Aircraft Scheduled Maintenance Programme Development

Decision Support Methodologies and Tools

Alireza Ahmadi
Aircraft Scheduled Maintenance Programme Development

Decision Support Methodologies and Tools

Alireza Ahmadi

Division of Operation and Maintenance Engineering
Luleå University of Technology
June 2010
Acknowledgements

The research work presented in this thesis has been carried out during the period January 2006 to June 2010 at the Division of Operation and Maintenance Engineering at Luleå University of Technology, under the supervision of Professor Uday Kumar.

First of all, I would like to express my deepest gratitude to my supervisor Professor Uday Kumar who enriched my knowledge of maintenance engineering through his supervision, stimulating discussions and fruitful guidance. You always believed in me, gave me motivation, and showed a positive attitude in my study.

Many thanks are also due to my co-supervisors, Associate Professor Peter Söderholm at the Swedish Transport Administration, and Dr. Ramin Karim from LTU, for valuable support and guidance given during my research studies. I really appreciate our fruitful discussions and your patience and support specifically during thesis writing.

Specific thank is acknowledged to Dr. Olov Candell, for his kind follow up, valuable support and arranging discussion meetings at Saab Aerospace. Furthermore, I wish to thank Mr. Christian Delmas, from Maintenance Programs Engineering-Airbus S.A.S., who initially encouraged the idea of this study and gave me the opportunity to start collaboration with his group. Specific gratitude also is extended to other members of the group, specifically to Mr. Jeremie Neveux, and Mr. Raphael Laforgue, for the many exciting discussions and for sharing their expertise.

I wish also to thank Professor K.B. Misra, RAMS Consultants limited, for his fruitful discussions, guidance, and support. I am also thankful to Dr. Suprakash Gupta for valuable discussion and sharing his ideas. Specific thanks also in acknowledge to Dr. Arne Nissen from the Swedish Transport Administration, for his fruitful discussion and support.

I am also grateful to all of my colleagues at the Division of Operation and Maintenance Engineering for their friendly and open-minded working environment. In particular, I would like to thank Associate Prof. Håkan Schunnnesson, Dr. Aditya Parida, Prof. Jan Lundberg, and Dr. Rupesh Kumar. They encouraged me through discussions and valuable advice. Specific gratitude also is acknowledged to Rajiv Dandotiya, Yuan Fuqing, and Iman Araste-Khouy, for their fruitfull discussions. The administrative support received from Cecilia Glover and Marie Fjällström is also gratefully acknowledged. I also wish to express my gratitude to Dr. Javad Barabady, Dr. Behzad Ghodrati and Dr. Parviz Pourgahramani, for their help and hospitality during my study in Sweden.

I would like to express my specific gratitude to my parents, Narges and Hossein, who introduced me into the world of love and sincerity. They have always believed in me and offered a full support through my life and academic career and taught me to enjoy hard work. Gratitude also is extended to my sister Mehrnaz, her husband Mohammad and my brother Mehrshad. I am really thankful for all the supports given to me. Specific thanks also are acknowledged to my parents-in-low, Hossein and Mahin, for their motivation and readiness to help.
I would like to express my deepest gratitude to my wife Sadaf and our beloved daughter Nika, for their enormous understanding and endless support during my study and late evening work at the university. Sadaf shouldered the household responsibilities, and encouraged me to go on, which made it possible to complete this journey.

Alireza Ahmadi

May, 2010
Abstract

The air transport business is large in its operations, integrated, automated and complex. Air carriers are constantly striving to achieve high standards of safety and simultaneously to attain an increased level of availability performance at minimal cost. This needs to be supported through an effective maintenance programme which has a major impact on the availability performance and which ultimately can enhance the aircraft’s capability to meet market demands at the lowest possible cost. The development of a maintenance programme is challenging, but can be enhanced by supporting methodologies and tools.

The purpose of this research is to develop decision support methodologies and tools for aircraft scheduled maintenance programme development within the framework of Maintenance Review Board (MRB) process, in order to facilitate and enhance the capability of making effective and efficient decisions and thereby achieve an effective maintenance programme. To achieve the purpose of this research, literature studies, case studies, and simulations have been conducted. Empirical data have been collected through document studies, interviews, questionnaires, and observations from the aviation industry. For data analysis, theories and methodologies within risk, dependability and decision making have been combined with the best practices from the aviation industry.

One result of this research is the identification of potential areas for improving the use of MSG-3 methodology in aircraft scheduled maintenance development. Another result is the development of a systematic methodology guided by the application of an Event Tree Analysis (ETA) for the identification and quantification of different operational risks caused by aircraft system failures, to support decision making for maintenance task development. A third result is a proposed methodology, based on a combination of different Multi-Criteria Decision Making (MCDM) methodologies, for selecting the most effective maintenance strategy for aircraft scheduled maintenance development. Finally, the fourth result is a proposed Cost Rate Function (CRF) model supported by graphical tools. The approach can be used to identify the optimum maintenance interval and frequencies of Failure Finding Inspection (FFI) and to develop a combination of FFI and restoration tasks for the aircraft’s repairable items which are experiencing aging.

These results are related to specific industrial challenges, and are expected to enhance the capability of making effective and efficient decisions during the development of maintenance tasks. The results have been verified through interaction with experienced practitioners within major aviation manufacturers and air operators.

Keywords: Cost-effectiveness, Cost Rate Function (CRF), Decision support, Event Tree Analysis (ETA), Failure consequences, Failure Finding Inspection (FFI), Inspection interval, Maintenance Review Board (MRB), Maintenance Steering Group (MSG-3), Multi-Criteria Decision Making (MCDM), Operational risk, Optimal inspection, Reliability-Centred Maintenance (RCM), Scheduled maintenance programme.
List of appended papers

**Paper I**

**Paper II**

**Paper III**
Ahmadi, A. and Kumar, U. (2010), Cost based risk analysis to identify inspection and restoration intervals of hidden failures subject to aging. Accepted for publication in: *IEEE Transaction on Reliability*.

**Paper IV**
List of related publications (not appended)

Paper A

Paper B

Paper C

Paper D

Paper E

Paper F
# Table of Content

ACKNOWLEDGEMENTS ....................................................................................................................... I

ABSTRACT ................................................................................................................................................ III

LIST OF APPENDED PAPERS ...................................................................................................................... V

LIST OF RELATED PUBLICATIONS (NOT APPENDED) ........................................................................ VII

TABLE OF CONTENT .............................................................................................................................. IX

## 1 INTRODUCTION ........................................................................................................................................

1.1 BACKGROUND .................................................................................................................................... 1

1.2 STATEMENT OF THE PROBLEM ........................................................................................................ 3

1.3 PURPOSE OF THE RESEARCH ........................................................................................................... 5

1.4 OBJECTIVES ...................................................................................................................................... 5

1.5 RESEARCH QUESTIONS ...................................................................................................................... 6

1.6 SCOPE AND DELIMITATIONS OF THE STUDY .................................................................................. 6

1.7 STRUCTURE OF THE THESIS ............................................................................................................. 7

## 2 THEORETICAL FRAMEWORK ............................................................................................................. 9

2.1 RELIABILITY-CENTRED MAINTENANCE (RCM) ................................................................................ 9

2.2 AIRCRAFT SCHEDULED MAINTENANCE PROGRAMME DEVELOPMENT ........................................ 11

2.3 SYSTEM LIFE CYCLE AND MAINTENANCE ..................................................................................... 13

2.4 SYSTEM DEPENDABILITY .................................................................................................................. 16

2.5 CONCEPT OF RISK ........................................................................................................................... 18

2.5.1 EVENT TREE ANALYSIS (ETA) ....................................................................................................... 20

2.6 RELIABILITY OF REPAIRABLE SYSTEM ......................................................................................... 21

2.7 UNAVAILABILITY CHARACTERISTICS OF REPAIRABLE UNITS SUBJECT TO HIDDEN FAILURES .... 23

2.8 MULTI-CRITERIA DECISION MAKING (MCDM) .................................................................................. 24

2.8.1 TOPSIS ........................................................................................................................................... 24

2.8.2 VIKOR ............................................................................................................................................ 26

2.8.3 THE ANALYTICAL HIERARCHICAL PROCESS (AHP) ................................................................. 27

## 3 RESEARCH METHODOLOGY ............................................................................................................. 29

3.1 RESEARCH PURPOSE ....................................................................................................................... 29

3.2 RESEARCH APPROACH .................................................................................................................... 30

3.3 DATA COLLECTION AND ANALYSIS .............................................................................................. 31

3.4 APPLIED DATA COLLECTION AND ANALYSIS .............................................................................. 32

3.5 RELIABILITY AND VALIDITY ........................................................................................................... 34

3.6 THE RESEARCH PROCESS ................................................................................................................ 35

## 4 SUMMARY OF APPENDED PAPERS ............................................................................................. 39

4.1 PAPER I ............................................................................................................................................ 39

4.2 PAPER II ......................................................................................................................................... 40

4.3 PAPER III ....................................................................................................................................... 41

4.4 PAPER IV ...................................................................................................................................... 42

## 5 DISCUSSION OF RESULTS AND CONCLUSIONS .......................................................................... 45

5.1 POTENTIAL AREAS OF IMPROVEMENT IN THE SCHEDULED MAINTENANCE DEVELOPMENT Process .... 45

5.2 SYSTEMATIC METHODOLOGIES TO SUPPORT ASSESSMENT OF THE RISK OF FAILURES IN AIRCRAFT SYSTEMS ................................................................................................................. 47

5.3 A METHODOLOGY FOR SELECTION OF THE MOST EFFECTIVE MAINTENANCE STRATEGY ............... 49

5.4 METHODOLOGIES FOR SELECTION OF THE MOST EFFECTIVE MAINTENANCE STRATEGY .......... 51

5.5 RESEARCH CONTRIBUTION ............................................................................................................ 54

5.6 FURTHER RESEARCH ...................................................................................................................... 54

REFERENCES ........................................................................................................................................ 57
1 Introduction

A brief introduction is given in this chapter to make the reader acquainted with the problem area. Moreover, the research purpose, research questions and research delimitations, as well as the thesis structure, are presented.

1.1 Background

The airline business is large, integrated, automated and complex, in which providing a safe, reliable and best-in-class service has become a strategic issue for air carriers, in order to meet customer requirements and gaining a global competitive advantage (Sachon and Paté-Cornell, 2000). Over the past decades, significant improvements in airline safety and services have taken place (see e.g. Boeing, 2009). However, passengers still expect an affordable service which is on schedule. Increased awareness, new generations of travellers and changing attitudes have led to a change in demand. Punctuality has become one of the most significant factors for defining a passenger’s satisfaction with an airline (Herinckx and Poubéau, 2002). This has made the on-time performance of an airline’s schedule a key factor in maintaining the satisfaction of current customers and attracting new ones (Institute of Air Transport, 2000). Therefore, airlines are continuously under pressure to improve their punctuality and provide on-time performance.

