6.2.2 The Requirements

Aircraft design process starts with the definition of the requirements. These requirements can be divided to three types, performance, constraints & specialty and design requirements.

The performance requirements are generated from marketing survey, customer requirement or derivative requirements and they are top-level requirements that it does not depend on any design solution.
The constraints requirements are those that are non-performance requirements, which can not be traced to a function.

Constraints are global requirements that can include mass properties, dimensions, environments and design standards. The specialty requirements mostly are qualitative and can be human factors, maintainability or any other requirements that are generated for special needs. These qualitative requirements should be converted to verifiable requirements.

The design requirements are the design characteristics which are the product of the performance and constraints requirements.
Dispatch reliability requirements are crucial top level requirements that are independent of the design solution. They are defined and allocated to the aircraft as a whole and to its systems and sub-systems.

It is not wise to have very ambitious dispatch reliability requirement that are very difficult and very expensive to attain. Thus, it is very important to define reasonable requirements that are achievable.

An aircraft requirement that does not include dispatch reliability requirement is incomplete, which leads to an aircraft that is ineffective.

Defining aircraft dispatch reliability requirements can be by many ways, including:

- Dispatch reliability prediction method developed by the author [10].
- Historical data for similar aircraft/systems.
- Comparison method.
- Any other available methods such as stated customer requirements.

Upon determination of the aircraft dispatch reliability requirements, design process continues to the conceptual design phase.

6.2.3 Conceptual Design Phase

Good concept design lays the foundations of a successful design project [106].
Engineering design concept can be explained as a concept defines and describes the principles and engineering features of a system, machine or component which is feasible and which has the potential to fulfil all the essential design requirements [106].

Aircrafts' concept design is the stage in design activates that comes after the requirements have been specified and before the detail design work begins to firm up.

At the conceptual design phase, a large number of design alternatives will be analysed, trade studies and development change to the aircraft concept will be performed to fulfil the requirements.

This design phase is a good opportunity to generate many ideas that suit the requirements and then using engineering judgment to evaluate them.

On the conceptual phase, the dispatch reliability requirements which have been set on the previous phase will be examined and different design options would be judge with regards to fulfilment of these requirements.

The usefulness of the developed design methodology (ASDMDR) is that it can be utilised at this stage to evaluate different design ideas with regards to dispatch reliability, and then trade-off studies can be performed to determine the optimum design approach that will meet the stated requirements.

Multiple design approaches will be considered during the conceptual design phase, thus requiring rapid reliability and maintainability analysis response which can be accomplished by using the developed design methodology (ASDMDR).

The conceptual design phase is the most important part of the aircraft design process and it consists of the following:

- Making a list of what the aircraft will do. This is a preliminary specification.
- Sizing the lifting and control surfaces.
- Selecting and designing airfoils.
- Making an inboard profile layout showing location of all major components.
- Performing a weight and balance and stability check and rearrange components to meet requirements.
- Calculating performance.
- Making an isometric drawing to show what aircraft looks like.
- Final aircraft specification.

The most important elements that form the conceptual design phase are:

a) Looking for Ideas

At this early aircraft design stage, designers are concentrating on finding ways to achieve the requirements. Many ideas will be born and designer should think about every idea with open view. As for dispatch reliability, designer needs to eliminate the ideas that did not serve the ultimate goal. Very general and obvious design features that affect the dispatch reliability should be considered at this stage and decision on the best option can be made.

These ideas would give a clue on the general aircraft design features like aircraft system location, number of subsystem on a specific system and an idea of the weight element.
This information can be used to evaluate the available design options with regards to dispatch reliability and the most suitable option that fulfils the dispatch reliability can be chosen.

b) Description & Development of Ideas

This step characterized by more detail development of the ideas and by the concentration on providing more description with the aid of sketches and engineering drawings and quantitative data. This is enable a sensible comparison between different options and dispatch reliability elements like reliability and maintainability can be evaluated with more confidence. At this stage, ideas starting to be transformed to concept.

c) Demonstration of Feasibility

Feasibility of an idea is investigated by qualitative and /or quantitative methods. Dispatch reliability characteristics should be tested to demonstrate the feasibility of particular idea.

As an example, designers would decide if the available space on particular design option is adequate to house specific system components with the required accessibility.

The developed design methodology (ASDMDR) can be used at this stage to evaluate particular idea with respect to dispatch reliability requirements and the result should make or break the feasibility of the idea.

d) Evaluation and choice (of alternative concepts)

There are some design criteria that could be used to evaluate different options with regards to dispatch reliability, these are:

- Simplicity and elegance of the design
- Minimum number of parts
- Suitability for modular construction

- Accessibility
- Interchangeability
- Ease of adjustment
- Minimum number of moving parts
- The use of new technology
- Systems general locations
- General physical characteristics of the components

These dispatch reliability design criteria are a key aspect of the design for dispatch reliability which ought to be looked after very seriously at this stage. These key dispatch reliability aspects if overlooked at this stage could cause failure of the whole project if, at the detail design stage, it proves too expensive or impossible to create a feasible design. The decision on which is the better option is very crucial and can make or break the project.

Implementing the develop design methodology (ASDMDR) at this stage can be very useful to compare different concepts with respect to dispatch reliability requirements.

6.2.4 Preliminary Design Phase

Preliminary design phase starts when the design concept is chosen and the major changes are over. It is characterized by a maturation of the selected design approach. At this stage, more insight of the design is taking place, information is more detailed, and systems designers start more in-depth design and analysis of their system where systems and subsystems development are performed.

Also, the aircraft system internal development is carried out which includes the determination of the number of subsystem and components and their functional relation. The exact location of the system components, their size and weight is defined.

At this stage, as the design evolves, more detailed information will be available, thus a full scale run of the developed design methodology (ASDMDR) would be appropriate. The outcome of this exercise can be used to improve the design by implementing some design changes.

6.2.5 Detail Design Stage

At the detail design phase no more big design changes and the general design features are well defined. At this stage the work start on defining the detail description of every item.

More R&M analysis will take place to make sure the detail design of components and other small details does not break the objective. The dispatch reliability allocations obtained by the methodology during the preliminary design phase will be checked and updated with detailed design information. Quantitative Dispatch reliability requirements will be allocated to each individual system, sub-system, and replaceable units.

6.3 Design for Dispatch Reliability Requirements

Design for dispatch reliability requirements are materialized from the general design reliability requirements and the specific dispatch reliability needs.

Given that dispatch reliability is affected by reliability and maintainability characteristics of the design, the design requirements are simply a reflection of this concept, thus it is a combined reliability and maintainability design requirements.

6.3.1 Reliability Requirements

Reliability is an inherent system or component attribute that can be largely influenced during design, but it also influenced throughout a product life by outside factors such as temperature, humidity and many different factors.

A very conventional approach to design for reliability is known as 'unity' [82]. It is by the elimination of the weak links on the design. This is could be achieved by creating a set of components on a system that are equally strong. Perhaps this approach would not always be possible and designers need to make some trade-offs to achieve the required reliability target. In general, there are two types of reliability requirements; these are qualitative and quantitative requirements.

The qualitative requirements cover many areas and it is necessary to express all of them in verifiable terms.

a) Qualitative Requirements

The qualitative requirements are enormous and they all evolve around the techniques that could be performed to achieve reliable design.
Some of these qualitative requirements are listed below:

- **Simplicity and Elegance**

Complicated designs tend to be unreliable and difficult to maintain where is simple design that serve the operational purpose and allow for easy maintenance is much reliable.

- **Minimum Number of Moving Parts**

Moving parts are essential in many machines but the objective should be to reduce them to a minimum. This is because moving parts tend to fail more frequently, due to wear, than those that are stationary.

- **Use of Known Technology**

The use of proven technology reduces the likelihood of encountering unexpected behaviour of the designed product.

- **Specific Criteria for Special Requirements**

Every design has special characteristics that may need the introduction of certain requirements. As an example, the performance of avionic equipment degrades in the presence of humidity. Good design should provide a protection against such environments which will improve reliability.

- **Functional Redundancy in Critical or High Failure Areas**

Redundancy includes both active and standby units. It is a design solution by which two or more identical components share the load or be on standby status to takeover when the main component fails. Reliability improvement can be achieved by introducing redundancy when necessary in system design. It should be noticed that this technique is not always effective as it sound. Common cause failure can eliminate the benefit of redundancy.

- **Use of Proven Highly Reliable Components**

The use of proven highly reliable components is very obvious method of improving the overall reliability of the system.

- **Elimination of Items with Poor Reliability Based on Historical Data**

Aircraft reliability historical data is very important source for the design of new aircraft. This reliability historical data bank should be reviewed and analysed to define the poor reliability items and exclude them from the new aircraft design.

- **Derating**

This is the design method of limiting the component stress to a level below its rated value. An example is operating an electronic component with a voltage or current strength below its rated value.

b) Quantitative Requirements

The quantitative reliability requirement is very important tool on designing for reliability. Stating very clear reliability requirement that can be verified will help designers to achieve the required objective.

Thompson [106] states two approaches that can be taken on the design for reliability:

1. To specify system minimum mean failure rate, then to select appropriate components with individual mean failure rates that, when combined, achieve the required reliability level.
2. To define reliability targets that, when met, achieve an optimum design with respect to overall reliability.

In practise, the two above methods would be used, because reliability is a function of the failure rate and vice versa. In general, design for reliability quantitative requirements is related to the failure frequency.

These quantitative requirements are:

- Failure rate (λ).

- LRU MTBF. The line replaceable unit (LRU) mean time between failures (MTBF) is the average time in LRU hours between confirmed LRU failures.

- LRU MTBUR. The LRU mean time between unscheduled removals (MTBUR) is the average time between LRU unscheduled removals.
- LRU MCBF. The LRU mean cycles between failures (MCBF) is the number of operating cycles between confirmed LRU failures.

The reliability of an item can be calculated by using Equation 6-1.

$$R(t)=e^{-\lambda t} \qquad \textbf{Equation 6-1}$$

Where,
t = time

λ = Mean Failure Rate (constant)= $\frac{1}{MTBF}$

Mean time to failure =mean time between failure = $\frac{1}{\lambda}$

6.3.2 Maintainability Requirements

There was a lack of emphasis on maintainability on many aircraft design projects, and in some cases, maintainability programs were cancelled early on as a cost saving [30].

Maintainability in design has traditionally not been thought of as a measurable concept and often regarded as a qualitative parameter. As result of this, many products suffered from the poor maintainability features.

Design for maintainability requirements would be view as of two types: quantitative and qualitative.

I. Quantitative maintainability design requirements

This type of requirements can be divided into two types [60]:

- **Maintenance cost**

That is, the aircraft maintenance cost per 1000 flight hours ($/1000FH), which can be converted into maintenance man-hours per 1000 flight hours (MMH/1000FH).

- **Mean Time to Repair (MTTR)**

The mean time to repair is the on-aircraft average repair time.

II. Qualitative maintainability design requirements

The qualitative maintainability design requirements are several, the most important being:

- **Accessibility**

This is a measure of the relative ease of admission to the various areas of an item for the purpose of operation or maintenance. Accessibility is an important design feature that enhances maintainability. Allowing for the required accessibility on the design will mean that corrective action will be less problematic and be carried out with minimum manpower.

Accessibility in design should be priorities to allow easier access to the more vulnerable components than to others with less probability of failure [53].

- **Modular Construction**

The basic idea underlying modular design is to organize a complex system (an electronic circuit, or a mechanical device) as a set of distinct components that can be developed independently and then connected together.
Modular replacement saves much time and effort and enhances maintainability.

- **Sensibly Sized Components**

Components should be designed to facilitate handling. The human capabilities are well-known and designers should make reference to these capabilities. Size, weight and shape are features that contribute to maintainability.

- **Ease of Adjustments**

Adjustments will be required following much maintenance work, and this task should be designed to be as simple as possible. For example, it is easier to locate components against 'stops' than align them visually against a mark.

- **Minimum Number of Components**

The increase of the number of components of a system will have an adverse effect on the system maintainability, this is obvious since more work, more adjustments and more time will be needed during maintenance activities.

This concept has been proven on many aircraft design projects such as the F-15 aircraft where less hydraulic filters, fuel system plumbing connections, cockpit instruments flight control devices and avionics boxes are all lid to better maintainability performance [66].

- **Interchangeability**

Designing similar aircraft LRU's with interchangeability features will contribute to maintainability improvement. This attribute reduces the MTTR and improves the spars and inventory status. Interchangeability does not necessarily mean that interchangeable items are identical or made by the same supplier. It can be achieved by assuring that their interfaces, both functional and physical, are identical

- **Identification**

Providing the necessary tags and labels on LRUs' can help considerably on speeding the maintenance actions which translated to better maintainability.

- **Replaceability (method of attachment and tool clearance)**

Easy and straightforward attachment methods help to reduce the MTTR.

- **Calibration, Rigging Requirements**

Some aircraft items needs calibrations and rigging following maintenance actions. Clear and simplified calibration and rigging procedure will help to perform the task in less time.

- **Redundancy**

Although redundancy is one of the methods that can be used to improve reliability, in some cases it can also be of help to maintainability. This is by designing redundant components that may be activated when needed so that the system continues to operate while the faulty unit is being repaired. In this way, system downtime may be positively impacted, which will produce the same effect on dispatch reliability.

- **Testability**

Is a measure of the ability to detect system faults and to isolate them at the lowest replaceable component level. The speed with which faults are diagnosed can greatly influence downtime and maintenance costs.

- **Visibility**

It is an element of maintainability design that provides the system maintainer with visual access to a system component for maintenance action. Designing for visibility greatly reduces maintenance times.

- **Fault Recognition, Location and Isolation**

Effective fault indicators can reduce significantly the corrective maintenance time. Built-in test capability, unambiguous maintenance procedures, explicit fault isolation capability and qualified maintenance personnel will reduce the maintenance corrective time.
Built in test equipment (BITE) very much improve aircraft maintainability and this is can be seen on the better maintainability performance of the F-15 aircraft compare to its predecessor the F-4 [66].

The above qualitative maintainability design requirements are very different in nature; and they should be translated to a measurable figure when possible.

Accessibility and interchangeability are, however, the most important and can be controlled by the aircraft designer. Accessibility can be converted to a quantitative requirement in two ways; first is by setting a time limit on the removal and replacement of an aircraft LRU; second is by setting a dimensional criterion for accessibility. That is to say, to specify the allowable space between an LRU and the adjacent structure or other LRU.

Maintainability as a design characteristic is often measured in terms of the time required to perform maintenance. The easier and faster it is to maintain a system/component, the better it is from the maintainability perspective. A schematic of the numerous maintenance-related time factors is shown in Figure 6-4 [12]. The sets of activities that comprise the mean time to repair are the red boxes shown in Figure 6-4.

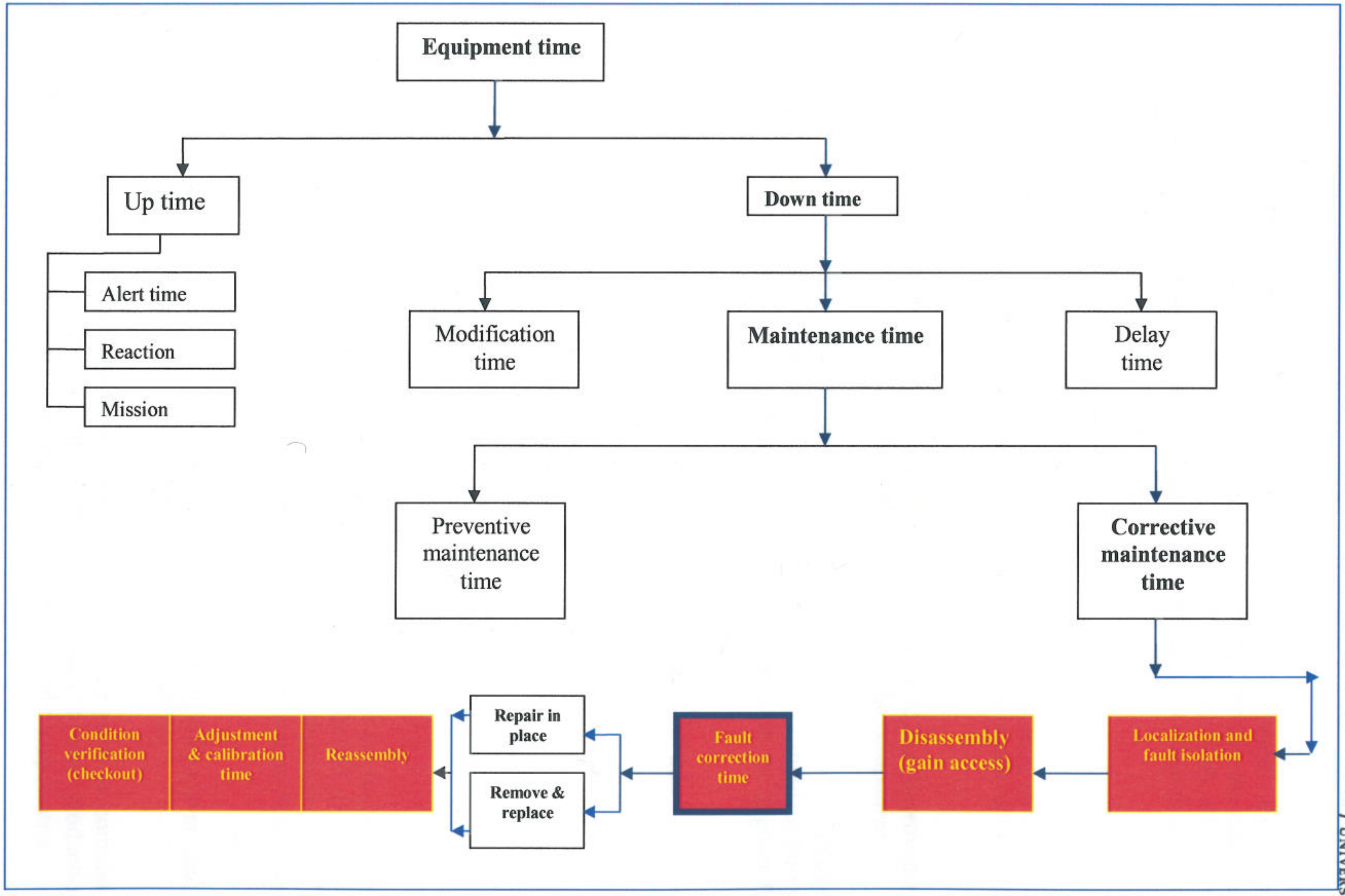


Figure 6-4: Maintenance time relationships

6.3.3 MTTR Calculations

Mean time to repair (MTTR) is the most important measurable parameter on the design for maintainability, especially for complex equipment and systems. By its nature, MTTR depends on the times it takes to repair or remove and replace the equipment as the different kinds of failures occur. Also, on the frequencies with which various replaceable or repairable components in equipment fails; that is, it depends on the repair time and failure rates.

The maintainability improvement that can be achieved in a given component is often proportional to the component's MTTR predicted value; i.e. a reduction of a component's MTTR by 1 hour would generally be easier to achieve in a component with a predicted MTTR of 10 hours than in a component with a predicted MTTR of 2 hours.

The sensitivity of an improvement on system maintainability to the improvement on component maintainability is proportional to the failure rate of the component.

There will be much more improvement on system maintainability if the improvement gained is for component that has high failure rate. Thus, the first candidate for system MTTR improvement should be the component in the system with the highest failure rate.

The total down time could be defined as the sum of the following times as shown in Figure 6-5 [38]:

- Supply delay time
- Maintenance delay time
- Access time
- Diagnosis time
- Replacement or repair time
- Verification and alignment time

The repair time here is meant to be the on-aircraft repair time or on-aircraft repair by replacement time. The actual on-aircraft repair time is the summation of access time, diagnosis time, replacement or repair time, and verification and alignment time. These times are added up to form the total time it takes to repair or replace an item when it is on-aircraft.

If the average time to repair an item has been observed many times over, and then calculated, this can be taken as the item's mean time to repair (MTTR).

Supply delay time is the average time needed to obtain spare parts to complete the repair process. This time include the administrative lead times, production or procurement lead times, repair of the failed component itself, and transportation times.

Supply delay time depends largely on the spares management policy; this differs among organizations, even if they are in the same business.

As an example, the supply delay time for an item on two airlines would be different according to the airline spares holding policy.

The equipment total down time and mean time to repair (MTTR), are shown graphically in Figure 6-5[38].

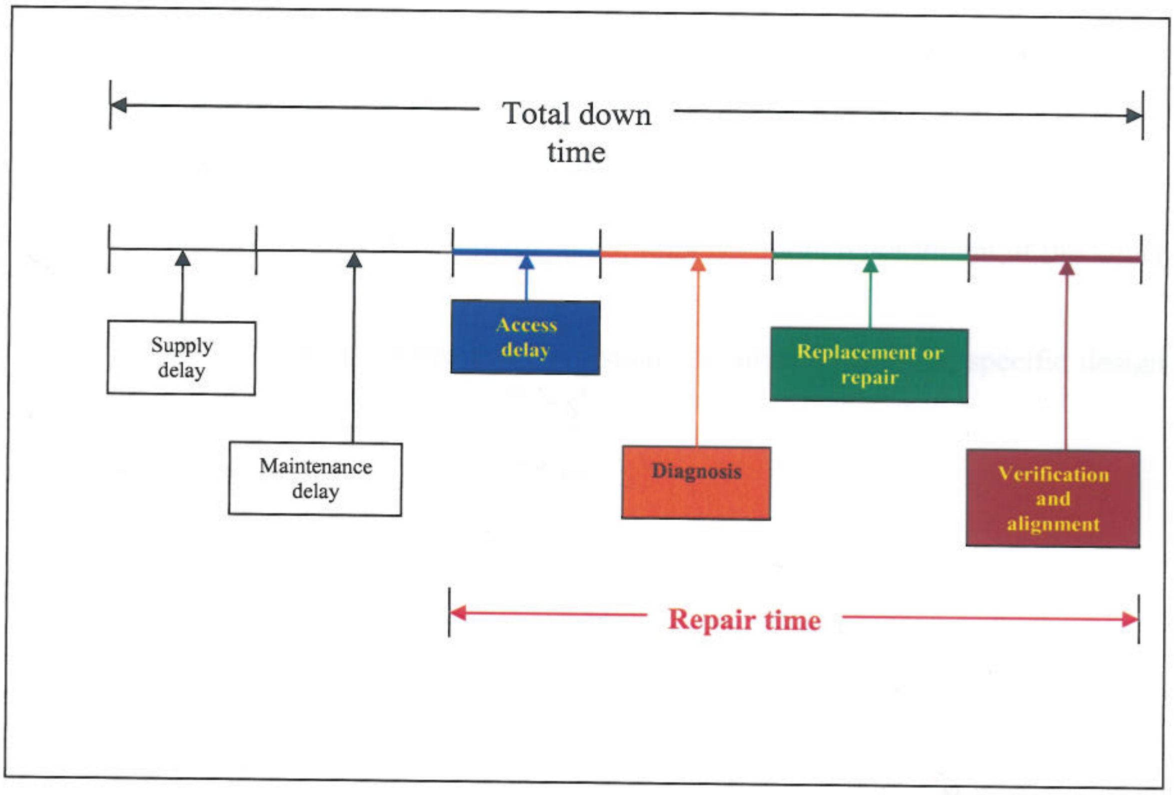


Figure 6-5: Repair time [38]

The component mean time to repair ($MTTR_i$) could be obtained in different ways, they are:

- Observation of the component repair time for many time and taking the average.
- From the manufacturer data.
- Historical data for similar component in similar location.
- By the use of MIL-472 method[12, 34,75].

Predicting the aircraft LRU mean time to repair is of vital important to the designers because of the adverse effect of it on dispatch reliability and as a result on mission success.

At the early design phase, when little is known about the components and their precise location, their mean time to repair prediction can become difficult and needs a lot of engineering knowledge.

No known technique apart from the MIL 472 was found to predict the component downtime at early design stage, thus, this technique was selected for this research to perform the LRU mean time to repair prediction.

With regard to dispatch reliability, the maintenance action performed for the failed component during the turnaround time is replacing it with serviceable one. This concept is called 'repair by replacement'. Thus, the LRU mean time to repair (MTTR) is the required time to replace the failed LRU with serviceable one.

The MIL-472 procedure 3, is a maintainability prediction procedure created by the US Department of Defence to predict the maintainability of ground electronic systems.
The procedure is based on the philosophy that failures are due to the malfunction of the replaceable items and hence, the downtime is equal to the total time required to carry out the various steps which are the preparation, fault isolation, replacement of the faulty item, adjustment and functional checks.

The length of the item downtime time is assumed to be a function of specific design parameters which relate to the following criteria [34]:

- The physical configuration of the system.
- The facilities provided for maintenance by the design.
- The degree of maintenance skills required of personnel charged with the repair responsibility.

The design check lists A, B, and C were developed for the above three criteria and each one of them is consists of several scores and scoring criteria. Check list A consists of 15 questions, Check list B consists of 7 questions and Check list C consists of 10 questions. The scoring of each question ranges from 0 to 4. Intermediate values of 1, 2 and 3 are provided for some questions where the nature of the characteristic being assessed may take on varying magnitudes.

The question scoring follows a simple logic, and an example is the scoring criteria for the first question in check list A, which is about external accessibility of the component. These scoring criteria scoring criteria are as follows:

- 4 is to be scored if the access adequate both for visual and manipulative tasks
- 2 is to be scored if the access adequate for visual, but not manipulative, tasks
- 2 is to be scored if the access adequate for manipulative, but not visual, tasks
- 0 is to be scored if access not adequate for visual or manipulative tasks

All these questions are shown in table 7-5, and more information about this procedure is available in reference [34].

The last step in the prediction process is to calculate the predicted downtime (MTTR) for the required maintenance task. This is accomplished by inserting the total check list scores for this maintenance task in Equation 6-2.

MTTR=10 ^ (3.54651- 0.02512A -0.03055B – 0.01093C) **Equation 6-2**

Application of this procedure needs adequate knowledge of the system design and operation with sound engineering judgment.

When components mean time to repair is obtained by prediction or from other sources, the system mean time to repair becomes a function of the failure rate and the actual repair time of those components.

equation 6-3 can be used to determine the MTTR for a specific system:

$$MTTR_s = \frac{\sum_{i=1}^{n} \lambda_i \bar{t}_i}{\sum_{i=1}^{n} \lambda_i}$$ **EQUATION 6-3**

Where,

N	THE TOTAL NUMBER OF REPLACEABLE OR REPAIRABLE COMPONENTS
λ_i	CONSTANT FAILURE RATE IN FAILURES PER UNIT OF TIME
$\bar{t}_i = MTTR_i$	MEAN EQUIPMENT REPAIR TIME WHEN THE ITH COMPONENT FAILS

Maintainability trade-off can be performed between λ_i and $\overline{t_i}$ to achieve the $MTTR_s$ goal.

Ebeling [38] suggested an alternative method to calculate system repair time $MTTR_s$, as shown in Equation 6-4.

$$MTTR_s = \frac{\sum_{i=1}^{n} q_i f_i MTTR_i}{\sum_{i=1}^{n} q_i f_i}$$ **EQUATION 6-4**

Where

$MTTR_i$	THE REPAIR TIME FOR COMPONENT *I*
q_i	THE NUMBERS OF IDENTICAL SUBSYSTEMS OF TYPE *I*.
f_i	THE NUMBER OF FAILURES OF THE *I*TH SUBSYSTEM OVER A SPECIFIED TIME

When all components have constant failure rates and the same number of operating hours, then f_i can be replaced by λ_i.

Equation 6-4 can be rewritten to be used to allocate maintainability to a component once the system maintainability goals have been defined, as shown in Equation 6-5.

$$MTTR_i = \frac{MTTR_s \sum_{i=1}^{n} q_i f_i}{\sum_{i=1}^{n} n\, q_i f_i} \qquad i=1,2,3 \ldots\ldots N$$

EQUATION 6-5

Thus f_i can be replaced with λ_i, that is:

$$MTTR_i = \frac{MTTR_s \sum_{i=1}^{n} q_i \lambda_i}{\sum_{i=1}^{n} n\, q_i \lambda_i}$$

EQUATION 6-6

The advantage of using the above equation to allocate the component repair time is that it will guarantee that component with high failure rate λ_i will have the smallest mean time to repair. But it should be emphasised that there is no guarantee however, that these MTTRi goals are attainable, unless there is a design methodology geared on achieving these goals.

Maintainability prediction accuracy can be improved tremendously by using computer aided design program. This is because it gives designers the ability to assess many aspects that affect maintainability such as accessibility, ease of maintenance and component location. As an example see Figure 6-6.

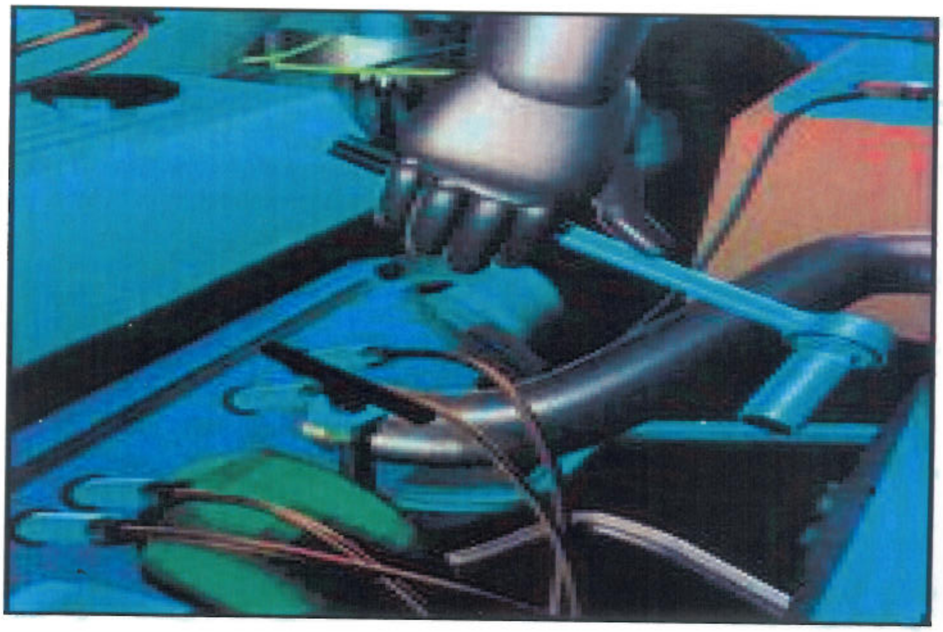


Figure 6-6:3D view of a design [31]

6.3.4 Reliability & Maintainability Trades-off

In general, it might be difficult to maximize both maintainability and reliability at the same time, and it is not the right approach. This is because equipment maintainability can be improved by incorporating features such as quick release device. The additional components have the effect of reducing the reliability of the equipment [106].
In the other hand, improving reliability can sometimes introduce redundancy which will reduce maintainability.
Searching for an optimum dispatch reliability design sometimes needs compromise. In some cases enhancing reliability might introduce an extra maintenance work which will jeopardise maintainability. On other occasions trade-off will be necessary between accessibility and reliability; in such circumstances, sound engineering judgment should come into force.

It should be the objective of the designer to compensate the drop in reliability by an increase in maintainability and doing the opposite so that an overall increase in equipment availability is achieved.

Component's reliability and maintainability are the two characteristics that made the component dispatch reliability. It is the combination of them that dictate the component ability to reach the desired dispatch reliability target.

These two parameters, reliability and maintainability, are often 'traded-off' in order to meet a higher-level requirement such as availability [12].

"The significant problems we face cannot be solved at the same level of thinking we were at when we created them." (Albert Einstein.)

Chapter 7

Aircraft Systems Design Methodology for Dispatch Reliability (ASDMDR)

7.1 ASDMDR Literature Review

Very little work has been published on aircraft design for dispatch reliability. This could be in part because of the commercial sensitivity of the issue, or of the late recognition of dispatch reliability as one means of evaluating an aircraft's performance.

Some aircraft manufacturers use a comparison technique as a design tool for dispatch reliability, based on previous aircraft as the basis for the new design.
Although the comparison technique is not an independent method and relies upon old design, but it can be seen as step forward for the design for dispatch reliability.

The first attempt to consider dispatch reliability on aircraft design was made by the Boeing company when they designed the B727 airplane in the 1960s [86]. In this design approach, the dispatch reliability design target was set by a simple arithmetic comparison of the flight time for the old aircraft and the new one, and the dispatch reliability target for the new aircraft was set to achieve the same target as that for the old aircraft

This approach was mainly a comparison procedure which takes a previous aeroplane as the basis for the design of a new aircraft. The method began by assigning dispatch

reliability design objective figures for the aeroplane. The dispatch reliability allocation for an individual system was followed, based on the B 707/720 aircraft experience.
This method utilizes a detailed evaluation of each system component to develop comparison factors. The detailed causes for B 707/720 delays of five minutes or more due to mechanical failures were categorised by ATA system breakdown. Each ATA system was further divided into its own individual components or subsystems, and the number of delays contributed by each component or subsystem was noted. Component comparison evaluation factors were then developed. These are:

- Number of units per aircraft delay factors
- Duty cycle delay factors
- Design delay factors
- Operating environment delay factors
- Accessibility delay factors

These delay factors are calculated for every component or subassembly on the B727 airplane by comparing it to the B 707/720. The product of unit delay factors produces the component comparison factors. The component comparison factors for certain systems were summated to obtain the total number of B727 delays for that particular system. As the above process was completed for each airplane system, the total number of delays for the B727 can then be obtained. The B727 total delays are converted to percentages which are then subtracted from 100 to obtain dispatch reliability.

A comparison between the allocated dispatch reliability and the calculated dispatch reliability was performed, allowing design change to be made for the system that is not achieving the required goal.

To consider dispatch reliability early on the design was a useful and effective initiative; it was also an effective way of controlling the dispatch reliability early on in the design phase. However, this method depends on derivative design, which makes it less practical.

Another comparison approach was used by McDonnell Douglas on the design of the MD-80 aircraft [11].
This approach began with the allocation of the dispatch reliability targets for the MD-80 based on the DC-9 aircraft as a baseline; a top-down allocation method was used to establish the individual system goals.

Also, Airbus Industries applied the comparison procedure to the design of the A310-200 aircraft where the baseline aircraft was A300B4 [3].

Lockheed Company adapted a simulation technique to aid on the design of the L-1101 aircraft [39]. This included the development of an airline simulation model, where its prime value was its ability to project the design into a realistic operational environment before the design was frozen or the airplane was delivered.

The simulation model flies the aircraft airline fleets over projected route structures to predict the current dispatch reliability for that fleet.

The inputs to the model are:

- Airline route structure
- Minimum equipment list logic
- Mean time between unscheduled removal (MTBUR)
- Component restoration times
- Physical and functional dependencies
- Percent of deferrable maintenance tasks discovered during pre-flight
- Severity coefficients
- Mean time between unscheduled maintenance action (MTBUMA)

As each airplane is flown over the route, a random number generator, based upon the inputted MTBUR and MTBUMA data, is employed for each component to determine if a failure of the components has occurred.

In the case of component failure, the minimum equipment list (MEL), which is stored in the computer, is examined to determine if the aircraft can dispatch with/without the restoration of the failed component.

The restoration time distribution is entered through a random number generator such that any time included in the distribution has a specific probability of being selected. If the selected restoration time extends beyond the time for the next scheduled departure, a delay is logged. If the selected restoration time is less than the time for the next scheduled departure, a successful departure is logged.

The outputs available from the model are many. Among them are the following:

- Dispatch reliability for the whole airplane as a function of ground time.
- Dispatch reliability for each airplane system.

The model outputs provide the necessary information to determine the levels of airplane (systems) dispatch reliability.
These data were then used to refine the design as the aircraft development progressed.

This method took into account issues of both reliability and maintainability; this is one of its advantages. However, this method is more directed towards advance design stage and not for early design stage.

On the military side, dispatch reliability, which is known as, in military terms, as 'mission reliability' was less addressed in the conceptual design and was left to come about as a result of the 'design for performance' approach. There might be many reasons for this, some of which are outlined below:

- It used to be that performance is the main design objective for military aircraft. Reliability, maintainability and cost come as secondary issues. However, this concept has changed nowadays, and mission cost and readiness becomes prime criteria on military aircraft.

- There is difficulty in defining a specific mission profile for military aircraft; some have more than 40 mission profiles.
- Different types of operation (for example, peace and war operations) make the design for mission reliability even harder when mission profiles are unpredictable.
- The huge difference in technology between new and old military aircraft makes the use of historical reliability data incompetent.
- Usually vast resources are available for military aircraft operation which compensate for the lack of reliability and maintainability

Information about the military approach towards dispatch reliability was unavailable in the literature. Perhaps, the confidentiality may be the main reason for this.

7.2 The Need for a Methodology

It was evident from the discussion on the previous sections that dispatch reliability is a very important issue in the aircraft business, and must be considered in the very early stage of the design process.

Although up-front dispatch reliability analysis is very important, dispatch reliability analysis should be a continuous exercise throughout the aircraft development process. As more analysis performed during the conceptual and preliminary design phases, the better the final product will be, and the less it will cost, as changes at early design stages are much easier and less expensive to correct.

The most important benefit of up-front dispatch reliability analysis is that the aircraft system designers will be able to perform a 'thorough' analysis to evaluate alternative approaches and explore different options during the design cycle to arrive at a superior design. Through this process, engineers and designers can quickly investigate many design variations and evaluate a range of ideas that would not be practical to test in hardware.

Aircraft systems have a very significant element in the aircraft design; this is due to many reasons. These are because the mass of aircraft systems accounts for about one third of the aircraft's empty mass, more than on third of the development and production costs of a medium civil transport can be allocated to aircraft systems, and this ratio can even be higher in case of military aircraft, and aircraft systems account roughly for one third of the direct operating costs and direct maintenance costs[93]. That to say, any improvement in aircraft systems design will affect the whole aircraft design very much.

Experience of manufacturers in many industries has shown that 85% of the total time and cost of product development is committed in the early stages of product development, when only 5% of project time and cost has been expended. This is because in the early conceptual stages, fundamental decisions are made regarding basic geometry, materials, system configuration, and manufacturing processes. Further along in the cycle, changes become harder to make.

Essentially, the amount of time and cost of correcting problems increases ten-fold with each step of the product development cycle: concept definition, detailed design, prototype manufacture, prototype testing, and production.
Thus, relatively minor changes that would have cost a few hundred dollars had they been made in the concept definition stage could end up costing hundreds of thousands of dollars in the production stage or millions if flawed products are shipped.

The aircraft industries have traditionally handled dispatch reliability as a secondary issue, whereby it is usually left to come about as result of the design for performance. The design is then modified after the product has been put together, or at a very advanced design stage, in order to reach the desired level. This modification usually takes place at a very late stage in the design project, and invariably at a very high cost.

This way of handling dispatch reliability is no longer appropriate, and the war against flight delays and cancellations is being waged on many fronts. The aircraft operators are fighting against technical delays, and the industry as a whole is reacting in many other ways.

Some of these reactions are taking the form of the introduction of new system modifications, improvements in maintenance procedures, enhancements to the quality of maintenance work and the introduction of new maintenance aid computer programs. The cost of performing such actions is in most cases very high and requires considerable resources.
Some or all of these actions might improve the situation, but they cannot replace the design-inherent dispatch reliability.

The aircraft delays and costs which result from poor dispatch reliability have been discussed in Chapter 3.3, where it was shown that they were very significant. The costs of delays are of two types, namely direct and indirect costs.

The direct costs include a number of obvious elements that range from lost ticket sales, the cost to passengers for lost connecting flights, maintenance costs, providing meals for the passengers during the delay, right through to the airport fees.

The less obvious costs are the indirect costs, which can sometimes have very significant effects. These include the ferry flight for repair, replacement costs, and most importantly, the damage to the airline's reputation. This last cost is very hard to restore, and can seriously affect the future of the airline.