When dealing with the complex technical systems involved in air transport and the extensive competition, the consequences of unreliable services become critical and may include a high cost of operation, a loss of productivity, incidents, and exposure to accidents. Unreliable services may also lead to annoyance, inconvenience and a lasting customer dissatisfaction that can create serious problems regarding the company’s marketplace position. This is crucial, since a company can rapidly be branded as unreliable after providing poor services, whereas building up a reputation for reliable services takes a long time. Therefore, it is critical for air carriers to achieve high standards of safety and reliable services, while optimizing their profits (Sachon and Paté-Cornell, 2000; Eggenberg et al., 2010).

To this end, aircraft operability is considered as one of the major requirements by air operators. Aircraft operability is the aircraft’s ability to meet the operational requirements in terms of operational reliability (i.e. the percentage of scheduled flights that depart and arrive without incurring a chargeable technical/operational interruption), operational risk (i.e. the combination of an unscheduled maintenance event and its consequences), and costs (i.e. maintenance and operation costs). The trade-off between these requirements is very complex and priorities may vary a great deal depending on the airline’s policy (Papakostas et al., 2010).

The identification and implementation of an appropriate maintenance policy will reduce premature replacement costs, maintain stable production capabilities, and prevent the deterioration of a system and its items (Vineyard et al., 2000). In addition, an aircraft costs its owner money every minute of every day, but makes money only when it is flying with freight and/or passengers. Therefore, it is expected that the aircraft will have to be in service as much as possible (Knezevic, 1997; Airline Handbook, 2000). Hence, with increasing awareness of the fact that maintenance not only ensures a high level of safety, reliability, and availability of the system, but also creates value in the business process, maintenance has...
become a focus of the strategic thinking of many companies all over the world (Kumar and Ellingsen, 2000; Markeset, 2003).

Maintenance is the combination of technical, administrative, and managerial actions carried out during the life cycle of an item and intended to retain it in, or restore it to, a state in which it can perform the required function (SS-EN 13306). In order to preserve the function of the system, it is vital to identify the maintenance strategies that are needed to manage the associated failure modes that can cause functional failure. There are different maintenance strategies, e.g. corrective, preventive, and proactive maintenance (see e.g. Nowlan and Heap, 1978; Gits, 1992; Moubray, 1997). Preventive maintenance strategy is carried out at predetermined intervals or according to prescribed criteria and is intended to reduce the probability of failure or the degradation of the functioning of an item (IEV, 2010). The complete collection of these preventive maintenance tasks is termed “scheduled maintenance programme”, which are scheduled in advance. Maintenance tasks are actions or set of actions required to achieve a desired outcome which restores an item to or maintain an item in serviceable condition, including inspection and determination of condition (IEC, 1999).

The identification of an effective maintenance programme is a critical issue in aviation, as it directly affects the operational regularity and the capability of the aircraft fleet to meet the demands as planned. In fact, a large portion of the maintenance-related Life Cycle Cost (LCC) stems from the consequences of decisions made during the initial maintenance programme development (Blanchard et al., 1995; Savio, 1999). Therefore, the preventive and corrective maintenance and inspection requirements, which highly influence both the system dependability and the LCC, have to be defined in order to perform only the preventive maintenance actions which are absolutely necessary and cost-effective.

The occurrence of unscheduled maintenance can introduce costly delays and cancellations if the problem cannot be rectified in a timely manner (Papakostas et al., 2010). The occurrence of any unexpected events upsets the plans and leads to less effective maintenance policies. A report released by EUROCONTROL (2004) contains four scenario-based forecasts of air traffic demand for the next 20 years. In the highest growth scenario, the annual demand rises up to 21 million flights a year with more than 60 airports congested, the top 20 airports being saturated at least eight to ten hours a day. Given this forecast, it is obvious that an operational disruption would have deeper operational and economic consequences in future than today (Eggenberg et al., 2010).

A commercial aircraft costs as much as $200 million, and an additional $2 billion is required for operation, maintenance, and support throughout its economic life, which is around 20 to 25 years. For most equipment, 80 to 85% of the total LCC is spent during the operation and maintenance of the equipment. A significant part of the LCC is spent on maintenance alone (Saranga and Kumar, 2006). Evidence shows that maintenance costs also make a significant contribution to an aircraft’s cost of ownership (Wu et al., 2004). In the competitive airline industry, low Direct Operating Costs (DOC) are key to airline profitability (Heisey, 2002). Taking into consideration the estimations reported by the airline companies, the maintenance costs range typically from 10 to 20% of the aircraft-related DOC, depending on the fleet size, age, and usage (Airline Handbook, 2000; Maple, 2001; Heisey, 2002; Papakostas et al., 2010). In fact, the contribution of the maintenance costs to the average direct operating costs has not been reduced significantly over the past two decades (Papakostas et al., 2010). Moreover, the downward pressure on revenues has led many carriers to focus their attention
on controlling maintenance and personnel costs (Sriram and Haghani, 2003). However, an effective way to decrease maintenance costs is to improve the scheduled maintenance programme (Liang and Zuo, 2004), setting ambitious and very challenging objectives.

The majority of air carriers are showing concern over the competitive advantage that maintainability and maintenance can provide to a company, due to their role in keeping aircraft availability performance, safety requirements, and total cost-effectiveness at high levels (Knezevic, 1997). Hence, maintenance should be considered as an important part of the air transport business process that serves and supports flight production. Therefore, in the move towards world-class competition, many manufacturers and air operators are realizing that there is a critical need for development of efficient and effective aircraft scheduled maintenance programme. (for further discussion see e.g. Jensen, 2007; Homsi, 2007; Karim, 2008; Candell, 2009).

On the other hand, improper maintenance decisions or incorrectly performed maintenance tasks may affect the safety of the system negatively, and thereby contribute to extensive losses and disasters (Knezevic, 1997; Holmgren, 2005; Reason, 1997). There have been a number of accidents in which incorrect maintenance decisions have been the major contributing factor. One example is the accident that hit Alaska Airlines Flight 261, in which an intuitive decision on postponing lubrication tasks led to damage to the horizontal stabilizer jack screw, which resulted in a loss of aircraft longitudinal control and finally a crash (for detailed discussions see NTSB, 2002).

Since the decisions made for developing or adjusting scheduled maintenance programmes strongly affect aircraft safety, it is crucial to consider the effectiveness of maintenance tasks in terms of risk reduction, in order to fulfil the safety requirements and assure safe operation. Moreover, in view of the fact that decisions on maintenance task development or adjustments to maintenance programmes may affect the aircraft availability performance and the LCC, it is crucial to apply optimal maintenance programmes. However, the design of maintenance is complex, and structuring the problem into autonomous steps is necessary for reducing this complexity (Gits, 1992).

1.2 Statement of the problem

The methodology applied within the aviation sector to determine maintenance tasks is mainly based on the Maintenance Steering Group (MSG-3) logic. Furthermore, the analysts who are engaged in the Maintenance Review Board Report (MRBR) process consult the experience gained from similar aircraft, and the methodology for determining maintenance tasks and intervals mainly relies on their engineering experience (Liu et al., 2006; Viniacourt et al., 2007). Even though this approach contributes to airworthiness requirements being fulfilled, there is no sufficient evidence for claiming that the maintenance programme derived from this process is optimal or the most effective one, from operator point of view. In fact, MSG-3, like any RCM-based methodology, is not a “silver bullet” on its own. For a successful implementation of any preventive maintenance tasks and assessment of the time for action (i.e. maintenance tasks interval), decision support methodologies and tools are required to make such implementation and assessment viable (Mokashi et al., 2002; Sharma et al., 2005). Examples of methodologies and tools that can support the analysis process include those which aid the identification of maintenance-significant items and their consequences (i.e. reliability and risk management), the assignment of intervals (i.e. maintenance optimization),
and selection of the most effective strategy among the applicable ones (i.e. maintenance decision-making).

Obviously, without acquiring appropriate supporting methodologies and tools, the decisions made by experts for scheduled maintenance development are subjective, experience-based, and conservative, which may lead to intensive and/or unnecessary maintenance (see Sherwin, 1998, for a detailed discussion). The extreme formality of this process may lead to a high maintenance frequency, which ultimately affects the aircraft availability performance and economy. For example, Papakostas et al. (2010) claim that almost 80% of the inspections and related access activities do not lead to a subsequent repair, but only increase the overall cost. Here, the major concern is not only the direct and indirect costs associated with repetitive inspection, but also the opportunity cost of the aircraft’s lost production due to inspection. There is also a risk that the maintenance and inspection activities may contribute to the introduction of failures (Nowlan and Heap, 1978; Reason, 1997; Moubray, 1997; Rankin, 2000). Dhillon (2002) states that the occurrence of maintenance errors increases as the equipment becomes older, due to an increase in the maintenance frequency.

There are two types of inspection tasks that are developed within the MRB process by the use of MSG-3 for aircraft systems. The first type is a kind of functional check (i.e. on-condition inspection), which aims to detect potential failures, and the second one includes an operational check-visual inspection (failure finding inspection), which aims to detect hidden failures (Nowlan and Heap, 1978; NAVAIR 403, 2005; ATA MSG-3, 2007). According to Lienhardt at al. (2008), up to one third of the tasks generated by comprehensive, correctly applied maintenance strategy development programmes are Failure Finding Inspection (FFI) tasks. However, these tasks have received less attention than the other types of maintenance tasks.

In the case of hidden failures with safety consequences, the FFI tasks should reduce the risk of failure to assure safe operation. For hidden failures with consequences that do not affect safety, the task should be cost-effective, meaning that the total cost of the proposed task should be less than the cost of multiple failures (ATA MSG-3, 2007). While the selection of a shorter inspection interval reduces the cost associated with the occurrence of a multiple failure and undesired consequences, it leads to an increased cost for inspection and restoration, and a higher opportunity cost for the aircraft’s lost production due to maintenance downtime. The selection of a longer inspection interval has the opposite effect. In fact, the extent and magnitude of inspection intervals directly affect the task effectiveness. Therefore, the problem arises of how to determine an optimal interval for FFI tasks related to hidden failures that achieves the best trade-off between the associated costs and satisfies the risk constraints.

MSG-3 and RCM, as well as other general approaches to reliability and risk management, include identification of the hazards and the objects that are likely to be harmed, and controls for reducing the frequency or consequences of unwanted events. The most important part of risk analysis is risk identification. Only those risks which have been identified can be managed in a systematic and conscious way (Njå and Nokland, 2005). Hence, the consideration of risk as a criterion for selecting the maintenance policy is crucial (Arunraj and Maiti, 2010). The results of the risk assessment are used to determine the need for a failure management strategy and, if one is needed, the risk provides a means to assess the effectiveness of the failure management strategy (Conachey and Montgomery, 2003), i.e.
how well the task reduces the risk of failure. When analyzing the consequences of failures, one major challenge is the assessment of the operational risk of failures, and its associated costs. Assessment of the operational risk of failures in aircraft operation is a challenge due to a long list of influencing factors and a lack of supporting methodologies within the MRB process. It is therefore important to provide a methodology to support decision making within the MRB process to assess the operational risk of failures in aircraft operation.