Although some authors have tackled dispatch reliability, there is very little published work that addresses dispatch reliability as one of the objectives for an aircraft design project.
Very few aircraft system design methodologies for dispatch reliability were reported in the literature, and those that are described earlier are mainly based on comparisons

between old and new aircraft designs, using the baseline aircraft as the main vehicle for addressing dispatch reliability in the design.

The main aim of these methods was to assign dispatch reliability targets to the whole aircraft, after which individual systems are assigned quantitative dispatch reliability targets on the basis of experience with older aircraft. The design then was optimised to achieve this target.

This dependence on the comparison method is limiting its use. Because of its type-specific necessity and it cannot be applied to a wide range of aircraft designs, it does not allow for technological improvements. It also has the disadvantages of limited accuracy and needs excessive analysis time.

For all the above reasons, a new aircraft systems design methodology for dispatch reliability was required that gives a realistic approach for the design for dispatch reliability, both early in the design phase, and throughout the design process.

7.3 Methodology Requirements

It is necessary for the new methodology to be used during the iterative phases of design; and it should be independent, generic and uncomplicated to apply.
Both military and civil aircraft require such a methodology, because the targeted dispatch reliability is important for both of them, and is affected by similar factors in both applications.

Any proposed methodology may be limited by the desire of the design team to keep using the same techniques they are used to, unless they are convinced that the proposed one is better than what they have. This explains the importance of having an uncomplicated methodology which can produce a very effective solution.

It would be appropriate at this stage to draw attention to the fact that the developed dispatch reliability design methodology should be used in conjunction with the safety design methodology. This is well explained in chapter 6.2.1 Figure 6.3.

This means that the designer will design a particular system aiming for safety and performance targets, while at the same time using the developed methodology to design for the required aircraft dispatch reliability target.

In summary, the requirements for the methodology are:

- Independent of particular company data
- Generic for both civil and military aircraft
- Appropriate for use during the conceptual design phase
- Uncomplicated to use

7.4 Methodology Data Source & Ground Rules

A number of important issues need to be addressed before proceeding with the development of the methodology. These are the developed methodology parameters, failure rate sources, failure rate types, and the methodology's general ground rules.

7.4.1 Availability, Reliability and Maintainability Relationships

Inherent availability (A_{inh}) is a measure of system availability with respect only to operating time and corrective maintenance time. Under these idealised conditions, preventative maintenance time, maintenance delay times, and administrative delay times are ignored. Because only unscheduled maintenance actions are considered in this definition, the mean operating time can be defined as the mean time between unscheduled removals (MTBUR).

Inherent availability is a useful term to describe combined reliability and maintainability characteristics. It can also be used to define one characteristic in terms of the other during the early design phase, but it is not suitable to be used to support an operational assessment because it provides no indication of the time required to obtain required field support such as logistical issues.

Ebeling [38] asserts that inherent availability can therefore be viewed as an equipment design parameter, and reliability-maintainability trade-offs can be based on this interpretation.

Dispatch reliability has been defined earlier as the probability that an airplane will begin a scheduled flight within 5-15 minutes of the scheduled departure time.

As well, availability was defined as the probability that a system or component will perform its required function at a given point in time or over a stated period of time when operated and maintained in a prescribed manner. Both definitions are about the probability that an aircraft, system or component is ready to do a specific task at a given time or over a period of time.

In fact, when an aircraft is not ready to dispatch (that is, 100-dispatch reliability), means that this aircraft is unavailable.

Blanchard [12] defines inherent availability as the probability that the system will operate satisfactorily when called upon to do so at any point in time, under specified operating conditions and in an ideal logistic support environment. Ideal operating conditions refers to readily available maintenance, personnel, spare parts, test and support equipment, and facilities. It does not consider logistics or administrative time delays; it also excludes preventative or scheduled maintenance tasks.

This is of central interest since the other factors which affect maintainability, and hence availability, such as logistics and management factors, are not included in inherent availability.

While an aircraft's dispatch reliability is associated with the ability to depart as scheduled, at the component level, technical dispatch reliability becomes precisely the inherent availability of that component to function at a particular time.

Delay rate can be defined as the percentage of scheduled departures which are more than 15 minutes late, or which are cancelled. This is can be taken as the percentage of time that the aircraft is not available. Hence, the complement of the delay rate, which is the dispatch reliability, is the percentage of time that the aircraft is available.

Since dispatch reliability is a form of reliability, it can be assumed that dispatch reliability is equal to reliability ($DR= R= e^{-\lambda t}$) for a single component subjected to random failure.

However, this is not a correct assumption because it assumes that dispatch reliability is affected only by reliability, and does not consider the effects of maintainability, when it is evident that dispatch reliability is influenced by both reliability and maintainability. The required aircraft dispatch reliability is only achievable by designing for reliability and maintainability [70].

Furthermore, availability is equal to reliability for non-repairable components, and it is equal to or greater than reliability for the repairable component.

When considering aircraft dispatch reliability, an aircraft system can be treated as it is made of non-repairable components, and components that have failed are removed and replaced with serviceable ones. Thus, only removals and replacements time are considered, while repair time is not considered. Thus, component dispatch reliability is equal to its availability.

Therefore, the assumption that technical dispatch reliability and inherent availability are equal is justifiable.

As a result, the two parameters that affect dispatch reliability are reliability and maintainability, and the technical dispatch reliability equation can be written as in Equation 7-1, where it is the result of dividing the LRU mean time between failure by the summation of the mean time between failures and the mean time between repairs.

$$\textbf{Dispatch Reliability} = \frac{\textbf{MTBF}}{\textbf{MTBF+MTTR}} \qquad \textbf{Equation 7-1}$$

Therefore, the developed aircraft systems design methodology for dispatch reliability considered the MTTR as the quantified value for maintainability, MTBF or MTBUR as the quantified value for reliability.

Improving aircraft technical dispatch reliability can be achieved through improvement in reliability and maintainability. This includes performing one or more of the four following options:

Option 1: Increase the reliability of the item concerned (cost and /or weight may increase).

Option 2: Introduce redundancy for the less reliable items (direct cost increase plus maintenance cost increase).

Option 3: Increase the maintainability of that particular component by reducing the MTTR.

Option 4: changing system architecture.

Any improvement to the dispatch reliability should be sought through one or more of the above methods, i.e. it is a trade-off between reliability and maintainability. Trade-off studies are a technique to find the best among several system design proposals.

It is a very useful design approach when designing for dispatch reliability because in general, it would not be possible to maximise both maintainability and reliability, and the designer's objective should be to compensate for a reduction in reliability by an increase in maintainability, so that an overall increase in equipment availability is achieved [106].

Aircraft dispatch reliability is affected by both technical and logistical factors but only technical factors are under the designer direct control, the assumption has been made that the logistical factors are perfect.

With the assumption that aircraft availability and dispatch reliability are equal and that aircraft technical dispatch reliability is equal to the aircraft inherent availability, Equation 7-1 can be used to calculate dispatch reliability.

7.4.2 Failure Rate Sources

Failure rate is defined as the rate of occurrence of failures. This value is normally expressed as failures per million hours. Failure rate is basically the actual number of times that an item fails in a specified period of time.

Reliability and maintainability analysis requires the processing of large amounts of failure rate data. There are different sources for the component failure rate data, and these data are gathered for different operating conditions.

In some cases, the base failure rate should be multiplied by factors to compensate for different operating environments and stress levels [106].

However, aircraft reliability information is very limited in the literature, and it should be treated with caution [78].

Using failure rate data of similar aircraft, systems and components should enhance the accuracy of such calculations.

Most work on reliability uses the component mean time between failures (MTBF) as the source for the component failure rate.
These times are collected by different methods, and are usually provided by the component manufacturers.

Mean time between failures (MTBF) is generated from component testing and observation over a long period, whereby the component service time is divided by the component accumulative failure.

Different operating conditions, working environments and collection techniques cause the component MTBF to be different from the actual component performance in the field.
This introduces an on-field component failure rate, which is created by the observation of in-service component behaviour.

Another component failure rate source is the mean time between unscheduled removals (MTBUR).
This is generated by the unscheduled removal of the equipment due to a suspected defect.
The mean time between unscheduled removals (MTBUR) is the average time between the unscheduled removals of a component, which is calculated by dividing the total unit flying hours (airborne) accrued in a period by the number of unscheduled unit removals that occurred during the same period.

The relationship between the MTBUR and MTBF can be expressed mathematically as shown in Equation 7-2.

$$MTBUR = FTRR * MTBF \qquad \textbf{Equation 7-2}$$

Where, FTRR is the failure to removal ratio

The difference between the MTBF and MTBUR is that the former deals with the expected time between failures, whereas the latter is about the actual time between failures. This difference is the result of an item which has been removed, but proves to be serviceable (no fault found).

The reliability data which emerges from unscheduled removals reflects what happens on the flight line during flight preparation.

Another failure rate data source is the Non-electrical parts failure rate data can be useful in specific prediction applications, such as aircraft, petrochemical plant, and other applications[78].

When aircraft maintenance actions were viewed with regard to their influence on the dispatch reliability, and subsequently on aircraft delays, a number of points were noticed. These include:

- The primary maintenance processes, which include airworthiness limitations, hard time, on-condition maintenance, and maintenance mentoring, should not contribute to aircraft delays provided these maintenance tasks are performed perfectly and they do not introduce errors. They are usually planned to be undertaken at suitable times that do not have a direct knock-on effect on turnaround time. These times might be overnight, during programmed maintenance down time, or any time at which the aircraft is out of service.

- The only aircraft maintenance actions that can cause delays if not completed during the turn-around time are the unscheduled removals or on-aircraft adjustments. The unscheduled removals are maintenance actions in response to an unpredictable component discrepancy. On-aircraft adjustments are different maintenance actions to rectify unusual condition such as tighten-up nut. Because of the random nature of such failures, the corrective action time might take longer than the turnaround time, and a delay could occur.

- Whether the removed component is actually faulty or not (no fault found) will not affect the fact that the aircraft is not ready for departure due to the removal action.

The above important points when looked at on the dispatch reliability context lead to the conclusion that only unscheduled maintenance actions can contribute to aircraft delay, and this is only when the need for maintenance cannot be determined in sufficient time to allow corrective maintenance before the planned use of the system.

The mean time between unscheduled removals was thus used in the methodology as the source for the components' failure rate for the following reasons:

- Programmed maintenance does not contribute to down time if it can fit within the scheduled down time.

- Programmed maintenance for an aircraft (which includes on-condition removal) will be designed to replace most of the aircraft components before, and close to its designed life ($\leq$MTBF), and it will be planned to be accomplished during aircraft down time.

- Checks and inspections that are necessary for the on-condition maintenance policy would be performed during the turnaround time. This may result in removal and replacement tasks being included in the unscheduled removal rate.

- MTBF is related to the probability of an item performing its purpose adequately for a specific period of time, and usually the item has a design life of a certain time. On today's aircraft, only a small percentage of aircraft components are lifed (around 10%); the rest are accounted for by the on-condition removal policy.

- Technical delays occur only when the aircraft undergoes an unscheduled on-aircraft work.

- The action taken to correct suspected defective components that affects aircraft technical dispatch reliability, i.e. when a component is removed; the aircraft remains on the ground while the action is being carried out.

- Whether the removed component has failed or not (no fault found), it does not affect the status of the aircraft at that time, i.e. the aircraft is not ready for departure due to the removal action, and a delay occurs as a consequence.

- Most aircraft operators report the failure on the form for unscheduled removal rate, which is very important for them, as it describes the component's behaviour.

- Pilot report (PIREP) and pre-flight inspections are the two actions that can initiate delays. Both of them require certain actions to be taken before the aircraft can depart.
- Tasks generated by the pilot report could be of two types, they are:

  a) Tasks that require component removal. The timing of these removal actions will be embedded in the aircraft components removal rate.

  b) Tasks which do not require component removal, such as minor adjustments, monitoring, checking, or servicing. This type of tasks would be accomplished during the available turnaround time and should not cause delays. Thus, it is not considered in the generation of the delay rate.

Component reliability prediction calculation method used in this work was parts count. Parts count is a reliability prediction calculation method whereby the system reliability is a function of its complexity. It is a bottom-up approach where the system reliability is calculated from the reliability of its components. This method of calculation assumes that the components have a constant failure rate.

One of its main advantages is the ability to be used when little detailed information is known about the system and its components. Obviously, this approach has the disadvantages of been not able to include other aspects such as role of the maintainer or operator.

Failure rate allocation is the process of translating the overall system failure rate requirement to requirements at the lower level specifically for sub-systems and the configuration item level.

7.4.3 Failure Rate Type

A constant failure rate is a common assumption for the reliability of electrical and complex systems, and the aircraft industry has been making this assumption for a long time in order to make reliability calculations possible.

Failure rate is constant when events occur in a random fashion with respect to time; hence the probability of an event occurring during any small interval of time is constant.

Usually, over the period between overhauls, failures crop up in a random fashion, regardless of whether the components are new or old. In such cases, the probability of failure (failure rate) is simply the reciprocal of the MTBF [68].

In most cases of aircraft maintenance, common practice would be to remove the component for overhaul, or to replace it before the onset of the increasing risk of failure.

Some research has estimated that 89% of aircraft components do have a constant failure rate during their maturation phase [114].
Others say that in the case of aircraft components, assuming a constant failure rate is justifiable [68].

The assumption of a constant failure rate could be made for complex equipment and military equipment systems [78], because the failure rates between overhauls for most of the components were found to be reasonably constant.

However, where a component deteriorates with time, due to fatigue or wear, the failure rate increases with age, but common practice in aircraft maintenance would be to remove the component for overhaul or replacement before the onset of this increasing risk. Hence the constant failure rates still apply.

Ebeling [38] states that the renewal process, in which a failed component is immediately replaced with a new one, which is usually the case in aircraft maintenance practice, will cause the system to reach a steady state, with a constant number of failures per unit of time.

Studies performed on civil aircraft showed that 4% of the items conformed to the bathtub curve pattern [32]. It showed that 2% of the items show a constant probability of failure, finishing in a wear-out zone; 5% of the items show a constant probability of failure, but there is no identifiable wear-out age; 7% of the items show a low probability of failure when the item is new, then a rapid increase to a constant level, and 14% of the items show a constant probability of failure at all ages (random failure).

It also showed that no less than 68% of the items start with high failure rate which drops eventually to a constant failure rate.

A total of about 89% of aircraft components exhibited a constant failure rate. Hence, the assumption that aircraft components possess constant failure rate is justifiable. For more detail about aircraft component failure rate type see chapter 2.7.2 Figure 2.4.

For all the above reasons, this work has made the assumption that these failures occur due to completely random or chance events, hence, all components have been assumed to possess a constant failure rate with equal operating hours.

7.4.4 Methodology Ground Rules

Certain rules have to be laid down which govern the application of the developed methodology. These are:

- Aircraft dispatch reliability is affected by technical and logistical factors. However, only technical factors were considered in the methodology development.

- The proposed technical dispatch reliability design methodology should be used in conjunction with the design for safety programme.

- MTBUR is the main source for the component failure rate, which is affected by technical and logistical elements. Logistical elements include preventative maintenance, maintenance personnel skills, maintenance manual quality, and many other factors. However, only technical factors are considered with regard to the mean time between unscheduled removals (MTBUR), because it has been assumed that the maintenance is performed by qualified personnel, and that the spares and logistical issues are adequate, thus MTBUR is purely reliability-related, and logistical factors do not exist.

- Maintenance tasks which do not require component removal, such as minor adjustments, monitoring, checking, or servicing, were not considered in the generation of the delay rate. This type of task would be accomplished during the available turnaround time and should not cause delays.

7.5 Minimum Equipment List (MEL)

Aircraft technical dispatch reliability is driven by the minimum equipment list (MEL). This is a list of equipment which can be inoperative and yet the aircraft can still be flown safely. Aircraft manufacturers have established a master minimum equipment list (MMEL), which the appropriate civil aviation authority reviews and approves.

However, the airline may choose to delay a departure on criteria more severe than those stipulated by the aviation authority. For this reason airlines issue the minimum equipment list (MEL) for a particular aircraft type. This is an MEL that is customised to the particular airline's style of operation and aircraft operation.

The optimum design solution for dispatch reliability would be to design all aircraft components on the MEL, and the most effective way to do this is by building redundancy into the system. Of course, this is usually not practical and trade-offs of redundancy against cost and reliability are necessary.

The way that the MEL influences dispatch reliability is by its direct affect on reliability, whereby those components on the MEL are actively redundant.

The methodology refers to the components on the MEL as actively redundant and has considered them in the construction of the reliability block diagram (RBD).

7.6 Methodology Requirements

Studying aircraft dispatch reliability and current aircraft design process generated a number of essential requirements that should be satisfied by the proposed methodology. These are:

- It must be generic, that is, it could be applied to any aircraft.
- It must be able to be used during the early stages of design.
- It needs to be independent; that is, it does not depend on other designs as a baseline.
- It must be user friendly.
- It has to incorporate the MEL.

7.7 The Developed Methodology

The previous sections have endeavoured to establish that aircraft technical dispatch reliability is controlled by two design features, namely reliability and maintainability.

Additionally, as most aircraft components exhibit a constant failure rate, MTBUR is the best source of component failure rates, and that MEL should be considered when dealing with dispatch reliability. It laid down the ground rules for the proposed methodology by specifying the rules that govern its usage. Finally, the proposed aircraft design should comply with the relevant airworthiness requirements such as that on reference 64.

7.7.1 Methodology Assumptions

The develop methodology used certain assumptions, which are as follows:

1. Aircraft components exhibit constant failure rates.
2. Aircraft components exhibit constant repair rates.
3. Only the technical factors that affect dispatch reliability were considered in this methodology.
4. Qualified personnel and suitable spare parts are available for conducting maintenance tasks.
5. Failure rate data were obtained from the mean time between unscheduled removals (MTBUR), and when this is not available, mean time between failures (MTBF) was used.

6. All aircraft sub-system/component structures were modelled as series configurations. Any other type of arrangement was converted to a series type configuration.

7. In the construction of the reliability block diagram (RBD), LRUs (components) on the MEL were considered as actively redundant.

8. No common cause failures were considered on the RBD failure rate calculations.

9. System dispatch reliability was equal to the multiplication of the sub-system dispatch reliability estimations.

$$\boldsymbol{Dispatch\ reliability_s = \prod_{i=1}^{n} Dispatch\ reliability_i} \qquad \text{Equation 7-3}$$

10. The system failure rate was equal to the summation of the sub-system failure rates.

$$\lambda_s = \sum_{i=1}^{n} \lambda_i \qquad \text{Equation 7-4}$$

7.7.2 Description of the Methodology

Reliability and maintainability (R&M) are the two elements that govern aircraft technical dispatch reliability, and there are two design approaches in the aircraft industry with regard to R&M. The first utilises a bottom-up approach whereby the designer works from the bottom by selecting or designing components based on their performance characteristics, and then works upwards towards the system level.

With this approach, the designer is not aiming at specific R&M and waits for the system behaviour to be acceptable in terms of meeting R&M requirements targets.

This design technique has been used extensively in the past but has proved to be unsuccessful with regard to R&M[12], because no objective was set for dispatch reliability, and the resulting designs reflect this.

The second approach follows a top-down approach, whereby the designer works from the system level down to the required component level. This approach gives the designer control over the required R&M characteristics, but, it will not ensure a successful design with regard to dispatch reliability, unless it is directed towards a specific dispatch reliability target.

Nevertheless, the ultimate goal of this approach is that when combined, the various system components should fulfil the requirements of the overall system R&M targets.

The methodology developed in this research has adapted two ways system approach, whereby it concentrates on the two design parameters of reliability and maintainability from the system level down to the component level by allocating the required dispatch reliability values from aircraft level through system level, and to the component level. The second way was by predicting dispatch reliability from the bottom level (component level) up to the system level, and to the aircraft level.

The methodology flowchart is shown in Figure 7.1, and consists of the following steps:

1. Allocation of dispatch reliability for aircraft systems. This could be performed by using one of the following methods:
    - Dispatch reliability prediction method developed by the author [10].
    - Historical data for similar aircraft/systems
    - Comparison method
    - Any other available methods, such as stated customer requirements.
2. Construction of the aircraft's system reliability block diagram (RBD) based on the system design architecture.
3. Allocation of the aircraft system failure rate requirement $(\lambda_{sr})_s$, which was obtained from historical data or extrapolation of test results for new components.
4. Allocation of the sub-system failure rate $(\lambda_{sr})_{sub}$ based on the system architecture and using Relex RBD package.
5. Allocation of the components' failure rates (λ_{ia}) by using the combined method, as shown in Equation 7-5. The failure rate allocation used for this work was a derivative method using part of Boyd's [20]combined method, where the value of the constant K is equal to 0.5. This is because it is the value where the two allocation methods are combined and their advantages are utilised to the optimum level (see Chapter 2.6.2 (d)).

$$\lambda_{ia} = \lambda_{sr}(K / N + (1-K)\lambda_{ip} / \lambda_{sp}) \qquad \text{Equation 7-5}$$

Where,

λ_{ia}	The allocated failure rate for the *ith* component
$\lambda_{sr})_{sub}$	The failure rate requirement for the sub-system (can be obtained from historical data for a similar aircraft system or from the system manufacturer)
K	Constant value $= 0.5$
N	Number of components of a sub-system
λ_{ip}	The predicted failure rate for the *ith* component, which could be obtained from historical data for a similar aircraft/system, or by using Equation 7-6
λ_{sp}	The total predicted failure rate for the component = $\sum_{i=1}^{N} \lambda_{ip}$

$$\lambda_{ip} = \lambda_{sr} \times \sum WF \qquad \text{Equation 7-6}$$

Where, WF signifies weighting factors. These are:

CF	Component complexity factor
TDF	Time on demand factor (criticality)
WCF	Working condition factor (operational profile)
TF	Type factor (electrical/mechanical)
NF	Novelty factor (state of the art)

The weighting factors may be determined by engineering judgment, whereby the designers use their experience to estimate these factors. In cases where the work is performed by inexperienced designer, the component predicted failure rate data can be obtained from historical data for similar components or from other sources such as NPRD-95 and Relex software library.

6. Calculation of the components' allocated mean time between failures ($MTBF_i$) by using Equation 8-7.

7-7

$$MTBF_{ia} = \frac{1}{\lambda_{ia}} \qquad \textbf{Equation 7-7}$$

7. Dispatch reliability allocation for the aircraft's sub-system/components (LRU), performed using the Equation 7-8.

$$DR_{ia} = \sqrt[n]{DR_s} \qquad \textbf{Equation 7-8}$$

8. Prediction of the component mean time to repair $MTTR_i$ by using MIL-STD 472 [34].

9. Calculation of the predicted component dispatch reliability (DR_{ip}) by inputting the calculated $MTBF_i$ and $MTTR_i$ into Equation 7-9.

$$DR_{ip} = \frac{MTBF_i}{MTBF_i + MTTR_i} \qquad \textbf{Equation 7-9}$$

10. Comparison of the predicted component dispatch reliability ($\mathrm{DR}_{\mathrm{ip}}$) and the allocated dispatch reliability ($\mathrm{DR}_{\mathrm{ia}}$). If the predicted dispatch reliability is equal or greater than the allocated dispatch reliability, and the difference between them is less than (0.085), this means the design is acceptable and the process moves to Step 11. If not, it is necessary to return to Step 2.

Note:

a) The margin between the predicted and allocated dispatch reliability was set to a specific value to prevent over-designing with regard to reliability and maintainability, which, if it happens, will mean extra cost without justification. This value was set to be (0.085) to make the difference between the allocated and the predicted component dispatch reliability as low as possible. It was defined after many dispatch reliability analyses, which showed that it was the minimum possible value. It is possible to set the difference gauge to any desired value, if there is justification.

b) The methodology makes provision for a reliability and maintainability trade-off studies by sorting the components according to their failure rates. Those components with a high failure rate would be designed with better maintainability characteristics. The sensitivity of an improvement of system maintainability to the improvement of component maintainability is proportional to the failure rate of the component.

Their will be much more improvement on system maintainability if the improvement gained is for component that has high failure rate. Thus, the first candidate for system MTTR improvement should be the component in the system with the highest failure rate.

11. The MTBF and MTTR inserted into the spreadsheet.

The EXCEL optimisation process was used to achieve the optimum result. The objective was to determine the target level of dispatch reliability for all components, i.e. that which greater or equal to the allocated component dispatch reliability, and hence the best sub-system and system dispatch reliability.

The result would be an aircraft with the desired and required dispatch reliability. The methodology predicts the component dispatch reliability based on the components' mean time between failure and mean time to repair.

The optimum component MTBF and MTTR design data to satisfy the dispatch reliability requirements are printed in a table for all components of the whole system.

In Step 11, changing the design to achieve the required dispatch reliability could be performed by one or more of the following options:

- Fault avoidance, i.e. making the less reliable components more reliable
- Fault tolerance, i.e. introducing redundancy for the less reliable components
- Increasing the maintainability for the less reliable components, i.e. reducing the mean time to repair.

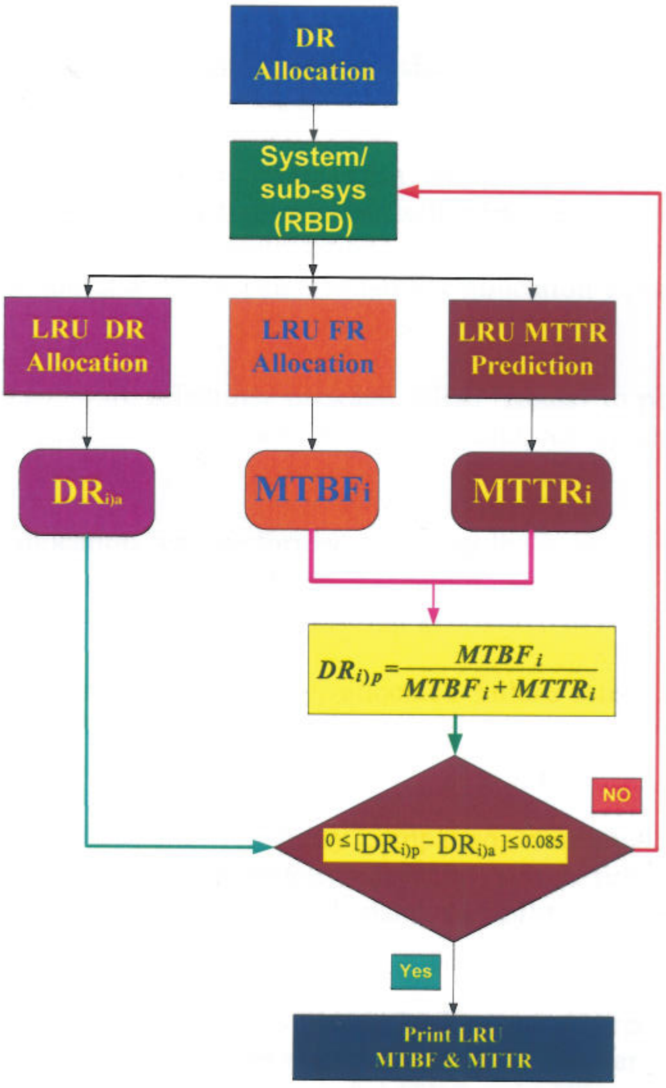


Figure 7-1: Methodology flow chart

7.8 Methodology program

The whole methodology was programmed using the EXCEL spread sheet capability. The input information about the system under investigation was entered into the master sheet.

Maintainability prediction was entered into a separate sheet, which has been designed so that it can feed MTTR data into the master sheet.

The user will have to enter the basic information about the system, sub-system, component failure rate and so on, and the program will perform a component failure rate and dispatch reliability allocation optimisation. This step is performed using the failure rate allocation method and the dispatch reliability allocation equation to define these variables.

The methodology uses a software reliability package called 'Relex' to perform system reliability block diagram (RBD) construction and system and sub-system failure rate calculations [24].

Component failure rate allocation was performed by using the component's predicted failure rates as the input file and applied the allocation equation to calculate the component's allocated failure rate.

The component's allocated dispatch reliability, allocated failure rates, and the mean time to repair data are fed to the data processing section, which performs the dispatch reliability prediction calculations.

At this stage, the component dispatch reliability comparison was made between the component's allocated and predicted dispatch reliability. If the predicted dispatch reliability is equal or greater than the allocated dispatch reliability, this means that the component passed the design criteria. If not, it fails.

Whether or not a particular line replaceable unit (LRU) meets the required dispatch reliability is a decision based on the previous dispatch reliability comparison. If it meets the requirement, a print out page of the component's MTBF and MTTR is performed.

Any component that failed to achieve the required level of dispatch reliability (i.e. the predicted dispatch reliability was less than the allocated dispatch reliability) was tagged by the phrase 'try again', which indicates the need for design modification. This is could be performed either by improving the component's reliability, or by enhancing its maintainability, or by a combination of both.

Upon accomplishing the required design modification for the failed components, the process may be repeated for the modified components.
The resulting methodology provides the designer with a powerful tool to enable him/her to achieve the desired dispatch reliability level at a minimal cost.

7.9 Methodology Examples

For illustration purposes, below are two examples which demonstrate the application of the methodology.

7.9.1 Example 1

- **The case**

The aircraft sub-system in this example was assumed to consist of three line replaceable unit (LRU) connected in series.

- **The requirement**

To design this aircraft sub-system to a specific dispatch reliability target.

- **The specified information**

The required dispatch reliability target for this particular sub-system was *(99.90%)*
The required sub-system failure rate was *(0.00078* hr^{-1}*)*

The LRUs technical information

Table 7.1 presents the relevant technical information about the three LRUs.

LRU	Mass (kg)	Size (cm)	Location	Accessibility
LRU1	3	20 × 25 × 15	Starboard wing	Very easy to access & no obstruction
LRU2	5	30 ×30 × 20	Starboard inner-wing	Not very accessible & no obstruction
LRU3	8	40 × 50 × 20	Starboard wing	Not very accessible & blocked

Table 7-1: LRUs technical information

- **Input file calculations**

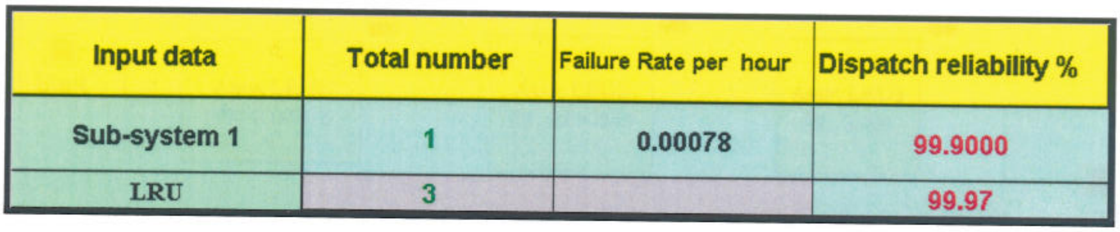
Initial calculations were performed for the basic data and the results are:

The required sub-system dispatch reliability was set to be = *(99.90%)*

There were three LRU in the sub-system as shown in Figure 7-2.

The LRUs' allocated dispatch reliability was equal to *(99.97%)*, which was calculated by Equation 7-8.

The input file calculations are shown in Table 7-2 below.



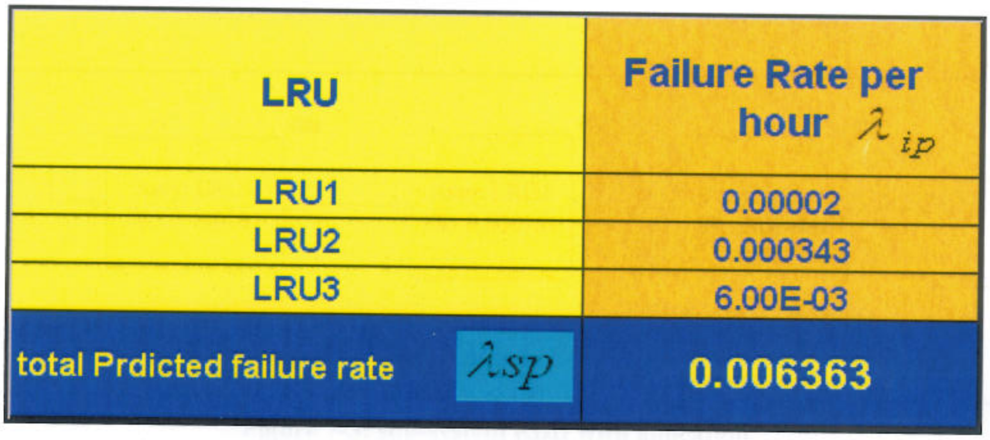
Input data	Total number	Failure Rate per hour	Dispatch reliability %
Sub-system 1	1	0.00078	99.9000
LRU	3		99.97

Table 7-2: Input data

- **The methodology process**

1. Obtaining the LRU predicted failure rates

In a real life situation, the LRU's predicted failure rate will be obtained from historical data. As this example was for illustration purposes, the LRU's predicted failure rate was assumed to be as shown in Table 7-3 below.



LRU	Failure Rate per hour λ_{ip}
LRU1	0.00002
LRU2	0.000343
LRU3	6.00E-03
total Prdicted failure rate λsp	0.006363

Table 7-3: LRU predicted failure rate

2. Construction of the sub-system reliability block diagram (RBD)

This was done by using the Relex software. This is shown in Figure 7-2 below. Also, by using the Relex software, the total sub-system predicted failure rate was calculated, which was equal to 0.006363hr^{-1}.

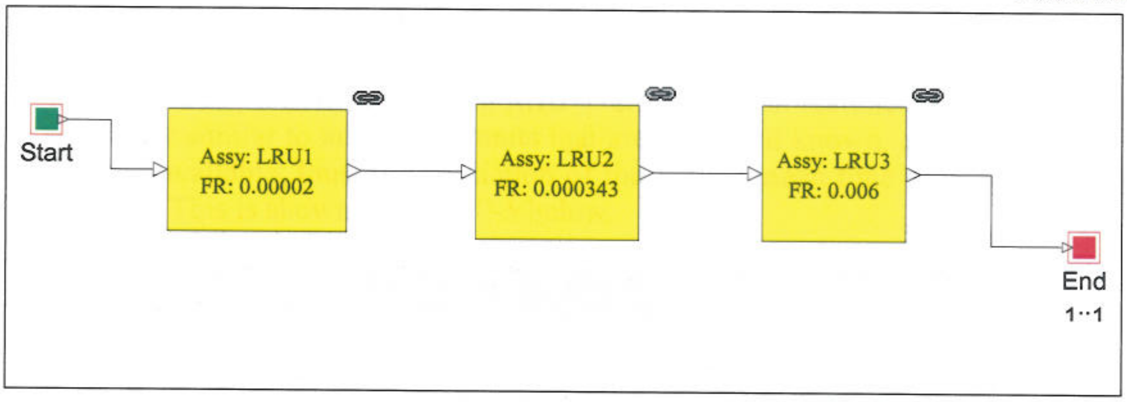


Figure 7-2: Sub-system RBD

3. Allocation of LRU failure rate

This was performed by using the methodology allocation method. This process is shown in Table 7-4 below.

The total sub-system failure rate was calculated by feeding the LRU's allocated failure rate to the Relex RBD module for this sub-system as shown in Figure 7-3. This total sub-system allocated failure rate was (*0.00078* hr^{-1}).

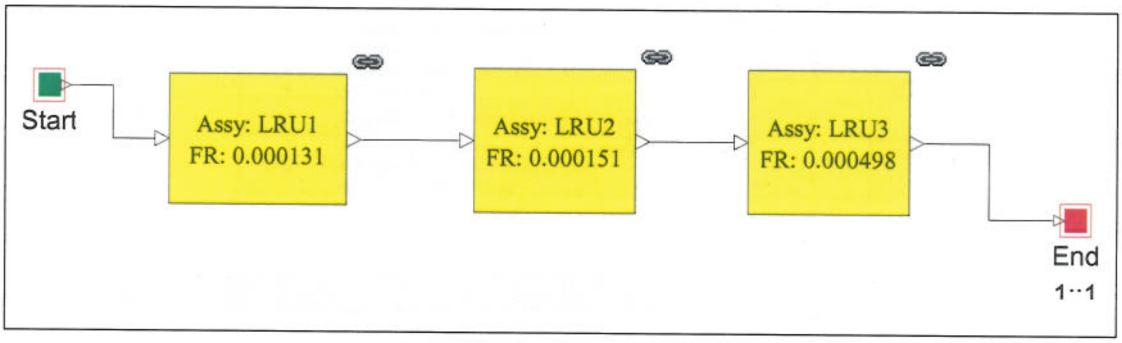


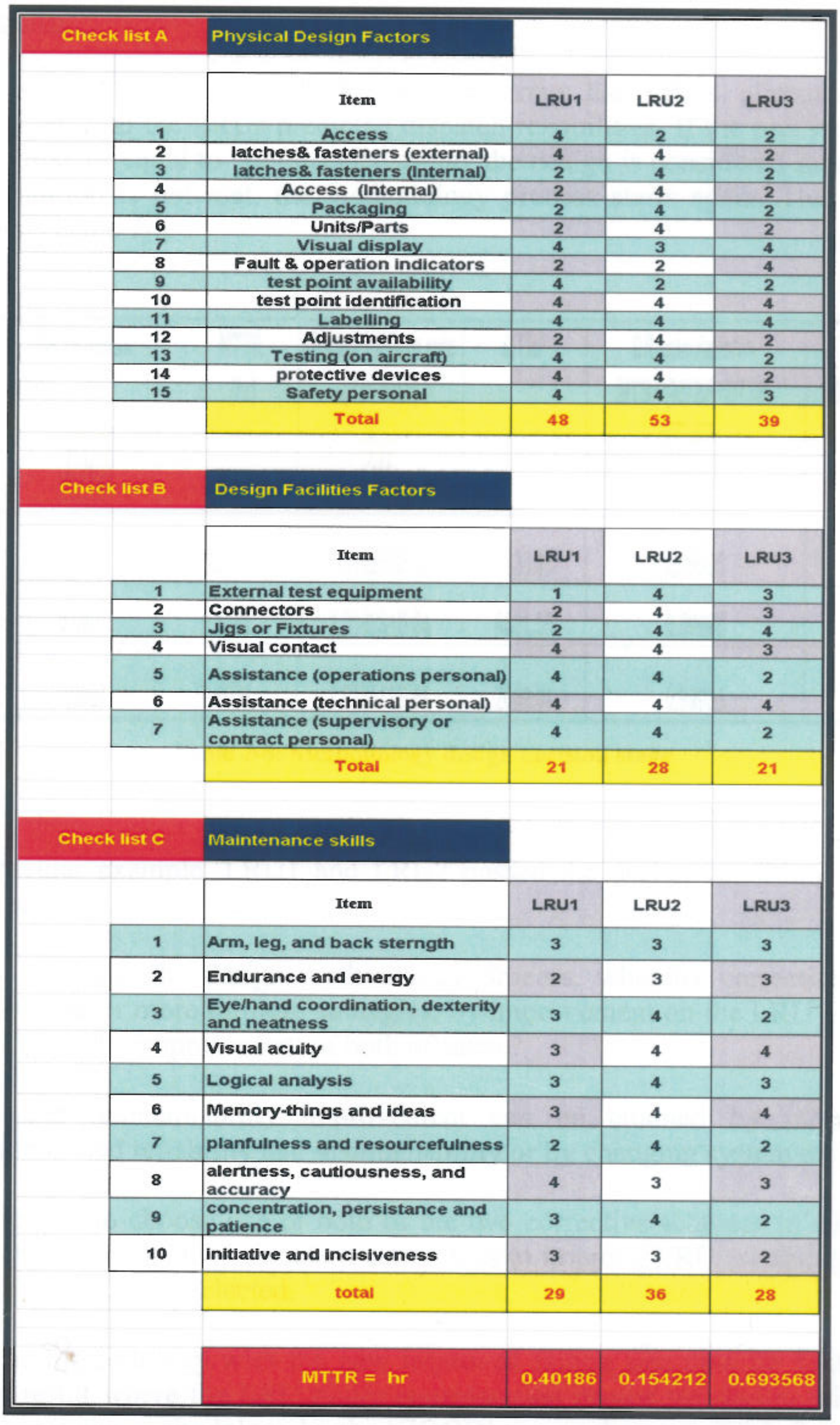
Figure 7-3: sub-system RBD with allocation

LRU	Failure rate hr^{-1}
LRU1	0.000131
LRU2	0.000151
LRU3	0.000498
Total FR	**0.000780**

Table 7-4: LRU allocated failure rate

4. Prediction of the LRUs' mean time to repair (MTTR)

This step was performed by using MIL 472. It has been assumed that these LRUs' were very similar to an existing units that are very well known, and their technical data are available; thus, the prediction of the LRU's mean time to repair becomes feasible. This is shown in Table 7-5 below.