Merely considering an optimum interval for a specific maintenance task does not mean that it is the most effective alternative. The overall effectiveness of a maintenance task depends on a variety of factors that determine the positive and negative contribution of maintenance tasks to dependability of aircraft operation and a reduction of the maintenance efforts. Moreover, in the context of maintenance programme development, the characteristics of the technical system and the stakeholders’ requirements affect the effectiveness of the decision making process (Söderholm, 2005). Consequently, measurement of the maintenance performance should be based on the evaluating criteria that are defined according to the characteristics of the technical system and the requirements of the stakeholders (Parida and Kumar, 2006). Since decision making in practice is often characterized by the need to satisfy multiple objectives, there is a need to formulate multi-criteria decision models for selection of the most effective scheduled maintenance task.

Summing up, there is a need to provide decision support methodologies and tools for the identification of appropriate maintenance tasks to prevent the consequence of failures, improve the safety levels, optimize the maintenance intervals, reduce the unnecessary costs, and achieve stable air operation capabilities.

1.3 Purpose of the research

The purpose of this research is to develop decision support methodologies and tools for aircraft scheduled maintenance development within the MRB process, in order to facilitate and enhance the capability of making effective and efficient decisions and thereby achieve a more effective maintenance programme.

1.4 Objectives

The specific objectives of this research are to:

1. identify potential areas of improvement in the scheduled maintenance development process
2. propose systematic methodologies and tools that support assessment of the risk of failures in aircraft systems,
3. propose an appropriate methodology for identifying the optimum inspection and restoration intervals for both the non-safety and the safety effect category of hidden failures,
4. propose appropriate methodologies for selection of the most effective maintenance strategy.
1.5 Research questions

In order to fulfil the above-stated objectives, the following research questions have been raised:

1. What are the potential areas of improvement in the scheduled maintenance development process using the MSG-3 methodology?
2. How can the risk of an aircraft system’s failure be assessed?
3. How to determine the optimum Failure Finding Inspection (FFI) interval?
4. How to identify an optimum interval for a combination of Failure Finding Inspection (FFI) and restoration tasks?
5. How to select the most effective maintenance strategy?

1.6 Scope and delimitations of the study

Based on the available resources and according to the research purpose and objectives, as well as industrial interests, the scope and limitation of this study are as follows:

- The maintenance programme is considered as a “living” document which includes the initial maintenance programme development when the aircraft has been manufactured and further adjustment of the programme when operation has matured and appropriate and applicable data have become available (Nowlan and Heap, 1978; NAVAIR 403, 2005). The focus of this study is on the initial maintenance development, since this development has a major impact on the whole life cycle of the aircraft. However, to support the operator in this challenge, the study also partly includes scheduled maintenance development from an operator’s point of view.

- Aircraft scheduled maintenance analysis within the MRB process is divided into four main groups: system-powerplant analysis, structural analysis, zonal analysis, and L/HIRF1 (ATA MSG-3, 2007). Each of these groups follows a specific procedure and specific regulations, which means that they have their own characteristics, problems, and solutions. Since the industrial partner in the present study prioritized the system part of the aircraft, this is the focus of the study.

- Maintenance task analysis within the framework of RCM-based methodologies may be carried out as a sequence of activities or steps, including study preparation, system selection and identification, functional failure analysis, critical item selection (significant item selection), data collection and analysis, Failure Mode, Effects and Criticality Analysis (FMECA), selection of maintenance actions, the determination of maintenance intervals, preventive maintenance comparison analysis, treatment of non-critical items, implementation and in-service data collection and updating (Rausand, 1998). Due to industrial interests and time constraints, this study focuses on the assessment of the risk of failures, the determination of maintenance intervals and the area of preventive maintenance comparison analysis. Other preliminary steps and post-activities (e.g. treatment of non-critical items, implementation and in-service data collection and updating) are outside the scope of the present research work.

---

1 Lightning/High Intensity Radiated Field analysis procedure.
Humans play an important role in maintenance effectiveness. Human error may be defined as the failure to perform a specified task (or the performance of a forbidden action), which can lead to the disruption of scheduled operations or result in damage to property and equipment. There are various reasons for the occurrence of human errors, including inadequate lighting in the work area, inadequate training or skill of the manpower involved, high noise levels, an inadequate work layout, improper tools, and poorly written equipment maintenance and operating procedures (Dhillon and Liu, 2006). In fact, in aviation industries, it is expected that maintenance errors due to human factors are controlled by specific regulations, the incorporation of safety management systems and quality assurance programmes. Moreover, during the design phase, systems are guarded against some aspect of human errors. Hence, the influence of human factors on maintenance effectiveness has not been considered in this study.

1.7 Structure of the thesis

The structure of this thesis is divided into five chapters as follow:

Chapter 1: Introduction and Background – This chapter presents a brief background dealing with the importance of aircraft scheduled maintenance development. The chapter also discusses the problems related to the research area. Moreover, it describes, explains and outlines the research purpose, the research objectives, the research questions and the limitations of the research. The chapter explains the extent of the theoretical framework, which is described in more detail in Chapter 2.

Chapter 2: Theoretical Framework – This chapter provides a description of the state of the art concerning the main concepts and theories that are related to this research. It describes theories that support aircraft scheduled maintenance programme development, including theories concerning the system life-cycle, availability performance, the concept of risk, the reliability of repairable systems and some of the Multi-Criteria Decision Making methodologies. The theoretical framework has been used to achieve an understanding of the research area.

Chapter 3: Research Methodology – This chapter describes some aspects of the research methodology, e.g. approaches, purposes, strategies, data collection, and analysis. It also states the reasons for making the research choices related to these aspects. The selection of research methodologies has been performed based on the research purpose, the objective and the research questions, described in Chapter 1, and the theoretical framework described in Chapter 2.

Chapter 4: Summary of Appended Papers – This chapter provides a summary of the four appended papers and highlights the important findings of each appended paper.

Chapter 5: Discussion and Conclusions – This chapter discusses and draws conclusions from the results of the conducted research work. The discussions are structured based on the stated research objectives. The chapter also provides a summary of the research contributions, as well as some suggestions for further research.

References: A list of references is provided.
Appended Papers: This part of the thesis consists of four appended papers. The contents of these papers are summarized in different chapters of this thesis, e.g. Chapter 3, Research methodology, Chapter 4, Summary of appended Papers and Chapter 5, Discussion and conclusions.
2 Theoretical framework

This chapter provides the theoretical framework and the basic concepts used within this research.

2.1 Reliability-Centred Maintenance (RCM)

Reliability-Centred Maintenance (RCM) is a well-structured, logical decision process used to identify the policies needed to manage failure modes that could cause the functional failure of any physical item in a given operating context. The RCM methodology is used to develop and optimize the preventive maintenance and inspection requirements of equipment in its operating context, to achieve its inherent reliability where, inherent reliability can be achieved by using an effective maintenance programme. The methodology is based on the assumption that the inherent reliability of equipment is a function of the design and the built quality (Nowlan and Heap, 1978; Moubray, 1997; Rausand and Vatn, 1998a; Dhillon, 2002; Smith and Hinchcliffe, 2004).

RCM is a methodology for evaluation of the system, in terms of the life cycle, to determine the best overall programme for preventive (scheduled) maintenance. The emphasis is on the establishment of a cost-effective preventive maintenance programme based on reliability information derived from Failure Mode Effect and Criticality Analysis (FMECA); i.e. analysis of the modes, effects, frequency, and criticality of failure, and compensation through preventive maintenance (Blanchard, 2008). It is a systematic approach to the development of a focused, effective, and cost-efficient preventive maintenance programme and control plan for a system or product. This technique is best initiated during the early system design process and evolves as the system is developed, produced, and deployed. However, the technique can also be used to evaluate preventive maintenance programmes for existing systems, with the objective of continuous product/process improvement (Blanchard, 2008).

RCM recognizes that the only reason for performing any kind of maintenance is not to avoid failures per se, but to avoid, or at least to reduce, the consequences of failure. Hence, RCM concentrates on the preservation of function instead of focusing on the hardware per se (Nowlan and Heap, 1978; Kumar, 1990; Moubray, 1997). By using an approach based on the system level and function preservation, RCM treats components differently in terms of relative importance according to the correlation between the equipment and the system function. In fact, the probability of the consequences of undesired events, i.e. losses, and its magnitude depend to a great extent on the applicability and effectiveness of the barriers that are in place to avert the release of such consequences. Preventive maintenance acts as a preventive barrier whose aim is to eliminate the consequences of failure or reduce them to a level which is acceptable to the user.

In contrast to earlier methodologies supporting maintenance programme development, the RCM methodology is based on (for details see e.g. Nowlan and Heap, 1978; Moubray, 1997; Dhillon, 2002):

- A system level and top-down approach for function identification, instead of a component level and bottom-up approach.
- A consequence-driven approach, to assure controls of the risk of failure.
Function preservation instead of failure prevention, to assure the system function and the availability of protective devices.

A task-oriented approach instead of a maintenance process-oriented approach to preparation of a maintenance programme.

The RCM analysis may be carried out as a sequence of activities or steps, including study preparation, system selection and identification, functional failure analysis, critical item selection (significant item selection), data collection and analysis, Failure Mode Effect and Criticality Analysis (FMECA), selection of maintenance actions, determination of maintenance intervals, preventive maintenance comparison analysis, treatment of non-critical items, implementation and in-service data collection and updating (Rausand, 1998). Any RCM methodology shall ensure that all the following seven questions are answered satisfactorily in the order given below, to assure the success of the programme (SAE JA1011):

1. What are the functions and associated performance standards of the item in its present operating context (functions)?
2. In what ways does it fail to fulfil its functions (functional failures)?
3. What is the cause of each functional failure (failure modes)?
4. What happens when each failure occurs (failure effects)?
5. In what way does each failure matter (failure consequences)?
6. What can be done to prevent each failure (proactive tasks and task intervals)?
7. What should be done if a suitable preventive task cannot be found (default actions)?