Check list A Physical Design Factors

	Item	LRU1	LRU2	LRU3
1	Access	4	2	2
2	latches& fasteners (external)	4	4	2
3	latches& fasteners (internal)	2	4	2
4	Access (internal)	2	4	2
5	Packaging	2	4	2
6	Units/Parts	2	4	2
7	Visual display	4	3	4
8	Fault & operation indicators	2	2	4
9	test point availability	4	2	2
10	test point identification	4	4	4
11	Labelling	4	4	4
12	Adjustments	2	4	2
13	Testing (on aircraft)	4	4	2
14	protective devices	4	4	2
15	Safety personal	4	4	3
	Total	48	53	39

Check list B Design Facilities Factors

	Item	LRU1	LRU2	LRU3
1	External test equipment	1	4	3
2	Connectors	2	4	3
3	Jigs or Fixtures	2	4	4
4	Visual contact	4	4	3
5	Assistance (operations personal)	4	4	2
6	Assistance (technical personal)	4	4	4
7	Assistance (supervisory or contract personal)	4	4	2
	Total	21	28	21

Check list C Maintenance skills

	Item	LRU1	LRU2	LRU3
1	Arm, leg, and back sterngth	3	3	3
2	Endurance and energy	2	3	3
3	Eye/hand coordination, dexterity and neatness	3	4	2
4	Visual acuity	3	4	4
5	Logical analysis	3	4	3
6	Memory-things and ideas	3	4	4
7	planfulness and resourcefulness	2	4	2
8	alertness, cautiousness, and accuracy	4	3	3
9	concentration, persistance and patience	3	4	2
10	initiative and incisiveness	3	3	2
	total	29	36	28
	MTTR = hr	0.40186	0.154212	0.693568

Table 7-5: LRU mean time to repair (MTTR) prediction

5. Calculation of the LRUs' predicted dispatch reliability

Calculating the LRUs' predicted dispatch reliabilities were performed by substituting the LRUs' mean time between failures (MTBF) and mean time to repair (MTTR) on the dispatch reliability equation (Equation 7-1).

6. Results

The design decision was made by comparing the LRUs allocated dispatch reliabilities with the LRUs predicted dispatch reliabilities. If the predicted value is greater than or equal to the allocated value, the design is considered satisfactory. If this condition is not met, the methodology process starts again. This process is shown in Table 7-6.

LRUs	DR Allocation DR_a	MTTR (hr)	allocated failure rate (Per hour) λ_{a_i}	MTBF	DR calculation = MTBF/(MTBF+MTTR) DR_p	DESIGN DECISSION
LRU1	0.9997	0.4019	1.312258E-04	7620.45	0.99995	GOOD
LRU2	0.9997	0.1542	1.510231E-04	6621.50	0.99998	GOOD
LRU3	0.9997	0.6936	4.977511E-04	2009.04	0.99965	Try again

Table 7-6: Methodology design decision stage

In this particular example, LRU1 and LRU2 passed the design condition, but LRU3 failed to meet it.

LRU3 has to repeat the design methodology process, whereby corrections may be performed by one or more of these strategies; by improvement on the LRU's reliability, maintainability or by improvement of both of them.

Reliability and maintainability improvement can be attained by increasing the component inherited reliability and maintainability or by changing system architecture.

The designer has to choose one or both of the two corrective schemes to alleviate this defect. In this example, the correction action was to improve LRU reliability, whereby a more reliable LRU was selected.

Applying the methodology with the new improved failure rate data for LRU3 offer a satisfactory result where the LRU under consideration passes the design criteria. This was presented in the methodology by the 'GOOD' tag, as shown in Table 7-7.

LRUs	DR Allocation DR_a	MTTR (hr)	allocated failure rate (Per hour) λ_{a_i}	MTBF	DR calculation = MTBF/(MTBF+MTTR) DR_p	DESIGN DECISSION
LRU1	0.9997	0.4019	1.417647E-04	7053.94	0.99994	GOOD
LRU2	0.9997	0.1542	3.317647E-04	3014.18	0.99995	GOOD
LRU3	0.9997	0.6936	3.064706E-04	3262.96	0.99979	GOOD

Table 7-7: Revised methodology design decision stage

7.9.2 Example 2

- **The case**

The aircraft sub-system number two in this example was assumed to be consists of six LRUs, linked as shown in the sub-system reliability block diagram (RBD) Figure 7-4.

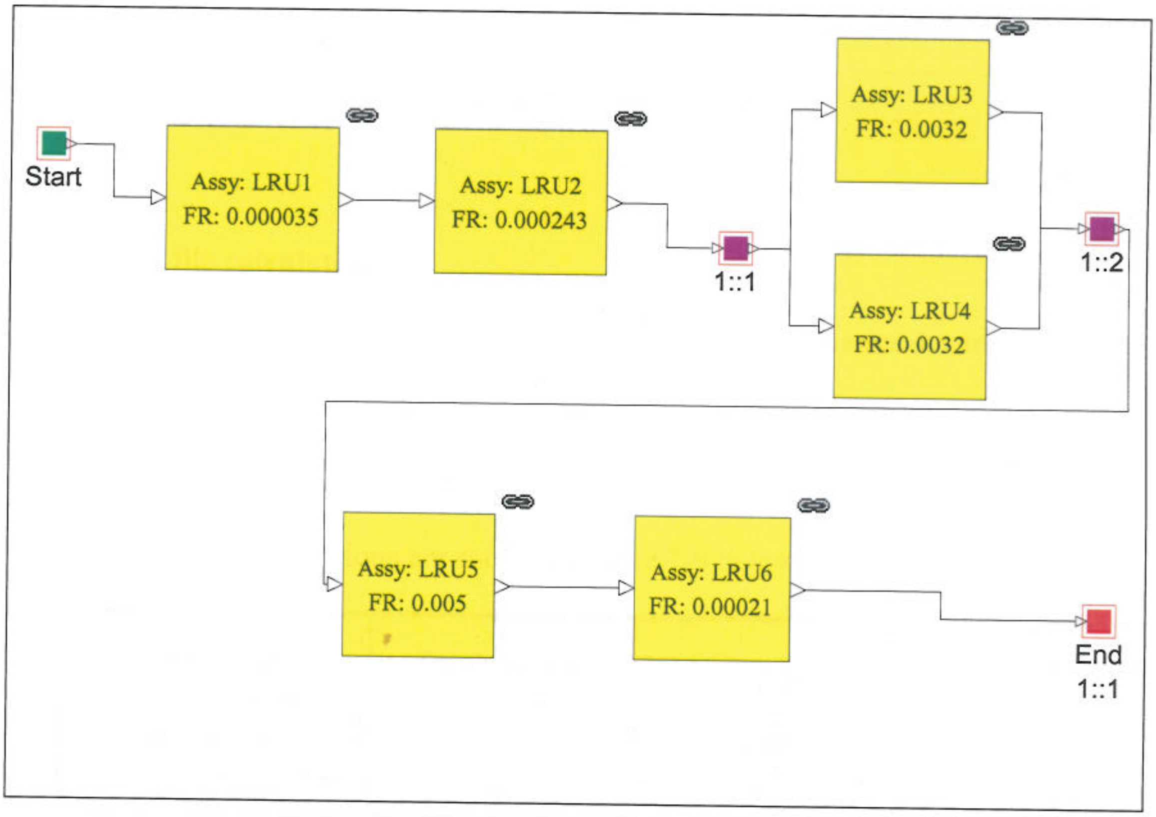


Figure 7-4: Sub-system (2) RBD

- **The requirement**

To design this aircraft sub-system to a specific dispatch reliability target.

- **The specified information**

The required dispatch reliability target for this particular sub-system was *(99.89%)*
The required sub-system failure rate was *(0.00078* hr^{-1}*)*

- **The LRUs Technical Information**

Table 7-8 presents some technical information about the three LRUs.

LRU	Mass (kg)	Size (cm)	Location	Accessibility
LRU1	3	20 × 25 × 15	Starboard wing	Very easy to access & no obstruction
LRU2	5	30 ×30 × 20	Starboard wing	Not very accessible & no obstruction
LRU3	8	40 × 50 × 20	Starboard wing	Not very accessible & blocked
LRU4	8	40 × 50 × 20	Starboard inner-wing	Relatively accessible
LRU5	2	10 × 10 × 10	Starboard wing	very accessible
LRU6	8	30 × 30 × 30	Starboard wing	Not very accessible & blocked

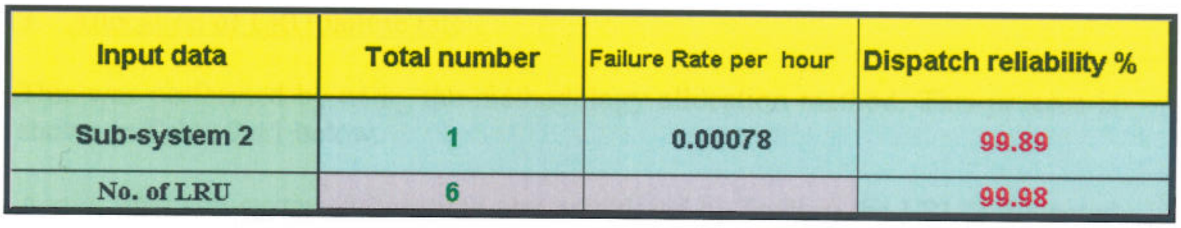
Table 7-8: LRUs technical information

- **Input file calculations**

Initial calculations were performed for the basic data and the results are:

The required sub-system dispatch reliability was set to be = *(99.89)*
The LRU allocated dispatch reliability was equal to *(99.98)*, this was calculated using Equation 7-8.

The input file calculations are shown in Table 7-9 below.



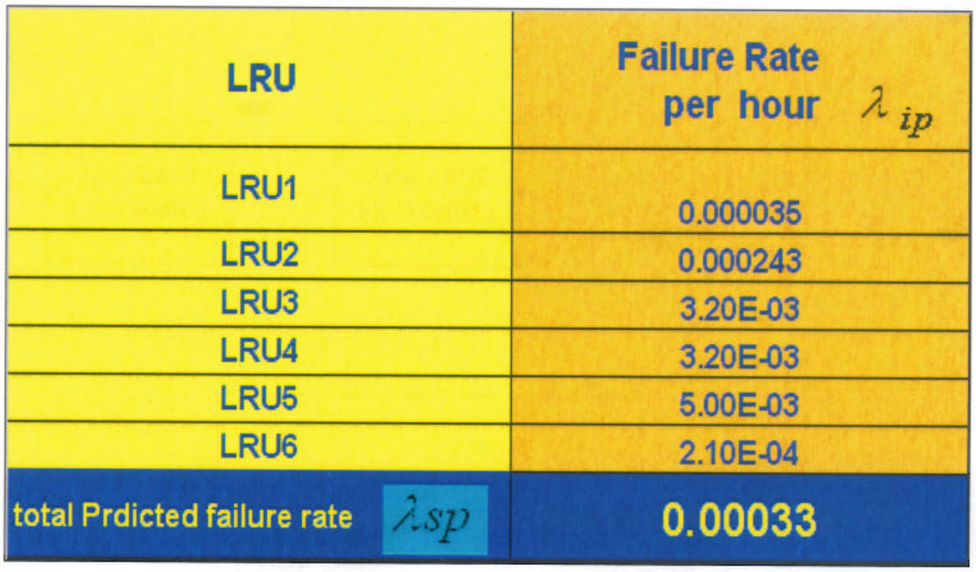
Input data	Total number	Failure Rate per hour	Dispatch reliability %
Sub-system 2	1	0.00078	99.89
No. of LRU	6		99.98

Table 7-9: Sub-system (2) input data

- **The methodology process**

1. Obtaining the LRU's predicted failure rate

In a real life situation, the LRU's predicted failure rate will be obtained from historical data. As this example was for illustration purposes, the LRU's predicted failure rate was assumed to be as shown in Table 7-10 below.



LRU	Failure Rate per hour λ_{ip}
LRU1	0.000035
LRU2	0.000243
LRU3	3.20E-03
LRU4	3.20E-03
LRU5	5.00E-03
LRU6	2.10E-04
total Prdicted failure rate λsp	0.00033

Table 7-10: LRU predicted failure rate

2. <u>Construction of the sub-system reliability block diagram (RBD).</u>

This was done by using Relex software. This is shown in Figure 7-4 above. Also, by using the Relex software, the total sub-system predicted failure rate was calculated, which was equal to 0.00033 hr^{-1}.

3. <u>Allocation of LRU failure rate</u>

This was performed by using the methodology allocation method. This process is shown in Table 7-11 below.

Again, total sub-system failure rate was calculated by feeding the LRU's allocated failure rate to the Relex RBD module for this sub-system as shown in Figure 7-5. The total sub-system allocated failure rate was (*0.000052* hr^{-1}).

LRU	Failure rate hr^{-1}
LRU1	0.000106
LRU2	0.000352
LRU3	0.000384
LRU4	0.000384
LRU5	0.005974
LRU6	0.000313
Total FR	**0.000052**

$\Sigma\ 7.513 \times 10^{-3}$
(.007513)

Table 7-11: Sub-system (2) failure rate allocation

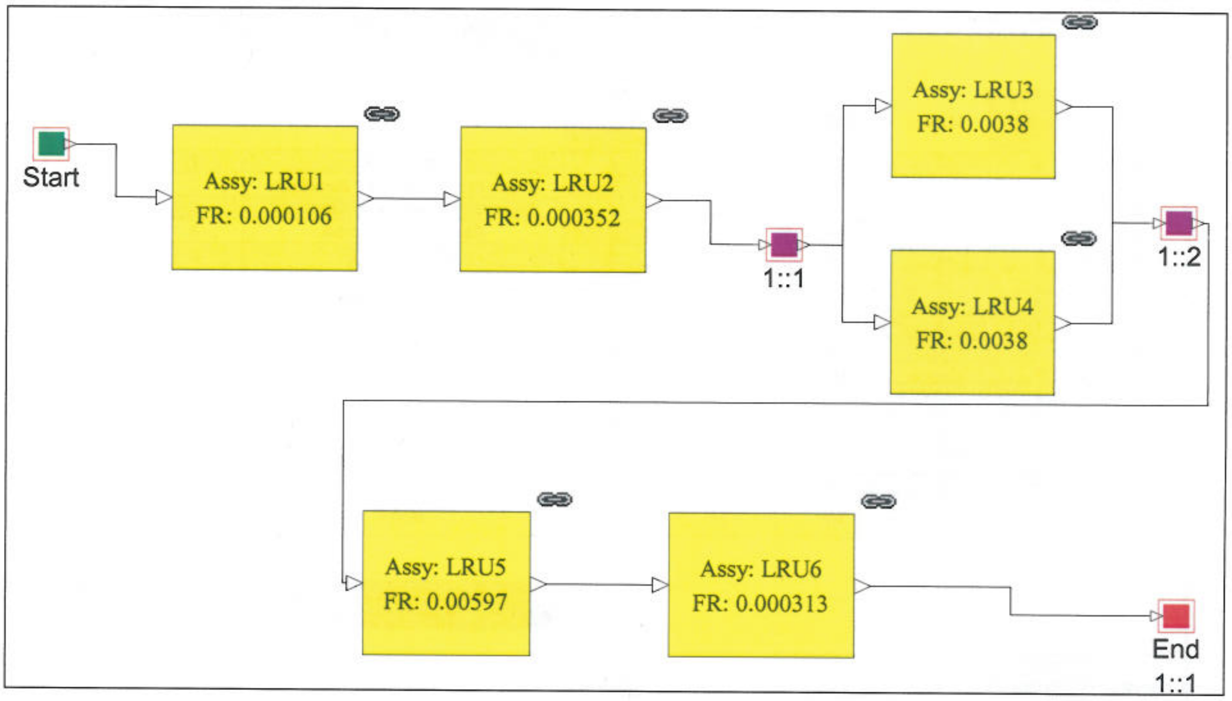


Figure 7-5: Sub-system (2) RBD after allocation

4. Prediction of the LRU mean time to repair (MTTR)

This step was performed by using MIL 472. It has been assumed that these LRU's were very similar to existing units which were very well known, and their technical data were available; thus, the prediction of the LRU's mean time to repair becomes feasible. This is shown in Table 7-12 below.

Check list A **Physical Design Factors**

	Item	LRU1	LRU2	LRU3	LRU4	LRU5	LRU6
1	Access	4	2	4	4	4	2
2	latches& fasteners (external)	4	4	2	2	2	4
3	latches& fasteners (Internal)	2	4	4	4	4	4
4	Access (Internal)	2	4	4	4	4	4
5	Packaging	2	4	4	4	2	4
6	Units/Parts	2	4	4	4	2	4
7	Visual display	4	3	4	4	4	3
8	Fault & operation indicators	2	2	4	4	4	2
9	test point availability	4	2	2	2	2	2
10	test point identification	4	4	4	4	4	4
11	Labelling	4	4	4	4	4	4
12	Adjustments	2	4	2	2	2	4
13	Testing (on aircraft)	4	4	2	2	2	4
14	protective devices	4	4	2	2	2	4
15	Safety personal	4	4	3	3	3	4
	Total	48	53	49	49	45	53

Check list B **Design Facilities Factors**

	Item	LRU1	LRU2	LRU3	LRU4	LRU5	LRU6
1	External test equipment	4	4	4	4	3	4
2	Connectors	2	4	3	3	3	4
3	Jigs or Fixtures	4	4	4	4	4	4
4	Visual contact	4	4	3	3	3	4
5	Assistance (operations personal)	4	4	2	2	2	4
6	Assistance (technical personal)	4	4	4	4	4	4
7	Assistance (supervisory or contract personal)	4	4	4	4	2	4
	Total	26	28	24	24	21	28

Check list C **Maintenance skills**

	Item	LRU1	LRU2	LRU3	LRU4	LRU5	LRU6
1	Arm, leg, and back sterngth	4	4	3	3	4	4
2	Endurance and energy	2	3	3	3	3	3
3	Eye/hand coordination, dexterity and neatness	4	4	2	2	2	4
4	Visual acuity	4	4	4	4	4	4
5	Logical analysis	3	4	3	3	4	4
6	Memory-things and ideas	3	4	4	4	4	4
7	planfulness and resourcefulness	4	4	2	2	2	4
8	alertness, cautiousness, and accuracy	4	3	3	3	3	3
9	concentration, persistance and patience	3	4	2	2	2	4
10	initiative and incisiveness	3	4	4	4	4	3
	total	34	38	30	30	32	37
	MTTR = hr	0.24928	0.146642	0.299488	0.29949	0.44325	0.15038

Table 7-12: Sub-system two LRU mean time to repair (MTTR) prediction

5. Calculation of LRU predicted dispatch reliability

Calculating the LRU's predicted dispatch reliability was performed by substituting the LRU mean time between failures (MTBF) and mean time to repair (MTTR) in the dispatch reliability equation (Equation 7-1).

6. Results

The design decision was made by comparing the LRU's allocated dispatch reliability with the LRU's predicted dispatch reliability. If the predicted value is greater than or equal to the allocated value, the design is considered satisfactory. If this condition is not met, the methodology process starts again. This process is shown in Table 7-13.

LRU	DR Allocation A_a	MTTR (hr)	allocated failure rate (Per hour) λ_{a_i}	MTBF	DR = MTBF/(MTBF+MTTR) A_p	DESIGN DECISSION
LRU1	0.99982	0.24928	1.063636E-04	9401.71	0.99997	GOOD
LRU2	0.99982	0.14664	3.521818E-04	2839.44	0.99995	GOOD
LRU3	0.99982	0.29949	3.846818E-03	259.96	0.99885	Try again
LRU4	0.99982	0.29949	3.846818E-03	259.96	0.99885	Try again
LRU5	0.99982	0.44325	5.974091E-03	167.39	0.99736	Try again
LRU6	0.99982	0.15038	3.131818E-04	3193.03	0.99995	GOOD

Table 7-13: Methodology design condition stage

0.01xx 39 xx 5

In this particular example, LRU1, 2 & 6 passed the design condition, while LRU3, 4& 5 failed to meet it.

These failed LRUs had to repeat the design methodology process, whereby correction action performed by one or more of these strategies; by improvement on the LRU's reliability, maintainability or by improvement of both of them.

The designer has to choose one or more of the above solutions to alleviate this defect.

In this example, the correction action was to improve LRU3&4 reliability characteristics, while it was to improve LRU5 reliability and maintainability characteristics.

Improving reliability characteristics can be by many ways such as simplicity, redundancy, and derating. Maintainability improvement can be achieved by many techniques such as enhancing accessibility, ease of adjustments, reducing the number of components and providing interchangeability.

Applying the methodology with the new improved data offer a satisfactory result where the LRU's under consideration passed the design criteria. This was presented in the methodology by the 'GOOD' tag as shown in Table 7-14.

LRU	DR Allocation A_a	MTTR (hr)	allocated failure rate (Per hour) λ_{a_i}	MTBF	DR = MTBF/(MTBF+MTTR) A_p	DESIGN DECISSION
LRU1	0.99982	0.24928	1.063636E-04	9401.71	0.99997	GOOD
LRU2	0.99982	0.14664	3.521818E-04	2839.44	0.99995	GOOD
LRU3	0.99982	0.29949	4.431818E-04	2256.41	0.99987	GOOD
LRU4	0.99982	0.29949	4.431818E-04	2256.41	0.99987	GOOD
LRU5	0.99982	0.20000	5.377273E-04	1859.68	0.99989	GOOD
LRU6	0.99982	0.15038	3.131818E-04	3193.03	0.99995	GOOD

Table 7-14: Revised methodology design decision stage

$\Sigma\ 2.195818 \times 10^{-3}$

"Experience serves not only to confirm theory, but differs from it without disturbing it, it leads to new truths which theory only has not been able to reach".

Dalembert, Quoted in introduction to PS Girard Traite Analytique de la Resistance des Solides

Chapter 8

Validation and Use of ASDMDR

8.1 Introduction

The developed aircraft systems design methodology for dispatch reliability (ASDMDR) was implemented using a case study to validate it.

A twin-engine long-haul aircraft was selected as the platform for this study. The aircraft mean time between unscheduled removals (MTBUR), mean time between failures (MTBF), mean time to repair (MTTR), and dispatch reliability data were obtained or predicted.

The fundamental argument here was that if the methodology works for any particular aircraft system, it should do the same for any other aircraft system, because the methodology has no steps or rules that are specific to any one system, sub-system or component.

A hydraulic power system was selected for this study, due to the availability of information. Four cases were planned for the examination of the effectiveness and applicability of the methodology. These cases are:

1. Applying the methodology using real values for the failures rate, predicted values for the mean time to repair (MTTR) and dispatch reliability.

2. Applying the methodology using real field data for failures rate, MTTR, and dispatch reliability from an aircraft operator (A)

3. Applying the methodology using real field data for failures rate, MTTR, and dispatch reliability from an aircraft operator (B)

4. Applying the methodology using generic data from the Nonelectronic Parts Reliability Data (NPRD-95) for the failures rate and predicted data for the MTTR and dispatch reliability.

The hydraulic system and sub-system failure rates were obtained from different aircraft operator databases, and the reliability prediction calculation method used was parts count.

8.2 Hydraulic Power System

The hydraulic power system selected for this validation study was for long-haul aircraft. It consists of three sub-systems; right, left and centre. The three sub-systems must be operative in order for the aircraft departure to take place. This means from a dispatch reliability perspective that the three sub-systems were in series configuration.

The three sub-systems provide hydraulic power to different aircraft systems such as flight control, landing gear systems and engine control. For safety reasons, a redundancy concept was implemented, whereby critical aircraft components were provided with the hydraulic power from more than one hydraulic sub-system.

The left and right hydraulic power sub-systems and their components were identical, while centre sub-system was slightly different and more information about it and the validation results are presented in appendix F.

A schematic diagram of the hydraulic system was obtained, which showed that it consists of three sub-systems which were linked in series from dispatch reliability stand point of view as shown in Figure 8-1.

The hydraulic sub-systems were assumed to have equal failure probability. With this assumption, the sub-system failure rate was calculated by dividing the system failure rate by the number of sub-systems. In other cases when more failure rate data are available, real failure rate data will be used for each sub-system.

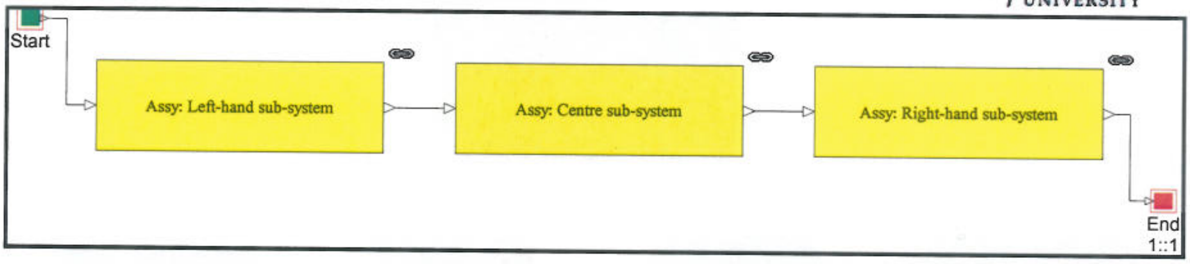


Figure 8-1: Hydraulic sub-systems

8.3 Validation Process

The validation process was applied for all the three hydraulic sub-systems and consists of the following steps:

1. Running the developed methodology using real data for MTBUR, and predicted data for MTTR and dispatch reliability. The outcome of this design methodology will be the sub-system design decision which will determine the success of the design, based on a comparison between the predicted and allocated dispatch reliability.

2. Running the developed methodology using real field data for all the three parameters from the first data source; (A) aircraft operator. The sub-system design decision was thus obtained.

3. Running the developed methodology using the real field data for all the three parameters from the second data source; (B) aircraft operator. The sub-system design decision was thus obtained.

4. Running the developed methodology using NPRD-95 for the MTBF, predicted data for MTTR and dispatch reliability. The sub-system design decision was thus obtained.

5. Comparing the four output parameters.

6. Analyzing the result.

The methodology process was applied for each sub-system independently. A flowchart of the validation process is presented in Figure 8-2.

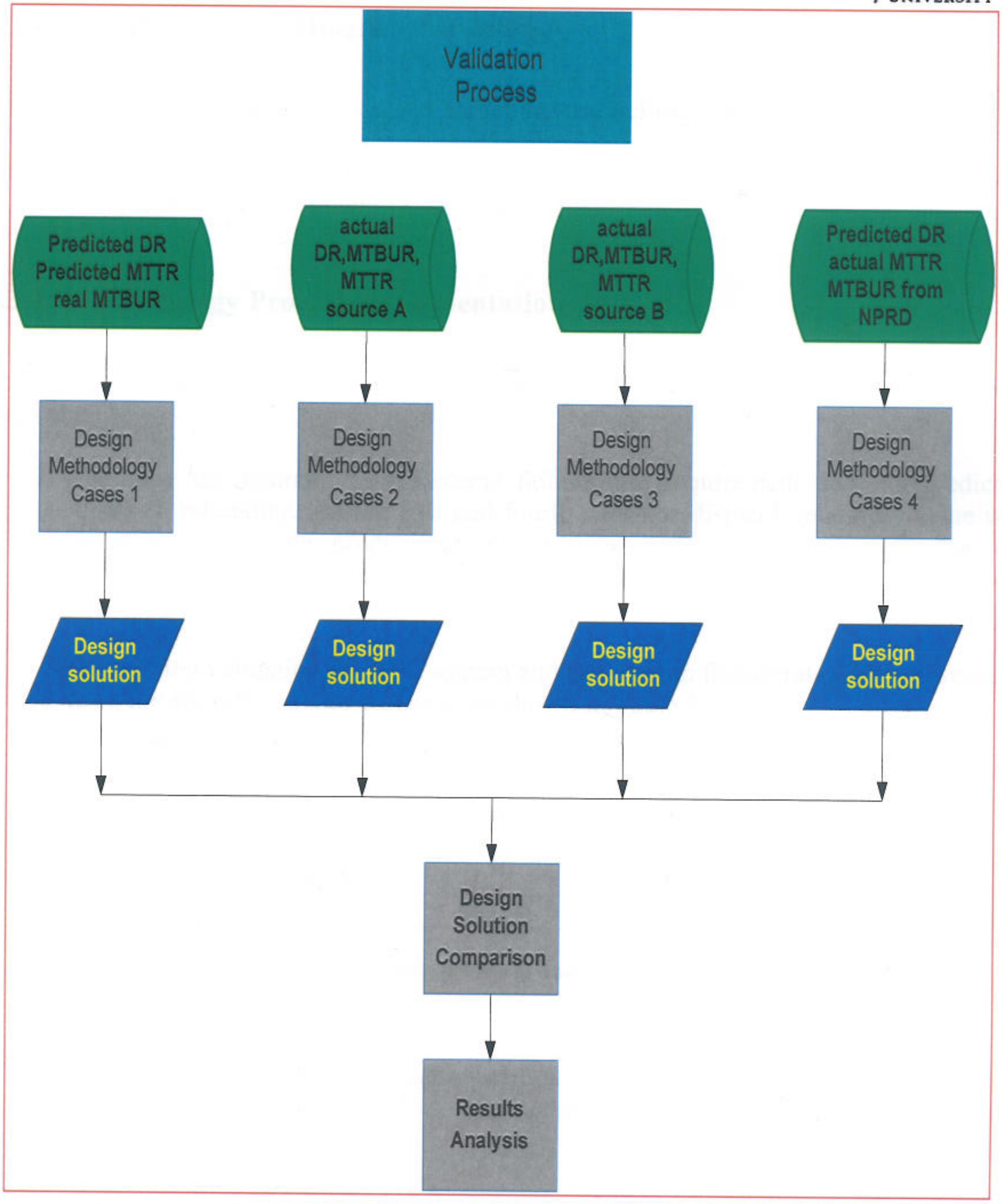


Figure 8-2: Validation process flowchart

8.3.1 Reliability Block Diagram Modelling

The hydraulic system and sub-systems reliability modelling was performed using Relex software [89].

The modelling was undertaken according to the unpublished aircraft schematic diagram and to the aircraft minimum equipment list (MEL)[14].

8.3.2 Methodology Process Implementation

The following methodology steps were performed for each hydraulic sub-system. These steps are:

1. Defining the hydraulic sub-systems failure rate requirement and the predicted dispatch reliability. For the first and fourth case, the dispatch reliability value was predicted using the prediction method developed by the author [10]. For the remaining two validation cases, dispatch reliability was obtained from real field data.

   For the first validation case, the system and sub-system failure rates were collected from the aircraft operator database, as shown in Table 8-1.

Input Data	Total number	Failure Rate hr^{-1}	Dispatch Reliability %
Hydraulic sys.	1	0.0033	99.915
Hyd. Sub-system R	3	0.0011	99.971
LRU	23		

Table 8-1: Hydraulic system basic data for (case 1)

2. Defining the right-hand side sub-system components (LRU). This step was carried out using the hydraulics sub-system architecture. These components (LRU) are shown in Table 8-2.

3. Defining the LRUs' actual failure rates, as shown in Table 8-2. This step was performed using current aircraft operator data for the aircraft under study.

	Component	Failure Rate per hour
1	**Hand Pump**	**0.00002**
2	**Reservoir Fill Selection Valve (RFSV)**	**0.000028**
3	**Pressure Valve (PV)**	**2.80E-05**
4	**Reservoir**	**1.30E-07**
5	**Non Return Valve (NRV)**	**2.70E-05**
6	**Engine Driven Pump (EDP)**	**4.80E-05**
7	**Non Return Valve**	**2.70E-05**
8	**Aircraft Motor Pump (ACMP))**	**8.20E-06**
9	**Non Return Valve**	**2.70E-05**
10	**Pipe**	**1.40E-06**
11	**Pump Overheat Light (POL1)**	**7.11E-05**
12	**Pump Overheat Light (POL2)**	**7.11E-05**
13	**Pump Low Light (PLL1)**	**6.05E-04**
14	**Pump Low Light (PLL2)**	**6.05E-04**
15	**Heat Exchanger (HEX)**	**1.12E-06**
16	**Hydraulic Low Light (HLL1)**	**3.13E-04**
17	**Hydraulic Low Light (HLL2)**	**3.13E-04**
18	**Hydraulic Low Light (HLL3)**	**3.13E-04**
19	**Hydraulic Quantity Indicator (HQI)**	**1.50E-05**
20	**Hose**	**1.10E-05**
21	**Depressurization Valve (DPV)**	**1.07E-04**
22	**Non Return Valve (NRV)**	**2.70E-05**
23	**Moisture Vent Trap (MVT)**	**1.48E-05**

Table 8-2: Actual Hydraulic right-hand side sub-system LRU failure rate (case 1)

4. Constructing the right-hand side sub-system reliability block diagram (RBD) using Relex software, as shown in Figure 8-3. In this step, the general LRU information such as weight, location, accessibility and interchangeability were obtained and documented.

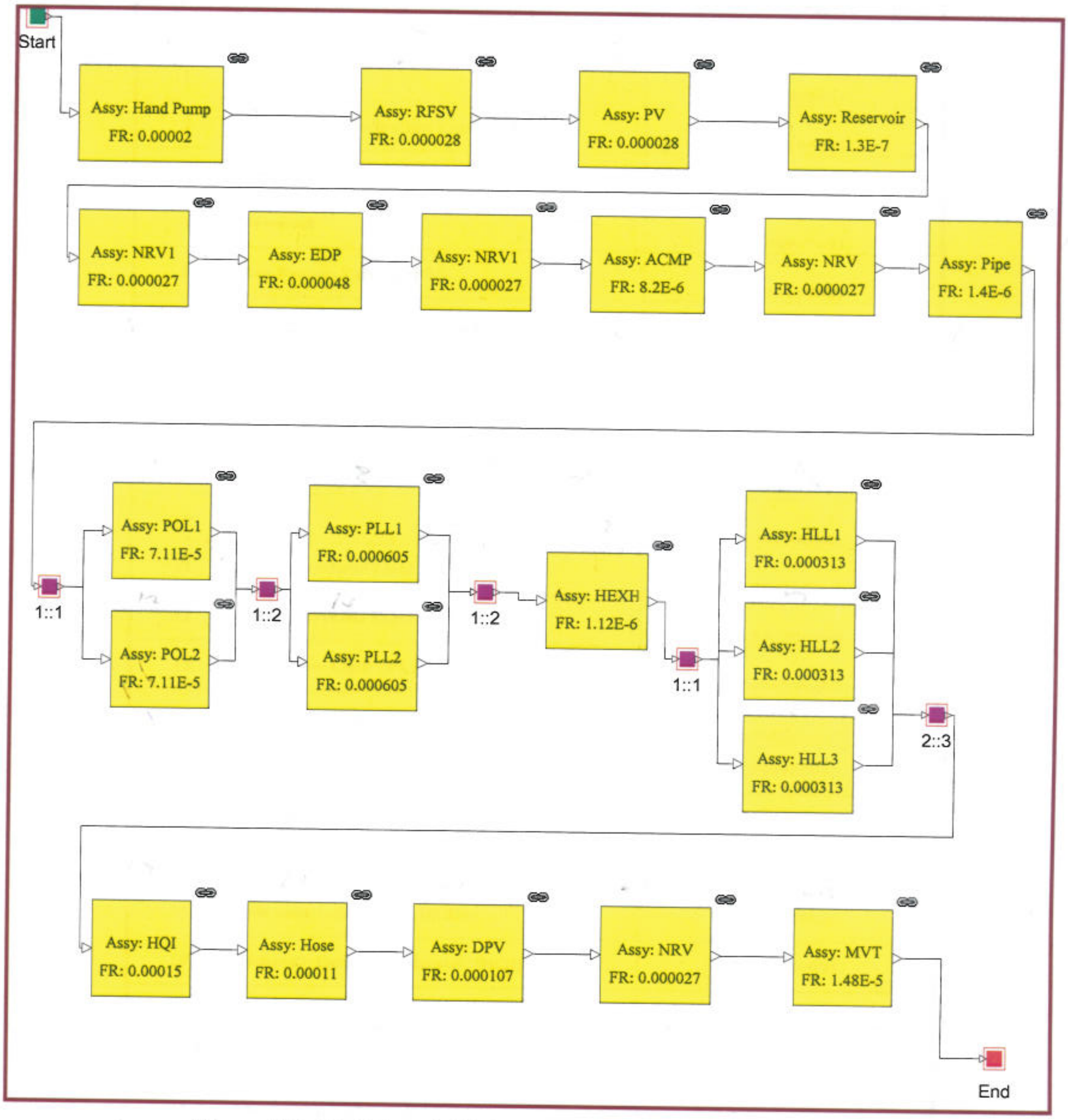


Figure 8-3: Right-hand side hydraulic sub-system RBD (case 1)

5. Allocating the LRU dispatch reliability, as shown in Table 8-3. This was performed using Equation 7-8.

No.	LRU	Dispatch Reliability Allocation
1	Hand Pump	0.999985081
2	Reservoir Fill Selection Valve (RFSV)	0.999985081
3	Pressure Valve (PV)	0.999985081
4	Reservoir	0.999985081
5	Non Return Valve (NRV)	0.999985081
6	Engine Driven Pump (EDP)	0.999985081
7	Non Return Valve	0.999985081
8	Aircraft Motor Pump (ACMP))	0.999985081
9	Non Return Valve	0.999985081
10	Pipe	0.999985081
11	Pump Overheat Light (POL1)	0.996200000
12	Pump Overheat Light (POL2)	0.996200000
13	Pump Low Light (PLL1)	0.996200000
14	Pump Low Light (PLL2)	0.996200000
15	Heat Exchanger (HEX)	0.999985081
16	Hydraulic Low Light (HLL1)	0.975400000
17	Hydraulic Low Light (HLL2)	0.975400000
18	Hydraulic Low Light (HLL3)	0.975400000
19	Hydraulic Quantity Indicator (HQI)	0.999985081
20	Hose	0.999985081
21	Depressurization Valve (DPV)	0.999985081
22	Non Return Valve (NRV)	0.999985081
23	Moisture Vent Trap (MVT)	0.999985081

Table 8-3: Allocated LRU dispatch reliability (case 1)

6. Predicting the LRU mean time to repair (MTTR) using the MIL 472 for the first and fourth case. This is shown in Table 8-4, Table 8-5 and Table 8-6.
   For the other two cases, MTTR were obtained from the operator's databases.