Regardless of the standard that is used to develop a scheduled maintenance programme, task justification should be based on the criteria that show whether the selected maintenance task is able to fulfil its objectives or not. Hence, maintenance task selection in RCM is based on overriding criteria, i.e. applicability (technical feasibility) and effectiveness (the extent to which the task is worth doing). The applicability of a task depends on the reliability of the item (Rausand and Vatn, 1998a), the item’s failure characteristics, and the type of task (Nowlan and Heap, 1978, MIL-STD-2173, 1986; SAE JA-1012, 2002). The effectiveness of a task is a measure of the result of the fulfilment of the maintenance task objectives, which is dependent on the failure consequences (Nowlan and Heap, 1978; MIL-STD-2173, 1986). In other words, the maintenance task’s effectiveness is a measure of how well the task accomplishes the intended purpose and the extent to which it is worth doing. In general, a preventive maintenance task must reduce the expected loss to an acceptable level, to be effective (Rausand and Vatn, 1998; Rausand and Hoyland, 2004).

The available failure management strategies offered by RCM consist of specific scheduled maintenance tasks selected on the basis of the actual reliability characteristics of the equipment which they are designed to protect, and they are performed at fixed, predetermined intervals. The objective of these tasks is to prevent deterioration of the inherent safety and reliability levels of the system. The four basic forms of preventive maintenance offered by RCM include (Nowlan and Heap, 1978; SAE JA1011, 1999; NAVAIR, 2005):

- **Scheduled on-condition inspection**: a scheduled task used to detect a potential failure.
- **Scheduled restoration** (rework or hard time): a scheduled task that restores the capability of an item at or before a specified interval (age limit), regardless of its condition at the time, to
a level that provides a tolerable probability of survival to the end of another specified interval.

- **Scheduled discard** (or hard time discard): a scheduled task that entails discarding an item at or before a specified age limit regardless of its condition at the time.
- **Scheduled failure finding inspection**: a scheduled task used to determine whether a specific hidden failure has occurred. The objective of a failure finding inspection is to detect a functional failure that has already occurred, but is not evident to the operating crew during the performance of normal duties.

In some cases it may not be possible to find a single task which on its own is effective in reducing the risk of failure to a tolerably low level. In these cases it may be necessary to employ a “combination of tasks” such as “on-condition inspection” and “scheduled discard”. Each of these tasks must be applicable in its own right and in combination they must be effective (Defence Standard 02-45 NES 45, 2000). These tasks are applicable to failure with safety consequences and, when applied, the probability of failure must be reduced to a tolerable level. In reality, a combination of tasks is rarely used. It is assumed, however, that in most instances this is a stoppage measure, pending redesign of the vulnerable part (Nowlan and Heap, 1978). If no task is found to be applicable and effective, default strategies are introduced, which include:

- No scheduled maintenance (no preventive maintenance, run to failure)
- Redesign

When it is technically unfeasible to perform an effective scheduled maintenance task, and when a failure will not affect safety, or may entail only a minor economic penalty, the “no-scheduled-maintenance” or “run-to-failure” option will be accepted. Selection of the “no-scheduled-maintenance” option means that the consequence of failure is accepted. In cases where the failure has a safety effect and there is no form of effective scheduled maintenance task, “redesign” is mandatory. In other cases where the failure may produce a significant cost, a trade-off analysis identifies the desirability of redesign (Nowlan and Heap, 1978). In fact, the decision ordinarily depends on the seriousness of the consequences. Hence, if the consequences entail a major loss, the default action is redesign of the item to reduce the frequency of failures and their consequences.

### 2.2 Aircraft scheduled maintenance programme development

As a common practice in aviation, the initial scheduled maintenance tasks and intervals are specified in Maintenance Review Board (MRB) Reports (MRBR). The MRBR outlines the initial minimum scheduled maintenance and inspection requirements to be used in the development of an approved continuous airworthiness maintenance programme for the airframe, engines, systems and components of a given aircraft type. The MRBR is generated as an expeditious means of complying in part with the maintenance instruction requirements for developing Instructions for Continued Airworthiness. Through the MRB process, manufacturers, regulatory authorities, vendors, operators, and industry work together to develop the initial scheduled maintenance/inspection requirements for new aircraft and/or on-wing powerplant. It is intended that the MRB report will be used as a basis for each operator to develop its own continuous airworthiness maintenance programme subject to the approval of its regulatory authority. After approval, the requirements outlined in the MRBR become a basis
on which each air carrier develops its own individual maintenance programme (Transport Canada, 2003).

In the commercial aviation industry, increasing emphasis is now being placed on using the MSG-3 methodology to develop an initial scheduled maintenance programme for the purpose of developing an MRB report. The reason is that it is a common means of compliance for the development of minimum scheduled maintenance requirements within the framework of the instructions for continued airworthiness promulgated by most of the regulatory authorities. MSG-3 was a combined effort involving manufacturers, regulatory authorities, operators, and the Air Transport Association of the USA (AC 121-22A, 1997; Transport Canada, 2003). The MSG-3 methodology implicitly incorporated the principles of the Reliability Centred Maintenance (RCM) philosophy (fundamentals) to justify task development, but stopped short of fully implementing reliability-centred maintenance criteria to audit and substantiate the initial tasks being defined (Transport Canada, 2003).

MSG-3 outlines the general organization and decision process for determining the scheduled maintenance requirements initially projected for preserving the life of the aircraft and/or powerplants, with the intent of maintaining the inherent safety and reliability levels of the aircraft. The tasks and intervals developed become the basis for the first issue of each airline’s maintenance requirements, intended to govern its initial maintenance policy. As operating experience is accumulated, additional adjustments may be made by the operator to maintain efficient scheduled maintenance (ATA MSG-3, 2007). As stated by ATA MSG-3 (2007), the objectives of efficient scheduled maintenance of aircraft are:

1. To ensure realization of the inherent safety and reliability levels of the aircraft.
2. To restore safety and reliability to their inherent levels when deterioration has occurred.
3. To obtain the information necessary for design improvement of those items whose inherent reliability proves to be inadequate.
4. To accomplish these goals at a minimum total cost, including maintenance costs and the costs of resulting failures.

The analysis process identifies all the scheduled tasks and intervals based on the aircraft’s certificated operating capabilities. The analysis steps include (ATA MSG-3, 2007):

1. Maintenance-Significant Item (MSI) selection,
2. The MSI analysis process (identification of functions, functional failures, failure effects, and failure causes),
3. Selection of maintenance actions using decision logic, which includes:
   a. Evaluation of the failure consequence (level 1 analysis)
   b. Selection of the specific type of task(s) according to the failure consequence (level 2 analysis)

The maintenance strategies recommended by ATA MSG-3 (2007) include:

- Lubrication/Servicing
- Operational/Visual Check (for hidden failures)
- Inspection/Functional Check
• Restoration
• Discard
• Combination of tasks (for safety categories)
• Redesign (for a safety effect)

2.3 System life cycle and maintenance

The life cycle refers to the entire spectrum of activities for a given system or product, commencing with the identification of a consumer need and extending through system design and development, production and/or construction, operational use, sustaining maintenance and support, and system retirement and phase-out. Since the activities in each phase interact significantly with activities in other phases, it is essential that one should consider the overall life cycle when addressing maintainability or any other system characteristic (Blanchard et al., 1995).

There are different approaches to the concept of life cycle perspectives, though they often focus on particular properties of the system during its lifetime, like technical reliability (O’Connor, 1991) or LCC and economic analysis (Blanchard and Fabrycky, 1998). A life cycle perspective also needs to address the importance of the support system and continuous improvements for a system-of-interest with a life expected to span over decades (Sandberg and Strömberg, 1999).

When dealing with the aspect of cost, one often addresses only the short-term costs, or those expenses associated with the initial procurement of a system or product. Design development and manufacturing costs are usually fairly well known, as there is some historical basis for the prediction of such! However, the long-term costs associated with system operation and support are often hidden, yet experience has indicated that these costs often constitute a large percentage of the total life cycle cost for a given system (Blanchard et al., 1995). For example, the purchase of a commercial aircraft can cost as much as $200 million, and an additional $2 billion is required for operation, maintenance, and support throughout its economic life, which is around 20 to 25 years (Saranga and Kumar, 2006).

Additionally, when looking at the “cause-and-effect relationship”, one finds that a major portion of the projected life cycle cost for a system stems from the consequences of decisions made during the early phase of advance planning and conceptual design. Those decisions pertaining to the utilization of new technologies, the selection of components and material, the identification of equipment packaging schemes and diagnostic routines, and so on, have a great impact on the life cycle cost. Referring to the general projections in Figure 2.1, there is a large “commitment” to the life cycle cost in the early phases of system/product development. In the figure there are three different projections, presented in a generic manner, which may vary with the system in question. Although the actual expenditures on a given project will accumulate slowly at first, building up during the later phases of design and in production, the commitment to the life cycle cost will be larger during the early stage of system development. For some systems, from 60 to 70% of the projected life cycle cost is “locked in” by the end of preliminary design. In other words, the maintenance and support costs for a system, which often constitute a large percentage of the total, can be highly impacted by early design decisions (Blanchard et al., 1995).
While the technical characteristics of system performance have received emphasis in system design and construction, very little attention has been directed towards such design characteristics as reliability, maintainability, serviceability, supportability, human factors, environment factors, and the like. In particular, when reliability and maintainability are not considered during design, high maintenance and support costs result downstream. Additionally, rather extensive maintenance and support requirements have had a definite degrading impact on the overall system effectiveness or productivity (Blanchard et al., 1995; Blanchard, 2008). Furthermore, insufficient or erroneous maintenance efforts may result in decreased quality, incidents, and accidents. It is therefore of paramount importance that maintenance and support concepts are designed correctly during the initial phase of a system’s life cycle (Blanchard et al., 1995; Goffin, 2000). Moreover, as the maintenance and support system should compensate for deficiencies in the design of the system of interest, insufficient reliability and maintainability performance incur the need for expensive logistic resources such as spares, manpower, ICT and facilities, all of which increase the Life Support Cost (LSC) and LCC (Candell, 2009). The correct design of maintenance during the initial phase is important for a complex system, not only to secure the performance of the complex system, but also because maintenance has a major impact on the complex system’s Life Cycle Cost (LCC) (Blanchard, 1998; Markezet and Kumar, 2003). From another viewpoint, the purpose of the maintenance process is to sustain the capability of a system to meet the demand for deliveries and thereby achieve customer satisfaction (for detailed see e.g. Liyanange and Kumar, 2003; Barabady, 2007; IEC, 2008). To this end, an efficient and effective maintenance process needs to be
horizontally aligned with the operation and modification processes and vertically aligned with the requirements of external stakeholders (Liyanage and Kumar, 2003; Söderholm et al., 2007). As illustrated in Figure 2.2, the maintenance process covers a spectrum of activities required for managing, support planning, preparing, executing, assessing and improving maintenance. This process description highlights the importance of continuous improvement within the maintenance area, as described by Nowlan and Heap (1978), Coetzee (1999), Campbell and Jardine (2001) and Murthy et al. (2002), as well as in NAVAIR 403 (2005).

Murthy et al. (2002) view maintenance as a multi-disciplinary activity which involves: understanding the degradation mechanism and linking it to data collection and analysis; providing quantitative models for prediction of the impacts of different maintenance actions; and strategic maintenance management. They also pinpoint three main steps involved in maintenance management: understanding the system-of-interest; planning optimal maintenance actions; and implementing these actions. There are two main maintenance strategies (i.e. actions): preventive and corrective maintenance. Figure 2.3 depicts these strategies. Preventive maintenance implies proactive activities to avoid possible future problems.
Corrective maintenance, on the other hand, implies reactive activities performed to correct faults. Examples of corrective and preventive activities are: adjustment, calibration, cleaning, lubrication, refurbishment, repair, and replacement.

2.4 System Dependability

Dependability is a collective term which describes the availability performance and its influencing factors, namely reliability performance, maintainability performance, and maintenance support performance (IEC, 2001) (see Figure 2.4).

**Availability performance:** Availability performance is the ability of an item to be in a state in which it can perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided (IEV, 2010). Blanchard (1995) also defines the term availability as “the measure of the degree a system is in the operable and committable state at the start of a mission when the mission is called for at an unknown random point in time”.

The most frequently used availability measure is the *steady-state availability* or *limiting availability*, which is defined as the mean of the instantaneous availability under steady-state conditions over a given time interval and is expressed by \( A_{\text{Lim}} = \lim_{t \to \infty} A_t \). This quantity is the probability that the system will be available after it has been run for a long time and is a significant performance measure for a system. Often steady-state availability is also defined, depending on whether the waiting time or preventive maintenance times are included in or excluded from the calculation. Therefore, depending on the definitions of uptime and downtime, there are three different forms of steady-state availability: inherent availability, achieved availability, operational availability (for a detailed discussion see e.g. Blanchard and Fabrycky, 1998; Blanchard et al., 1995; Kumar and Akersten, 2008).

The availability performance level is recognized by the equipment’s inherent design characteristics, i.e. its reliability and maintainability performances, and the maintenance support performance of the organisation providing maintenance (see Fig. 2.4). However, it should be noted that both reliability and maintainability are also influenced by the operating context and the maintenance support performance, which will be discussed in the following.

**Reliability performance:** Reliability can be defined as: “The probability that an asset will perform its intended function for a specified period of time under specified operating

![Diagram of availability performance](image-url)

*Figure 2.4 An illustration of the relationship between availability performance and its associated factors (IEV, 2010).*
conditions” (Blischke and Murthy, 2000; Klefsjö and Kumar, 1992). Reliability is a function of time/load and the operating environment of a product, which comprises factors such as the surrounding environment (e.g. temperature, humidity and dust), condition-indicating parameters (e.g. vibration and pressure), and human aspects (e.g. the skill of the operators) (Ghodrati, 2005). The maximum reliability which an item/unit can achieve is built into it during its design phase and manufacturing process and is called the inherent reliability. We cannot expect better reliability of a unit than what we build into it during its design and manufacturing phase (Misra, 2008). Hence, by maintenance we may increase an item’s operational reliability, but not its inherent reliability. Therefore, the organisation providing maintenance plays an important role in achieving the inherent reliability of aircraft at the lowest possible cost in its service life. Examples of the organisation’s responsibilities include selecting proper subcontractors, using a skilled crew for correct removal and installation, repair and testing, and providing a proper inventory environment and packaging schemes, etc.

**Maintainability performance:** Maintainability is defined as “the ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources” (IEV, 2010). Maintainability is an inherent characteristic of system or product design. It pertains to the ease, accuracy, safety, and economy in the performance of maintenance actions. A system should be designed in such a way that it can be maintained without large investments of time, at the minimum cost, with a minimum impact on the environment, and with the minimum expenditure of resources (e.g. personnel, material, facilities, and test equipment). One goal is to maintain a system effectively and efficiently in its intended environment, without adversely affecting the mission of that system. Maintainability is the “ability” of an item to be maintained, whereas maintenance constitutes a series of actions necessary to retain an item in, or restore it to an effective operational state. Maintainability is a design parameter. Maintenance is required as a consequence of design (Blanchard et al., 1995; Blanchard, 2008). High maintainability performance and, in turn, high availability performance are obtained when the system is easy to maintain and repair.

Maintenance task analysis is one of the most important parts of maintainability analysis and includes a detailed analysis and evaluation of the system to (a) assess a given configuration relative to the degree of incorporation of maintainability characteristics in the design and compliance with the initially specified requirements and (b) determine the maintenance and logistic support resources required to support the system throughout its planned life cycle. Such resources may include maintenance personnel quantities and skill levels, spares and repair parts and associated inventory requirements, tools and test equipment, transportation and handling requirements, facilities, technical data, computer software, and training requirements. Such an evaluation may be accomplished during the preliminary and detail design phases by utilizing the available design data as the source of information and/or by performing a review and assessment of an existing item using checklists as an aid (Blanchard, 2008). Figure 2.5 conveys examples of the relationships between the selected reliability and maintainability tools. Some design features of maintainability characteristics include interchangeability, easy accessibility, easy serviceability, and diagnostic and prognostic capabilities. The inherent maintainability is primarily determined by the design of the equipment and can be greatly enhanced if fault detection, isolation and repair procedures are worked out during the design stage itself in advance (Misra, 2008).


**Maintenance support performance:** Maintenance support performance is defined by IEV (2010) as: “the ability of a maintenance organization, under given conditions to provide upon demand the resources required to maintain an item, under a given maintenance policy”. Some of the essential features of a maintenance support system are the maintenance procedure, the procurement of maintenance tools, spare parts and facilities, logistic administration, documentation, and development and training programmes for maintenance personnel. Thus it can be seen that maintenance support performance is part of the wider concept of product support, which includes support to the product as well as support to the client (for detail discussion see e.g. Markeset, 2003; Ghodrati, 2005; Candell and Söderholm, 2006; Blanchard, 2008; Kumar and Akersten, 2008).

### 2.5 Concept of risk

Risk can generally be defined as “a potential of loss or injury resulting from exposure to a hazard or failure”. It is an expression of the probability and the consequences of an accidental event (Modarres, 2006).

\[
\text{Risk} = \text{Frequency} \times \text{Magnitude} = \frac{\text{Consequence}}{\text{Event}} \times \frac{\text{Event}}{\text{Unit of time or space}} = \frac{\text{Consequence}}{\text{Unit of time or space}}
\]
The term consequence is defined in a very broad sense, and is used to mean all the events causing any type of loss, such as injury or loss of life, a high repair cost, the loss of a system, and delay or flight cancellation.

According to Kaplan (1997) risk assessment consists of answering the following three questions:

1. What can happen? (Which scenarios are possible?)
2. How likely is it to happen? (probability)
3. What are the consequences of the event?

The most important part of risk analysis is risk identification. Only those risks which have been identified can be managed in a systematic and conscious way. However, identification is not enough. There is also a need for action, using risk evaluation to take the appropriate operational and maintenance decisions regarding risk reduction and control, thus ensuring that the system stays in a safe state, regarding both the technical and the organizational parts (Aven, 2003; Akersten, 2006).

Risk management is a systematic approach adopted to identify, analyze, and control areas or events with a potential for causing unwanted change. Through risk management, the risks associated with failures are assessed and systematically managed to reduce them to an acceptable level. Risk management can further be described as the act or practice of controlling risk, and the stages in a risk management process usually incorporate risk analysis, risk evaluation and risk mitigation.

Modelling and analysis of the causes and consequences of failures form a foundation for quantitative investigation of the reliability, safety, and risk related to the design entity (Virtanen et al., 2006). From this viewpoint, the process of a failure begins with a set of basic events which are known as “initiating events” (IEs) and which perturb the system, causing it to change its operating state or configuration. If the “initiating events” as the initial cause of failures cannot be managed at an early stage of their occurrence, this will lead to a number of so-called “undesired events” or top events (Modarres, 2006).

The basic events are often identified and modelled by fault tree (cause tree) analysis. The fault tree consists of such causes and interconnected causalities as can lead to the occurrence of a top event. If the failure rate and other necessary data are available for the basic events, the fault tree analysis will provide estimates of the frequency of occurrence of the various undesired events. The possible consequence chains starting from an undesired event are often identified and modelled by ETA, i.e. using a consequence tree (for details see e.g. Rausand and Vatn, 1998a; Modarres, 2006; Virtanen et al., 2006) (see Figure 2.6). Depending on the type of failure, the outcome of the ETA will be a set of possible consequences, such as delay, high repair cost, injury to people or loss of life. If the necessary input data are available for the barriers and physical models, the ETA will provide frequencies or probabilities of the various consequences. Other well-known methodologies for risk identification are the Failure Mode & Effects Analysis (FMEA) methodology, Preliminary Hazards Analysis (PHA), and Hazard & Operability Studies (HAZOP) (for more details see e.g. Andrews and Moss, 2002).
2.5.1 Event Tree Analysis (ETA)

ETA can be used for qualitative and quantitative reliability and risk analyses (Pate-Cornell, 1984; CCPS, 1992; Modarres, 1993). ETA is widely used for facilities provided with engineering accident mitigating features, in order to identify the sequences of events which lead to the occurrence of specified consequences, following the occurrence of an initiating event. It is appropriate to apply ETA in cases where the successful operation of a system depends on an approximately chronological, but discrete, operation of its subsystems, e.g. when the subsystems should work in a defined sequence for operational success (Modarres, 1993) or when there are a number of safety functions or barriers affecting the outcomes of the initiating event (CCPS, 1992).

The event tree is a commonly used graphical tool supporting the ETA methodology. The event tree is traditionally a horizontally built structure that starts on the left, with what is known as the “initiating event”. The initiating event may describe a situation where a legitimate demand for the operation of a system occurs. The development of the tree proceeds chronologically, with the requirement for each subsystem being postulated (Modarres, 1993). The event trees are usually developed in a binary format; e.g. the events are assumed to either occur or not occur, or to be either a success or a failure (IEC, 1995). At a branch point, the upper branch of an event usually shows the success of the event and the lower branch its failure. However, there may also be cases where a spectrum of outcomes is possible, in which situation the branching can proceed with more than two outcomes (Modarres, 1993).

The probabilities in an event tree are conditional probabilities, i.e. the probability of a subsequent event is not the probability obtained from tests under general conditions, but the probability of the event under the conditions arising from the chain of preceding events (IEC, 1995). The outcome of each sequence of events, or path, is illustrated at the end of each sequence. This outcome describes the final outcome of each sequence, i.e. whether the overall system succeeds, fails, initially succeeds but fails at a later time, or some other outcome.
The logical representation of each sequence of the event tree can also be shown in the form of a Boolean expression. The logical representation of each event tree heading, and ultimately each event tree sequence, is obtained and then reduced through the use of Boolean algebra rules. If an expression explaining all the failed states is desired, the sum of the reduced Boolean expressions for each sequence that leads to failure should be obtained and reduced. However, if the branching of the event tree has more than two outcomes, the qualitative representation of the branches in the Boolean sense is not possible. The quantitative evaluation of event trees is straightforward and similar to the quantitative evaluation of fault trees (Modarres, 1993).