Check list A	Physical Design Factors																
	Item	Hand Pump	PFSV	PV	reservoir	NRV	EDP	AMP	Pipe	POL	PLL	Heat Exchanger	HLL	HQI	Hose	Depressurization valve	Moisture vent trap
1	Access	4	2	2	2	2	2	2	2	3	3	2	3	3	4	4	2
2	latches& fasteners (external)	4	3	2	2	2	2	2	2	3	3	2	3	3	4	4	2
3	latches& fasteners (Internal)	2	3	3	2	2	2	3	3	4	4	2	4	3	4	4	3
4	Access (Internal)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
5	Packaging	2	3	3	2	2	4	2	3	3	4	2	4	3	4	4	3
6	Units/Parts	2	4	3	3	2	4	2	3	3	3	2	3	3	4	3	3
7	Visual display	4	3	4	2	2	4	3	2	3	4	2	4	3	4	4	3
8	Fault & operation indicators	2	2	3	2	2	4	3	3	3	4	2	4	3	4	4	3
9	test point availability	4	2	2	2	2	4	2	3	3	4	2	4	3	4	2	3
10	test point identification	4	3	2	3	2	4	2	3	3	4	2	4	4	2	3	3
11	Labelling	4	4	4	3	2	2	2	3	3	4	2	4	3	4	4	3
12	Adjustments	2	3	4	4	4	2	2	3	2	2	4	2	3	4	4	3
13	Testing (on aircraft)	4	2	2	4	4	2	2	2	2	2	2	2	3	4	4	3
14	protective devices	4	2	3	4	4	2	2	2	3	4	2	4	3	4	4	3
15	Safety personal	4	4	3	3	4	4	2	2	2	2	2	2	3	4	4	
	Total	50	44	44	42	40	46	35	40	44	51	34	51	47	58	56	41

Table 8-4: Predicted Right-hand side sub-system LRU mean time to repair (MTTR) (Check list A) (case 1)

Check list B	Design Facilities Factors																
	Item	Hand Pump	PFSV	PV	reservoir	NRV	EDP	AMP	Pipe	POL	PLL	Heat Exchanger	HLL	HQI	Hose	Depressurization valve	Moisture vent trap
1	External test equipment	1	4	3	2	4	2	2	3	2	2	2	2	3	4	4	2
2	Connectors	2	3	3	2	4	2	2	2	2	2	4	2	3	2	4	2
3	Jigs or Fixtures	2	3	4	3	4	2	2	3	4	4	2	4	4	4	4	2
4	Visual contact	2	3	3	3	4	2	2	3	3	4	4	4	3	4	4	3
5	Assistance (operations personal)	2	3	3	2	2	2	2	3	3	4	4	4	3	4	2	3
6	Assistance (technical personal)	4	3	3	2	2	2	2	3	2	2	2	2	3	4	4	3
7	Assistance (supervisory or contract personal)	4	3	3	2	4	2	2	2	2	2	2	2	3	4	4	3
	Total	17	22	22	16	24	14	14	19	18	20	20	20	22	26	26	18

Table 8-5: Predicted Right-hand side sub-system LRU mean time to repair (MTTR) (Check list B) (case 1)

Check list C **Maintenance skills**

	Item	Hand Pump	PFSV	PV	reservoir	NRV	EDP	AMP	Pipe	POL	PLL	Heat Exchanger	HLL	HQI	Hose	Depressurization Valve	Moisture Vent Trap
1	Arm, leg, and back strength	3	3	2	2	4	2	3	2	2	2	2	2	4	4	4	3
2	Endurance and energy	2	3	4	2	4	2	2	2	3	4	2	4	4	4	4	3
3	Eye/hand coordination, dexterity and neatness	3	4	4	2	4	2	2	2	3	3	2	4	4	4	4	3
4	Visual acuity	3	4	4	2	3	2	2	2	2	2	3	4	4	4	4	3
5	Logical analysis	3	4	4	2	3	4	2	2	2	2	2	3	4	3	3	3
6	Memory-things and ideas	3	4	4	2	3	3	2	2	2	2	3	4	4	4	2	3
7	playfulness and resourcefulness	2	4	4	2	3	4	2	2	2	2	2	4	3	4	2	3
8	alertness, cautiousness, and accuracy	4	3	3	2	3	3	2	2	3	4	2	4	3	4	4	3
9	concentration, persistence and patience	3	4	3	2	3	3	2	2	3	4	2	3	3	4	4	3
10	initiative and incisiveness	3	3	4	2	3	3	2	2	3	4	2	4	3	3	4	3
	total	29	36	36	20	33	28	21	20	25	29	22	36	36	38	35	30
	MTTR = hr	0.47428	0.395821	0.395821	1.01372171	0.467379	0.757005	1.7058	0.92153	0.6917175	0.36246723	1.15562985	0.303919628	0.33277	0.126403	0.153034289	0.725502227

Table 8-6: Predicted Right-hand side sub-system LRU mean time to repair (MTTR) (Check list C) (case 1)

7. The LRU mean time to repair, allocated failure rate and allocated dispatch reliability were fed to the master calculation sheet and the LRU predicted dispatch reliability was calculated using Equation 7-9.

8. The design decision was undertaken at this stage for all LRUs. Right-hand hydraulic sub-system methodology design decision output is shown in Table 8-7.

   The design decisions were based on the LRU dispatch reliability comparison process. The LRU dispatch reliability comparison is a process that compares the predicted and allocated dispatch reliability, and if the predicted dispatch reliability is equal or greater than the allocated dispatch reliability, which is categorized by the tag 'GOOD', the design meets the required target. If not, in which case it is categorized by the tag 'Try again', the design methodology process returns to step 4, where a solution will be sought and the methodology steps repeated.

No.	LRU	Failure Rate per hour	MTBF	MTTR (Hr)	Predicted Dispatch Reliability	Allocated Dispatch Reliability	DESIGN DECISION
1	Hand Pump	0.00002	50000.00	0.47	0.9999905	0.999985	GOOD
2	Reservoir Fill Selection Valve (RFSV)	0.00003	35714.29	0.40	0.9999889	0.999985	GOOD
3	Pressure Valve (PV)	0.00003	35714.29	0.40	0.9999889	0.999985	GOOD
4	Reservoir	0.00000	7692307.69	1.01	0.9999999	0.999985	GOOD
5	Non Return Valve (NRV)	0.00003	37037.04	0.47	0.9999874	0.999985	GOOD
6	Engine Driven Pump (EDP)	0.00005	20833.33	0.76	0.9999637	0.999985	Try again
7	Non Return Valve	0.00003	37037.04	0.47	0.9999874	0.999985	GOOD
8	Aircraft Motor Pump (ACMP))	0.00001	121951.22	1.71	0.9999860	0.999985	GOOD
9	Non Return Valve	0.00003	37037.04	0.47	0.9999874	0.999985	GOOD
10	Pipe	0.0000014	714285.71	0.92	0.9999987	0.999985	GOOD
11	Pump Overheat Light (POL1)	0.00007	14064.70	0.69	0.9999508	0.996200	GOOD
12	Pump Overheat Light (POL2)	0.00007	14064.70	0.69	0.9999508	0.996200	GOOD
13	Pump Low Light (PLL1)	0.00061	1652.89	0.36	0.9997808	0.996200	GOOD
14	Pump Low Light (PLL2)	0.00061	1652.89	0.36	0.9997808	0.996200	GOOD
15	Heat Exchanger (HEX)	0.00000	892857.14	1.16	0.9999987	0.999985	GOOD
16	Hydraulic Low Light (HLL1)	0.00031	3194.89	0.30	0.9999049	0.975400	GOOD
17	Hydraulic Low Light (HLL2)	0.00031	3194.89	0.30	0.9999049	0.975400	GOOD
18	Hydraulic Low Light (HLL3)	0.00031	3194.89	0.30	0.9999049	0.975400	GOOD
19	Hydraulic Quantity Indicator (HQI)	0.00002	66666.67	0.33	0.9999950	0.999985	GOOD
20	Hose	0.00001	90909.09	0.13	0.9999986	0.999985	GOOD
21	Depressurization Valve (DPV)	0.00011	9345.79	0.15	0.9999836	0.999985	Try again
22	Non Return Valve (NRV)	0.00003	37037.04	0.47	0.9999874	0.999985	GOOD
23	Moisture Vent Trap (MVT)	1.48E-05	67567.57	0.73	0.9999893	0.999985	GOOD

Table 8-7: Right-hand side hydraulic sub-system methodology design output (case 1)

9. The second validation case process was performed by applying the developed design methodology using the real field current data from first source (A) for the same aircraft sub-system, and the basic data are shown in Table 8-8. The output results are presented in Table 8-9 to Table 8-11 . For the third case, the basic data are shown in Table 8-12. The output results using the second data source (B) are presented in Table 8-13 to Table 8-15. For the fourth case, the basic data are shown in Table 8-16, and the methodology output results using the NPRD for MTBUR, predicted dispatch reliability and MTTR data are presented in Table 8-17 to Table 8-19.

10. The same procedure was performed for the centre sub-system and the results are shown in Appendix F.

Input Data	**Total number**	**Failure Rate hr^{-1}**	**Dispatch Reliability %**
Hydraulic sys.	1	0.00061	99.93
Hyd. Sub-system R	3	0.000203	99.9766
LRU	23		

Table 8-8: Hydraulic system basic data for (case 2)

Component	Failure Rate per hour
Hand Pump	2.30E-06
Reservoir Fill Selection Valve (RFSV)	4.60E-06
Pressure Valve (PV)	5.60E-06
Reservoir	1.28E-07
Non Return Valve (NRV)	1.72E-05
Engine Driven Pump (EDP)	3.69E-04
Non Return Valve	1.72E-05
Aircraft Motor Pump (ACMP))	1.69E-05
Non Return Valve	1.72E-05
Pipe	3.20E-08
Pump Overheat Light (POL1)	1.49E-04
Pump Overheat Light (POL2)	1.49E-04
Pump Low Light (PLL1)	3.98E-05
Pump Low Light (PLL2)	3.98E-05
Heat Exchanger (HEX)	1.18E-06
Hydraulic Low Light (HLL1)	1.49E-04
Hydraulic Low Light (HLL2)	1.49E-04
Hydraulic Low Light (HLL3)	1.49E-04
Hydraulic Quantity Indicator (HQI)	6.04E-06
Hose	1.16E-05
Depressurization Valve (DPV)	1.28E-06
Non Return Valve (NRV)	1.72E-05
Moisture Vent Trap (MVT)	4.80E-08

Table 8-9: Hydraulic right-hand side sub-system LRU failure rate (case 2)

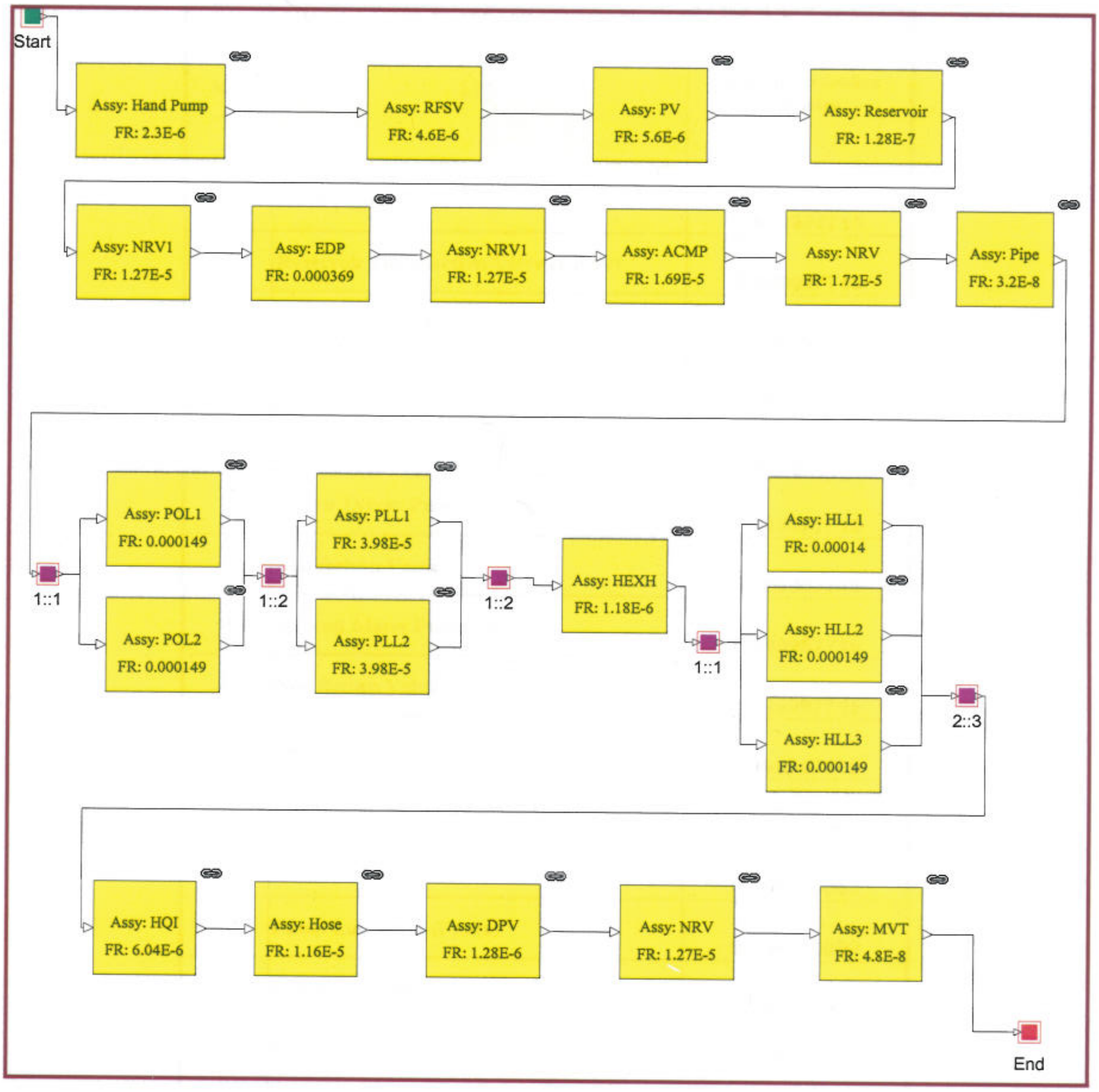


Figure 8-4: Right-hand side hydraulic sub-system RBD (case 2)

No.	LRU	Dispatch Reliability Allocation
1	Hand Pump	0.999987715
2	Reservoir Fill Selection Valve (RFSV)	0.999987715
3	Pressure Valve (PV)	0.999987715
4	Reservoir	0.999987715
5	Non Return Valve (NRV)	0.999987715
6	Engine Driven Pump (EDP)	0.999987715
7	Non Return Valve	0.999987715
8	Aircraft Motor Pump (ACMP))	0.999987715
9	Non Return Valve	0.999987715
10	Pipe	0.999987715
11	Pump Overheat Light (POL1)	0.996500000
12	Pump Overheat Light (POL2)	0.996500000
13	Pump Low Light (PLL1)	0.996500000
14	Pump Low Light (PLL2)	0.996500000
15	Heat Exchanger (HEX)	0.999987715
16	Hydraulic Low Light (HLL1)	0.977000000
17	Hydraulic Low Light (HLL2)	0.977000000
18	Hydraulic Low Light (HLL3)	0.977000000
19	Hydraulic Quantity Indicator (HQI)	0.999987715
20	Hose	0.999987715
21	Depressurization Valve (DPV)	0.999987715
22	Non Return Valve (NRV)	0.999987715
23	Moisture Vent Trap (MVT)	0.999987715

Table 8-10: LRU dispatch reliability allocation (case 2)

No.	LRU	Failure Rate per hour	MTBF	MTTR (Hr)	Predicted Dispatch Reliability	Allocated Dispatch Reliability	DESIGN DECISSION
1	Hand Pump	2.30E-06	434782.609	1.25	0.99999713	0.9999877	GOOD
2	Reservoir Fill Selection Valve (RFSV)	4.60E-06	217391.304	0.40	0.99999816	0.9999877	GOOD
3	Pressure Valve (PV)	5.60E-06	178571.429	1.25	0.99999300	0.9999877	GOOD
4	Reservoir	1.28E-07	7812500.000	2.00	0.99999974	0.9999877	GOOD
5	Non Return Valve (NRV)	1.72E-05	57999.930	0.40	0.99999310	0.9999877	GOOD
6	Engine Driven Pump (EDP)	3.69E-04	2711.497	1.20	0.99955764	0.9999877	Try again
7	Non Return Valve	1.72E-05	57999.930	0.40	0.99999310	0.9999877	GOOD
8	Aircraft Motor Pump (ACMP))	1.69E-05	59171.598	0.70	0.99998817	0.9999877	GOOD
9	Non Return Valve	1.72E-05	57999.930	0.40	0.99999310	0.9999877	GOOD
10	Pipe	3.20E-08	31250000.000	2.50	0.99999992	0.9999877	GOOD
11	Pump Overheat Light (POL1)	1.49E-04	6711.409	0.20	0.99997020	0.9965000	GOOD
12	Pump Overheat Light (POL2)	1.49E-04	6711.409	0.20	0.99997020	0.9965000	GOOD
13	Pump Low Light (PLL1)	3.98E-05	25125.628	0.20	0.99999204	0.9965000	GOOD
14	Pump Low Light (PLL2)	3.98E-05	25125.628	0.20	0.99999204	0.9965000	GOOD
15	Heat Exchanger (HEX)	1.18E-06	847457.627	1.00	0.99999882	0.9999877	GOOD
16	Hydraulic Low Light (HLL1)	1.49E-04	6711.409	0.20	0.99997020	0.9770000	GOOD
17	Hydraulic Low Light (HLL2)	1.49E-04	6711.409	0.20	0.99997020	0.9770000	GOOD
18	Hydraulic Low Light (HLL3)	1.49E-04	6711.409	0.20	0.99997020	0.9770000	GOOD
19	Hydraulic Quantity Indicator (HQI)	6.04E-06	165562.914	0.20	0.99999879	0.9999877	GOOD
20	Hose	1.16E-05	86355.786	1.00	0.99998842	0.9999877	GOOD
21	Depressurization Valve (DPV)	1.28E-06	781250.000	0.40	0.99999949	0.9999877	GOOD
22	Non Return Valve (NRV)	1.72E-05	57999.930	0.40	0.99999310	0.9999877	GOOD
23	Moisture Vent Trap (MVT)	4.80E-08	20833333.333	0.12	0.99999999	0.9999877	GOOD

Table 8-11: Right-hand side hydraulic sub-system methodology design output (case 2)

Input Data	Total number	Failure Rate hr^{-1}	Dispatch Reliability %
Hydraulic sys.	1	0.0004	99.91
Hyd. Sub-system R	3	0.000133	99.969
LRU	23		

Table 8-12: Hydraulic system basic data for (case 3)

Component	Failure Rate per hour
Hand Pump	2.00E-06
Reservoir Fill Selection Valve (RFSV)	9.50E-05
Pressure Valve (PV)	2.51E-05
Reservoir	6.18E-04
Non Return Valve (NRV)	9.50E-05
Engine Driven Pump (EDP)	4.86E-05
Non Return Valve	9.50E-05
Aircraft Motor Pump (ACMP))	3.69E-05
Non Return Valve	9.50E-05
Pipe	1.40E-06
Pump Overheat Light (POL1)	7.11E-05
Pump Overheat Light (POL2)	7.11E-05
Pump Low Light (PLL1)	7.11E-05
Pump Low Light (PLL2)	7.11E-05
Heat Exchanger (HEX)	1.12E-06
Hydraulic Low Light (HLL1)	1.49E-04
Hydraulic Low Light (HLL2)	1.49E-04
Hydraulic Low Light (HLL3)	1.49E-04
Hydraulic Quantity Indicator (HQI)	7.12E-05
Hose	1.16E-04
Depressurization Valve (DPV)	1.07E-04
Non Return Valve (NRV)	9.50E-05
Moisture Vent Trap (MVT)	2.55E-06

Table 8-13: Hydraulic right-hand side sub-system LRU failure rate (case 3)

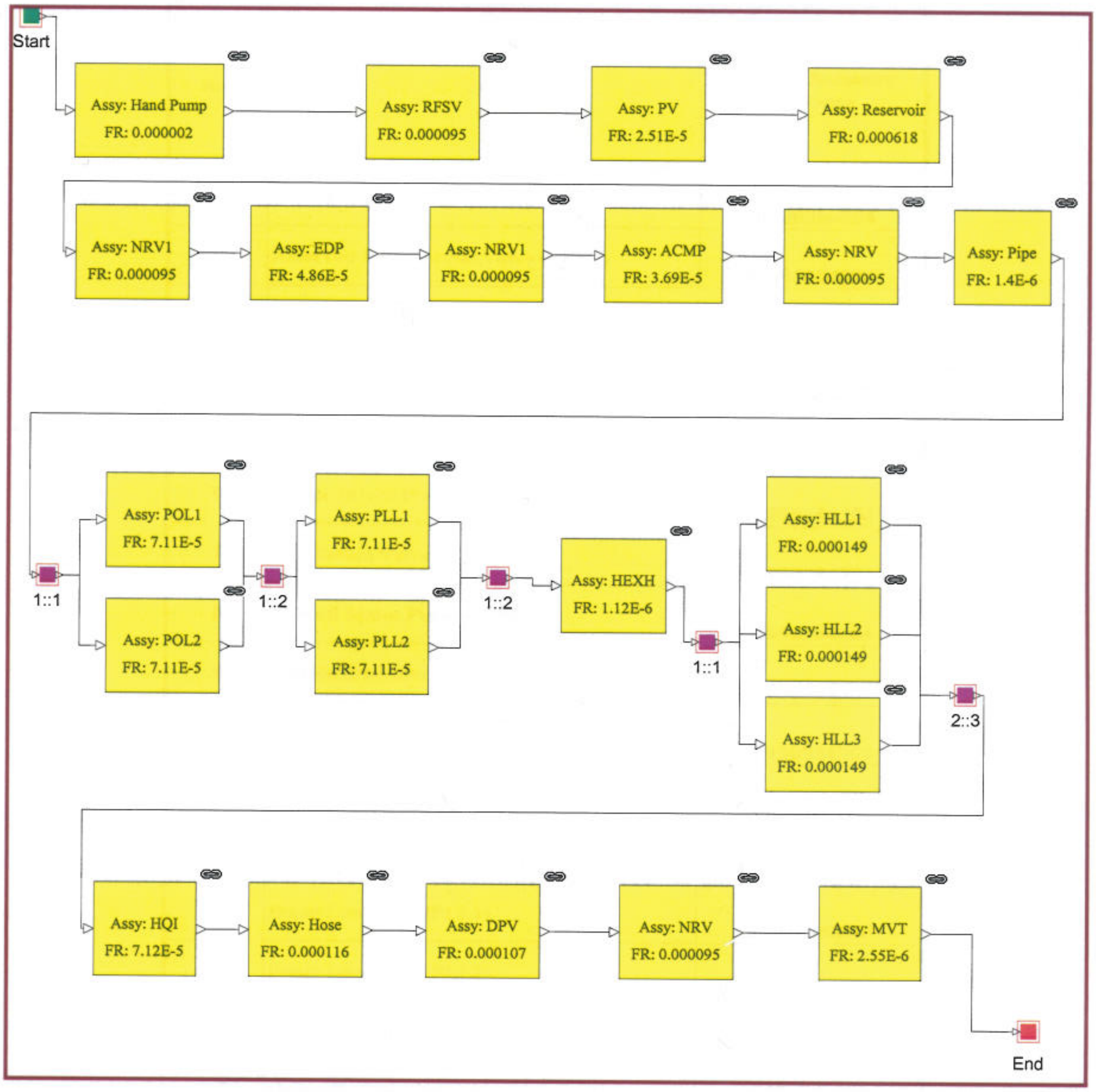


Figure 8-5: Right-hand side hydraulic sub-system RBD (case 3)

No.	LRU	Dispatch Reliability Allocation
1	Hand Pump	0.999984204
2	Reservoir Fill Selection Valve (RFSV)	0.999984204
3	Pressure Valve (PV)	0.999984204
4	Reservoir	0.999984204
5	Non Return Valve (NRV)	0.999984204
6	Engine Driven Pump (EDP)	0.999984204
7	Non Return Valve	0.999984204
8	Aircraft Motor Pump (ACMP))	0.999984204
9	Non Return Valve	0.999984204
10	Pipe	0.999984204
11	Pump Overheat Light (POL1)	0.996300000
12	Pump Overheat Light (POL2)	0.996300000
13	Pump Low Light (PLL1)	0.996300000
14	Pump Low Light (PLL2)	0.996300000
15	Heat Exchanger (HEX)	0.999984204
16	Hydraulic Low Light (HLL1)	0.975000000
17	Hydraulic Low Light (HLL2)	0.975000000
18	Hydraulic Low Light (HLL3)	0.975000000
19	Hydraulic Quantity Indicator (HQI)	0.999984204
20	Hose	0.999984204
21	Depressurization Valve (DPV)	0.999984204
22	Non Return Valve (NRV)	0.999984204
23	Moisture Vent Trap (MVT)	0.999984204

Table 8-14: LRU dispatch reliability allocation (case 3)

No.	LRU	Failure Rate per hour	MTBF	MTTR (Hr)	Predicted Dispatch Reliability	Allocated Dispatch Reliability	DESIGN DECISSION
1	Hand Pump	2.00E-06	500000.0	1.10	0.999998	0.999984	GOOD
2	Reservoir Fill Selection Valve (RFSV)	2.25E-05	44537.0	0.50	0.999989	0.999984	GOOD
3	Pressure Valve (PV)	2.51E-05	39825.0	0.60	0.999985	0.999984	GOOD
4	Reservoir	1.52E-05	65778.0	0.90	0.999986	0.999984	GOOD
5	Non Return Valve (NRV)	1.30E-05	76888.0	1.20	0.999984	0.999984	GOOD
6	Engine Driven Pump (EDP)	4.86E-05	23455.0	0.90	0.999962	0.999984	Try again
7	Non Return Valve	1.30E-05	76888.0	1.20	0.999984	0.999984	GOOD
8	Aircraft Motor Pump (ACMP))	1.24E-05	80544.0	1.25	0.999984	0.999984	GOOD
9	Non Return Valve	1.30E-05	76888.0	1.20	0.999984	0.999984	GOOD
10	Pipe	1.40E-06	714285.7	3.50	0.999995	0.999984	GOOD
11	Pump Overheat Light (POL1)	7.11E-05	14064.7	0.70	0.999950	0.996300	GOOD
12	Pump Overheat Light (POL2)	7.11E-05	14064.7	0.20	0.999986	0.996300	GOOD
13	Pump Low Light (PLL1)	7.11E-05	14064.7	0.70	0.999950	0.996300	GOOD
14	Pump Low Light (PLL2)	7.11E-05	14064.7	0.20	0.999986	0.996300	GOOD
15	Heat Exchanger (HEX)	1.12E-06	895776.4	1.80	0.999998	0.999984	GOOD
16	Hydraulic Low Light (HLL1)	1.49E-04	6711.4	2.00	0.999702	0.975000	GOOD
17	Hydraulic Low Light (HLL2)	1.49E-04	6711.4	2.00	0.999702	0.975000	GOOD
18	Hydraulic Low Light (HLL3)	1.49E-04	6711.4	0.50	0.999926	0.975000	GOOD
19	Hydraulic Quantity Indicator (HQI)	7.12E-05	14050.9	0.20	0.999986	0.999984	GOOD
20	Hose	1.16E-04	8620.7	1.00	0.999884	0.999984	Try again
21	Depressurization Valve (DPV)	1.31E-05	76552.0	1.20	0.999984	0.999984	GOOD
22	Non Return Valve (NRV)	1.30E-05	76888.0	1.20	0.999984	0.999984	GOOD
23	Moisture Vent Trap (MVT)	2.55E-06	392156.9	1.20	0.999997	0.999984	GOOD

Table 8-15: Right-hand side hydraulic sub-system methodology design output (case 3)

Input Data	Total number	Failure Rate hr^{-1}	Dispatch Reliability %
Hydraulic sys.	1	0.002	99.915
Hyd. Sub-system R	3	0.000666	99.971
LRU	23		

Table 8-16: Hydraulic system basic data for (case 4)

Component	Failure Rate per hour
Hand Pump	2.30E-06
Reservoir Fill Selection Valve (RFSV)	3.43E-05
Pressure Valve (PV)	2.90E-06
Reservoir	1.28E-07
Non Return Valve (NRV)	9.49E-05
Engine Driven Pump (EDP)	3.69E-04
Non Return Valve	9.49E-05
Aircraft Motor Pump (ACMP))	1.69E-05
Non Return Valve	9.49E-05
Pipe	3.20E-08
Pump Overheat Light (POL1)	1.49E-04
Pump Overheat Light (POL2)	1.49E-04
Pump Low Light (PLL1)	3.98E-05
Pump Low Light (PLL2)	3.98E-05
Heat Exchanger (HEX)	1.62E-05
Hydraulic Low Light (HLL1)	1.49E-04
Hydraulic Low Light (HLL2)	1.49E-04
Hydraulic Low Light (HLL3)	1.49E-04
Hydraulic Quantity Indicator (HQI)	7.12E-05
Hose	1.16E-04
Depressurization Valve (DPV)	1.28E-06
Non Return Valve (NRV)	9.49E-05
Moisture Vent Trap (MVT)	4.80E-08

Table 8-17: Hydraulic right-hand side sub-system LRU failure rate (case 4)

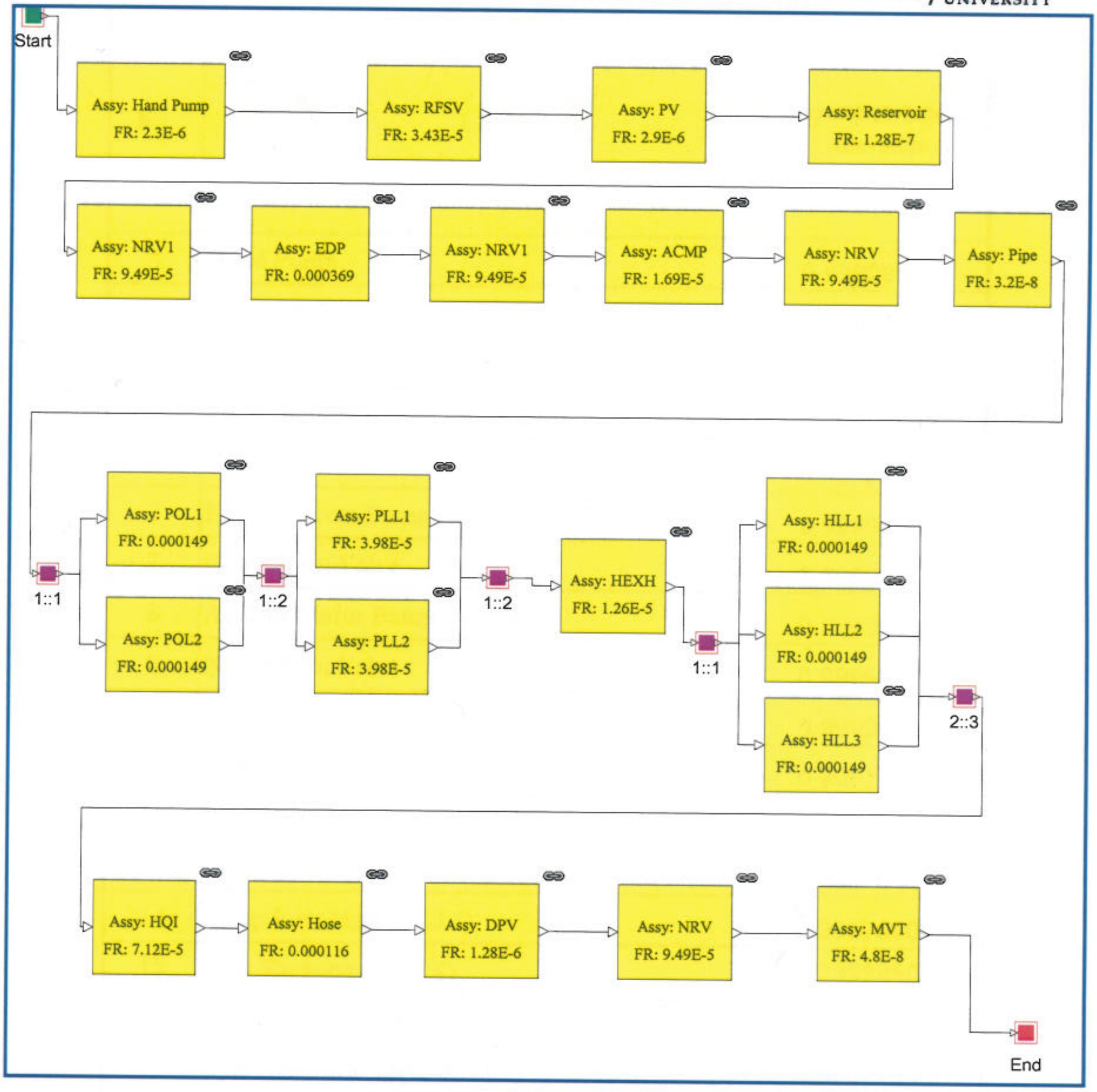


Figure 8-6: Right-hand side hydraulic sub-system RBD (case 4)

No.	LRU	Dispatch Reliability Allocation
1	Hand Pump	0.999985081
2	Reservoir Fill Selection Valve (RFSV)	0.999985081
3	Pressure Valve (PV)	0.999985081
4	Reservoir	0.999985081
5	Non Return Valve (NRV)	0.999985081
6	Engine Driven Pump (EDP)	0.999985081
7	Non Return Valve	0.999985081
8	Aircraft Motor Pump (ACMP))	0.999985081
9	Non Return Valve	0.999985081
10	Pipe	0.999985081
11	Pump Overheat Light (POL1)	0.995700000
12	Pump Overheat Light (POL2)	0.995700000
13	Pump Low Light (PLL1)	0.995700000
14	Pump Low Light (PLL2)	0.995700000
15	Heat Exchanger (HEX)	0.999985081
16	Hydraulic Low Light (HLL1)	0.973200000
17	Hydraulic Low Light (HLL2)	0.973200000
18	Hydraulic Low Light (HLL3)	0.973200000
19	Hydraulic Quantity Indicator (HQI)	0.999985081
20	Hose	0.999985081
21	Depressurization Valve (DPV)	0.999985081
22	Non Return Valve (NRV)	0.999985081
23	Moisture Vent Trap (MVT)	0.999985081

Table 8-18: LRU dispatch reliability allocation (case 4)

No.	LRU	Failure Rate per hour	MTBF	MTTR (Hr)	Predicted Dispatch Reliability	Allocated Dispatch Reliability	DESIGN DECISION
1	Hand Pump	2.30E-06	434782.6	0.47	0.99999891	0.999985	GOOD
2	Reservoir Fill Selection Valve (RFSV)	3.43E-05	29154.5	0.40	0.99998642	0.999985	GOOD
3	Pressure Valve (PV)	2.90E-06	344827.6	0.40	0.99999885	0.999985	GOOD
4	Reservoir	1.28E-07	7812500.0	1.50	0.99999981	0.999985	GOOD
5	Non Return Valve (NRV)	7.37E-06	135685.2	0.90	0.99999337	0.999985	GOOD
6	Engine Driven Pump (EDP)	3.69E-04	2711.5	1.50	0.99944711	0.999985	Try again
7	Non Return Valve	7.37E-06	135685.2	0.90	0.99999337	0.999985	GOOD
8	Aircraft Motor Pump (ACMP))	1.69E-05	59171.6	1.71	0.99997117	0.999985	Try again
9	Non Return Valve	7.37E-06	135685.2	0.90	0.99999337	0.999985	GOOD
10	Pipe	3.20E-08	31250000.0	0.92	0.99999997	0.999985	GOOD
11	Pump Overheat Light (POL1)	1.49E-04	6711.4	0.90	0.99986592	0.995700	GOOD
12	Pump Overheat Light (POL2)	1.49E-04	6711.4	0.90	0.99986592	0.995700	GOOD
13	Pump Low Light (PLL1)	3.98E-05	25125.6	0.90	0.99996418	0.995700	GOOD
14	Pump Low Light (PLL2)	3.98E-05	25125.6	0.90	0.99996418	0.995700	GOOD
15	Heat Exchanger (HEX)	1.62E-05	61728.4	1.16	0.99998128	0.999985	Try again
16	Hydraulic Low Light (HLL1)	1.49E-04	6711.4	0.90	0.99986592	0.973200	GOOD
17	Hydraulic Low Light (HLL2)	1.49E-04	6711.4	0.90	0.99986592	0.973200	GOOD
18	Hydraulic Low Light (HLL3)	1.49E-04	6711.4	0.90	0.99986592	0.973200	GOOD
19	Hydraulic Quantity Indicator (HQI)	7.12E-05	14050.9	0.33	0.99997632	0.999985	Try again
20	Hose	1.16E-04	8635.6	0.13	0.99998536	0.999985	GOOD
21	Depressurization Valve (DPV)	1.28E-06	781250.0	0.15	0.99999980	0.999985	GOOD
22	Non Return Valve (NRV)	7.37E-06	135685.2	0.47	0.99999656	0.999985	GOOD
23	Moisture Vent Trap (MVT)	4.80E-08	20833333.3	0.73	0.99999997	0.999985	GOOD

Table 8-19: Right-hand side hydraulic sub-system methodology design output (case 4)

8.4 Validation Results

The right and left-hand hydraulic sub-systems on the aircraft selected for this case study were identical, thus all the results are the same. The centre hydraulic sub-system results are shown in Appendix F.

In an ideal situation, when dispatch reliability, mean time between failures, and mean time to repair are all real and accurate data, the result should show that all LRUs pass the design criteria. This is because LRUs dispatch reliability was attained. Any case result was judged against this baseline. The design criterion is a condition whereby predicted component dispatch reliability should be equal or greater than allocated dispatch reliability.

The validation results were interpreted in percentage format, by calculating the design success percentage. Design success percentage represents the achieved (predicted) dispatch reliability by using the methodology to the allocated (required) dispatch reliability. The required, predicted and design success percentage for the four validation cases are presented in Table 8-20.

In the first validation case where dispatch reliability and mean time to repair (MTTR) were obtained by prediction, while failure rates were collected from aircraft operator data, the result revealed that all LRUs, except two, passed the design requirement. They were the engine driven pump (EDP) and depressurization valve. The success of the design methodology can be calculated as a percentage in terms of dispatch reliability, and the resulting design success percentage for the first case was 99.96%.

In the second and third cases, all the three variables were real field data from aircraft operator data. For case two, the results showed that only one LRU failed to pass the design criteria. This was the engine driven pump (EDP). The design success percentage for this case was 99.973%.

On the third validation case, two LRUs failed to meet the design criteria, those were engine driven pump (EDP) and the Hose item. The design success was more than 99.968%.

On the last validation case, four LRUs failed to meet the design criteria. Those were engine driven pump, aircraft motor pump, heat exchanger, and the warning light (HQI). The design success was about 99.93%.

Validation cases	No. of Failed LRU	Required dispatch reliability %	Predicted dispatch reliability %	Success %
Case 1	2	99.972	99.940	99.960
Case 2	1	99.976	99.949	99.973
Case 3	2	99.969	99.938	99.968
Case 4	4	99.972	99.900	99.930

Table 8-20: Validation results

8.5 Validation Discussions

The engine driven pump (EDP) failed to pass the design criteria in all validation cases which suggest that this might be due to some reasons specific to this LRU. These reasons could be inaccuracy of the collected aircraft operator data, or it might be true that this LRU lacks reliability, maintainability characteristics or both of them, but had been maintained in such away that did not reflect in the sub-system dispatch reliability. This is can be by performing more inspections to this LRU, imposing a life time limit, by introducing special preventive maintenance program or by combination of them.

However, applying the developed design methodology (ASDMDR) to the design of new aircraft, the methodology process will tackle this shortfall by implementing a design amendment action and then reapplying the methodology until the desired target is achieved. The design amendment actions could be modifying the LRU reliability, or maintainability features, or both. However in this validation exercise, this step is not implemented.

The LRU design criteria results for the second and third validation cases were the closest among all cases to complete success. This was the expected result since all the three variables were real data, obtained from aircraft operators.

In the first validation case, the result was very good, since dispatch reliability and MTTR data were predicted, which reflects the accuracy of the developed methodology and the prediction technique.

The fourth case result was as expected, as the less close among the four cases to the ideal result. This was understandable because all the three parameters dispatch reliability, MTTR and MTBF were predicted data, and the latter in particular was obtained from a generic source which would be anticipated to possess some inaccuracy.

However, the overall results for the left and right-hand sub-systems in all four cases showed high validity of the developed design methodology.

When combining the three sub-system results which form the total hydraulic system validation result, the first validation case showed that only six line replaceable unit (LRU) out of 71 LRUs failed to achieve the design criteria. For the second case, four LRUs failed to achieve the design criteria. For the third case, also four LRUs failed to achieve the design criteria.
For the fourth case, the hydraulic system validation results showed that ten LRUs failed to achieve the design criteria.

The main conclusion drawn out of this validation exercise was that the developed aircraft design methodology can be a very useful and effective tool to design an aircraft to a specific dispatch reliability target with great confidence. The methodology accuracy relies very heavily on the data used and effort should be exerted to find the most accurate.
The Relex reliability software used for this work proved to be very powerful tool for reliability work.

8.6 ASDMDR as Design Improvement Tool

8.6.1 Introduction

The main function of the developed ASDMDR is to design an aircraft system for dispatch reliability target during the very early design stage. Moreover, aircraft design improvement can be achieved by the methodology.

This is by providing aircraft system designer with a reliability design tool that can help them to evaluate and improve their design from dispatch reliability standpoint during early design stage. Actual reliability and maintainability design characteristics can be improved by implementing this design methodology.

The design improvement role of the ASMDR was evaluated in a case study, where the fuel supply sub-system of a selected aircraft was the platform for the study.

This exercise was performed by increasing the dispatch reliability target to a specific level, and implementing the design methodology to achieve this new goal.

8.6.2 Fuel Supply Sub-system Design Improvement Process

Aircraft fuel supply sub-system was selected to undergo a design improvement program using the developed aircraft system design methodology for dispatch reliability (ASDMDR).

This procedure was performed as follows:

1. Applying the ASDMDR with actual data for dispatch reliability (99.8899%), failure rate requirement, MTBUR and MTTR as shown in Table 8-21. The methodology steps are shown in Tables 8- 22 to 8-24.

Input Data	**Total number**	**Failure Rate hr^{-1}**	**Dispatch Reliability%**
Fuel Supply Sub-system	**1**	**0.0003**	**99.8899**
LRU	**33**		

Table 8-21: Fuel supply sub-system basic data

No.	Component	Failure Rate per hour
1	Negative 'G' Tank	1.60E-08
2	Vent Tank	1.67E-07
3	Syphon Pipe	2.40E-06
4	Water Drain1	1.60E-08
5	Water Drain2	1.60E-08
6	Flap Valve 1	3.76E-05
7	Flap Valve 2	3.76E-05
8	Flap Valve 3	3.76E-05
9	Flap Valve 4	3.76E-05
10	Collector Tank	4.76E-06
11	Scavenge Tank	4.15E-06
12	Low Pressure Valve	6.50E-05
13	Pipe	6.41E-08
14	Shut-Off Switch	3.17E-04
15	Vent Duct	1.60E-05
16	Flow Shut-Off Valve	9.94E-07
17	Engine Fuel Pump	2.25E-06
18	Non Return Valve (NRV)	4.29E-07
19	Scavenge Jet Pump1	6.90E-05
20	Scavenge Jet Pump2	6.90E-05
21	Primary Collector Pump	6.90E-05
22	Stand-By Collector Pump	6.90E-05
23	Non Return Valve (NRV)	4.29E-07
24	Cross Feed Valve	4.29E-05
25	Quantity Measure Probe	1.11E-06
26	Fuel Pressure Switch	1.38E-05
27	Fuel Low Pressure Warning Light	7.12E-05
28	Fuel Differential Pressure Switch	1.43E-04
29	Fuel Flow Warning Switch	3.50E-05
30	Fuel Temperature Switch	5.79E-06
31	Warning Switch	6.90E-05
32	Quantity Gauge	1.57E-06
33	Low fuel warning light	1.57E-06
Total Predicted Failure Rate =		8.16E-04

Table 8-22: Fuel supply sub-system LRU failure rate

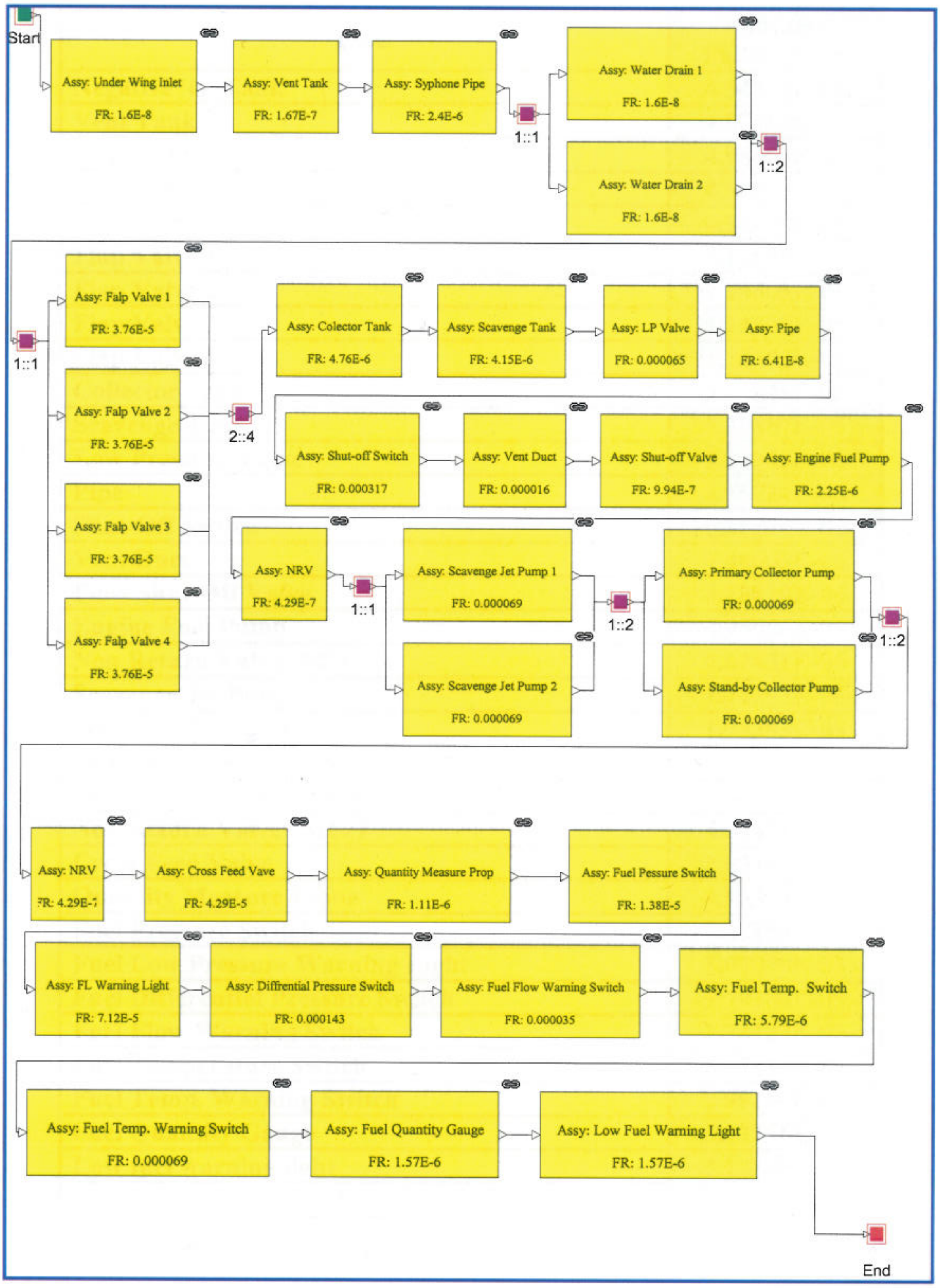


Figure 8-7: Fuel supply sub-system RBD

LRU	Allocated Failure Rate
Negative 'G' Tank	4.54840E-06
Vent Tank	4.57615E-06
Syphon Pipe	4.98663E-06
Water Drain1	4.54840E-06
Water Drain2	4.54840E-06
Flap Valve 1	1.14605E-05
Flap Valve 2	1.14605E-05
Flap Valve 3	1.14605E-05
Flap Valve 4	1.14605E-05
Collector Tank	5.42045E-06
Scavenge Tank	5.30867E-06
Low Pressure Valve	1.64940E-05
Pipe	4.55724E-06
Shut-Off Switch	6.28524E-05
Vent Duct	7.48663E-06
Flow Shut-Off Valve	4.72818E-06
Engine Fuel Pump	4.95906E-06
Non Return Valve (NRV)	4.62431E-06
Scavenge Jet Pump1	1.72293E-05
Scavenge Jet Pump2	1.72293E-05
Primary Collector Pump	1.72293E-05
Stand-By Collector Pump	1.72293E-05
Non Return Valve (NRV)	4.62431E-06
Cross Feed Valve	2.03168E-05
Quantity Measure Probe	4.95354E-06
Fuel Pressure Switch	9.61156E-06
Fuel Low Pressure Warning Light	3.07090E-05
Fuel Differential Pressure Switch	5.70380E-05
Fuel Flow Warning Switch	1.74127E-05
Fuel Temperature Switch	6.67338E-06
Fuel Temp. Warning Switch	2.99114E-05
Fuel Quantity Gauge	5.12266E-06
Low fuel warning light	5.12266E-06
Total	2.49000E-04

Table 8-23: Fuel supply sub-system LRU allocated failure rates

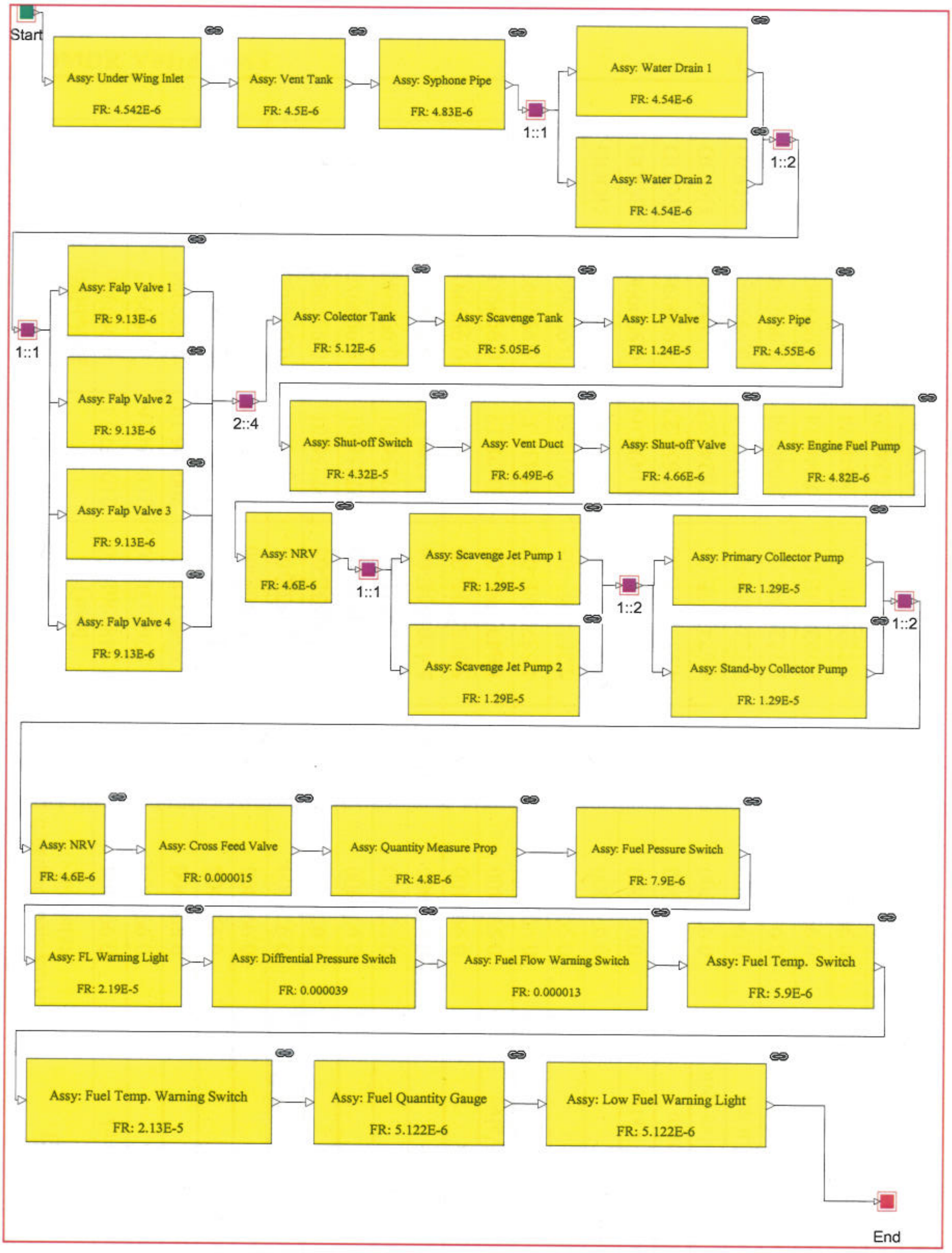


Figure 8-8: Fuel supply sub-system LRU allocated failure rates RBD

No	LRU	Allocated Dispatch Reliability	MTTR (hour)	Allocated failure rate (Per hour)	MTBF	Predicted Dispatch Reliability	Design Decision
1	Negative 'G' Tank	0.999966	0.87	4.548396E-06	219857.74	0.999996	GOOD
2	Vent Tank	0.999966	0.98	4.576153E-06	218524.16	0.999995	GOOD
3	Syphone Pipe	0.999966	1.04	4.986631E-06	200536.19	0.999994	GOOD
4	Water Drain1	0.996400	0.31	4.548396E-06	219857.74	0.999998	GOOD
5	Water Drain2	0.996400	0.31	4.548396E-06	219857.74	0.999998	GOOD
6	Flap Valve 1	0.978000	1.68	1.146053E-05	87256.01	0.999980	GOOD
7	Flap Valve 2	0.978000	1.68	1.146053E-05	87256.01	0.999980	GOOD
8	Flap Valve 3	0.978000	1.68	1.146053E-05	87256.01	0.999980	GOOD
9	Flap Valve 4	0.978000	1.68	1.146053E-05	87256.01	0.999980	GOOD
10	Collector Tank	0.978000	0.94	5.420455E-06	184486.37	0.999994	GOOD
11	Scavenge Tank	0.996400	1.68	5.308671E-06	188371.05	0.999991	GOOD
12	Low Pressure Valve	0.996400	0.71	1.649398E-05	60628.17	0.999988	GOOD
13	Pipe	0.996400	0.62	4.557238E-06	219431.17	0.999997	GOOD
14	Shut-Off Switch	0.996400	0.60	6.285244E-05	15910.28	0.999962	GOOD
15	Vent Duct	0.978000	0.85	7.486631E-06	133571.43	0.999993	GOOD
16	Flow Shut-Off Valve	0.978000	0.75	4.728175E-06	211498.09	0.999996	GOOD
17	Engine Fuel Pump	0.978000	0.88	4.959057E-06	201651.22	0.999995	GOOD
18	Non Return Valve (NRV)	0.978000	0.72	4.624315E-06	216248.25	0.999996	GOOD
19	Scavenge Jet Pump1	0.996400	0.77	1.722928E-05	58040.74	0.999986	GOOD
20	Scavenge Jet Pump2	0.996400	0.77	1.722928E-05	58040.74	0.999986	GOOD
21	Primary Collector Pump	0.996400	0.91	1.722928E-05	58040.74	0.999984	GOOD
22	Stand-By Collector Pump	0.996400	0.91	1.722928E-05	58040.74	0.999984	GOOD
23	Non Return Valve (NRV)	0.999966	0.72	4.624315E-06	216248.25	0.999996	GOOD
24	Cross Feed Valve	0.999966	0.62	2.031684E-05	49220.26	0.999987	GOOD

25	Quantity Measure Probe	0.999966	0.42	4.953542E-06	201875.74	0.999997	GOOD
26	Fuel Pressure Switch	0.999966	0.45	9.611561E-06	104041.37	0.999995	GOOD
27	Fuel Low Pressure Warning Light	0.999966	0.33	3.070903E-05	32563.71	0.999989	GOOD
28	Fuel Differential Pressure Switch	0.999966	0.44	5.703796E-05	17532.18	0.999974	GOOD
29	Fuel Flow Warning Switch	0.999966	0.48	1.741265E-05	57429.51	0.999991	GOOD
30	Fuel Temperature Switch	0.999966	0.45	6.673383E-06	149849.03	0.999996	GOOD
31	Fuel Temp. Warning Switch	0.999966	0.45	2.991135E-05	33432.12	0.999986	GOOD
32	Fuel Quantity Gauge	0.999966	0.32	5.122660E-06	195211.10	0.999998	GOOD
33	Low fuel warning light	0.999966	0.12	5.122660E-06	195211.10	0.999999	GOOD

Table 8-24: ASDMDR results for fuel supply sub-system with initial data

2. Increasing the fuel supply sub-system dispatch reliability target to higher level (from 99.8899% to 99.9650%) as shown in Table 8-25 while all other variables were kept constant and reapplying the design methodology. The methodology design result is shown in Table 8-26.

Input Data	Total number	Failure Rate hr^{-1}	Dispatch Reliability%
Fuel Supply Sub-system	1	0.0003	99.9650
LRU	33		

Table 8-25: Fuel supply sub-system basic data with increased DR

No	LRU	Allocated Dispatch Reliability	MTTR (hour)	Allocated failure rate (Per hour)	MTBF	Predicted Dispatch Reliability	Design Decision
1	Negative 'G' Tank	0.999989	0.87	4.548396E-06	219857.74	0.999996	GOOD
2	Vent Tank	0.999989	0.98	4.576153E-06	218524.16	0.999995	GOOD
3	Syphone Pipe	0.999989	1.04	4.986631E-06	200536.19	0.999994	GOOD
4	Water Drain1	0.996400	0.31	4.548396E-06	219857.74	0.999998	GOOD
5	Water Drain2	0.996400	0.31	4.548396E-06	219857.74	0.999998	GOOD
6	Flap Valve 1	0.978000	1.68	1.146053E-05	87256.01	0.999980	GOOD
7	Flap Valve 2	0.978000	1.68	1.146053E-05	87256.01	0.999980	GOOD
8	Flap Valve 3	0.978000	1.68	1.146053E-05	87256.01	0.999980	GOOD
9	Flap Valve 4	0.978000	1.68	1.146053E-05	87256.01	0.999980	GOOD
10	Collector Tank	0.978000	0.94	5.420455E-06	184486.37	0.999994	GOOD
11	Scavenge Tank	0.996400	1.68	5.308671E-06	188371.05	0.999991	GOOD
12	Low Pressure Valve	0.996400	0.71	1.649398E-05	60628.17	0.999988	GOOD
13	Pipe	0.996400	0.62	4.557238E-06	219431.17	0.999997	GOOD
14	Shut-Off Switch	0.996400	0.60	6.285244E-05	15910.28	0.999962	GOOD
15	Vent Duct	0.978000	0.85	7.486631E-06	133571.43	0.999993	GOOD
16	Flow Shut-Off Valve	0.978000	0.75	4.728175E-06	211498.09	0.999996	GOOD
17	Engine Fuel Pump	0.978000	0.88	4.959057E-06	201651.22	0.999995	GOOD
18	Non Return Valve (NRV)	0.978000	0.72	4.624315E-06	216248.25	0.999996	GOOD
19	Scavenge Jet Pump1	0.996400	0.77	1.722928E-05	58040.74	0.999986	GOOD
20	Scavenge Jet Pump2	0.996400	0.77	1.722928E-05	58040.74	0.999986	GOOD
21	Primary Collector Pump	0.996400	0.91	1.722928E-05	58040.74	0.999984	GOOD

22	Stand-By Collector Pump	0.996400	0.91	1.722928E-05	58040.74	0.999984	GOOD
23	Non Return Valve (NRV)	0.999989	0.72	4.624315E-06	216248.25	0.999996	GOOD
24	Cross Feed Valve	0.999989	0.62	2.031684E-05	49220.26	0.999987	Try again
25	Quantity Measure Probe	0.999989	0.42	4.953542E-06	201875.74	0.999997	GOOD
26	Fuel Pressure Switch	0.999989	0.45	9.611561E-06	104041.37	0.999995	GOOD
27	Fuel Low Pressure Warning Light	0.999989	0.33	3.070903E-05	32563.71	0.999989	GOOD
28	Fuel Differential Pressure Switch	0.999989	0.44	5.703796E-05	17532.18	0.999974	Try again
29	Fuel Flow Warning Switch	0.999989	0.48	1.741265E-05	57429.51	0.999991	GOOD
30	Fuel Temperature Switch	0.999989	0.45	6.673383E-06	149849.03	0.999996	GOOD
31	Fuel Temp. Warning Switch	0.999989	0.45	2.991135E-05	33432.12	0.999986	Try again
32	Fuel Quantity Gauge	0.999989	0.32	5.122660E-06	195211.10	0.999998	GOOD
33	Low fuel warning light	0.999989	0.12	5.122660E-06	195211.10	0.999999	GOOD

Table 8-26: ASDMDR results for fuel supply sub-system with enhanced DR target

3. Using the ASDMDR as design improvement tool resulted in a design modifications to the fuel supply sub-system. Reapplying the design methodology with these modifications incorporated; resulted in the improved design shown in Table 8-27.

No.	LRU	Allocated Dispatch Reliability	MTTR (hour)	Allocated failure rate (Per hour)	MTBF	Predicted Dispatch Reliability	Design Decision
1	Under Wing Inlet	0.999989	0.87	4.548396E-06	219857.74	0.999996	GOOD
2	Vent Tank	0.999989	0.98	4.576153E-06	218524.16	0.999995	GOOD
3	Syphon Pipe	0.999989	1.04	4.986631E-06	200536.19	0.999994	GOOD
4	Water Drain1	0.996400	0.31	4.548396E-06	219857.74	0.999998	GOOD
5	Water Drain2	0.996400	0.31	4.548396E-06	219857.74	0.999998	GOOD
6	Flap Valve 1	0.978000	1.68	1.146053E-05	87256.01	0.999980	GOOD
7	Flap Valve 2	0.978000	1.68	1.146053E-05	87256.01	0.999980	GOOD
8	Flap Valve 3	0.978000	1.68	1.146053E-05	87256.01	0.999980	GOOD
9	Flap Valve 4	0.978000	1.68	1.146053E-05	87256.01	0.999980	GOOD
10	Collector Tank	0.978000	0.94	5.420455E-06	184486.37	0.999994	GOOD
11	Scavenge Tank	0.996400	1.68	5.308671E-06	188371.05	0.999991	GOOD
12	Low Pressure Valve	0.996400	0.71	1.649398E-05	60628.17	0.999988	GOOD
13	Pipe	0.996400	0.62	4.557238E-06	219431.17	0.999997	GOOD
14	Shut-Off Switch	0.996400	0.60	6.285244E-05	15910.28	0.999962	GOOD
15	Vent Duct	0.978000	0.85	7.486631E-06	133571.43	0.999993	GOOD
16	Flow Shut-Off Valve	0.978000	0.75	4.728175E-06	211498.09	0.999996	GOOD
17	Engine Fuel Pump	0.978000	0.88	4.959057E-06	201651.22	0.999995	GOOD

18	Non Return Valve (NRV)	0.978000	0.72	4.624315E-06	216248.25	0.999996	GOOD
19	Scavenge Jet Pump1	0.996400	0.77	1.722928E-05	58040.74	0.999986	GOOD
20	Scavenge Jet Pump2	0.996400	0.77	1.722928E-05	58040.74	0.999986	GOOD
21	Primary Collector Pump	0.996400	0.91	1.722928E-05	58040.74	0.999984	GOOD
22	Stand-By Collector Pump	0.996400	0.91	1.722928E-05	58040.74	0.999984	GOOD
23	Non Return Valve (NRV)	0.999989	0.72	4.624315E-06	216248.25	0.999996	GOOD
24	Cross Feed Valve	0.999989	0.49	2.031684E-05	49220.26	0.999990	GOOD
25	Quantity Measure Probe	0.999989	0.42	4.953542E-06	201875.74	0.999997	GOOD
26	Fuel Pressure Switch	0.999989	0.45	9.611561E-06	104041.37	0.999995	GOOD
27	Fuel Low Pressure Warning Light	0.999989	0.33	3.070903E-05	32563.71	0.999989	GOOD
28	Fuel Differential Pressure Switch	0.999989	0.16	5.703796E-05	17532.18	0.999990	GOOD
29	Fuel Flow Warning Switch	0.999989	0.48	1.741265E-05	57429.51	0.999991	GOOD
30	Fuel Temperature Switch	0.999989	0.45	6.673383E-06	149849.03	0.999996	GOOD
31	Fuel Temp. Warning Switch	0.999989	0.45	2.292689E-05	43616.91	0.999989	GOOD
32	Fuel Quantity Gauge	0.999989	0.32	5.122660E-06	195211.10	0.999998	GOOD
33	Low fuel warning light	0.999989	0.12	5.122660E-06	195211.10	0.999999	GOOD

Table 8-27: ASDMDR results for fuel supply sub-system with enhanced DR target after design improvement

8.6.3 Fuel Supply Sub-system Design Improvement Results

Applying the ASDMDR with the initial basic data as shown in Table 8-21, resulted in all fuel supply sub-system components passed the design criteria as shown in Table 8-24. This was because all the data used were real data, and that dispatch reliability has been achieved.

Conducting the ASDMDR with the fuel supply sub-system dispatch reliability target rose from 99.8899% to 99.9650% while other variables were kept constant, as in the initial basic data, resulted in some LRUs failing to meet their design criteria. The design criterion was that the predicted dispatch reliability should be equal or greater than the allocated dispatch reliability. These failed LRUs are shown in Table 8-26, and they were LRU numbers 24, 28 and 31.

The next step was to change the design to achieve the new dispatch reliability target, which was performed by one or more of these options:

- Fault avoidance, i.e. making the failed components more reliable
- Fault tolerance, i.e. introducing redundancy for the failed components
- Improving the maintainability characteristics of the failed components, i.e. reducing the mean time to repair (MTTR)

The three solutions were all about the reliability and maintainability characteristics of the components. A trade-off study between the above three solutions should be conducted and the cost effective solution will be chosen.

The first failed component was the crossfeed valve which was located on the starboard wing near the wing-fuselage intersection. The crossfeed valve permits an engine to be fed with fuel from the opposite tank. The mean time to repair this component which is the on-aircraft time to remove and replace this LRU, was about 0.62 hour. The elected design improvement solution was to improve the maintainability characteristics of this component by providing an on-aircraft testing point, which reduced the MTTR to 0.49 hour.

The second failed component was the fuel differential pressure switch. It is located in the engine fuel control and provides a signal when a differential pressure greater than 8 psi is sensed, thus providing a warning of impending fuel filter blockage. Its mean time to repair (MTTR) in the first run was 0.44 hour. The opted for design improvement solution was to reduce the MTTR by providing clearer visual displays and offering an on-equipment test point. This is brought the improved MTTR to 0.16 hour.

The last failed component was the fuel temperature warning switch, which is located in the engine fuel control. Its function is to provide a signal when the fuel temperature is below 1.7°C, thus providing a warning of fuel heater failure.

The selected design improvement solution was to increase the reliability of this component. Its failure rate original value was about 0.00003, and it was improved to 0.0000229.

Reapplying the methodology with the new improved component characteristics resulted in all LRUs passed the design criteria, as shown in Table 8-27.

Hence increasing the dispatch reliability target to higher level has led to better characteristics of the supply fuel sub-system reliability and maintainability characteristics. This is can be translated to overall design improvement.

However, design improvement solutions come at cost, and careful evaluation of the available design solutions is necessary.

The ASDMDR has thus showed clear capability to be an effective design improvement tool which can help designers to achieve superior design features.

"The significant problems we face cannot be solved at the same level of thinking we were at when we created them." (Albert Einstein.)

Chapter 9

Discussion

9.1 Aircraft Dispatch Reliability

The first objective of this work as mentioned in the introduction was to develop a civil aircraft dispatch reliability prediction method that can be used during the conceptual design phase. Significant areas of interest identified at the beginning of this research program were:

- Importance of aircraft dispatch reliability
- Aircraft delay cost and magnitude
- Factors affecting aircraft dispatch reliability
- Aircraft systems that cause most of the delays
- The available dispatch reliability prediction techniques

9.1.1 Importance of Aircraft Dispatch Reliability

The importance of aircraft dispatch reliability comes primarily from its effect on cost and passenger satisfaction. Low aircraft dispatch reliability means more delays, which comes at very high cost for the aircraft operators, passengers and the whole community.

It also means aircraft spending more time at the ground, which put airports under unnecessary pressure, thus more costs are encountered. Current aircraft dispatch reliability levels are unacceptable, and statistics showed their very high costs.

9.1.2 Aircraft Delay Cost & Magnitude

Many sources reported aircraft delay time, where the reported figures were significant phenomena that required action[2,4,21,26].

The majority of the reported delay magnitudes were very high, with some sources quoted an average delay time of 44 minutes and around 26 % of the flights are delayed[41]. Aircraft delay costs reached a high level where the annual delay cost is between € 6.6-11.5 billion for the air transport delays in Europe[42].

9.1.3 Factors Affecting Aircraft Dispatch Reliability

The aircraft dispatch reliability evaluation led to the identification of the factors that effect aircraft dispatch reliability. These were categorized according to their origin into three types. These are design, operator and working conditions factors. They include system reliability and maintainability design, the characteristics and performance of the logistics support systems, the quantity and location of the logistics resources and working conditions. They are interrelated, but design factors have the most significant influence.

It was established throughout the course of this research that design factors were related to the reliability and maintainability characteristics of aircraft systems.

Design factors are very important since they are very difficult to amend once the aircraft is in-service. No matter how many resources are available for the other categories factors, this will not influence the dispatch reliability design factors.

However, one important point about aircraft dispatch reliability remains within the operator's control. This is to ensure that turnaround time is suitable and realistic to an individual aircraft type, which will help to reduce delays.

Aircraft designers also can use turnaround time to plan and facilitate different maintenance actions by considering the important aspects of maintainability.

9.1.4 Aircraft Systems that Cause Most Delays

Delays are the complement of dispatch reliability; more delays reduce dispatch reliability and vice versa. Although aircraft operators reported aircraft delays, they had no clear vision of what systems caused most of the delays. Large amounts of aircraft dispatch reliability data were obtained for this research, and they have been used to perform aircraft delay rate studies.

The finding of these studies showed that there were a few systems which caused most of the delays. Power plant and landing gear systems were the two systems that caused high percentages of the delays. Identifying these troublesome systems would be useful to place more attention into the design and maintenance of these systems.

It was found from the average delay rate study that the top five items on short and long-haul aircraft were responsible for about 68% and 66.5% respectively of the total aircraft delay.

The results also showed that long-haul aircraft had the worst delay rates, which could be attributed to their complexity and working conditions. This is because long-haul aircraft are usually large and complex aircraft that operated for long distance, and usually they are away from their home base for long periods, which make them accumulates defects, thus worsening the delay.

9.1.5 The Available Dispatch Reliability Prediction Techniques

The aircraft dispatch reliability literature review identified a few dispatch reliability prediction methods that can be used during the conceptual design phase. These were:

- Comparison Procedure [3,86]
- Transport Aircraft Dispatch Reliability Formula [45,36]
- Development of Conceptual Navy Aircraft Reliability Prediction Models [44].

The first dispatch reliability prediction technique was the comparison procedure which has been used by many aircraft makers. This technique always assumed high similarity between the to-be-designed aircraft and the old ones. The high similarity between the two aircraft and their systems is not always the case, unless the new aircraft is a derivative of the baseline aircraft. This makes the comparison procedure unsuitable for general use, especially for revolutionary design. It is also unsuitable to other aircraft companies, or organisations.

The second and third prediction techniques were the transport aircraft dispatch reliability formula [45]and the conceptual Navy aircraft reliability prediction models produced in the late seventies. Both methods were developed based upon the information available in the late 1970s, which may be considered as largely outdated [10]. The third method was specific for Navy aircraft thus making it inapplicable for general aircraft design usage.

It was therefore considered that a new dispatch reliability prediction method needed to be developed. Highly desirable features of the proposed prediction method included:

- It should be generic, i.e. capable of predicting dispatch reliability for any civil aircraft.
- It can be used during the conceptual design phase when very little amount of information is available.
- It should be easy to use

9.1.6 The Developed Civil Aircraft Dispatch Reliability Prediction Method

Development of the prediction method was based on the relationships between aircraft delay rates (i.e. reliability design parameters), and aircraft design or performance parameters.

The design /performance data base includes five basic parameters for each aircraft in the model, which are normally available at the conceptual design phase. Upon data analysis, it was necessary to find other derivative parameters that can produce the most suitable relationships. Two derivative parameters were calculated and included in the process.

All aircraft systems exhibited linear results, except the fuel system in short-haul aircraft which was best fitted by the inverse of the EXP function.

The result was a linear regression equation for each ATA chapter, which represent the delay rate as a function of a parameter. Two sets of equations were produced for short-haul and long-haul aircraft.

Some of the developed system prediction equations are related to a parameters where is no obvious causal link between that parameters and the delay rate, and a straight-line correlation existed. As an example, delay rate and cruise speed on the ATA 21 (Air conditioning system) for short-haul aircraft.

The reason can be due to the uncertainties of the data, the sample size, and because there are other factors that play a role on the aircraft dispatch reliability that were not included on the prediction equations.
This suggests that the delay rate prediction equations could use more than one parameter if prove to be more representative.

Two equations were also produced to predict the whole aircraft dispatch reliability without using the individual systems prediction equations. This is because in some occasions, only whole aircraft dispatch reliability is needed, such as an early comparison between two conceptual designs.

These two equations provide simplified predictions of dispatch reliability, but do not take into account detailed engineering links to the variables used. However, it provides a first-order prediction that is appropriate at the very beginning of the aircraft design process.

These two equations are intended to be used at the very early design conceptual stage when very little information is available, and their usage should be restricted to this stage.

The developed DRPM is suitable for aircraft conceptual design stage only and for latter stages, they might be a need for a multivariable prediction method.

The top aircraft systems that have high delay rate exhibited very strong correlations while those with low delay rate exhibited weaker correlations.

The validation exercise was performed for short and long-haul aircraft using data from four aircraft, produced reasonable prediction results as shown in table 5-11, 5-13, 5-15 and 5-17. The predictability of most of the individual system equations was reasonably accurate, and when summed for the whole aircraft lead to errors of about 10%.

However, the predictability of Equations 5-3 & 5-4 for the whole aircraft dispatch reliability was very high. The error percentages were 0.17-1.51% for short-haul aircraft and 0.30-0.58% for long-haul aircraft.

It was noticed that prediction results at the system level were less accurate compared to the total aircraft dispatch reliability prediction, and that systems with higher delay rates showed more prediction accuracy than those with lower delay rates.

Some of the reasons for the less accuracy of the individual prediction compared to the whole aircraft prediction could be:

I. The aircraft system individual delay rate equations may have small percentages of error which accumulate. This decreases the accuracy of this part of the methodology.

II. Differences of the delay rate input information among operators may also degrade the accuracy of the aircraft system individual delay rate equations.

III. Recording dispatch reliability for the whole aircraft is much easier and more accurate than for the individual system dispatch reliability, taking into account the fact that these individual systems dispatch reliability are calculated by deducting individual delay rate out of hundred.

DRPM can be an effective tool in the designers hand during the early aircraft design stage in pursuit of better dispatch reliability design. As an example, DRPM can be used at the very beginning of the aircraft design stage to predict the dispatch reliability for different design concepts, and the output of this prediction could be used on the evaluation of these design concepts.

Finally, the developed aircraft dispatch reliability prediction equations are produced based on empirical data for civil airliners and, therefore can be used for prediction of similar aircraft technology. Radically different types of aircraft would need new data, or a different approach. So development of similar prediction method for other aircraft types such as fast jet, turbo-props, and cargo aircraft would be useful.

9.2 Aircraft Systems Design Methodology for Dispatch Reliability

9.2.1 Filling the Gap

During the course of the literature work, it was evident that there is a need for a specific aircraft design methodology for dispatch reliability, which can be used during an early design stage. It should be independent of particular company data, generic for both civil and military aircraft, and uncomplicated to use.

In many aircraft design projects, very little emphasis is placed on the design for dispatch reliability. As a result, many aircraft suffered from poor dispatch reliability. To overcome this deficiency, aircraft usually undergo in-service modification programmes, in order to reach the desired level, and invariably at a very high cost.

There was very little published work that addressed dispatch reliability as one of the objectives for an aircraft design project. These were mainly based on comparisons between old and new aircraft designs, using the baseline aircraft as the main vehicle for addressing dispatch reliability in the design. The comparison technique has many disadvantages that are restraining its usage. Some of which are dependency, type-specific necessity, limited range of applications, no room for technological improvements, limited accuracy and the need for excessive analysis time. For all of these reasons, a new aircraft system design methodology for dispatch reliability was developed.

The developed ASDMDR has proved through a set of exercises that it can be of great help towards the design for dispatch reliability, and that it meets the above mentioned objectives as shown below.

9.2.2 Conceptualizing Dispatch Reliability

Dispatch reliability has been assumed to be equal to inherent availability and calculated using the same equation. The case for this assumption was made in chapter 7.4.1.

This conceptualization of dispatch reliability as a function of reliability and maintainability, and formulated mathematically using equation 7-1, allowed more work to be carried out towards the development of the methodology.

9.2.3 The developed ASDMDR

Technical reliability and maintainability parameters are based on component failure rates and mean time to repair, and the challenge was to decide on the most appropriate source to obtain these two parameters.

For the component failure rate, the first possible approach was to use the MTBUR for items that undergo unscheduled removal, and assume other components on the system that did not fail unpredictability (hence does not have MTBUR) are not contributing to the delays. Adopting this approach would make the methodology more inclined towards an optimistic solution that might neglect some important factors. The second approach was to use the MTBUR for only the components which undergo unscheduled removal and MTBF for the rest of components in the system. This approach has the advantages of utilizing the real data (MTBUR) together with other factors that might have an effect on the system/subsystem performance. This approach may sound pessimistic since it takes onboard all component failure rates whether they fail or not. However, since the aircraft industry has largely adopted on-condition maintenance policy for the majority of aircraft components, this means that MTBUR represents component service time.

This lead to the belief that the proposed methodology will produce more reliable solutions, because it takes a pessimistic approach with regard to components reliability by using the components MTBUR. The second approach was opted for the methodology.

Nevertheless, the methodology is workable using either MTBUR or MTBF and it is to the user's discretion to choose either of them.

The data collection was a very difficult and time-consuming task. Airlines vary in their reporting practices and in the completeness of their reports. As an example, delay rates in some operator reliability reports are tabulated while in other are presented graphically. Another example, some operator record delay rates at monthly basis and provide annual average delay rate, while other record them monthly. Many airlines do not keep an organised and ready to use record of the MTBF, MTBUR & MTTR.

Detailed information about the aircraft sub-system failure rate is very scarce and operators usually report failure rates by individual LRU and not for the entire sub-system. It was observed that considerable scatter occurred in the published aircraft failure rate data, and significant engineering knowledge is essential in the selection of suitable data.

Mean time to repair (MTTR) prediction was performed using MIL472 [34]. This was created many years ago, but because it deals with human capability that has not changed, it is a suitable method to predict MTTR. However, the use of this technique needs considerable experience of the users in order to produce rational predictions.

The methodology was designed to be used by aircraft system designers who have adequate knowledge about their components, thus reasonable engineering judgment is expected.

Some computer aided design programs can be of great help to the designer in many ways. In particular, they enable designers to assess component maintainability features that affect component mean time to repair. This will allow them to improve their design to achieve better MTTR.

Incorporating CATIA into the ASDMDR to model aircraft LRU's proved to be very effective, in particular for the maintainability prediction. This is because it gives designers the ability to assess many aspects that affect maintainability such as accessibility, ease of maintenance and component location (see Figure 6-6).
During MTTR prediction, scoring related to internal issues always had the highest value. This was because removal & replacement actions do not require the disassembly of the LRU.

Failure rate allocation is one of the ASDMDR steps; but the methodology process can be conducted using current failure rate values before allocation. This approach has been adapted for the validation exercises. The reason for that was to enable dispatch reliability comparisons to be based on real data.