### 2.6 Reliability of repairable system

A repairable system is a system which, after failing to perform one or more of its functions satisfactorily, can be restored to fully satisfactory performance by any method other than replacement of the entire system (Ascher and Feingold, 1984). The quality or effectiveness of the repair action is categorized as (Ascher and Feingold, 1984; Rausand and Høyland, 2004; Modarres, 2006):

1. Perfect repair, i.e. restoring the system to the original state, to a “like-new” condition,
2. Minimal repair, i.e. restoring the system to any “like-old” condition,
3. Normal repair, i.e. restoring the system to any condition between the conditions achieved by perfect and minimal repair.

Based on the quality and effectiveness of the repair action, a repairable system may end up in one of the following five possible states after repair (Ascher and Feingold, 1984; Rausand and Høyland, 2004; Modarres, 2006):

1. as good as new;
2. as bad as old;
3. better than old but worse than new;
4. better than new;
5. worse than old.

While perfect repair rejuvenates the unit to the original condition, i.e. to an as-good-as-new condition, minimal repair brings the unit to its previous state just before repair, i.e. an as-bad-as-old condition, and normal repair restores the unit to any condition between the conditions achieved by perfect and minimal repair, i.e. a better-than-old but worse-than-new condition. However, states four and five may also happen. For example, if through a repair action a major modification takes place in the unit, it may end up in a condition better than new, and if a repair action causes some error or an incomplete repair is carried out, the unit may end up in a worse-than-old condition.

Failures occurring in repairable systems are the result of discrete events occurring over time. These processes are often called stochastic point processes (Modarres, 2006). The stochastic point process is used to model the reliability of repairable systems, and the analysis includes the homogenous Poisson process (HPP), the renewal process (RP), and the non-homogenous Poisson process (NHPP). A renewal process is a counting process where the interoccurrence times are independent and identically distributed with an arbitrary life distribution (Rausand
and Høyland, 2004). Upon failure, the component is thus replaced or restored to an as-good-as-new condition.

The NHPP is often used to model repairable systems that are subject to a minimal repair. Typically, the number of discrete events may increase or decrease over time due to trends in the observed data. An essential condition of any homogenous Poisson process (HPP) is that the probability of events occurring in any period is independent of what has occurred in the preceding periods. Therefore, an HPP describes a sequence of independently and identically distributed (IID) exponential random variables. Conversely, an NHPP describes a sequence of random variables that are neither independently nor identically distributed. The NHPP differs from the HPP in that the rate of occurrences of failures varies with time rather than being a constant. The renewal process as well as the NHPP are generalizations of the HPP, both having the HPP as a special case. Recently the generalized renewal process (GRP) was also introduced to generalize the third point processes discussed above (Rausand and Høyland, 2004). To determine whether a process is an HPP or NHPP, one must perform a trend analysis and serial correlation test to determine whether an IID situation exists (Klefsjö and Kumar, 1992).

The failure of a component may be partial, and the repair work performed on a failed component may be imperfect. Therefore, the time periods between successive failures are not necessarily independent. This is a major source of trend in the failure rate. Furthermore, repairs made by adjusting, lubricating, or otherwise treating component parts that are wearing out provide only a small additional capability for further operation, and do not renew the component or system. These types of repair may result in a trend of increasing failure rates (Modarres, 2006).

Experience shows that, for many of the aged repairable units, the IID assumption is contradicted in reality. Different approaches are introduced to model the probability of failure for a non-IID data set, and in the present study the power law process has been selected. The utilization of a power law process to describe the data set is not contradicted. For a test of the power law process, readers are referred to Klefsjö and Kumar (1992).

In this study, minimal repair is considered, and hence the unit returns to an “as-bad-as-old” state after inspection and repair actions. On the other hand, the component keeps the state which it was in just before the failure that occurred prior to inspection and repair, and the arrival of the ith failure is conditional on the cumulative operating time up to the (i-1)th failure. Under this assumption, the rate of occurrence of failure (ROCOF) of the NHPP in the power law is defined as (Rigdon and Basu, 2000; Rausand and Høyland, 2004; Klefsjö and Kumar, 1992):

\[
h(t) = \frac{\beta}{\alpha} \left( \frac{t}{\alpha} \right)^{\beta-1}
\]

and the cumulative ROCOF will be:

\[
H(t) = \left( \frac{t}{\alpha} \right)^{\beta}
\]
where \( \alpha \) and \( \beta \) denote the scale and shape parameters. Considering NHPP, the reliability and failure probability (unreliability) functions at time \( t \) are defined as:

\[
R(t) = e^{-\lambda t} = \exp \left( -\frac{t}{\alpha} \right)
\]

\[
F(t) = 1 - R(t) = 1 - e^{-\lambda t} = 1 - \exp \left( -\frac{t}{\alpha} \right)
\]

In fact, we are interested in knowing, if the unit is tested and found functional at time \( t_1 \), what the probability of failure and survival will be at time \( t_2 \) after inspection at time \( t_1 \). Hence, the following conditional probability is defined:

\[
Pr\{t_2 | t_1\} = \frac{F(t_2) - F(t_1)}{R(t_1)} = 1 - \frac{R(t_2)}{R(t_1)} = 1 - \exp \left[ H(t_2) - H(t_1) \right]
\]

On the other hand, if the component is found functional (i.e. is found to have survived) at the \((N-1)\)th inspection (i.e. at \( T, 2T, 3T, \ldots, NT \) inspection times), the conditional probability and survival at any time, \( "t" \), within the \( N \)th inspection cycle are given by:

\[
F_N(t) = 1 - \exp \left[ \frac{(N-1)T}{\alpha} - \frac{(N-1)T + t}{\alpha} \right]
\]

\[
R_N(t) = \exp \left[ \frac{(N-1)T}{\alpha} - \frac{(N-1)T + t}{\alpha} \right]
\]

where \( "t" \) denotes the local time within the \( N \)th inspection cycle.

### 2.7 Unavailability characteristics of repairable units subject to hidden failures

The unavailability of hidden functions is usually measured by the Mean Fractional Dead Time (MFDT), i.e. the mean proportion of time during which the proposed item is not functioning as protection or a barrier (Rausand and Høyland, 2004). If dormant (undetected) failures occur while the system is in a non-operating state, the system availability can be influenced by the frequency at which the system is inspected. Note that inspection cannot improve reliability, but can only improve function availability (Ebeling, 1997).

According to Ebeling (1997), Vaurio (1997) and; Rausand and Vatn (1998b), the function availability at time \( "t" \) within the \( N \)th inspection cycle is equal to the conditional reliability, i.e. \( R_N(t) \) (see Eq. 3), and the corresponding function unavailability is equal to the conditional probability function, i.e. \( F_N(t) \) (see Eq. 4).

Consequently, the average unavailability within the \( N \)th inspection cycle with inspection at every \( "T" \) time, i.e. MFDT\(_{T,N} \), is given by (Vaurio, 1995; Rausand and Vatn, 1998b):

\[
MFDT_{T,N} = \frac{1}{T} \int_0^T F_N(t) \, dt
\]
As Rausand and Vatn (1998b) suggested, the conditional probability in the middle of the Nth inspection interval, i.e. $F[(N+0.5)T \mid NT]$, is a good approximation for $\text{MFDT}(T,N)$, as shown below:

$$
\text{MFDT}_{(T,N)} = 1 - e^{-\frac{T}{\sqrt{\frac{N}{a}}}} \left(1 - e^{-\frac{N}{a}}\right)^{N+0.5} \left(1 - e^{-\frac{N-1}{a}}\right)
$$

(5)

2.8 Multi-Criteria Decision Making (MCDM)

One of the most popular approaches for conflict management is Multi-Criteria Decision Making (MCDM). Multi-criteria optimization is the process of determining the best feasible solution according to the established criteria (representing different effects). Practical problems are often characterized by several incommensurable and conflicting (competing) criteria, and there may be no solution satisfying all the criteria simultaneously. Therefore, the solution is a set of non-inferior solutions, or a compromise solution according to the decision maker’s preferences. A compromise solution for a problem with conflicting criteria can help the decision makers to reach a final decision. The compromise solution is a feasible solution which is closest to the ideal, and a compromise means an agreement established by mutual concessions (Opricovic and Tzeng, 2004). In the following, the three MCDM methods that have been used in this thesis are described.

2.8.1 TOPSIS

TOPSIS (technique for preference by similarity to the ideal solution) is attractive in that limited subjective input is needed from decision makers. The only subjective input needed is weights (Olson, 2004). The solution of a multi-attribute decision making (MADM) problem through TOPSIS is based on the simple logic that the best solution is farthest from the negative ideal solution (NIS), and preferably closest to the positive ideal solution (PIS). It considers m alternatives as m points in an n-dimensional space of n attributes. The alternatives are ranked by their distances from two cardinal points: the positive ideal solution and the negative ideal solution. The different steps involved in TOPSIS are as follows (Opricovic and Tzeng, 2004):

(1) **Prepare the decision matrix**: $D^k = [x^k_{ij}]_{m \times n}$, where $x^k_{ij}$ is the score (appraisal rating) of the alternative $i$ for attribute $j$ given by expert $k$. $D^k$ is the decision matrix framed from the responses of the $k^{th}$ expert.

(2) **Calculate the normalized decision matrix**: The element $r^k_{ij}$ of the normalized appraisal (decision) matrix ($R^k$) may be calculated using the expression for linear normalization.

(3) **Assign the importance of attributes ($w_j$)**: the importance of each attribute can be elicited from the pairwise comparison matrix of the experts’ judgements following the AHP methodology.

(4) **Calculate the weighted normalized decision matrix** $V^k$: The elements of the weighted normalized matrix are formed after giving due importance to the elements of matrix ($R^k$). The elements of the matrix $V^k$ are evaluated by multiplying the elements of the matrix ($R^k$) with the corresponding weight ($w_j$) of the attributes, i.e. $V^k = [v^k_{ij}]_{m \times n} = [w_j \times r^k_{ij}]_{m \times n}$. 
(5) **Formulation of aggregated decision matrix:** The aggregated decision matrix $V = \left[ v_{ij}^{a} \right]_{n \times n}$ is formed from the weighted normalized matrix of all experts. The aggregated experts’ judgements can be calculated by geometric mean, in which the elements of the aggregated decision matrix are:

$$v_{ij}^{a} = \left( \prod_{k=1}^{n} v_{ij}^{k} \right)^{1/n}$$

(6) **Determine the positive and negative ideal solutions:** PIS ($v^+$) contains all the highest scores of the benefit criteria and all the lowest scores of the cost criteria. NIS ($v^-$) contains all the lowest scores of the benefit criteria and all the highest scores of the cost criteria. The PIS and NIS of a group of experts are:

$$v^{+} = \left[ v_{j}^{+} \right]_{j=1,2,\ldots,n} = \left[ v_{1}^{+}, v_{2}^{+}, \ldots, v_{n}^{+} \right] = \left( \max_{i} v_{ij} \mid j \in J \right) \cdot \left( \min_{i} v_{ij} \mid j \in J' \right)$$

$$v^{-} = \left[ v_{j}^{-} \right]_{j=1,2,\ldots,n} = \left[ v_{1}^{-}, v_{2}^{-}, \ldots, v_{n}^{-} \right] = \left( \min_{i} v_{ij} \mid j \in J \right) \cdot \left( \max_{i} v_{ij} \mid j \in J' \right)$$

where $J$ is the set of benefit criteria and $J'$ is the set of cost criteria.