Otherwise, when using the ASDMDR to design new aircraft, failure rate allocation is a necessary step that should be performed. The application of this step was described in the case study for using the ASDMDR as a design improvement tool.

Some may consider the use of failure rate and MTTR calculations to be insufficiently accurate, since they incorporate estimates relating to working environment conditions. However, it is useful to compare their use with stress analysis calculations which most designers readily use in their work. In stress analysis, assumptions are made with respect to boundary conditions to enable calculations to proceed and knowledge of loadings in practice is generally a first approximation. The reason that few failures occur is that safety factors are applied, to account for the inaccuracy of the mathematical models and loading conditions [106]. It might be feasible for reliability engineers to consider applying safety factors, to account for the inaccuracy of the failure rate and maintainability data.

It is very important to mention that the proposed methodology could be used during the early phases of aircraft design, that is, the conceptual and preliminary phases and it is also applicable to be used in the detail phase.

The ASDMDR possess the potential for the following:

- Aircraft design optimization based on the dispatch reliability criteria.
- A comparison method for discrimination between different design options
- It can be used for any type of aircraft.
- It is applicable for both civilian and military aircraft, where is the operational readiness is the criterion for the later, rather than dispatch reliability.

It should be noticed that the degree of accuracy of the methodology depends on the user. The more accurate and updated data fed into the methodology, the more accurate the results will be.

ASDMDR users should always consult maintenance technicians especially during the component MTTR prediction. This is to benefit from their accumulated experience of maintainability aspects, which can be of crucial important for the ASDMDR effectiveness

Military and civil aircraft would benefit from the ASDMDR. This is because the developed methodology will improve aircraft reliability and maintainability that can be translated into an improvement in the dispatch reliability of civil aircraft and operational readiness performance of military aircraft.

ASDMDR design solutions to improve dispatch reliability are improving LRU reliability characteristics, maintainability, changing system architecture, and /or by combination of them. As an example, is a hydraulic pump on hydraulic sub-system that is below the required dispatch reliability level. The design solution could be by selecting an alternative pump that is more reliable, plus improving the maintainability aspect by making it more accessible.

The methodology makes provision for a reliability and maintainability trade-off studies by sorting components according to their failure rates. Those components with a high failure rate would be designed with better maintainability characteristics. The sensitivity of an improvement on system maintainability to the improvement on component maintainability is proportional to the failure rate of the component.

The methodology relies on the iterative process to achieve the optimum design solution. The first methodology iteration will reveal results in respect to meeting the required dispatch reliability target. There will be some LRUs that do not achieve their required targets on the first iteration, and the methodology will be reiterated with the suitable design amendments until the system meets the required targets.

Design solutions that would improve items dispatch reliability are likely to have cost implications, and a careful selection of the available design solution that is cost-effective is a must.

By its nature, conceptual design will have many concepts that are evaluated to determine which design approach is preferred. The methodology would fit very adequately on this phase by providing a tool to evaluate each concept against the dispatch reliability target.

The methodology can be used later on the design process to analyse the selected concept with regards to the dispatch reliability target. It will also provide a design mechanism to modify the design features to suit the required target.

It is possible to use the ASDMDR at very early design stages when very little information about the exact number and type of components on sub-system/system is available. This can be achieved by making some assumptions, about these components and implementing the ASDMDR according to them.

The proposed methodology gives a realistic approach for the design for dispatch reliability at an early design phase, and a test tool throughout the design process.

ASDMDR is an independent approach that does not rely on confidential data. If such data, however, is available, results should be more accurate.

Applying an aircraft system design methodology to achieve a specific dispatch reliability target is not a straightforward exercise, since it requires a considerable amount of team work and a great deal of design reiteration, that can slow down the design progress during the early design stages. Nevertheless, this should not be seen as draw back. This is because encouraging team work culture is very healthy practice for the design team and, will assure a better design.

The design reiteration is also beneficial for the design because better designs will emerge and this is will be at a cost that certainly less than if these adjustments carried out later on the design stage. The ASDMDR adopted the combined tasks engineer philosophy, which believes that the basic responsibility for design dispatch reliability rests solely on each engineering designer.

There are two schools of design in the aircraft industry with regard to R&M. The first utilises a bottom-up approach whereby the designer works from the bottom by selecting or designing components based on their performance characteristics, and then works upwards towards the system level.

With this approach, the designer is not aiming at specific R&M and waits for the system behaviour to be acceptable in terms of meeting R&M requirements targets.
This design technique has been used extensively in the past but has proved to be unsuccessful with regard to R&M[12], because no objective was set for dispatch reliability, and the resulting designs reflect this.

The second school of design follows a top-down approach whereby the designer works from the system level down to the required component level. This approach gives the designer control over the required R&M characteristics. But, it will not ensure a successful design with regard to dispatch reliability, unless it is directed towards a specific dispatch reliability target.

The methodology developed in this research has adapted two ways system approach, whereby it concentrates on the two design parameters of reliability and maintainability from the system level down to the component level by allocating the required dispatch reliability values from aircraft level through system level, and to the component level. The second way was by predicting dispatch reliability from the bottom level (component level) up to the system level, and to the aircraft level.

Fundamental to any plan to achieve high dispatch reliability is to have discipline from design through production and into service and to follow it through.

9.2.4 Validation

Failure rate and maintainability data that have been used on some of the validation cases might have some non-technical elements incorporated. The effect of this was assumed to be negligible.

Evaluation of the design methodology output can be by two ways. Either by the difference in percentage between the total system/sub-system required dispatch reliability target and the predicted dispatch reliability, or by the percentage of the number of failed LRUs to the total number of LRUs in the system/sub-system.

The validation exercise showed that it was more meaningful to evaluate the design methodology output by the percentage of the number of failed LRU to the total number of LRUs.

This was because when the first approach was used, unless the number of failed components was large, the difference in percentage would be very low, to the extent that it could be regarded as negligible, but in reality there were numbers of components that failed to meet the required dispatch reliability target, which was the important issue.

This is can be appreciated when considering the fourth validation case results for the right-hand sub-system. It showed that the total right-hand hydraulic sub-system predicted dispatch reliability was 99.90 and the required dispatch reliability was 99.972. The shortage of the predicted to the required dispatch reliability when expressed in percentage was 0.07%. This is very low difference, however, in reality four LRUs failed to meet the dispatch reliability target.

In the validation exercise, a baseline was set, to enable all cases results to be judged against it. It is an ideal situation, where dispatch reliability, failure rate, and mean time to repair were all real and accurate data. In the baseline result, all LRUs will pass the design criteria. The validation exercise showed that when the ASDMDR used real data for all the three parameters; i.e. MTBUR, MTTR and the required dispatch reliability, it produced an accurate result that was very close to the baseline result. This was evident in cases two and three with four LRUs out of 71 failed to meet the design criteria. The least accurate result was in case four when failure rate and dispatch reliability were predicted.

ASDMDR showed that it was easier to improve component maintainability characteristics than reliability characteristics at very early design stage. On the other hand, it is very difficult to alter maintainability characteristics when the design is at later stages. One of the very important findings of the validation exercise was that dispatch reliability performance was more affected by maintainability characteristics than reliability characteristics, which coincides with another finding that reported by Meth [70].

In general, a reduction in LRU mean time to repair (MTTR) would reduce it's delay rate thus, dispatch reliability will be improved. However, this is possible only as long as the component MTTR is equal or less than the allocated turn-around time plus 15 minutes. Also, a reduction on MTTR below 15 minutes will not improve dispatch reliability, and the designer should look for other improvement solutions such as enhancing reliability or/and changing system architecture.

The three hydraulic sub-systems were assumed to possess equal failure probability. This assumption was made because of the unavailability of specific sub-systems failure rate data, but it was felt that it was justified since the three sub-systems were almost identical in their functions, components and architecture. Therefore, the effect of this assumption on the validation results would be very little.

9.2.5 Design Improvement Tool

Although, the methodology was intended to be used during the early design stage, it can also be used during any design stage. As the design becomes better defined, and more data becomes available, the methodology would be fed with more detailed and accurate data hence the result would be better design.
The design improvement exercise was executed to asses the methodology usability during different design stages and its functionality as design improvement tool.

The outcomes of this exercise showed that it is very important to set a reasonable dispatch reliability target that can be achieved.

High dispatch reliability will come at a cost, and trade-off studies are necessary for the selection of the most cost-effective design solution.

"I think we can build a better plane."

William Boeing, The Boeing Company, later a company's motto, 1914.

Chapter 10

Conclusions & Future Work

10.1 Conclusions

10.1.1 Civil Aircraft Dispatch Reliability Prediction Method (DRPM)

- The author established during the course of this research, that there was a need for new civil aircraft dispatch reliability prediction method that could be used during the very early design stages. The developed prediction method should use the minimum amounts of data that normally would be available at the conceptual design stage.

- The author has developed DRPM that has met the above objectives, with good accuracy.

- The author produced prediction equations for each aircraft system and also produced the total aircraft predicted dispatch reliability by summing the individual prediction equations. Moreover, the prediction equations were developed for two categories of aircraft: long and short haul.

- The calculations and source data used to develop the DRPM were incorporated into a computer program, which allows for periodic update. This is easily performed by updating the delay rates and dispatch reliability data in the master sheet, an automatic updating of the whole method will follow. This is to ensure that the prediction method is always up to date.

- The analysis of the ATA average delay rate for all the aircraft in the data sample showed that dispatch reliability improvement could be achieved by placing more emphases on the design, operation and maintenance of the power plant, landing gear, flight control, hydraulic systems and fuel systems since they are the systems that cause most of the delays. More reliable and maintainable design of the above systems, suitable operation procedure, and adequate maintenance practice will decrease their contribution to the delay. As examples, performing components non-destructive inspection more frequently could reduce the failure frequency, which will in-turn improve dispatch reliability. Planning adequate turnaround time that can accommodates the required maintenance tasks will contributes positively to the aircraft dispatch reliability performance.

- The validity of this method is restricted to the aircraft system-level predictions. More detailed dispatch reliability predictions, such as aircraft sub-systems and LRU, are not possible by this method, and it might prove to be difficult to develop one due to the unavailability of delay rate data at that level.

- Although the help from the aerospace community was vital to the accomplishment of this methodology and it is appreciated, there was reluctant attitude from some operators. Unfortunately, many airlines consider that reliability information is commercially sensitive, since it reveals their performance.

- It would be very useful to the researchers, specialists and to the entire aerospace community to have a data bank for aircraft systems delay rates, and dispatch reliability. This data bank could be established by an organization and get fed by these data from aircraft operators and manufacturer. The origins of the data could be treated as confidential, to protect commercial interests. See reference [46].

- The DRPM can be an effective tool in the aircraft designers' tools box during the early aircraft design stage in pursuit of better dispatch reliability design.

- The developed aircraft dispatch reliability prediction equations were based on empirical data for civil airliners and, therefore can be used for the prediction of aircraft of similar technology. Radically different types of aircraft would need new data and/or a different approach. Therefore, development of similar prediction methods for other aircraft types such as fast jet, turbo-props, and cargo aircraft would be very useful.

- The DRPM equations provide simplified predictions of dispatch reliability, but do not take into account detailed engineering links to the variables used. However, they provide a first-order prediction that is appropriate at the very beginning of the aircraft design process.

10.1.2 Aircraft Systems Design Methodology for Dispatch Reliability (ASDMDR)

- Very few aircraft dispatch reliability design methodologies exist, and these use the comparison technique. These methodologies were unable to address dispatch reliability requirements effectively, because they depend on old design data to drive the new design, rely on proprietary data that are not available in the public domain, and can be used only for similar aircraft types. They are applicable for advanced design stages, but not for an early design stage.

- The developed methodology is a step towards producing better designs for dispatch reliability. The main objective of the methodology was to provide the aircraft system designers with an effective design tool that would help them to design and evaluate their design from the dispatch reliability point of view during the early design stages. The developed ASDMDR has showed a dependable capability to achieve this objective.

- Several design iterations are considered during the conceptual design phase, thus requiring rapid reliability and maintainability analysis responses, which can be accomplished in a user-friendly manner by using the ASDMDR.

- Although reliability analysis is of crucial importance in the design of aircraft [24], the cost of implementing such analysis can be sometimes prohibitive. However, the cost of applying the ASDMDR will be very low, since it can be performed by the system designer, needs no outside resources, consumes little time, and thus is cost-effective.

- ASDMDR can be used to design for a specific dispatch reliability target for a whole aircraft, or to a specific aircraft system/sub-system.

- ASDMDR can also be used to determine component dispatch reliability, even if there is no defined dispatch reliability target, i.e. it can be used to predict component-level dispatch reliability.

- It is imperative in use of ASDMDR to set an upper limit for the wished-for dispatch reliability. This is to prevent over-specifying dispatch reliability, which can increase the design project costs dramatically.

- ASDMDR allows investigation of three design approaches relative to the reliability and maintainability characteristics of the components. The first of these is fault avoidance which involves making failed components more reliable. Secondly, fault tolerance, which involves introducing redundancy for the failed components. Third, improving the maintainability characteristics of the failed components, thus reducing the mean time to repair (MTTR).

- A trade-off study between the above three solutions should be conducted and the most cost-effective solution should be chosen.

- ASDMDR accuracy relies very heavily on the dispatch reliability, failure rate, and MTTR data and efforts should be exerted to find most accurate possible set of data and avoidance of seasonal varieties.

- The author found during the research work, that dispatch reliability in design can be influenced greatly by maintainability; which meant that reducing MTTR was the most effective option for performance improvement.
- Only very limited failure rate data, and surprisingly little MTTR data exist for aircraft components, which limits the amount of work that can be done in the reliability area.

- Reliability software such the one used for this work which was Relex software, proved to be very powerful tool for reliability work.

10.2 Research Contribution

This research contributes to the existing body of knowledge in four areas: knowledge of the aircraft dispatch reliability and delay topic, to the academic theory, to the prediction methods, and to the aircraft design practice. Below is a brief review of these contributions.

10.2.1 Contribution to the Aircraft Dispatch Reliability & Delay Topic

Dispatch reliability is an integral part of aircraft design features, that plays an essential role in aircraft success. Aircraft delay is a major cause to the aircraft losses, and they can be attributed to technical and non-technical factors. This research investigated aircraft delay by conducting three studies. The first study concentrated on identifying the average delay rate per aircraft system for long and short-haul aircrafts. The second study calculated the average pilot reports (PIREPS) for the long and short-haul aircraft for every ATA system. The last study compared the two study results, and identified the most troublesome aircraft systems.

This research contributed to the existing knowledge of aircraft delay by pinpointing the most troublesome aircraft systems that cause delay. Actions can be taken by different organization bodies to reduce the effect of these defined systems on aircraft delay.

10.2.2 Contribution to Academic Theory

Aircraft dispatch reliability is defined operationally in many sources, but technical and mathematical descriptions are usually overlooked. This research concluded that technical dispatch reliability is a function of reliability and maintainability characteristics of the product or system, and can be obtained by dividing the component mean time between failures over the summation of mean time between failures and mean time between repairs.

This research contributes to the general aircraft reliability discipline by conceptualising dispatch reliability which is very important because the conceptualization allows more analysis work to be carried out

10.2.3 Contribution to Prediction methodologies

This thesis argues that previous approaches for predicting dispatch reliability at the conceptual design phase were outdated or unsuitable for general aircraft designs. This research builds on previous work that has developed dispatch reliability prediction formula, and uses up-to-date dispatch reliability data to derive a new prediction method.

This research therefore contributes to the existing body of knowledge by providing a new civil aircraft dispatch reliability prediction method that is based on empirical data which can be used during the very early aircraft conceptual design stage. It also can easily be updated periodically.

10.2.4 Contribution to Aircraft Design Practice

Previous design processes were found to undervalue the importance of dispatch reliability, despite the continuing rise of delays and air travel volume. Traditional design practice was reviewed and a new design approach was suggested that incorporates dispatch reliability (see Figure 6-3).

This research contributes to the aircraft design practice by providing an aircraft system design methodology that takes into account the dispatch reliability requirement from the design outset, and allows time-efficient trade-studies in terms of reliability and maintainability.

10.3 Recommendations for Future Work

- A similar dispatch reliability prediction methodology should be developed for different aircraft, such as fast jets, turbo-props and cargo aircraft taking into account the use of appropriate parameters.

- The developed ASDMDR could be extended into a computer program that contains a library for component failure rate, MTTR and dispatch reliability. It needs to incorporate the RELEX or similar software to benefit from its capability. The recommended software is preferable to have some visual demonstration capability to enable designers to assess maintainability characteristics. The proposed software will speed up the design process and improve the accuracy of the methodology.

- Design solutions that would improve an item's dispatch reliability are likely to have cost implications, and a careful selection of an available design solution that is cost-effective is a must. Further research should be conducted into the cost implications of alternative design solutions. This would then permit the outcome of this research to be added to the ASDMDR.

- Given that maintainability is major driver for dispatch reliability, more research should be undertaken to improve maintainability predictions, using the latest available techniques such as 3D simulation.

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Appendices

Appendix A

APPENDIX A · Aircraft Dispatch Reliability Prediction Method Calculations

Introduction

This appendix contains additional description of the development of commercial airplane dispatch reliability perdition model.
Development of such prediction method requires large amounts of information for different aircraft type over a long period of time in order to give a reasonable result and to avoid the seasonal effects.

The aircraft selected for this method were from different manufacturer and for different roles; this was to make it general and not subject to particular size, role or technologies.

The number of aircraft in the method was sought to be as large as possible because it offers more mature aircraft delay rates.

The selected aircraft were divided in two types, according to flight times. Three hours or less was considered short haul while the rest was long haul.
Some of obtained delay rate data was ready to use, and other needs some data processing.

The Aircraft Database

The data base for the delay rate was established on Excel spread sheet. It contained the basic information about the aircraft used on this method such as the cruise speed, maximum thrust, maximum take-off weight, flight length, number of passengers, delay rate and dispatch reliability. Two other calculated parameters were also shown on the database sheet which was the number of passengers divided by the flight time and take-off weight divided by the flight time.
These aircraft data was collected from the aircraft manufacturer's documents and aircraft operators.

No.	Design parameter	Notation	Units
1	Maximum Aircraft Takeoff Weight	MTW	Kg
2	Total Number of Passengers	NP	-
3	Maximum Aircraft Engine Thrust	Thr	kN
4	Flight Length	FL	Hr
5	Cruise Speed	CS	Kts
6	Maximum Aircraft Weight / Flight Length	MTW/FL	Kg/Hr
7	Total Number of Passengers / Flight Length	NP/FL	hr^{-1}

Table A-0-1: Prediction methods Parameters

Data Analysis

Correlation coefficient measures the degree to which two things vary together or oppositely.

If the parameter variables under study vary positively and perfectly with the delay rate variables, then the correlation will equal 1.00. On the other hand, if the two things vary negatively and perfectly, then the correlation will equal -1.00. And when the two data vary separately, which means there is no correlation between them, the correlation will equal 0.0.

The correlation coefficient was calculated using equation A-1 as follows:

$$r = \frac{\sum xy - \frac{\sum x \sum y}{N}}{\sqrt{(\sum x^2 - \frac{(\sum x)^2}{N})\ (\sum y^2 - \frac{(\sum y)^2}{N})}} \qquad \textbf{Equation A-1}$$

Where:

r	the correlation coefficient
X	Anything that varies; a variable that need to be examined, which were in this work the seven parameters
Y	A specific variable which in this work was the delay rate
N	Number of cases for a variable. In this work it was the number of aircraft on the analysis

Correlation coefficient for all the parameters with the delay rate, were calculated and the parameter which has got the highest correlation coefficient was selected. The confidence of the correlation coefficient is obtained by using the probabilities for correlation coefficient shown in table C [103]

As an example, Table A-2 shows the correlation coefficient calculations for the ATA system number 36 which was the pneumatic system for short-haul aircraft. It shows that the highest correlation was between cruise speed and delay rate which was about 0.87.

In this particular case, there is obvious causal link between delay rate and cruise speed for the pneumatic system. This is because cruise speed is usually linked to aircraft performance, and high performance aircraft is more able to provide the required pneumatic power than lower performance aircraft. Thus, high performance aircraft will have less problematic pneumatic system.

Using the above mentioned table, the probabilities for correlation coefficient is found to be 98.2 %. The correlation in this case can be regarded as significant and the cruise speed was selected as the candidate for deriving the delay rate equation for the pneumatic system for short-haul aircraft.

The relationship between delay rate and cruise speed for the pneumatic system was represented graphically and a trendline was drawn with the R-squared value which measure the degree of the trendline accuracy and delay rate equation was derived from the graph. As an example see Figure A.1.

When analysing ATA system 28 for short-haul aircraft, the correlation coefficient was very low, i.e. the correlations between the delay rate and all the parameters were weak, natural log of the delay rate was used and the correlation coefficient was then calculated. This process was performed for the all aircraft ATA systems for both type of aircrafts, and the correspondent delay rate equations were obtained.

ATA 36 Pneumatic	No. of passengers / flight time	Max.takeoff weight(kg) / flight time	No. of passengers	Average Flight length (hr)	Max.takeoff weight (kg)	Cruise Speed (kts)	Max. A/C Thrust (kN)	Delay Rate %	
Aircraft 1	81.44	37876.00	79	0.97	36740	462	123.2	0.0500	
Aircraft 2	150.00	61250.00	180	1.20	73500	448	235.8	0.0400	
Aircraft 3	55.68	23410.00	49	0.88	20600	450	62.6	0.0800	
Aircraft 4	62.31	21719.00	162	2.60	56470	530	215.2	0.0140	
Aircraft 5	69.23	36509.00	189	2.73	99792	459	332.8	0.0600	
Aircraft 6	65.56	28977.78	177	2.7	78240	530	220	0.0220	
Aircraft 7	61.11	21111.11	165	2.7	57000	530	220	0.0001	
Aircraft 8	81.00	41200.00	243	3	123600	458	387	0.0500	
N	8	8	8	8	8	8	8	0.316	Σy
Σx	626.33	272052.89	1244.00	16.78	545942.00	3867.00	1796.60	0.01728001	Σy^2
Σx^2	55501.72	10521634717.16	220610.00	40.95	44971199364.00	1879793.00	478334.52		
Σx^2- (Σx)^2 /N	6465.525486	1270037847	27168	5.75215	7714615944	10581.875	74863.075		
Σxy	25.05119758	11410.82827	44.7385	0.57677	21110.08	146.593	67.7928		
Σxy- Σx Σy/N	0.303323763	661.3384549	-4.41505	-0.08624975	-461.453275	-6.2018375	-3.1953575		
Σy^2- (Σy)^2 /N	0.004790109	0.004790109	0.004790109	0.004790109	0.004790109	0.00479011	0.004790109		
r=1/((2)(3))^0.5	0.054504434	0.268128364	-0.387020621	-0.519601094	-0.075909808	-0.8710967	-0.168738015		

Table A-2: Pneumatic system ATA 36 Correlation coefficient calculations

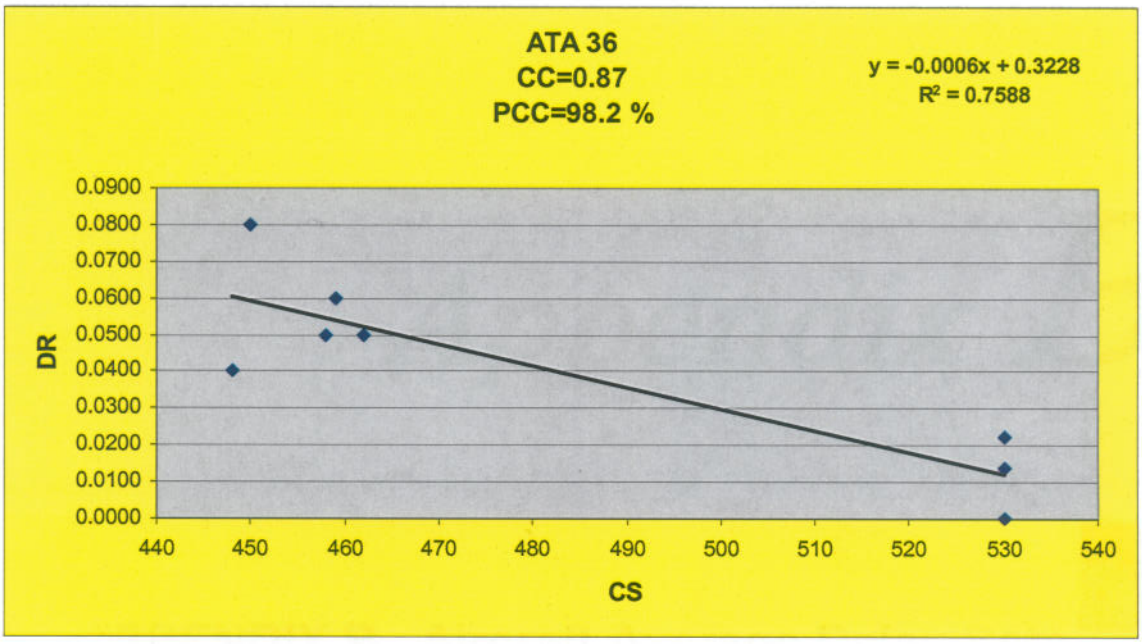


Figure A-1: Pneumatic system ATA 36 delay rate Vs cruise speed

Appendix B

APPENDIX B Aircraft Average Delay Rate Calculations

Introduction

An aircraft delay rate data analysis was performed to investigate the contribution of aircraft systems to the delays.

This study would be useful to identify the most problematic aircraft systems that cause delays. The availability of such information would help aircraft designers and operators to direct more efforts towards these systems to resolve the discrepancy.

The study used different aircraft delay rate data to obtain the average delay rate per ATA system.

The aircraft delay rate data was divided into two categories according to their flying time. Three hours or less flying time aircraft is regarded as short-haul, the rest are long-haul aircraft.

When there are more than one set of delay rate data for the same aircraft that comes from different operators, the average delay rate was calculated for this particular aircraft type. The average delay rates per ATA system were then calculated for both short and long haul groups.

The numerical result of the average delay rate per ATA system for short and long-haul aircrafts are shown in Table B.1 and B.2 respectively.
The study's results, in graphical format are shown in Figures B.3 and B.4 for short and long-haul aircraft respectively.

ATA	Name	Average Delay Rate%
No.21	Air-Condition	0.06
No.22	Auto Pilot	0.02
No.23	Communications	0.02
No.24	Electrical	0.04
No.25	Equipment/ furnisher	0.05
No.26	Fire Protection	0.03
No.27	Flight Control	0.13
No.28	Fuel	0.04
No.29	Hydraulic	0.09
No.30	Ice Protection	0.04
No.31	Instrument	0.04
No.32	Land Gear	0.16
No.33	Light	0.02
No.34	Navigation	0.09
No.35	Oxygen	0.01
No.36	Pneumatic	0.05
No.38	Water Waste	0.01
No.49	APU	0.04
No.51	Structure	0.03
No.52	Doors	0.06
71-80	Power plant	0.20

Table B-1: ATA systems average delay rate for short-haul aircraft

ATA	Name	Average Delay Rate%
No.21	Air-Condition	0.06
No.22	Auto Pilot	0.01
No.23	Communications	0.08
No.24	Electrical	0.08
No.25	Equipment/ furnisher	0.06
No.26	Fire Protection	0.07
No.27	Flight Control	0.14
No.28	Fuel	0.15
No.29	Hydraulic	0.16
No.30	Ice Protection	0.04
No.31	Instrument	0.02
No.32	Land Gear	0.22
No.33	Light	0.04
No.34	Navigation	0.16
No.35	Oxygen	0.00
No.36	Pneumatic	0.12
No.38	Water Waste	0.05
No.49	APU	0.06
No.51	structure	0.02
No.52	doors	0.13
No.53	fuselage	0.00
No.54	nacelles/pylons	0.00
No.56	windows	0.01
No.57	wings	0.00
No.71-80	power plant	0.42

Table B-2: ATA systems average delay rate for long-haul aircraft

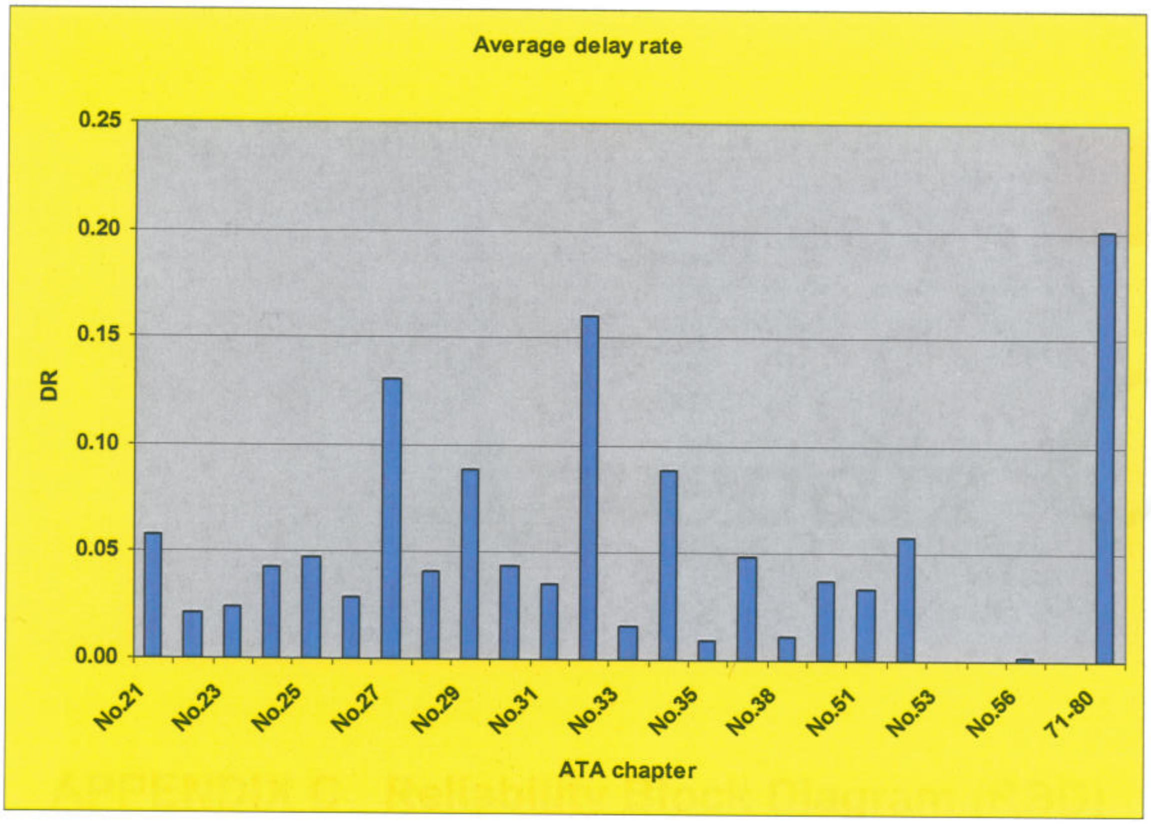


Figure B-1: Short-haul aircraft average delay rate%

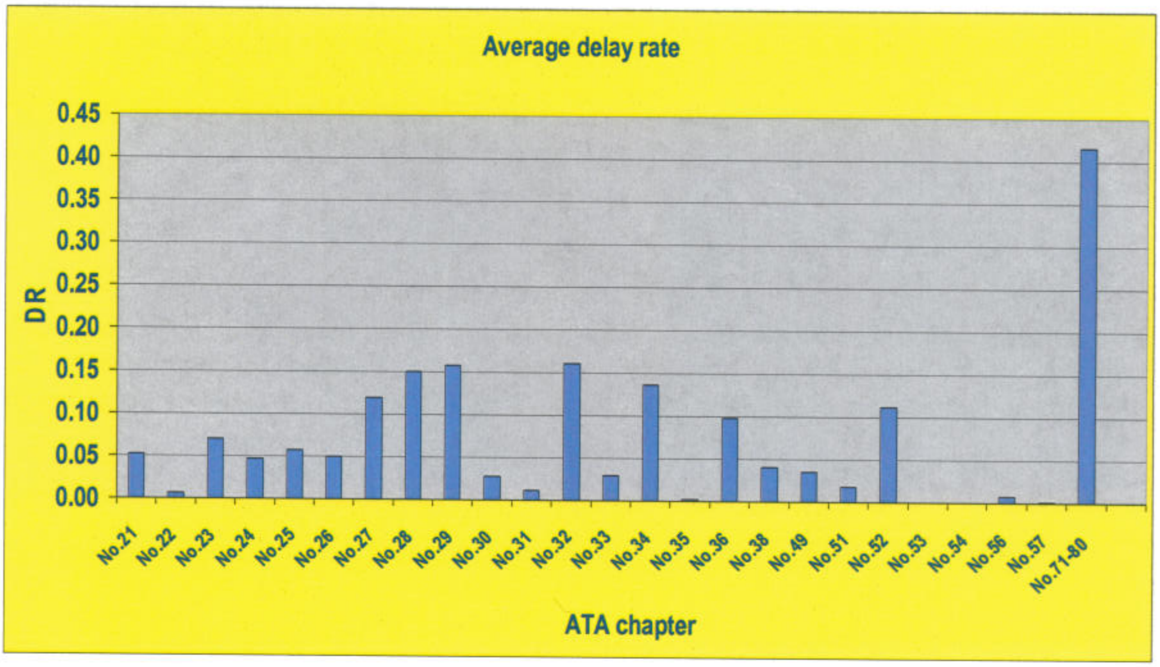


Figure B-2: Long-haul aircraft average delay rate%

Appendix C

APPENDIX C Reliability Block Diagram (RBD)

Introduction

Block diagram is a diagram that shows the operation, interrelationships and interdependencies of components in a system. Boxes, or blocks (hence the name), represent the components; connecting lines between the blocks represent interfaces.

There are two types of block diagrams: a functional block diagram, which shows a system's subsystems and lower level products and their interrelationships and which interfaces with other systems; and a reliability block diagram, which is similar to the functional block diagram except that it is modified to emphasize those aspects influencing reliability.

RBDs in general are used as input to simulation or analytic models that calculate system reliability and availability. This highly structured approach is used to model systems such as propulsion, electrical, steering, combat, external communications, etc. Reliability block diagrams (RBD) have been around for a long time, and have been widely used to model systems. A reliability block diagram is a graphical representation of how the components of a system are reliability-wise connected.

This RBD presentation of the system was used on this work to explain the reliability relationships of systems, sub-systems and components and to calculate the failure rate and reliability of systems and sub-system.

The RBD of a system or sub-system was constructed such that it reflects the components relationship from reliability standpoint of view.
RBD of a particular system was fed with the failure rate data of the components that comprise it and the overall failure rate of the system was obtained.

Complex system RBD can be very large and difficult to analysis, but with the aid of the computer based programme, very complex RBD can be analysed with relative ease.

For reliability analysis and calculation purpose, commercial software called Relex was used to perform these tasks. For more information about this software see appendix I.

The Relex software includes a reliability block diagram (RBD) module. It is powerful software that can build and analyse very complex system easily.

The Reliability Block Diagram (RBD) methodology was used to provide a graphic model of the impact failure of an item has on a system. It is oriented toward evaluating the expected operational success of elements of a system operating in parallel or in series.

Reliability Block Diagram Models

The Relex software reliability block diagram module was used as both a drawing and calculations tool. It allows for complex configurations and for the reliability calculations to incorporate redundancy. Several RBD model were built using the Relex software capability and the Left-hand hydraulic sub-system initial RBD model which is shown in Figure C.1.

A list of the abbreviations used in these figures is presented below.

LRU	Abbreviation
Reservoir Fill Selection Valve	**RFSV**
Pressure Valve	**PV**
Non Return Valve	**NRV**
Engine Driven Pump	**EDP**
Aircraft Motor Pump	**ACMP**
Aircraft Ram Air Turbine Driven Pump	**ARTDP**
Pump Overheat Light	**POL**
Pump Low Light	**PLL**
Heat Exchanger	**HEXH**
Hydraulic Low Light	**HLL**
Hydraulic Quantity Indicator	**HQI**
Depressurization Valve	**DPV**
Moisture Vent Trap	**MVT**

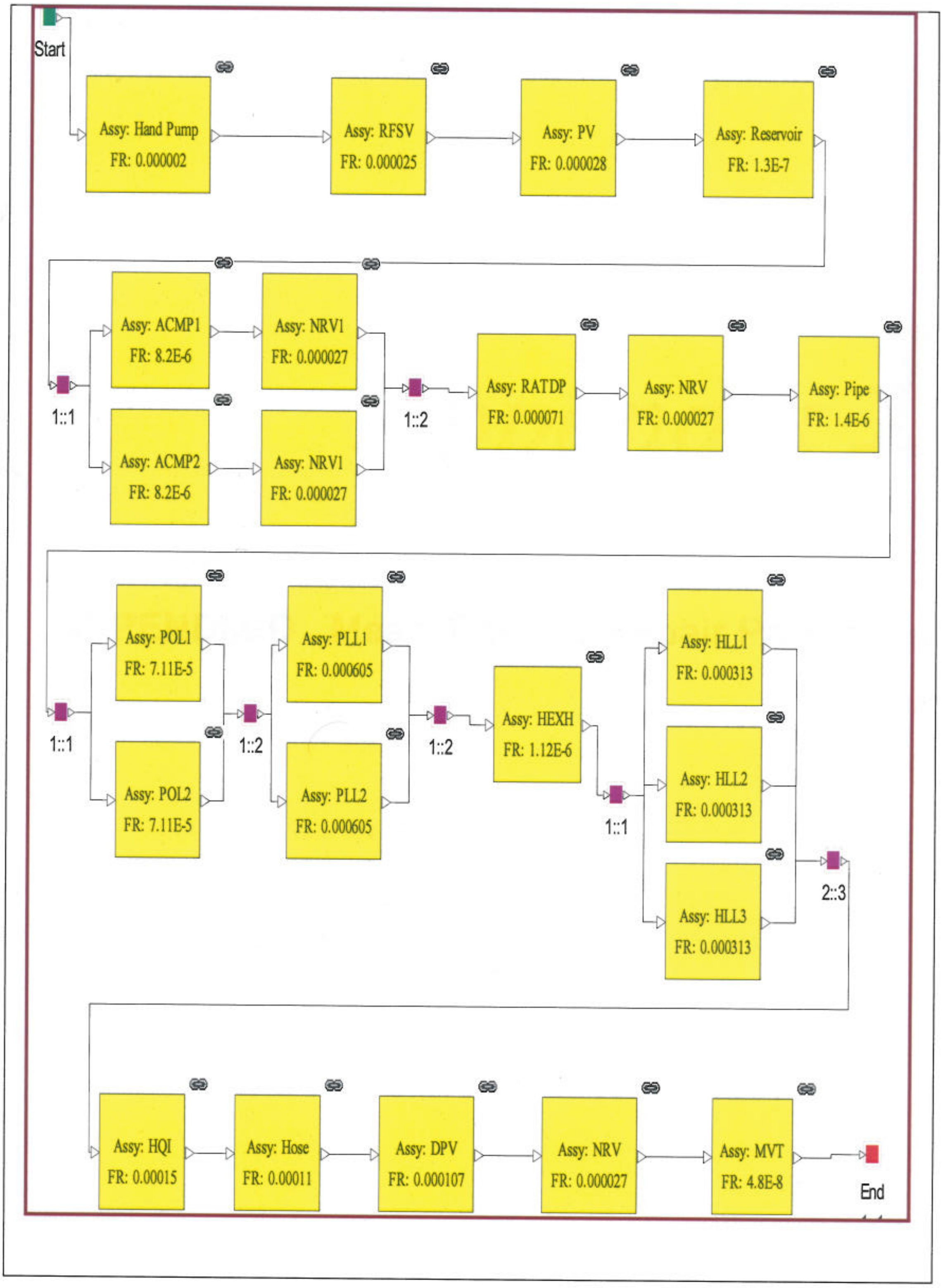


Figure C-1: Left hydraulic sub-system initial RBD

Appendix D

APPENDIX D Mean Time To Repair Prediction

Introduction

Maintainability is one of the aircraft design feature that affect very strongly dispatch reliability.
It is an inherent characteristic of system or product design [75].
Maintainability related to the measures taken during design, development and installation of a manufactured product that reduce the required maintenance actions, man-hours, tools logistic costs, skill level, facilities, and ensure that the product meets the requirements for its intended use. It does so by providing a built-in design features that ensure accessibility, serviceability, parts interchangeability and first and foremost reliability.

By its nature, MTTR depends on the frequencies with which various replaceable or repairable components in the equipments fail. I.e. on the failure rates or replacement rates and on the times it takes to repair the equipment as the different kinds of failure occur.
Mean Time To Repair (MTTR) is the total time required to return a machine to a satisfactory working condition [91].

MTTR Estimation

The fault correction time is in effect the MTTR. It can take the simple form such as the required time to repair an item in-place (i.e. on-aircraft) or it could be the required time to remove the faulty item and replace it with good one.

The mean time to repair (MTTR) in this research was meant to be the on-aircraft repair time or on-aircraft repair by replacement time. The actual on-aircraft repair time is the summation of access time, diagnosis time, replacement or repair time, and verification and alignment time. These times are added up to form the total time it takes to repair or replace an item when it is on-aircraft.

The MIL-472 Procedure III

The MIL-472 procedure 3 is a maintainability prediction procedure created by the US Department of Defence to predict the maintainability of ground electronic systems.
The procedure is based on the philosophy that failures are due to the malfunction of the replaceable items and hence, the downtime is equal to the total time required to carry out the various steps which are the preparation, fault isolation, replacement of the faulty item, adjustment and functional checks.
The length of the item downtime time is assumed to be a function of specific design parameters which relate to the following criteria [34]:

- The physical configuration of the system.
- The facilities provided for maintenance by the design.

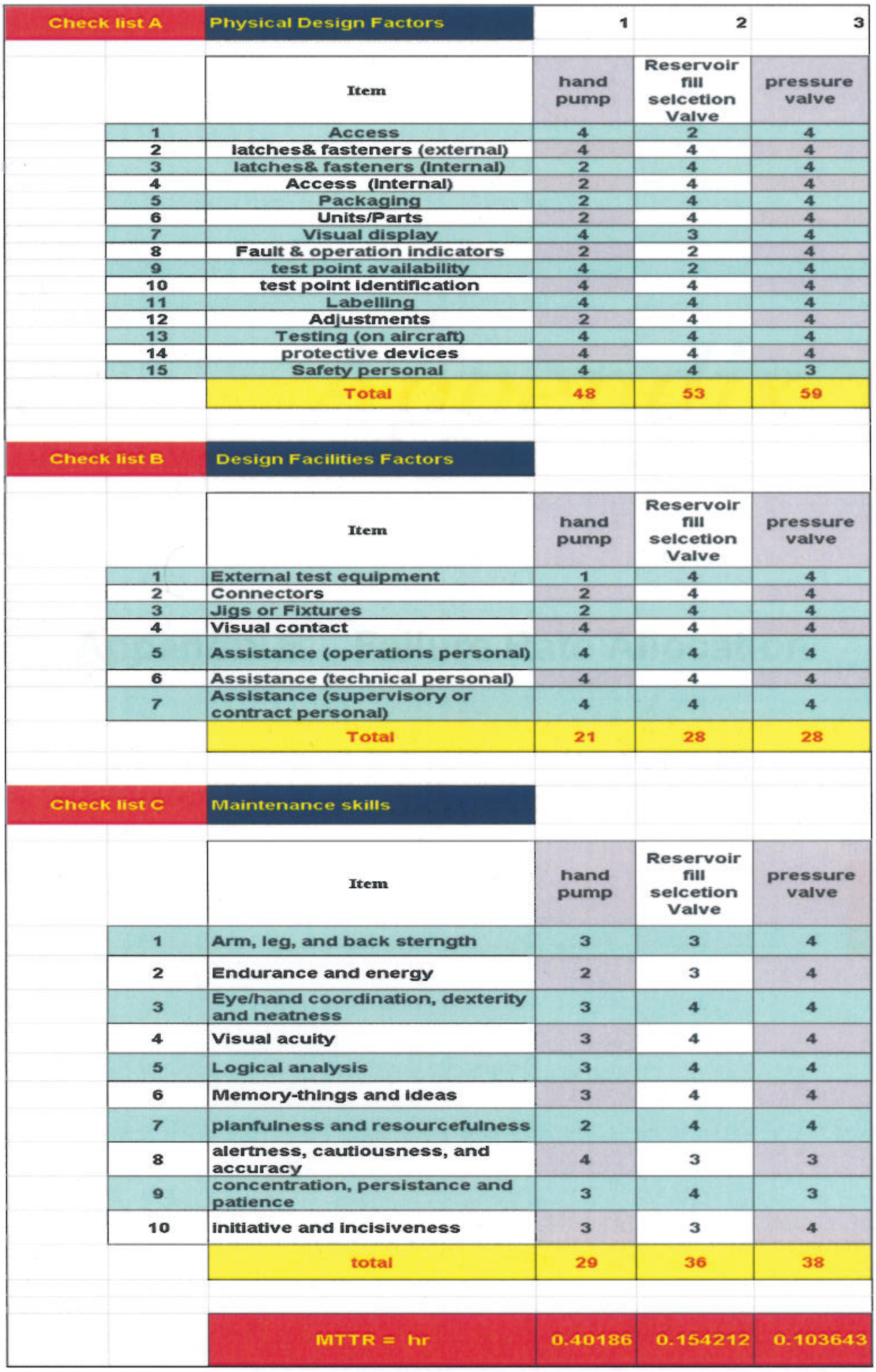
- The degree of maintenance skills required of personal charged with the repair responsibility.

The design check lists A, B, and C is developed for the three criteria and each one of them is consists of several scores and scoring criteria. The scoring of each criteria ranges from 0 to 4.

These design checklists were placed on spreadsheet and the LRU's under investigation are tabulated against the design criteria checklist. The total scoring is calculated for each LRU and entered in Equation D-1.

$$\mathbf{MTTR=10\text{^}(3.54651-0.02512A-0.03055B-0.01093C)} \qquad \textbf{Equation D-1}$$

As an example, the mean time to repair calculation for some of the hydraulic system components is shown in Table D-1.



Check list A	Physical Design Factors		1	2	3
		Item	hand pump	Reservoir fill selcetion Valve	pressure valve
	1	Access	4	2	4
	2	latches& fasteners (external)	4	4	4
	3	latches& fasteners (internal)	2	4	4
	4	Access (internal)	2	4	4
	5	Packaging	2	4	4
	6	Units/Parts	2	4	4
	7	Visual display	4	3	4
	8	Fault & operation indicators	2	2	4
	9	test point availability	4	2	4
	10	test point identification	4	4	4
	11	Labelling	4	4	4
	12	Adjustments	2	4	4
	13	Testing (on aircraft)	4	4	4
	14	protective devices	4	4	4
	15	Safety personal	4	4	3
		Total	48	53	59

Check list B	Design Facilities Factors				
		Item	hand pump	Reservoir fill selcetion Valve	pressure valve
	1	External test equipment	1	4	4
	2	Connectors	2	4	4
	3	Jigs or Fixtures	2	4	4
	4	Visual contact	4	4	4
	5	Assistance (operations personal)	4	4	4
	6	Assistance (technical personal)	4	4	4
	7	Assistance (supervisory or contract personal)	4	4	4
		Total	21	28	28

Check list C	Maintenance skills				
		Item	hand pump	Reservoir fill selcetion Valve	pressure valve
	1	Arm, leg, and back sterngth	3	3	4
	2	Endurance and energy	2	3	4
	3	Eye/hand coordination, dexterity and neatness	3	4	4
	4	Visual acuity	3	4	4
	5	Logical analysis	3	4	4
	6	Memory-things and ideas	3	4	4
	7	planfulness and resourcefulness	2	4	4
	8	alertness, cautiousness, and accuracy	4	3	3
	9	concentration, persistance and patience	3	4	3
	10	initiative and incisiveness	3	3	4
		total	29	36	38
		MTTR = hr	0.40186	0.154212	0.103643

Table D-1: Maintainability Prediction

Appendix E

Appendix E Failure Rate Allocation

Introduction

The source of the base failure rate was the operator's reliability data, where the unscheduled removal was the starting point.
The failure rate allocation was performed using spreadsheet and Relex software.
The sub-system reliability block diagram was constructed on the Relex software module.
The predicted components failure rate data was fed to the RBD, and the total sub-system predicted failure rate was calculated.
These predicted failure rate data were used on the allocation equation to calculate the component allocated failure rate.

The component failure rate allocation performed in several steps as shown in Figure E-1, they are:

I. Constriction of the sub-system reliability block diagram (RBD) based on the sub-system architecture. As an example, the RBD for the right-hand side hydraulic sub-system is shown in Figure E.2.
II. Composing the components predicted failure rate from historical data for similar aircraft.
III. Calculating the sub-system total predicted failure rate.
IV. Component failure rate allocation by using the combined allocation method

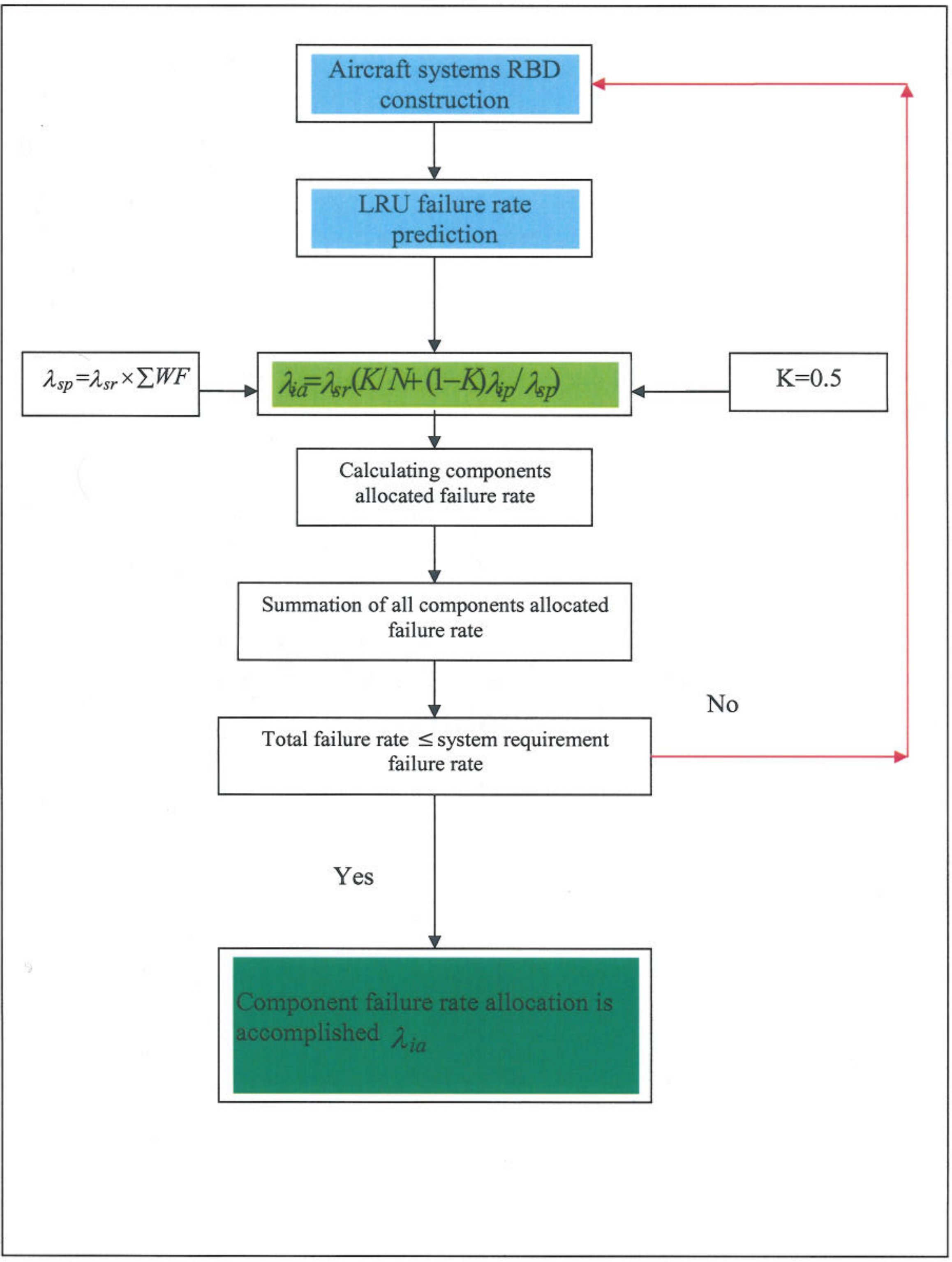


Figure E-1: failure rate allocation

Appendix F

Appendix F Hydraulic Centre Sub-system Validation

Introduction

The validation process was applied for all the three hydraulic sub-systems as shown in chapter 9.3, and the validation results for the centre sub-system is shown in the following section.

Validation Results for the Centre sub-system

In the first validation case where dispatch reliability and mean time to repair (MTTR) were obtained by prediction, while failure rates were collected from aircraft operator data, the result revealed that all LRUs, except two, passed the design requirement. They were the ram air turbine driven pump and depressurization valve. The success of the design methodology can be calculated as a percentage in terms of dispatch reliability and it is shown for the four cases in Table F-1, and the resulting design success percentage for the first case was more than 91.70%.

In the second and third cases, all the three variables were real field data from aircraft operator data. For case two, the results showed that two LRUs failed to pass the design criteria. They were the ram air turbine driven pump and moisture vent trap. The design success percentage for this case was more than 91.70%.

On the third validation case, all LRUs passed the design criteria. The design success was 100%.

On the last validation case, three LRUs failed to meet the design criteria. They were the ram air turbine driven pump, heat exchangers, and warning light. The design success was about 87.50%.

Validation cases	No. of Failed LRU	Required dispatch reliability %	Predicted dispatch reliability %	Success %
Case 1	**2**	**99.970**	**99.95**	**99.98**
Case 2	**2**	**99.977**	**99.96**	**99.98**
Case 3	**0**	**99.969**	**99.969**	**100.0**
Case 4	**3**	**99.970**	**99.940**	**99.97**

Table F-1: Validation results

Input Data	**Total number**	**Failure Rate hr^{-1}**	**Dispatch reliability%**
Hydraulic sys.	1	0.0033	99.915
Hyd. Sub-system C	3	0.0011	99.970
LRU	24		

Table F-2: Hydraulic system basic data for (case 1)

No.	LRU	Failure Rate per hour
1	**Hand Pump**	0.00002
2	**Reservoir fill selection Valve**	0.000028
3	**Pressure Valve (PV)**	2.80E-05
4	**Reservoir**	1.30E-07
5	**Aircraft Motor Pump (ACMP1)**	8.20E-06
6	**Non return valve**	2.70E-05
7	**Aircraft Motor Pump (ACMP2)**	8.20E-06
8	**Non return valve**	2.70E-05
9	**Ram Air Turbine Driven Pump (RATDP)**	7.10E-05
10	**Non return valve**	2.70E-05
11	**Pipe**	1.40E-06
12	**Pump Overheat Light (POL1)**	7.11E-05
13	**Warning light (POL2)**	7.11E-05
14	**Warning light (PLL1)**	6.05E-04
15	**Warning light (PLL2)**	6.05E-04
16	**Heat Exchanger**	1.12E-06
17	**Hydraulic Low Light (HLL1)**	3.13E-04
18	**Hydraulic Low Light (HLL2)**	3.13E-04
19	**Hydraulic Low Light (HLL3)**	3.13E-04
20	**Warning light (HQI)**	1.50E-05
21	**Hose**	1.10E-05
22	**Depressurization Valve (DPV)**	1.07E-04
23	**Non Return Valve (NRV)**	8.20E-06
24	**Moisture Vent Trap (MVT)**	1.48E-05

Table F-3: Hydraulic Centre sub-system LRU failure rate (case 1)

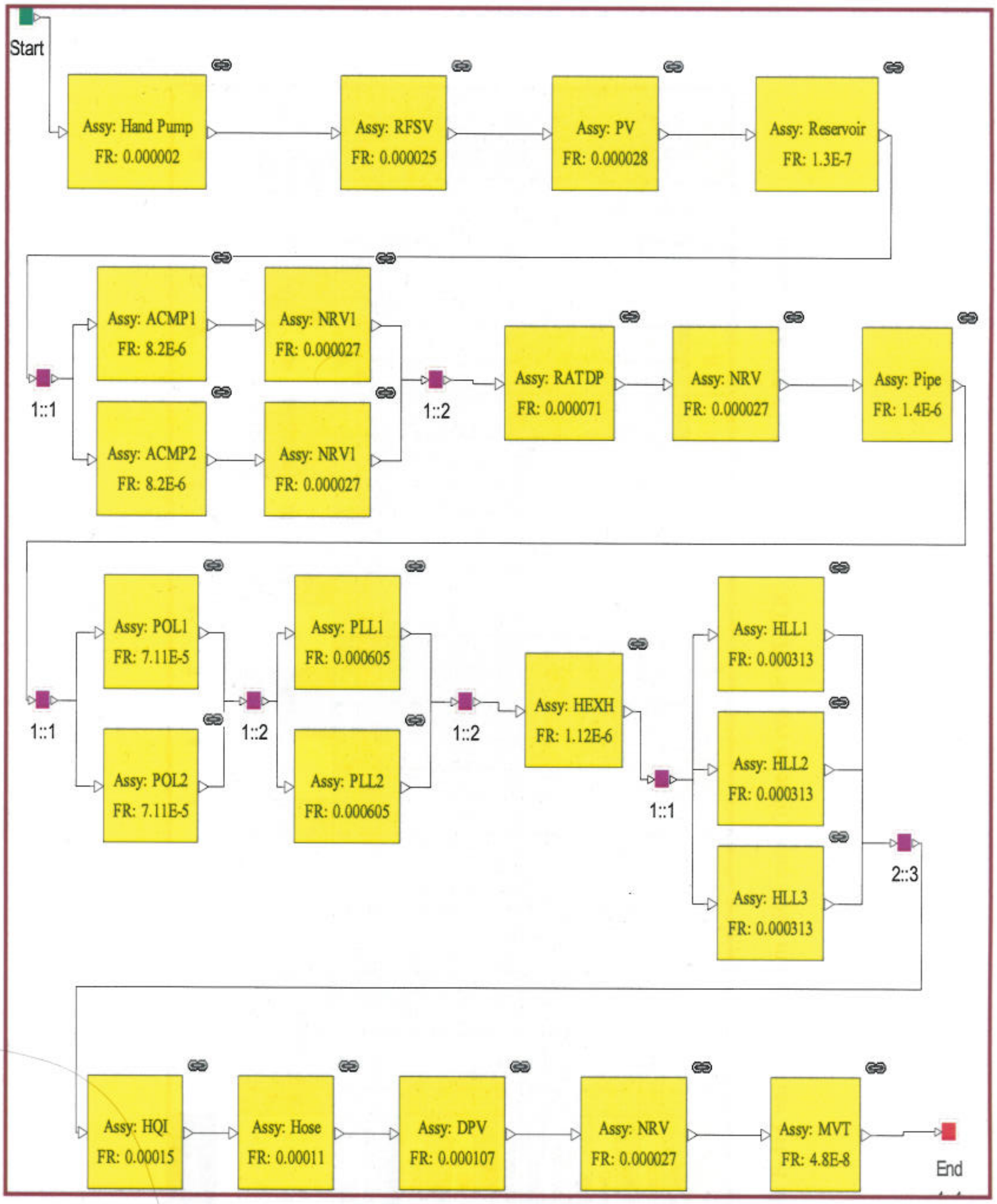


Figure F-1: Centre sub-system RBD

Check list A	Physical Design Factors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Item	Hand Pump	Reservoir fill selcetion Valve	PV	Reservoir	ACMP	NRV	RATDP	Pipe	POL	PLL	Heat Exchanger	HLL	HQI	Hose	Depressurazation valve	Moisture vent trap
1	Access	4	2	2	2	3	2	3	2	3	3	2	3	3	4	4	2
2	latches& fasteners (external)	4	3	2	2	3	2	3	2	3	3	2	3	3	4	4	2
3	latches& fasteners (Internal)	2	3	3	2	3	2	3	3	4	4	2	4	3	4	4	3
4	Access (Internal)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
5	Packaging	2	3	3	2	3	2	3	3	3	4	2	4	3	4	4	3
6	Units/Parts	2	4	3	3	3	2	3	3	3	3	2	3	3	4	3	3
7	Visual display	4	3	4	2	3	2	3	2	3	4	2	4	3	4	4	3
8	Fault & operation indicators	2	2	3	2	3	2	3	3	3	4	2	4	3	4	4	3
9	test point availability	4	2	2	2	3	2	3	3	3	4	2	4	4	4	2	3
10	test point identification	4	3	2	3	3	2	3	3	3	4	2	4	3	2	3	3
11	Labelling	4	4	4	3	2	2	2	3	3	4	2	4	3	4	4	3
12	Adjustments	2	3	4	4	3	4	3	3	2	2	4	2	3	4	4	3
13	Testing (on aircraft)	4	2	2	4	4	4	4	2	2	2	2	2	3	4	4	3
14	protective devices	4	2	3	4	4	4	4	2	3	4	2	4	4	4	4	3
15	Safety personal	4	4	3	3	4	4	4	2	2	2	2	2	3	4	4	
	Total	50	44	44	42	48	40	48	40	44	51	34	51	48	58	56	41

Table F-4: Centre sub-system LRU mean time to repair (MTTR) prediction (Check list A) (Case 1)

Check list B	Design Facilities Factors																
	Item	Hand Pump	Reservoir fill selcetion Valve	PV	Reservoir	ACMP	NRV	RATDP	Pipe	POL	PLL	Heat Exchanger	HLL	HQI	Hose	Depressurazation valve	Moisture vent trap
1	External test equipment	1	4	3	2	4	4	4	3	2	2	2	2	3	4	4	2
2	Connectors	2	3	3	2	2	4	2	2	2	2	4	2	3	2	4	2
3	Jigs or Fixtures	2	3	4	3	4	4	4	3	4	4	2	4	3	4	4	2
4	Visual contact	2	3	3	3	4	4	4	3	3	4	4	4	3	4	4	3
5	Assistance (operations personal)	2	3	3	2	4	2	4	3	3	4	4	4	4	4	2	3
6	Assistance (technical personal)	4	3	3	2	2	2	2	3	2	2	2	2	4	4	4	3
7	Assistance (supervisory or contract personal)	4	3	3	2	4	4	4	2	2	2	2	2	3	4	4	3
	Total	17	22	22	16	24	24	24	19	18	20	20	20	23	26	26	18

Table F-5: Centre sub-system LRU mean time to repair (MTTR) prediction (Check list B) (Case 1)

Check list C	Maintenance skills																
	Item	Hand Pump	Reservoir fill selcetion Valve	PV	Reservoir	ACMP	NRV	RATDP	Pipe	POL	PLL	Heat Exchanger	HLL	HQI	Hose	Depressurization Valve	Moisture Vent Trap
1	Arm, leg, and back sterngth	3	3	2	2	4	4	4	2	2	2	2	2	3	4	4	3
2	Endurance and energy	2	3	4	2	4	4	4	2	3	4	2	4	3	4	4	3
3	Eye/hand coordination, dexterity and neatness	3	4	4	2	4	4	4	2	3	3	2	4	3	4	4	3
4	Visual acuity	3	4	4	2	2	3	2	2	2	2	3	4	3	4	4	3
5	Logical analysis	3	4	4	2	2	3	2	2	2	2	2	3	3	3	3	3
6	Memory-things and ideas	3	4	4	2	3	3	3	2	2	2	3	4	3	4	2	3
7	planfulness and resourcefulness	2	4	4	2	3	3	3	2	2	2	2	4	3	4	2	3
8	alertness, cautiousness, and accuracy	4	3	3	2	2	3	2	2	3	4	2	4	3	4	4	3
9	concentration, persistance and patience	3	4	3	2	3	3	3	2	3	4	2	3	3	4	4	3
10	initiative and incisiveness	3	3	4	2	3	3	3	2	3	4	2	4	4	3	4	3
	total	29	36	36	20	30	33	30	20	25	29	22	36	31	38	35	30
	MTTR = hr	0.47	0.40	0.40	1.01	0.32	0.47	0.32	0.92	0.69	0.36	1.16	0.30	0.33	0.13	0.15	0.73

Table F-6: Centre sub-system LRU mean time to repair (MTTR) prediction (Check list C) (Case 1)

No.	LRU	Failure Rate per hour	MTBF	MTTR	Predicted Dispatch Reliability	Allocated Dispatch Reliability	DESIGN DECISSION
1	Hand Pump	0.000020	50000.000	0.47	0.9999905	0.999984	GOOD
2	Reservoir fill selection Valve	0.000028	35714.286	0.40	0.9999889	0.999984	GOOD
3	Pressure Valve (PV)	0.000028	35714.286	0.40	0.9999889	0.999984	GOOD
4	Reservoir	0.000000	7692307.692	1.01	0.9999999	0.999984	GOOD
5	Aircraft Motor Pump (ACMP1)	0.000008	121951.220	0.32	0.9999974	0.996100	GOOD
6	Non return valve	0.000027	37037.037	0.47	0.9999874	0.996100	GOOD
7	Aircraft Motor Pump (ACMP2)	0.000008	121951.220	0.32	0.9999974	0.996100	GOOD
8	Non return valve	0.000027	37037.037	0.47	0.9999874	0.996100	GOOD
9	Ram Air Turbine Driven Pump (RATDP)	0.000071	14084.507	0.32	0.9999775	0.999984	Try again
10	Non return valve	0.000027	37037.037	0.47	0.9999874	0.996100	GOOD
11	Pipe	0.000001	714285.714	0.92	0.9999987	0.996100	GOOD
12	Pump Overheat Light (POL1)	0.000071	14064.698	0.69	0.9999508	0.996100	GOOD
13	Warning light (POL2)	0.000071	14064.698	0.69	0.9999508	0.996100	GOOD
14	Warning light (PLL1)	0.000605	1652.893	0.36	0.9997808	0.996100	GOOD
15	Warning light (PLL2)	0.000605	1652.893	0.36	0.9997808	0.996100	GOOD
16	Heat Exchanger	0.000001	892857.143	1.16	0.9999987	0.999984	GOOD
17	Hydraulic Low Light (HLL1)	0.000313	3194.888	0.30	0.9999049	0.999984	GOOD
18	Hydraulic Low Light (HLL2)	0.000313	3194.888	0.30	0.9999049	0.999984	GOOD
19	Hydraulic Low Light (HLL3)	0.000313	3194.888	0.30	0.9999049	0.999984	GOOD
20	Warning light (HQI)	0.000015	66666.667	0.33	0.9999950	0.999984	GOOD
21	Hose	0.000011	90909.091	0.33	0.9999963	0.999984	GOOD
22	Depressurization Valve (DPV)	0.000107	9345.794	0.15	0.9999836	0.999984	Try again
23	Non Return Valve (NRV)	0.000008	121951.220	0.15	0.9999987	0.999984	GOOD
24	Moisture Vent Trap (MVT)	0.000015	67567.568	0.73	0.9999893	0.999984	GOOD

Table F-7: Centre hydraulic sub-system methodology design output (case 1)

Input Data	Total number	Failure rate hr^{-1}	Dispatch reliability%
Hydraulic sys.	1	0.00061	99.93
Hyd. Sub-system C	3	0.000203	99.9766
LRU	24		

Table F-8: Hydraulic system basic data for (case 2)

No.	Component	Failure Rate per hour
1	Hand Pump	2.30E-06
2	Reservoir fill selection Valve	4.60E-06
3	Pressure Valve (PV)	5.60E-06
4	Reservoir	1.28E-07
5	Aircraft Motor Pump (ACMP1)	8.20E-06
6	Non return valve	1.72E-05
7	Aircraft Motor Pump (ACMP2)	8.20E-06
8	Non return valve	1.72E-05
9	Ram Air Turbine Driven Pump (RATDP)	7.10E-05
10	Non return valve	1.72E-05
11	Pipe	3.20E-08
12	Pump Overheat Light (POL1)	1.49E-04
13	Warning light (POL2)	1.49E-04
14	Warning light (PLL1)	3.98E-05
15	Warning light (PLL2)	3.98E-05
16	Heat Exchanger	1.18E-06
17	Hydraulic Low Light (HLL1)	1.49E-04
18	Hydraulic Low Light (HLL2)	1.49E-04
19	Hydraulic Low Light (HLL3)	1.49E-04
20	Warning light (HQI)	6.04E-06
21	Hose	1.16E-05
22	Depressurization Valve (DPV)	1.28E-06
23	Non Return Valve (NRV)	1.72E-05
24	Moisture Vent Trap (MVT)	4.80E-08

Table F-9: Hydraulic right-hand side sub-system LRU failure rate (case 2)

No.	LRU	Failure Rate per hour	MTBF	MTTR (Hr)	Predicted Dispatch Reliability	Allocated Dispatch Reliability	DESIGN DECISSION
1	Hand Pump	2.30E-06	434782.6	1.25	0.9999971	0.9999870	GOOD
2	Reservoir fill selection Valve	4.60E-06	217391.3	0.40	0.9999982	0.9999870	GOOD
3	Pressure Valve (PV)	5.60E-06	178571.4	1.25	0.9999930	0.9999870	GOOD
4	Reservoir	1.28E-07	7812500.0	2.00	0.9999997	0.9999870	GOOD
5	Aircraft Motor Pump (ACMP1)	8.20E-06	121951.2	1.00	0.9999918	0.9967000	GOOD
6	Non return valve	1.72E-05	57999.9	0.70	0.9999879	0.9967000	GOOD
7	Aircraft Motor Pump (ACMP2)	8.20E-06	121951.2	1.00	0.9999918	0.9967000	GOOD
8	Non return valve	1.72E-05	57999.9	0.70	0.9999879	0.9967000	GOOD
9	Ram Air Turbine Driven Pump (RATDP)	7.10E-05	14084.5	0.40	0.9999716	0.9999903	Try again
10	Non return valve	1.72E-05	57999.9	0.70	0.9999879	0.9967000	GOOD
11	Pipe	3.20E-08	31250000.0	2.50	0.9999999	0.9965000	GOOD
12	Pump Overheat Light (POL1)	1.49E-04	6711.4	0.20	0.9999702	0.9965000	GOOD
13	Warning light (POL2)	1.49E-04	6711.4	0.20	0.9999702	0.9965000	GOOD
14	Warning light (PLL1)	3.98E-05	25125.6	0.20	0.9999920	0.9965000	GOOD
15	Warning light (PLL2)	3.98E-05	25125.6	0.20	0.9999920	0.9999903	GOOD
16	Heat Exchanger	1.18E-06	847457.6	1.00	0.9999988	0.9770000	GOOD
17	Hydraulic Low Light (HLL1)	1.49E-04	6711.4	0.20	0.9999702	0.9780000	GOOD
18	Hydraulic Low Light (HLL2)	1.49E-04	6711.4	0.20	0.9999702	0.9780000	GOOD
19	Hydraulic Low Light (HLL3)	1.49E-04	6711.4	0.20	0.9999702	0.9780000	GOOD
20	Warning light (HQI)	6.04E-06	165562.9	0.20	0.9999988	0.9999903	GOOD
21	Hose	1.16E-05	86355.8	1.00	0.9999884	0.9999870	GOOD
22	Depressurization Valve (DPV)	1.28E-06	781250.0	0.40	0.9999995	0.9999870	GOOD
23	Non Return Valve (NRV)	1.72E-05	57999.9	0.40	0.9999931	0.9999870	GOOD
24	Moisture Vent Trap (MVT)	4.80E-08	20833333.3	0.12	0.9997894	0.9999870	Try again

Table F-10: Centre hydraulic sub-system methodology design output (case 2)

Input Data	Total number	Failure rate hr^{-1}	Dispatch reliability
Hydraulic sys.	1	0.0004	99.91
Hyd. Sub-system C	3	0.000133	99.969
LRU	24		

Table F-11: Hydraulic system basic data for (case 3)

No.	Component	Failure Rate per hour
1	Hand Pump	2.30E-06
2	Reservoir fill selection Valve	9.50E-05
3	Pressure Valve (PV)	2.50E-05
4	Reservoir	6.18E-04
5	Aircraft Motor Pump (ACMP1)	3.69E-05
6	Non return valve	9.50E-05
7	Aircraft Motor Pump (ACMP2)	3.69E-05
8	Non return valve	9.50E-05
9	Ram Air Turbine Driven Pump (RATDP)	2.69E-05
10	Non return valve	9.50E-05
11	Pipe	1.40E-06
12	Pump Overheat Light (POL1)	7.11E-05
13	Warning light (POL2)	7.11E-05
14	Warning light (PLL1)	7.11E-05
15	Warning light (PLL2)	7.11E-05
16	Heat Exchanger	1.12E-06
17	Hydraulic Low Light (HLL1)	1.49E-04
18	Hydraulic Low Light (HLL2)	1.49E-04
19	Hydraulic Low Light (HLL3)	1.49E-04
20	Warning light (HQI)	7.12E-05
21	Hose	1.16E-04
22	Depressurization Valve (DPV)	1.07E-04
23	Non Return Valve (NRV)	9.50E-05
24	Moisture Vent Trap (MVT)	2.55E-06

Table F-12: Hydraulic centre sub-system LRU failure rate (case 3)

No.	LRU	Failure Rate per hour	MTBF	MTTR (Hr)	Predicted Dispatch Reliability	Allocated Dispatch Reliability	DESIGN DECISSION
1	Hand Pump	2.30E-06	434782.6	1.10	0.999997	0.999983	GOOD
2	Reservoir fill selection Valve	2.25E-05	44537.0	0.50	0.999989	0.999983	GOOD
3	Pressure Valve (PV)	2.50E-05	40000.0	0.60	0.999985	0.999983	GOOD
4	Reservoir	1.52E-05	65778.0	0.90	0.999986	0.999983	GOOD
5	Aircraft Motor Pump (ACMP1)	1.30E-05	76888.0	0.98	0.999987	0.996000	GOOD
6	Non return valve	9.50E-05	23455.0	1.20	0.999949	0.996000	GOOD
7	Aircraft Motor Pump (ACMP2)	1.30E-05	76888.0	0.98	0.999987	0.996000	GOOD
8	Non return valve	1.24E-05	80544.0	1.20	0.999985	0.996000	GOOD
9	Ram Air Turbine Driven Pump (RATDP)	1.30E-05	76888.0	0.98	0.999987	0.999983	GOOD
10	Non return valve	9.50E-05	10526.3	1.20	0.999886	0.996000	GOOD
11	Pipe	1.40E-06	714285.7	3.50	0.999995	0.999983	GOOD
12	Pump Overheat Light (POL1)	7.11E-05	14064.7	0.20	0.999986	0.999983	GOOD
13	Warning light (POL2)	7.11E-05	14064.7	0.20	0.999986	0.999983	GOOD
14	Warning light (PLL1)	7.11E-05	14064.7	0.20	0.999986	0.999983	GOOD
15	Warning light (PLL2)	7.11E-05	14064.7	0.20	0.999986	0.999983	GOOD
16	Heat Exchanger	1.12E-06	895776.4	1.80	0.999998	0.999983	GOOD
17	Hydraulic Low Light (HLL1)	1.49E-04	6711.4	0.50	0.999926	0.975000	GOOD
18	Hydraulic Low Light (HLL2)	1.49E-04	6711.4	0.50	0.999926	0.975000	GOOD
19	Hydraulic Low Light (HLL3)	1.49E-04	6711.4	0.50	0.999926	0.975000	GOOD
20	Warning light (HQI)	7.12E-05	14050.9	0.20	0.999986	0.999983	GOOD
21	Hose	1.31E-05	76552.0	1.00	0.999987	0.999983	GOOD
22	Depressurization Valve (DPV)	1.30E-05	76888.0	1.20	0.999984	0.999983	GOOD
23	Non Return Valve (NRV)	9.50E-05	10526.3	1.20	0.999886	0.996000	GOOD
24	Moisture Vent Trap (MVT)	2.55E-06	392156.9	1.20	0.999997	0.999983	GOOD

Table F-13: Centre hydraulic sub-system methodology design output (case 3)

Input Data	Total number	Failure rate hr^{-1}	Dispatch reliability%
Hydraulic sys.	1	0.002	99.89
Hyd. Sub-system C	3	0.000666	99.970
LRU	24		

Table F-14: Hydraulic system basic data for (case 4)

No.	Component	Failure Rate per hour
1	Hand Pump	0.00000230
2	Reservoir fill selection Valve	0.00003430
3	Pressure Valve (PV)	0.00000290
4	Reservoir	0.00000013
5	Aircraft Motor Pump (ACMP1)	0.00003689
6	Non return valve	0.00009490
7	Aircraft Motor Pump (ACMP2)	0.00003689
8	Non return valve	0.00009490
9	Ram Air Turbine Driven Pump (RATDP)	0.00002689
10	Non return valve	0.00009490
11	Pipe	0.00000003
12	Pump Overheat Light (POL1)	0.00014900
13	Warning light (POL2)	0.00014900
14	Warning light (PLL1)	0.00003980
15	Warning light (PLL2)	0.00003980
16	Heat Exchanger	0.00001620
17	Hydraulic Low Light (HLL1)	0.00014900
18	Hydraulic Low Light (HLL2)	0.00014900
19	Hydraulic Low Light (HLL3)	0.00014900
20	Warning light (HQI)	0.00007117
21	Hose	0.00011580
22	Depressurization Valve (DPV)	0.00000128
23	Non Return Valve (NRV)	0.00009490
24	Moisture Vent Trap (MVT)	0.00000005

Table F-15: Hydraulic Centre sub-system LRU failure rate (case 4)

No.	LRU	Failure Rate per hour	MTBF	MTTR (Hr)	Predicted Dispatch Reliability	Allocated Dispatch Reliability	DESIGN DECISSION
1	Hand Pump	0.00000230	434782.6	1.18	0.99999730	0.99998425	GOOD
2	Reservoir fill selection Valve	0.00003430	29154.5	0.45	0.99998457	0.99998425	GOOD
3	Pressure Valve (PV)	0.00000290	344827.6	0.93	0.99999732	0.99998425	GOOD
4	Reservoir	0.00000013	7812500.0	1.45	0.99999981	0.99998425	GOOD
5	Aircraft Motor Pump (ACMP1)	0.00003689	27111.0	1.00	0.99996312	0.99700000	GOOD
6	Non return valve	0.00009490	10537.4	0.80	0.99992409	0.99700000	GOOD
7	Aircraft Motor Pump (ACMP2)	0.00003689	27111.0	1.00	0.99996312	0.99700000	GOOD
8	Non return valve	0.00009490	10537.4	0.80	0.99992409	0.99700000	GOOD
9	Ram Air Turbine Driven Pump (RATDP)	0.00002689	37189.0	0.95	0.99997446	0.99998508	Try again
10	Non return valve	0.00009490	10537.4	0.80	0.99992409	0.99700000	GOOD
11	Pipe	0.00000003	31250000.0	3.00	0.99999990	0.99998425	GOOD
12	Pump Overheat Light (POL1)	0.00014900	6711.4	0.20	0.99997020	0.99700000	GOOD
13	Warning light (POL2)	0.00014900	6711.4	0.20	0.99997020	0.99570000	GOOD
14	Warning light (PLL1)	0.00003980	25125.6	0.20	0.99999204	0.99570000	GOOD
15	Warning light (PLL2)	0.00003980	25125.6	0.20	0.99999204	0.99570000	GOOD
16	Heat Exchanger	0.00001620	61728.4	1.40	0.99997732	0.99998425	Try again
17	Hydraulic Low Light (HLL1)	0.00014900	6711.4	0.35	0.99994785	0.97500000	GOOD
18	Hydraulic Low Light (HLL2)	0.00014900	6711.4	0.35	0.99994785	0.97500000	GOOD
19	Hydraulic Low Light (HLL3)	0.00014900	6711.4	0.35	0.99994785	0.97500000	GOOD
20	Warning light (HQI)	0.00007117	14050.9	0.33	0.99997651	0.99998425	Try again
21	Hose	0.00011580	8635.6	0.13	0.99998495	0.99998425	GOOD
22	Depressurization Valve (DPV)	0.00000128	781250.0	0.80	0.99999898	0.99998425	GOOD
23	Non Return Valve (NRV)	0.00009490	10537.4	0.80	0.99992409	0.99700000	GOOD
24	Moisture Vent Trap (MVT)	0.00000005	20833333.3	0.66	0.99999997	0.99998425	GOOD

Table F-16: Centre hydraulic sub-system methodology design output (case 4)

Appendix G

Appendix G Reliability Reports

Introduction

Aircraft industry reports aircraft reliability performance in different formats, and to different time duration. These reports are very valuable assets that are used to perform different analysis, such as individual aircraft performance, fleet performance, maintenance quality, logistics performance, system, sub-system and components performance.