(7) **Calculate the separation measures of each alternative from the PIS and NIS points:** The separation measure from the cardinal points is calculated through Minkowski’s $L_p$ metric. The separation measure of the $i$th alternative from the PIS is ($D_i^+$) and from the NIS is ($D_i^-$):

$$D_i^+ = \left( \sum_{j=1}^{n} (v_{ij} - v_{ij}^+)^p \right)^{1/p} \quad D_i^- = \left( \sum_{j=1}^{n} (v_{ij} - v_{ij}^-)^p \right)^{1/p}$$

Here, $p$ is an integer $\geq 1$ and for $p = 2$ the metric is a Euclidean distance.

(8) **Calculate the relative closeness to the ideal solution:** The relative closeness index of the $i$th alternative is calculated from the following expression:

$$C_i^* = \frac{D_i^-}{D_i^+ + D_i^-}$$

(9) **Rank the $p$ reference order:** The ranking of the decision alternatives is performed on the basis of their relative closeness index ($C_i^*$). The alternatives are ranked according to the descending order of $C_i^*$ values.
2.8.2 VIKOR

The VIKOR method was developed to solve MCDM problems with conflicting and incommensurable (different units) criteria, assuming that compromising is acceptable for conflict solution, that the decision maker wants a solution that is the closest to the ideal, and that the alternatives are evaluated according to all the established criteria (Opricovic and Tzeng, 2007).

This technique ranks the alternatives based on two measures: the utility measure (the weighted distance from the ideal solution) and the regret measure (the weighted distance from the negative-ideal solution). The alternative with the least VIKOR index is the best alternative, as it has the maximum group utility and the least regret. This method includes the following steps in which step one and two being the same as the corresponding steps in TOPSIS:

1. Calculate the normalized decision matrix: See step one in TOPSIS
2. Prepare the decision matrix: See step two in TOPSIS
3. Determine the best and the worst values of all the criterion functions: Two cardinal values of each criterion represent the best and the worst values. The association of the best criteria values gives the ideal solution (IS), while the set of all the worst values gives the anti-ideal solution (AIS) (Vahdani et al., 2009). Therefore, IS ($I_k^+$) contains all the highest scores of the benefit criteria and all the lowest scores of the cost criteria. AIS ($I_k^-$) contains all the lowest scores of the benefit criteria and all the highest scores of the cost criteria. The $I_k^+$ and $I_k^-$ of the $k$th expert are:

\[
I_k^+ = \{ r_{kj}^+ | j = 1,2, \ldots, n \} = \{ \max_{i} w_j | i \in J \} \cdot \{ \min_{i} r_{ij}^+ | i \in J \}.
\]

\[
I_k^- = \{ r_{kj}^- | j = 1,2, \ldots, n \} = \{ r_{kj}^- | j \in J \} \cdot \{ \max_{i} w_j | i \in J \}.
\]

where $J$ is the set of benefit criteria and $J'$ is the set of cost criteria.

4. Compute the values of the utility and regret measures: The utility measure ($S_k^+$) of the $k$th alternative is calculated from all the criteria values and their respective weights ($w_j$). The regret measure ($R_k$) of the $k$th alternative gives the most influential criteria and their corresponding values. The values of $S_k^+$ and $R_k$ are calculated using the expressions given below:

\[
S_k^+ = \sum_{j=1}^{n} w_j \times \frac{r_{kj}^+ - r_o^d}{r_o^j - r_o^d}, \quad R_k = \max_{j} \left[ w_j \times \frac{r_{kj}^- - r_o^d}{r_o^j - r_o^d} \right].
\]

The group utility measure ($S_k$) and group regret measure ($R_k$) of an alternative are computed by the aggregation of $K$ experts’ $S_k^+$ and $R_k$ values. The group measures for each alternative are calculated through the geometric mean of all the individual expert’s measures as given below:

\[
S_k = \left( \prod_{k=1}^{K} S_k^+ \right)^{\frac{1}{K}}, \quad R_k = \left( \prod_{k=1}^{K} R_k \right)^{\frac{1}{K}}.
\]

\[1\] ViskeKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) (in Serbian), meaning Multi-criteria Optimization and Compromise Solution, is a compromise decision making method in multi-criteria environments.
5) Compute the VIKOR index \( Q_i \) for the \( i \)th alternative: The VIKOR index \( Q_i \) for the \( i \)th alternative is computed as:

\[
Q_i = v \times \frac{S_i - S^{-}}{S^{+} - S^{-}} + (1 - v) \times \frac{R_i - R^{-}}{R^{+} - R^{-}}
\]

where \( S^{-} = \min_i S_i \cdot S^{+} = \max_i S_i \cdot R^{-} = \min_i R_i \) and \( R^{+} = \max_i R_i \) and \( v \) is a weighting factor of the decision-making strategy. If the decision making is performed on the basis of “consensus”, \( v \) is 0.5, and when the “voting by majority” rule is followed, \( v \) is >0.5. \( v \) is <0.5 when the decision is made with a “veto”. Here the term \( \frac{S_i - S^{-}}{S^{+} - S^{-}} \) is the scaled distance from the ideal solution and measures the overall closeness of alternative \( i \), and the second term \( \frac{R_i - R^{-}}{R^{+} - R^{-}} \) gives the scaled distance for the most influential criteria.

6) Rank the decision alternatives: The ranking of the decision alternatives is carried out by sorting the \( (S_i) \), \( (R_i) \), and \( (Q_i) \) values in increasing order, which results in three ranking lists denoted as \( S[.], R[.], \) and \( Q[.]. \)

2.8.3 The Analytical Hierarchical Process (AHP)

The Analytical Hierarchy Process (AHP) helps the analyst to organize the critical aspects of a problem into a hierarchical structure similar to a family tree (Saaty, 1980). It is based on the pairwise comparison of the importance of attributes instead of actual scores, as comparative importance parallels human logic and makes the participants’ task easier (Chu et al., 2007). By reducing complex decisions to a series of simple comparisons and rankings, then synthesizing the results, AHP helps the analysts to provide a clear rationale for the importance of evaluating criteria.

In principle, it is more difficult to evaluate \( n \) elements (where \( n > 2 \)) simultaneously than to compare two such elements at a time. Hence, AHP employs pairwise comparison, in which experts compare the importance of two factors on a relatively subjective scale. In this way a judgment matrix of importance is built according to the relative importance given by the experts. Each participant generates his own pairwise comparison matrix for each evaluating criterion. As pointed out by Aczel and Saaty (1983), the same pairwise comparison for each expert can be aggregated into a group comparison by taking the geometric mean of all the comparisons. The geometric mean is the only averaging process that maintains the reciprocal relationship \( (a_{ij}=1/a_{ji}) \) in the aggregate matrix. So, the weighted mean value for a group response is:

\[
a_{ij} = \left( \prod_{k=1}^{n} w_k \cdot a_{ij}^k \right)^{1/ \sum_{k=1}^{n} w_k}
\]
where $a^k_i$ is the $k^{th}$ expert’s paired comparison value, $n$ is the number of experts, and $w_k$ is the weight of the $k^{th}$ expert. In this study we have assumed that all the experts have equal expertise in their judgments and therefore $w_k = 1$ for all $k$ experts.

The AHP technique also allows the analyst to evaluate the correctness and the consistency of a given pairwise comparison, by means of an inconsistency ratio. The judgement can be considered acceptable if and only if the inconsistency ratio is less than 0.1 (Saaty, 1980). If the obtained value of consistency ratio is not within the acceptable range, the experts may be asked to modify their judgments in the hope of obtaining a modified and consistent matrix.

Based on Saaty (1980) some of the advantages of AHP are:

- **Unity**: It provides a single, easily understood, flexible model for a wide range of unstructured problems.
- **Complexity**: The AHP integrates the deductive and system approaches in solving complex problems.
- **Hierarchic structuring**: It helps to sort elements of a system into different levels.
- **Synthesis**: It leads to an overall estimate of the desirability of each alternative (criteria).
- **Consistency**: It tracks the logical consistency of judgments used in determining priorities.
- **Trade-offs**: The AHP takes into consideration the relative priorities of factors in a system and enables people to select the best alternative based on their goals.
3 Research methodology

In general the reason for performing research is to find out why things happen as they do (Carey, 1994). To conduct research, a suitable research methodology must be selected. The term research methodology refers to the way in which the problem is approached in order to find an answer to it (Taylor and Bogdan, 1984). Denzin and Lincoln (1994) state that the term research methodology focuses on “the best means for gaining knowledge about the world”. In other words, research is a systematic examination of observed information, performed to find answers to problems. Research methodology is the link between thinking and evidence (Sumser, 2000).

3.1 Research purpose

The ultimate goals of research are to formulate questions and find answers to those questions (Dane, 1990). There are basically three different ways of classifying research, i.e. as exploratory (to explore a new topic), descriptive (to describe a phenomenon), or explanatory (to explain why something occurs) (see Table 3.1 for details).

The exploratory study aims at generating basic knowledge and demonstrating the character of a problem by collecting information through exploration. Exploratory studies are conducted in order to create an understanding of different conditions and events. An explorative study may be used for unstructured research problems which are difficult to delimit (Marshall and Rossman, 1999; Yin, 2003).

A descriptive study is appropriate when the research problem is structured for identifying relations between certain causes. The aim of a descriptive study is to perform empirical generalizations (Marshall and Rossman, 1999).

Explanatory research aims at establishing causal connections between different phenomena (Dane, 1990). An explanatory study may therefore be used to analyze causes and relationships, which together explain a certain phenomenon.

To fulfil the purpose of the present research, a combined exploratory, descriptive, and explanatory approach was chosen. The first research question is related to the above stated motives for approaching research in an exploratory way. An exploratory approach was chosen for this question to generate knowledge and understanding about aircraft maintenance programme development in general and the concept of RCM and MSG-3 more specifically.
The knowledge gained from the explorative approach was used to formulate four sharper research questions and narrow down the purpose.