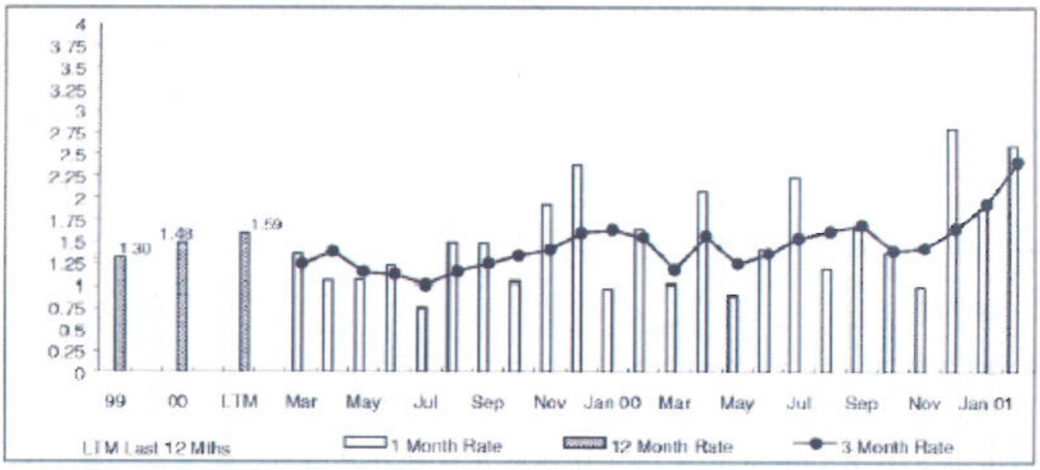
Dispatch reliability and component failure rate data are reported usually in monthly basis which contain different information such as dispatch reliability performance per aircraft type, aircraft system delay rate, component unscheduled removals rate, and so on.

Although the reliability report is very important in monitoring aircraft performance, the quality of these reports is usually different. However, some of these reports possess very high accuracy. The reasons of the low accuracy of some of the reliability report can be:

- Less attention is taken by the management towards reliability report.
- Reliability report is gathered by incompetent personal.
- Lack of supervision.
- Weak training.

Examples of these reports are shown in Tables G-1 to G-7.

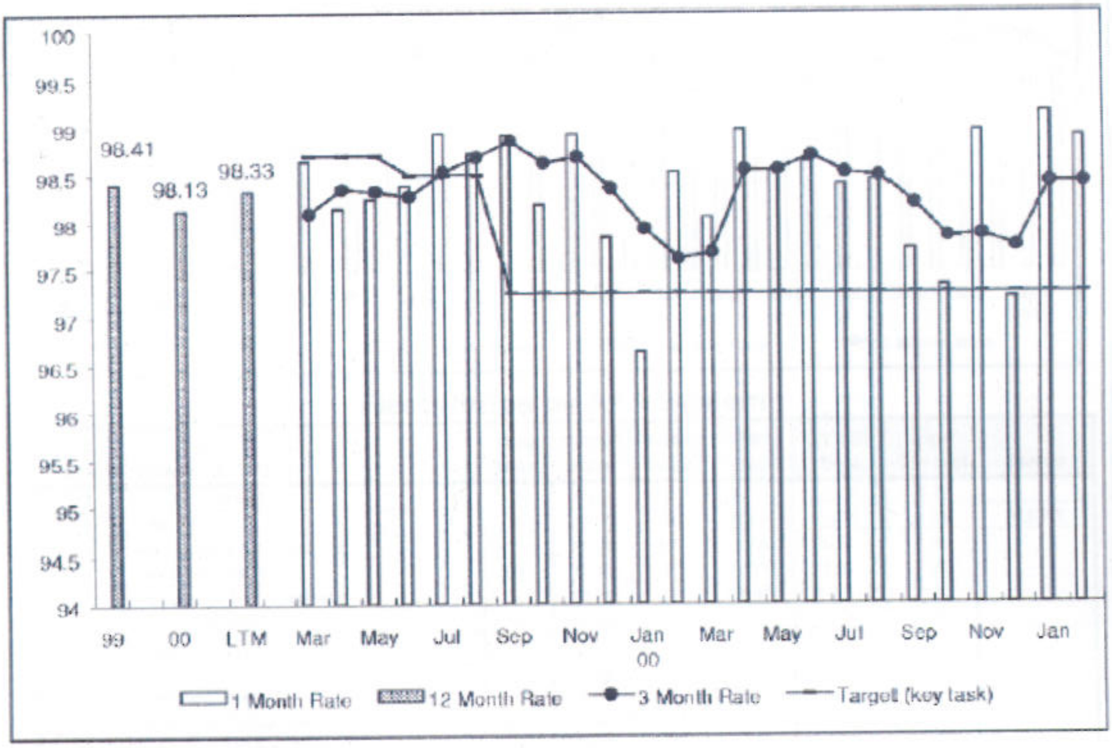
Fleet Technical Interruptions



ATA	System	Delay Time	Feb Delays	Feb Rate	3 mth Total	3 mth Rate	12 mth Total	12 mth rate	Upper Ctrl Lmt	Status	Top 5 by 3mth rate
05	Maintenance Checks		0	0.00	0	0.00	6	0.08	0.14		
21	Air Conditioning	01:15	2	0.58	2	0.19	2	0.03	0.34	ALERT	
22	Auto Pilot		0	0.00	0	0.00	1	0.01	0.12		
23	Communication		0	0.00	0	0.00	0	0.00	0.15		
24	Electrical Power		0	0.00	2	0.19	8	0.11	0.20		1
25	Equipment & Furnishings		0	0.00	1	0.09	3	0.04	0.28		
26	Fire Protection		0	0.00	0	0.00	2	0.03	0.10		
27	Flight Controls		0	0.00	1	0.09	14	0.20	0.42		
28	Fuel		0	0.00	1	0.09	5	0.07	0.24		
29	Hydraulic Power	00:50	2	0.58	5	0.46	11	0.15	0.21	ALERT	3
30	Ice & Rain Protection		0	0.00	0	0.00	1	0.01	0.21		
31	Indicating & Recording		0	0.00	0	0.00	1	0.01	0.21		
32	Landing Gear		0	0.00	0	0.00	7	0.10	0.24		
33	Lights	12:35	1	0.29	2	0.19	3	0.04	0.19	ALERT	5
34	Navigation		0	0.00	0	0.00	5	0.07	0.17		
35	Oxygen		0	0.00	0	0.00	0	0.00	0.10		
36	Pneumatics		0	0.00	6	0.56	11	0.15	0.30		2
38	Water & Waste		0	0.00	0	0.00	0	0.00	0.10		
49	APU		0	0.00	0	0.00	6	0.08	0.13		
51	Structures		0	0.00	0	0.00	0	0.00	0.10		
52	Doors		0	0.00	0	0.00	0	0.00	0.13		
53	Fuselage		0	0.00	0	0.00	0	0.00	0.10		
54	Nacelles / Pylons		0	0.00	0	0.00	0	0.00	0.10		
56	Windows		0	0.00	0	0.00	2	0.03	0.12		
57	Wings		0	0.00	0	0.00	0	0.00	0.10		
71	Powerplant		0	0.00	0	0.00	1	0.01	0.13		
72	Engines	00:25	1	0.29	1	0.09	3	0.04	0.28	ALERT	
73	Engine Fuel & Control	48:00	3	0.87	4	0.37	8	0.11	0.37	ALERT	4
74	Engine Ignition		0	0.00	0	0.00	0	0.00	0.10		
75	Engine Air		0	0.00	0	0.00	0	0.00	0.10		
76	Engine Controls		0	0.00	0	0.00	1	0.01	0.11		
77	Engine Indicating		0	0.00	0	0.00	0	0.00	0.11		
78	Exhaust		0	0.00	0	0.00	6	0.08	0.18		
79	Engine Oil		0	0.00	0	0.00	3	0.04	0.16		
80	Starting		0	0.00	1	0.09	3	0.06	0.10		
	Sub Total	63:05	9	2.60	26	2.41	113	1.59			

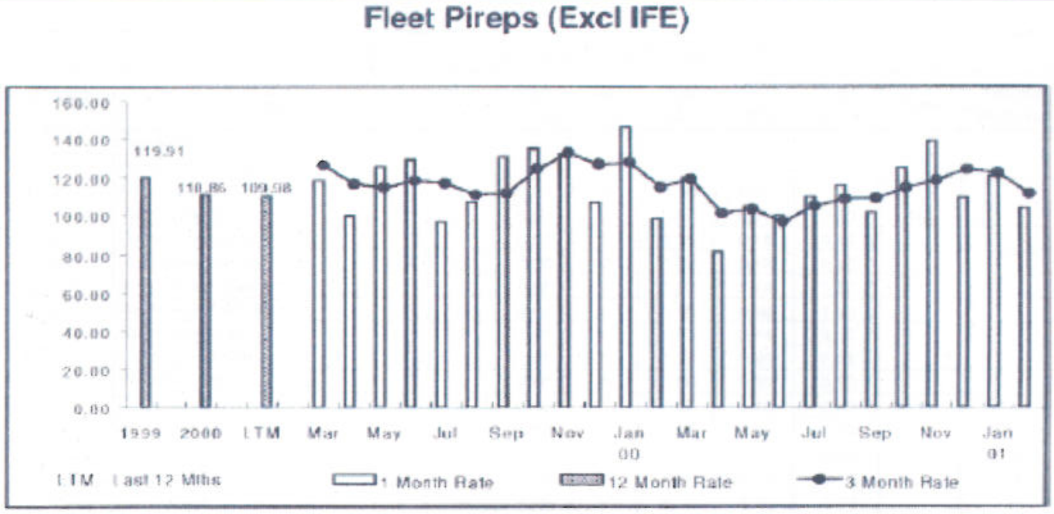
Table G-1: Aircraft system delay rate report

Despatch Reliability
(Reliability Management Program)



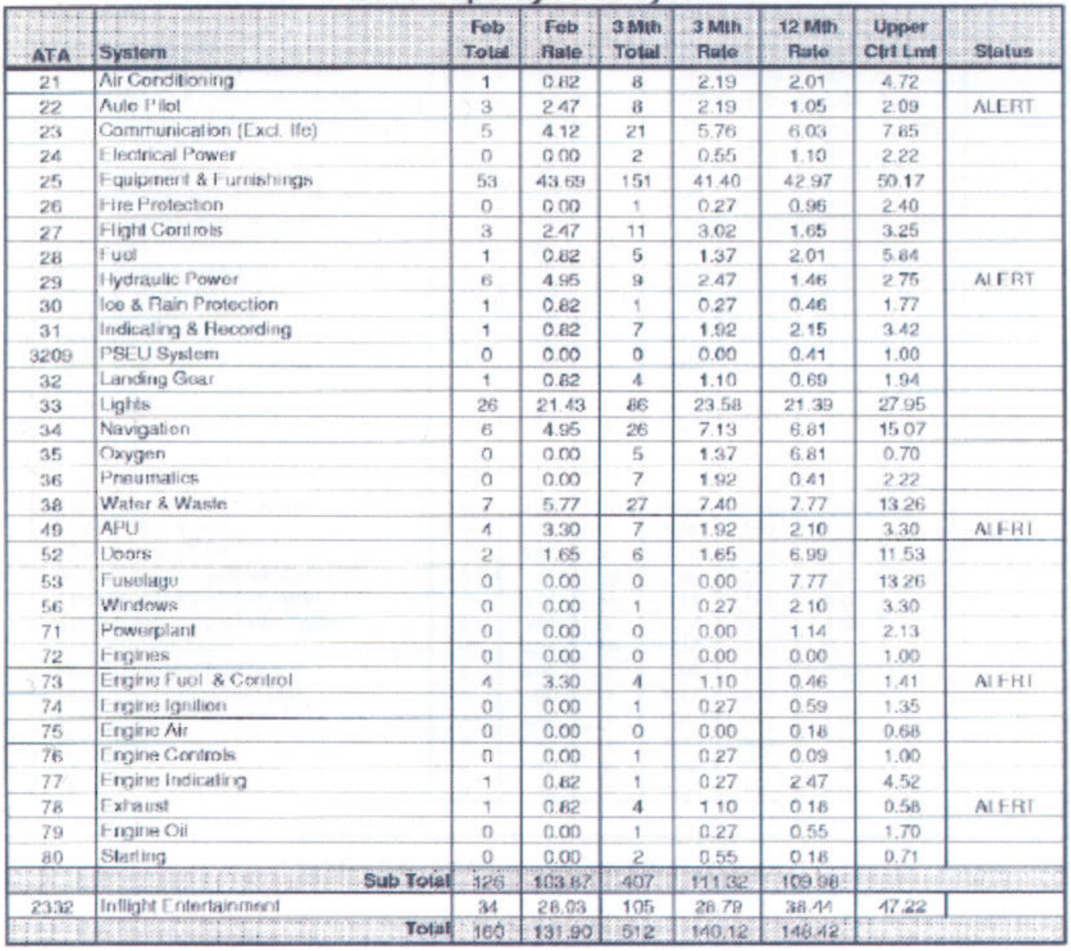
	1999	2000	Feb 01	Last 3 Months	Last 12 Months
Movements	9045	8183	541	1511	8126
Delays >15 Minutes	144	153	6	24	136
Air Turnback	1	3	0	0	3
Diversions - All	1	7	1	3	9
Return to Stand	13	41	1	9	43
Despatch Reliability >15 minutes	98.41	98.13	98.89	98.41	98.33
Excluding German Operation			98.89	98.45	98.39
Dispatch Reliability Target (Key Target)	98.70	98.70	97.25	97.25	97.25
Boeing Fleet (through Sept 00)				98.73	98.69

Table G-2: Dispatch reliability report



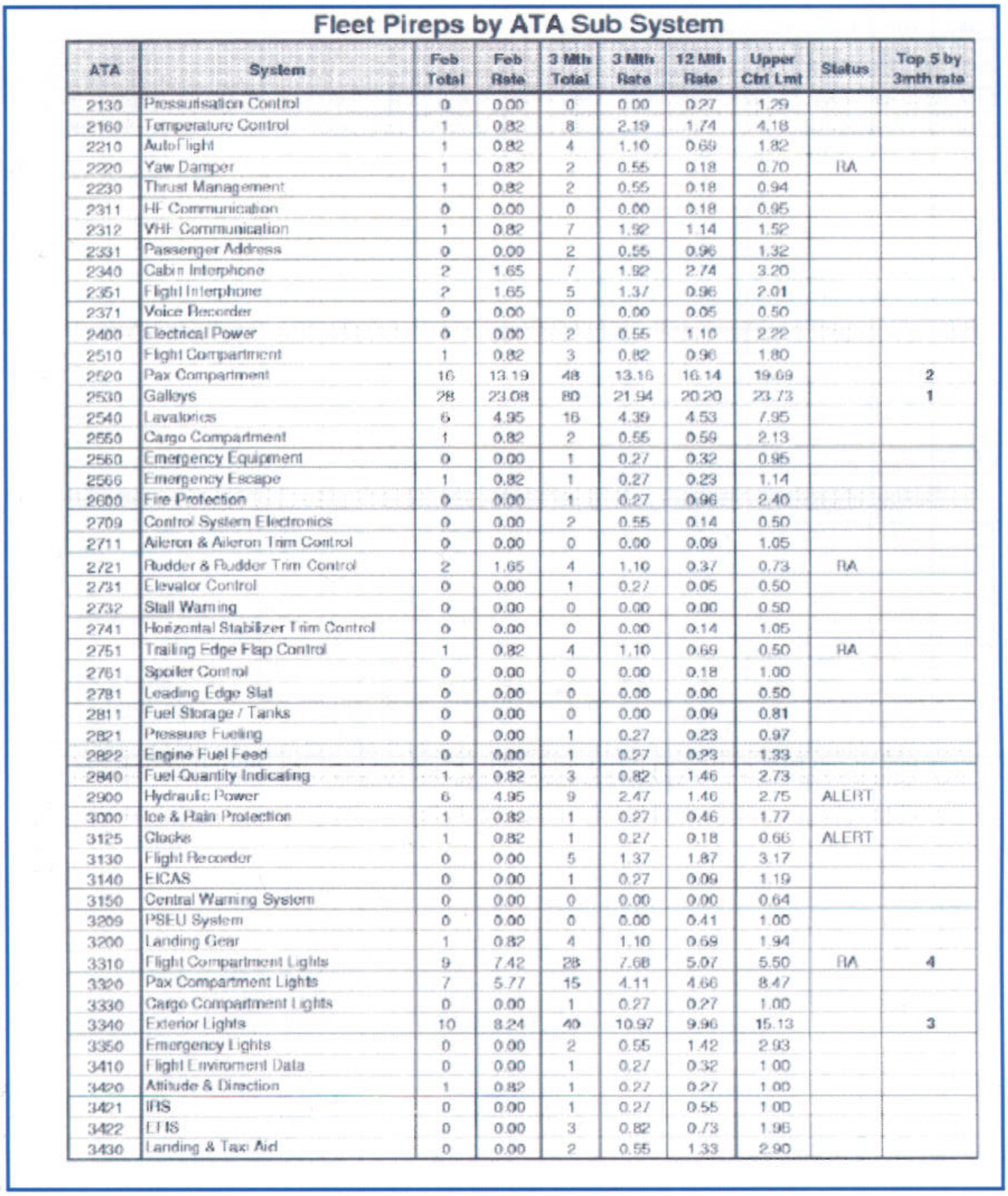
Fleet Pireps (Excl IFE)

Fleet Pireps by ATA System



ATA	System	Feb Total	Feb Rate	3 Mth Total	3 Mth Rate	12 Mth Rate	Upper Ctrl Lmt	Status
21	Air Conditioning	1	0.82	8	2.19	2.01	4.72	
22	Auto Pilot	3	2.47	8	2.19	1.05	2.09	ALERT
23	Communication (Excl. Ife)	5	4.12	21	5.76	6.03	7.65	
24	Electrical Power	0	0.00	2	0.55	1.10	2.22	
25	Equipment & Furnishings	53	43.69	151	41.40	42.97	50.17	
26	Fire Protection	0	0.00	1	0.27	0.96	2.40	
27	Flight Controls	3	2.47	11	3.02	1.65	3.25	
28	Fuel	1	0.82	5	1.37	2.01	5.84	
29	Hydraulic Power	6	4.95	9	2.47	1.46	2.75	ALERT
30	Ice & Rain Protection	1	0.82	1	0.27	0.46	1.77	
31	Indicating & Recording	1	0.82	7	1.92	2.15	3.42	
3209	PSEU System	0	0.00	0	0.00	0.41	1.00	
32	Landing Gear	1	0.82	4	1.10	0.69	1.94	
33	Lights	26	21.43	86	23.58	21.39	27.95	
34	Navigation	6	4.95	26	7.13	6.81	15.07	
35	Oxygen	0	0.00	5	1.37	6.81	0.70	
36	Pneumatics	0	0.00	7	1.92	0.41	2.22	
38	Water & Waste	7	5.77	27	7.40	7.77	13.26	
49	APU	4	3.30	7	1.92	2.10	3.30	ALERT
52	Doors	2	1.65	6	1.65	6.99	11.53	
53	Fuselage	0	0.00	0	0.00	7.77	13.26	
56	Windows	0	0.00	1	0.27	2.10	3.30	
71	Powerplant	0	0.00	0	0.00	1.14	2.13	
72	Engines	0	0.00	0	0.00	0.00	1.00	
73	Engine Fuel & Control	4	3.30	4	1.10	0.46	1.41	ALERT
74	Engine Ignition	0	0.00	1	0.27	0.59	1.35	
75	Engine Air	0	0.00	0	0.00	0.18	0.68	
76	Engine Controls	0	0.00	1	0.27	0.09	1.00	
77	Engine Indicating	1	0.82	1	0.27	2.47	4.52	
78	Exhaust	1	0.82	4	1.10	0.18	0.58	ALERT
79	Engine Oil	0	0.00	1	0.27	0.55	1.70	
80	Starting	0	0.00	2	0.55	0.18	0.71	
	Sub Total	126	103.87	407	111.32	109.98		
2332	Inflight Entertainment	34	28.03	105	28.79	38.44	47.22	
	Total	160	131.90	512	140.12	148.42		

Table G-3: System Pilot reports



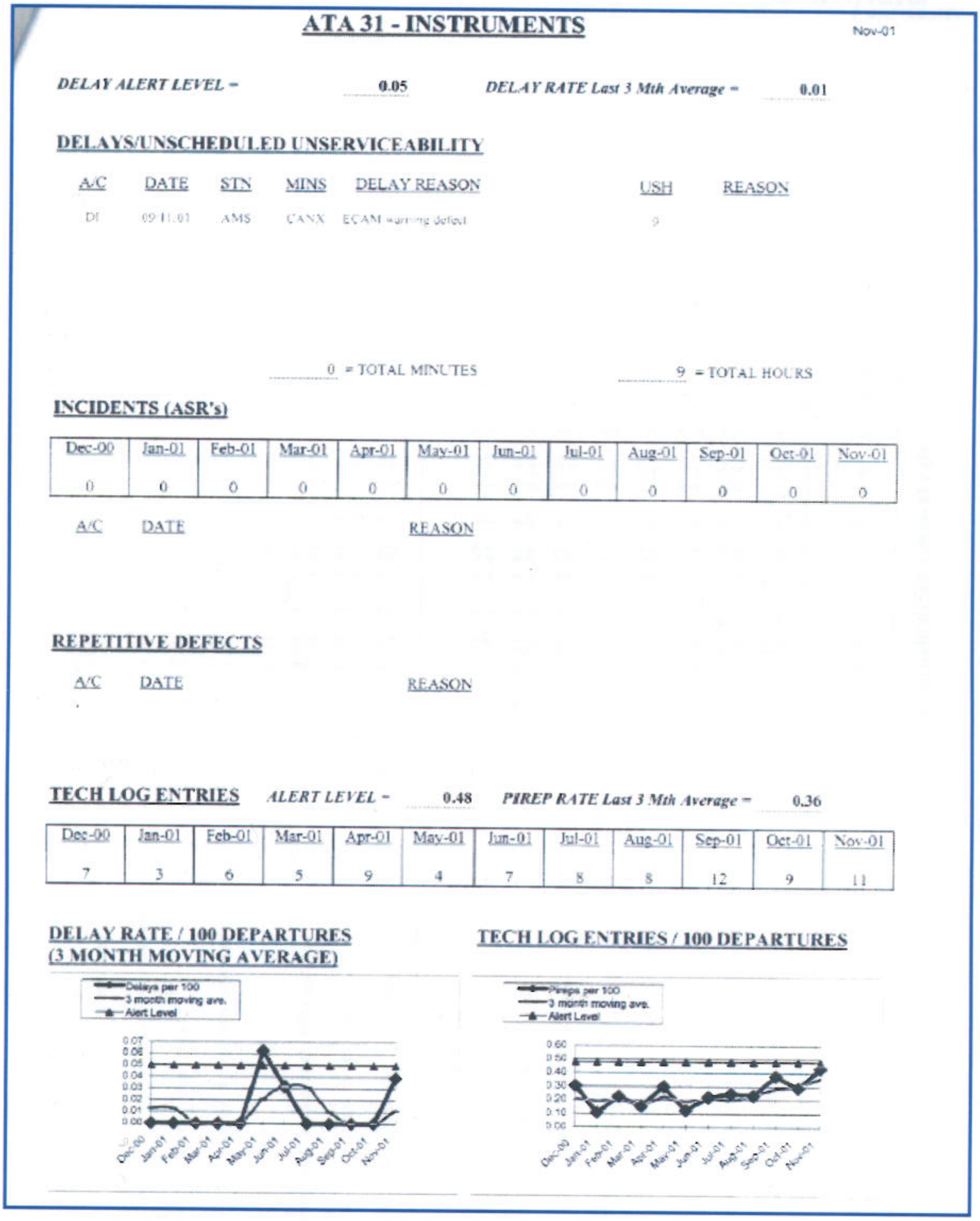
Fleet Pireps by ATA Sub System

ATA	System	Feb Total	Feb Rate	3 Mth Total	3 Mth Rate	12 Mth Rate	Upper Ctrl Lmt	Status	Top 5 by 3mth rate
2130	Pressurisation Control	0	0.00	0	0.00	0.27	1.29		
2160	Temperature Control	1	0.82	8	2.19	1.74	4.18		
2210	AutoFlight	1	0.82	4	1.10	0.69	1.82		
2220	Yaw Damper	1	0.82	2	0.55	0.18	0.70	RA	
2230	Thrust Management	1	0.82	2	0.55	0.18	0.94		
2311	HF Communication	0	0.00	0	0.00	0.18	0.95		
2312	VHF Communication	1	0.82	7	1.92	1.14	1.52		
2331	Passenger Address	0	0.00	2	0.55	0.96	1.32		
2340	Cabin Interphone	2	1.65	7	1.92	2.74	3.20		
2351	Flight Interphone	2	1.65	5	1.37	0.96	2.01		
2371	Voice Recorder	0	0.00	0	0.00	0.05	0.50		
2400	Electrical Power	0	0.00	2	0.55	1.10	2.22		
2510	Flight Compartment	1	0.82	3	0.82	0.96	1.80		
2520	Pax Compartment	16	13.19	48	13.16	16.14	19.69		2
2530	Galleys	28	23.08	80	21.94	20.20	23.73		1
2540	Lavatories	6	4.95	16	4.39	4.53	7.95		
2550	Cargo Compartment	1	0.82	2	0.55	0.59	2.13		
2560	Emergency Equipment	0	0.00	1	0.27	0.32	0.95		
2566	Emergency Escape	1	0.82	1	0.27	0.23	1.14		
2600	Fire Protection	0	0.00	1	0.27	0.96	2.40		
2709	Control System Electronics	0	0.00	2	0.55	0.14	0.50		
2711	Aileron & Aileron Trim Control	0	0.00	0	0.00	0.09	1.05		
2721	Rudder & Rudder Trim Control	2	1.65	4	1.10	0.37	0.73	RA	
2731	Elevator Control	0	0.00	1	0.27	0.05	0.50		
2732	Stall Warning	0	0.00	0	0.00	0.00	0.50		
2741	Horizontal Stabilizer Trim Control	0	0.00	0	0.00	0.14	1.05		
2751	Trailing Edge Flap Control	1	0.82	4	1.10	0.69	0.50	RA	
2761	Spoiler Control	0	0.00	0	0.00	0.18	1.00		
2781	Leading Edge Slat	0	0.00	0	0.00	0.00	0.50		
2811	Fuel Storage / Tanks	0	0.00	0	0.00	0.09	0.81		
2821	Pressure Fueling	0	0.00	1	0.27	0.23	0.97		
2822	Engine Fuel Feed	0	0.00	1	0.27	0.23	1.33		
2840	Fuel Quantity Indicating	1	0.82	3	0.82	1.46	2.73		
2900	Hydraulic Power	6	4.95	9	2.47	1.46	2.75	ALERT	
3000	Ice & Rain Protection	1	0.82	1	0.27	0.46	1.77		
3125	Clocks	1	0.82	1	0.27	0.18	0.66	ALERT	
3130	Flight Recorder	0	0.00	5	1.37	1.87	3.17		
3140	EICAS	0	0.00	1	0.27	0.09	1.19		
3150	Central Warning System	0	0.00	0	0.00	0.00	0.64		
3209	PSEU System	0	0.00	0	0.00	0.41	1.00		
3200	Landing Gear	1	0.82	4	1.10	0.69	1.94		
3310	Flight Compartment Lights	9	7.42	28	7.68	5.07	5.50	RA	4
3320	Pax Compartment Lights	7	5.77	15	4.11	4.66	8.47		
3330	Cargo Compartment Lights	0	0.00	1	0.27	0.27	1.00		
3340	Exterior Lights	10	8.24	40	10.97	9.96	15.13		3
3350	Emergency Lights	0	0.00	2	0.55	1.42	2.93		
3410	Flight Enviroment Data	0	0.00	1	0.27	0.32	1.00		
3420	Attitude & Direction	1	0.82	1	0.27	0.27	1.00		
3421	IRS	0	0.00	1	0.27	0.55	1.00		
3422	EFIS	0	0.00	3	0.82	0.73	1.96		
3430	Landing & Taxi Aid	0	0.00	2	0.55	1.33	2.90		

Table G-4: ATA sub-system Pilot reports

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Fleet size	14	16	18	18	18	18	18	18	18	18	18	
No. of A/C days out of service	1	3	26	37	24	18	19	7	9	19	119	
No. of A/C days in service	433	445	532	503	534	522	539	551	531	539	421	
Average No. of A/C available	14	16	17	17	17	17	17	18	18	17	14	16.6
Total Hrs. flown Hrs/Mins	2746.42	2583.23	3207.51	3335.38	4458.08	4299.14	4529.15	4681.25	4534.11	4194.15	2274.03	
Average daily utilization Hrs/Mins	6.21	5.48	6.02	6.38	8.21	8.14	8.24	8.30	8.32	7.47	5.24	
Total landings	2887	2762	3248	3088	3308	3172	3282	3442	3226	3153	2554	
Hrs/Ldgs ratio	0.951	0.935	0.988	1.080	1.348	1.355	1.380	1.360	1.406	1.330	0.890	
Average flight duration (Hrs:min)	0.57	0.56	0.59	1.05	1.21	1.21	1.23	1.22	1.24	1.20	0.53	1.2
Non rev/training flights	5	9	24	32	42	19	29	24	31	42	10	
Total No. of rev. departures	2854	2658	3218	3018	3200	3165	3248	3412	3191	3115	2545	
-15+3 [illegible] 100												
Canx due tech.	3	2	4	0	2	1	1	2	2	2	3	
Diversions due tech.	0	0	0	0	0	0	0	1	0	0	0	
Delays over 15 Mins.	16	21	33	26	33	32	28	36	24	21	14	
Delays per 100 departures	0.7	0.9	1.1	0.9	1.1	1.0	0.9	1.1	0.8	0.7	0.7	0.9
Technical Despatch Reliability	99.33%	99.13%	98.85%	99.14%	98.91%	98.96%	99.11%	98.89%	99.19%	99.26%	99.33%	99.1
No. of scheduled flights	2655	2474	3032	2867	2531	2450	2493	2643	2415	2483	2543	
Technical despatch reliability	99.32%	99.15%	98.98%	99.13%	99.17%	98.98%	99.20%	99.21%	99.38%	99.23%	99.33%	
No. of charter flights	199	184	186	151	669	715	755	769	776	632	2	
Technical despatch reliability	99.50%	98.91%	96.77%	99.34%	97.91%	98.88%	98.81%	97.79%	98.58%	99.37%	100.00%	
No. of pireps	603	528	691	603	630	655	681	708	690	684	638	
% change from last month	0	-12.44	30.87	-12.74	4.48	3.97	3.97	3.96	-2.54	-0.87	-6.73	
same day defect clearance rate	62.69%	63.07%	68.31%	63.35%	62.38%	65.65%	66.67%	62.43%	62.46%	63.89%	68.18%	
Pireps per 1000 hours	219.54	204.38	215.41	180.78	141.31	152.35	150.36	151.24	152.18	163.08	280.56	

Table G-5: Fleet operational data



ATA 31 - INSTRUMENTS

Nov-01

DELAY ALERT LEVEL = **0.05** ***DELAY RATE Last 3 Mth Average =*** **0.01**

DELAYS/UNSCHEDULED UNSERVICEABILITY

A/C	DATE	STN	MINS	DELAY REASON	USH	REASON
DI	09.11.01	AMS	CANX	ECAM warning defect	9	

0 = TOTAL MINUTES

9 = TOTAL HOURS

INCIDENTS (ASR's)

Dec-00	Jan-01	Feb-01	Mar-01	Apr-01	May-01	Jun-01	Jul-01	Aug-01	Sep-01	Oct-01	Nov-01
0	0	0	0	0	0	0	0	0	0	0	0

A/C DATE REASON

REPETITIVE DEFECTS

A/C DATE REASON

TECH LOG ENTRIES ***ALERT LEVEL =*** **0.48** ***PIREP RATE Last 3 Mth Average =*** **0.36**

Dec-00	Jan-01	Feb-01	Mar-01	Apr-01	May-01	Jun-01	Jul-01	Aug-01	Sep-01	Oct-01	Nov-01
7	3	6	5	9	4	7	8	8	12	9	11

DELAY RATE / 100 DEPARTURES (3 MONTH MOVING AVERAGE)

TECH LOG ENTRIES / 100 DEPARTURES

Table G-6: Aircraft technical performance

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Manufacturers Part Number                          12Mth-Removals   May          Jun          Jul          Aug          Sep          Oct              A Sta Tren
    Component Description                          UnscR No  MTBUR  No  UnscR No  UnscR No  UnscR No  UnscR No  UnscR No  UnscR
                                                   ConfR No  MTBCF  No  ConfR No  ConfR No  ConfR No  ConfR No  ConfR No  ConfR
    PUMP FUEL MOT&IMPLR ASSY-OVRD/JET/STAB         0.03   9 23,361  0   0.00  3   0.19  0   0.00  0   0.00  0   0.00  0   0.00

60-72101-2          T                              0.05   4 18,663  0   0.00  2   0.34  0   0.00  0   0.00  2   0.43  0   0.00             INC
    PUMP FUEL MOT&IMPLR ASSY-OVRD/JET/STAB         0.03   3 24,884  0   0.00  1   0.17  0   0.00  0   0.00  2   0.43  0   0.00

60-98906A           T                              0.01   2 84,672  0   0.00  0   0.00  0   0.00  0   0.00  1   0.08  0   0.00             INC
    PUMP FUEL MAIN TANK BOOST                      0.01   1 169344  0   0.00  0   0.00  0   0.00  1   0.08  0   0.00  0   0.00

218386-3            T                              0.05   1 19,851  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00  1   0.59
    PUMP FUEL CENTRE WING TANK SCAVENGE            0.00   0      0  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00

218387              T                              0.03   1 38,952  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00
    PUMP FUEL APU                                  0.00   0      0  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00

60B92018-56         T                              0.01   1 116857  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00
    COMPENSATOR PROBE FUEL COMPENSATOR             0.00   0      0  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00

285U0143-201        T                              0.01   2 75,927  1   0.08  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00
    VALVE, UNIT, PCA, POS. LOGIC                   0.01   1 151853  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00

32P116              T                              0.03   1 38,952  1   0.30  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00
    VALVE, CHECK-ENGINE, FUEL, FEED                0.00   0      0  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00
---------------------------------------------------------------------------------------------------------------------------------------------------

ATA : 29 - A/C HYDRAULIC POWER

109300-14           T                              0.18   3  5,609  0   0.00  0   0.00  1   0.73  0   0.00  0   0.00  0   0.00
    DRIVE TURBINE AIR DRIVEN PUMP                  0.12   2  8,413  0   0.00  0   0.00  1   0.73  0   0.00  0   0.00  0   0.00

109300-16           T                              0.05   1 19,671  0   0.00  0   0.00  0   0.00  1   0.81  0   0.00  0   0.00             INC
    DRIVE TURBINE AIR DRIVEN PUMP                  0.00   0      0  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00

109300-20           T                              0.05   2 19,886  1   0.28  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00
    DRIVE TURBINE AIR DRIVEN PUMP                  0.05   2 19,886  1   0.28  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00

109501-501          T                              0.02   1 59,167  0   0.00  1   0.22  0   0.00  0   0.00  0   0.00  0   0.00
    VALVE, ADP, SHUTOFF, CONTROL                   0.02   1 59,166  0   0.00  1   0.22  0   0.00  0   0.00  0   0.00  0   0.00

4205401             T                              0.04   2 24,917  0   0.00  1   0.24  0   0.00  0   0.00  0   0.00  0   0.00
    PUMP HYDRAULIC ENG DRIVEN ABEX CURE            0.02   2 24,917  0   0.00  1   0.24  0   0.00  0   0.00  0   0.00  0   0.00

887673              T                              0.04   4 27,292  0   0.00  2   0.24  0   0.00  0   0.00  0   0.00  0   0.00
    PUMP HYDRAULIC ENGINE DRIVEN VICKERS           0.02   3 36,389  0   0.00  1   0.12  0   0.00  0   0.00  0   0.00  0   0.00

FP0207A             T                              0.03   2 38,908  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00  2   0.35 *
    TRANSMITTER, QTY HYDRAULIC OUTBOARD            0.00   0      0  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00

65066-06            T                              0.05   1 18,359  0   0.00  0   0.00  1   1.10  0   0.00  0   0.00  0   0.00
    PUMP HYDRAULIC ENG DRIVEN ABEX CURE            0.00   0      0  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00  0   0.00
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ATA : 30 - A/C ICE & RAIN PROTECTION

2790583-108         T                              0.03   3 32,649  0   0.00  1   0.14  0   0.00  1   0.12  0   0.00  0   0.00
```

Table G-7: Aircraft component unscheduled removal rate

Appendix H

Appendix H Relex Software

Introduction

The Relex software packages version 7.6 was used for this research to perform RBD construction, failure rate calculations and failure rate allocations.

The Relex software package can come with many modules, such as reliability prediction, RBD, maintainability prediction, FMEA, FTA and Markov simulation.
The Relex Reliability Prediction Engine allows the evaluation of the failure rate and MTBF of the product and pinpoints areas for potential reliability improvement.

It supports the most widely accepted reliability models in the industry, including MIL-HDBK-217, Telcordia (Bellcore) SR-332, Parts Count, and many others.

The Relex Reliability Prediction Engine performs reliability allocation calculations, supports derating analyses, and provides a visual report designer to display your results in an informative and professional style.
It has got the capability to export and import data and files to and from different programme.

Prediction Analysis also provides access to the comprehensive Relex parts libraries, containing hundreds of thousands of parts with associated data parameters.

Relex RBD is a complete, fully featured graphical reliability block diagram evaluator. It provides a highly graphical interface that enables quick evaluation of the reliability, availability, and MTBF of complex redundant systems.
It uses the built-in Monte Carlo simulation engine for complex diagrams.

A major advantage of the Relex Reliability Prediction software is the availability of extremely large parts libraries. These libraries contain hundreds of thousands of parts with their associated data parameters, and provide for significant time savings.
The Relex libraries contain a great deal of part data which is automatically retrieved based on part number. The major part parameters needed for reliability calculations are available, and only the operating conditions particular to your design need to be entered.
The data included in the Relex libraries varies, dependent on part type. For example, parameters for integrated circuits include the number of pins, number of gates or transistors, power dissipation, and thermal resistance, while resistor parameters include the rated power dissipation and resistance value.

The Electronic Parts Reliability Data (EPRD) and the Nonelectronic Parts Reliability Data (NPRD), which are published by the Reliability Analysis Centre (RAC), each include a wide variety of components.
Having these failure rate databases is greatly broadens the options for the prediction analyses.
However, users must have the knowledge to make the right decision on selecting the suitable information among a vast variety. For example, the ranges of failure rates available for a certain component on specific environment are massive with huge difference, which needs the right expertise to pick up the appropriate data.

RELEX software capability reduces the analysis and calculations time of vast and complicated system architecture, and it can do so with great accuracy.
However, like any software, the users of RELEX need to have proper training.
For more detail of Relex software features, see http://www.relexsoftware.co.uk.