In addition, a descriptive approach was used to identify the needs, in order to describe how to model the risk associated with the aircraft system’s failure (e.g. Event Tree Analysis and Mean Fractional Dead Time), how to determine the optimum interval for Failure Finding Inspection (FFI) and for a combination of FFI and restoration strategies, and how to select the most effective maintenance strategy which satisfies the overall effectiveness criteria. The descriptive part is also intended to give valuable support to practitioners.

However, the present research also possesses some explanatory characteristics, e.g. regarding the relationships between issues and challenges in maintenance programme development, the comparison of RCM and MSG-3 methodologies, the modelling of aircraft failure’s operational consequences, the assessment of the risks associated with these consequences, the cost-based risk analysis performed to identify the optimum interval and to ascertain the hierarchy of the effectiveness criteria.

3.2 Research approach

One way to classify research is to categorize it as fundamental or applied research, depending upon the kind of knowledge sought about a certain area and the solution intended. Fundamental research aims to widen the knowledge of a particular subject so that future research initiatives may be based on the extended knowledge. This kind of research is designed to solve problems of a theoretical nature, with little direct impact on strategic decisions. Applied research addresses existing problems and opportunities (Cooper and Schindler, 2006).

According to Alvesson and Sköldberg (1994) the research approach may be based on deduction, induction, or abduction. The deductive approach strives to generate hypotheses, which are testable statements, based on existing theory. Deductive research uses general rules and theories to explain a specific case. The deduction approach can be applied to generate hypotheses based on existing theories, the results of which are derived by logical conclusions (Sullivan, 2001). The results of a deductive study are derived by logical conclusions. The induction approach uses observations, a knowledge base, and empirical data to explain and develop theories. Inductive research uses empirical data from many cases to explain and develop theories and general rules. The approach involves inferring something about a whole group or class of objects from our knowledge of one or a few members of the group or class (Sullivan, 2001). The inductive approach is based on empirical data and conclusions are drawn from the experience gained from the study. Abductive research is a combination of the deductive and inductive research approaches. The researcher can start with a deductive approach and make an empirical collection based on a theoretical framework, and then continue with the inductive approach to develop theories based on the previously collected empirical data. During the research process, an understanding of the phenomenon is developed and the theory is adjusted with respect to the new empirical findings (Alvesson and Sköldberg, 1994).

Research may also be divided into research using a qualitative approach and research adopting a quantitative approach. Quantitative information is conveyed by numbers (or more precisely ratio and interval scales) and qualitative information is generally conveyed by words (or more precisely nominal and ordinal scales). In simple terms, quantitative research uses numbers,
counts, and measures of things, whereas qualitative research adopts questioning and verbal analysis (Sullivan, 2001). The quantitative approach emphasizes the measurement and analysis of causal relationships between different variables (Denzin and Lincoln, 1994). The qualitative approach aims at giving an explanation of causal relationships between different events and consequences (Miles and Huberman, 1994).

The problems presented in the present research were defined based on the needs and requirements within commercial aviation. Through discussions, interviews and consultations with experts within manufacturers and air carriers, and based on the knowledge created through an extensive literature study, the research questions were identified, refined, structured and finalized. Consequently, the research objectives associated with the identified problems were defined and verified within an industrial setting. Thereafter, the knowledge gathered was applied to delineate the usefulness and appropriateness of identified decision support methodologies in aircraft maintenance programme development, so as to make a more effective and goal-oriented maintenance programme. The methodologies were developed together with experienced practitioners, who judged the relevance and validity of the proposed methodologies. The practitioners also provided empirical data to enable an exemplification of the adapted methodologies. Some conclusions could be drawn with the support of the empirical data and comparisons could be made with the theory. Hence, the research approach utilized is similar to the abductive approach. In short, this thesis concerns applied research whose purpose is to develop and provide decision support methodologies and tools, for maintenance programme development within the MRB process for systems, to arrive at a more effective maintenance programme.

The research approach of the study presented in this thesis is both qualitative and quantitative. The qualitative approach aimed at exploring drivers, issues and challenges in maintenance programme development and the concepts of methodologies supporting maintenance programme development. Furthermore, the qualitative approach also aimed at describing the different operational risks of failures in aircraft systems. A quantitative approach has been chosen to explore the operational risk of aircraft system failures and to identify the optimum interval for inspection and for a combination of inspection and restoration strategies. In order to identify the most effective maintenance alternatives, a mixture of qualitative and quantitative approaches has been used. For defining the hierarchy of overall effectiveness, a qualitative approach has been used, while a quantitative approach has been selected for ranking the maintenance alternatives.

3.3 Data collection and analysis

In qualitative research, six sources of evidence are typically used for gathering information: documentation, archival records, interviews, direct observations, participant-observation and physical artefacts (Marshall and Rossman, 1999; Yin, 2003). The strengths and weaknesses of these methodologies are tabulated in Table 3.2.

Data may also be divided into primary and secondary data. Data collected by the researcher for the purpose of the study are called primary data. Data already collected by other people and used by the researcher are called secondary data (Dahmström, 1996). One advantage of secondary data is that they may be an easy and cheap way of receiving information. Some disadvantages are that it may be difficult to find relevant material and to assess the quality and usefulness of secondary data. As a related consequence, the reliability of the research may also
be difficult to evaluate when using secondary data. It is important that every investigation should have a general analytic strategy to guide the decisions regarding what will be analyzed and the reason for analyzing it. Data analysis includes aspects of: examining, categorizing, tabulating, or recombining the evidence to address the propositions of a study (Yin, 2003).

Table 3.2 The selection of appropriate data collection methodologies for different research situations (Yin, 2003).

<table>
<thead>
<tr>
<th>Source of Evidence</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Documentation</td>
<td>- Stable – can be reviewed repeatedly</td>
<td>- Retrievability – may be low</td>
</tr>
<tr>
<td></td>
<td>- Unobtrusive – not created as a result of the case study</td>
<td>- Biased selectivity, if collection is incomplete</td>
</tr>
<tr>
<td></td>
<td>- Exact - contains exact names, references, and details of an event</td>
<td>- Reporting bias - reflects (unknown) bias of author</td>
</tr>
<tr>
<td></td>
<td>- Broad coverage – long span of time, many events, and many settings</td>
<td>- Access - may be deliberately blocked</td>
</tr>
<tr>
<td>Archival Records</td>
<td>- Same as above for documentation</td>
<td>- Same as above for documentation</td>
</tr>
<tr>
<td></td>
<td>- Precise and quantitative</td>
<td>- Accessibility due to privacy reasons</td>
</tr>
<tr>
<td>Interviews</td>
<td>- Targeted – focus directly on case study topic</td>
<td>- Bias due to poorly constructed questions</td>
</tr>
<tr>
<td></td>
<td>- Insightful – provide perceived causal inference</td>
<td>- Response bias</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Inaccuracies due to poor recall</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Reflexivity - interviews give what interviewer wants to hear</td>
</tr>
<tr>
<td>Direct Observations</td>
<td>- Reality – cover events in real time</td>
<td>- Time-consuming</td>
</tr>
<tr>
<td></td>
<td>- Contextual – cover context of event</td>
<td>- Selectivity – unless broad coverage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Reflexivity – events may proceed differently because they are being observed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Cost – hours needed by human observers</td>
</tr>
<tr>
<td>Participant-Observations</td>
<td>- Same as above for direct observations</td>
<td>- Same as above for direct observations</td>
</tr>
<tr>
<td></td>
<td>- Insightful into interpersonal behaviour and motives</td>
<td>- Bias due to investigator's manipulation of events</td>
</tr>
<tr>
<td>Physical Artefacts</td>
<td>- Insightful into cultural features</td>
<td>- Selectivity</td>
</tr>
<tr>
<td></td>
<td>- Insightful into technical operations</td>
<td>- Availability</td>
</tr>
</tbody>
</table>

3.4 Applied data collection and analysis

Two main types of data were collected in the present study, i.e. theoretical and empirical data. Theoretical data were collected to deal with all five research questions. Empirical data were
mainly collected in relation to research questions two to five, but to some extent also in relation to research question one.

Theoretical data were collected from different databases and scientific journals. First of all appropriate books were identified through LIBRIS (the national Swedish library data system). The database contains more than four million titles representing the holdings of about 300 Swedish libraries, mainly research libraries, including foreign literature.

Other databases were also used to search for documents and research papers, e.g. Scopus, Compendex, Scirus, Science Citation Index, Emerald, and Elsevier Science Direct. Different keywords were formulated, such as: Reliability-Centred Maintenance (RCM), MSG-3, maintenance programme, and operational consequences. These keywords were used in different combinations to search in the different databases, resulting in a large number of hits.

In order to find relevant data, all the titles were read and compared to the purpose of the study. This reduced the data of the material collected from the databases. Secondly, the abstracts of the remaining material were read carefully, which further reduced the material. Finally, the remaining full articles were read. The data collection approach used for databases is illustrated in Figure 3.1.

![Figure 3.1 The data collection approach used for searching in different databases. The arrows represent the steps taken to reduce the amount of information, and to find relevant information.](image)

Empirical data were collected using four different approaches: archival records, interviews, observations and documents. The archival records consisted of databases containing descriptions, experienced consequences of failures, and historical data.

The interviews and observations were conducted by selecting objects representing a major part of the aviation sector, including airlines, Maintenance Repair Organizations (MROs), authorities, and manufacturers. The interviews were performed with experienced practitioners at both aircraft manufacturers and airlines. The documentation consisted of different descriptions, policies, and procedures pertaining to maintenance programme development, failure consequence categories, and MRB procedures, as well as documents supporting maintenance programme development (e.g. standards).

As a basis for the interviews, both the outcomes from the literature studies and the author’s pre-understanding of problems related to maintenance programme development guided the different areas of discussion. During the informal interviews, only short notes were taken. The
interviews that were considered vital for this study were verified with the interviewed personnel through an iterative interview process and using the developed documents that acted as guidance during the interviews, e.g. the constructed event tree and hierarchy of the effectiveness of evaluating criteria. Furthermore, the involved practitioners actively took part in the enhancement of the proposed methodologies, e.g. by discussing, reading and making comments, and providing valuable and applicable documents and data. The practitioners were mostly involved in one of the biggest aircraft manufacturing projects in the world.

In addition, a survey was performed in order to test the applicability of the proposed MCDM approach for implementing a rigorous approach for maintenance task selection by extracting expert judgments, and for estimating the operational risk of an aircraft system’s failure.

Expert judgment was used as a qualitative assessment tool to find out the relative importance of the evaluating criteria for the overall effectiveness of maintenance tasks, and in this connection the Analytical Hierarchical Process (AHP) was used. Moreover, the benefit-cost ration, TOPSIS and VIKOR methodologies were used to rank each alternative maintenance strategy after due consideration of the positive and negative consequences of choosing any one of the strategies from the standpoint of various evaluating criteria.

A pre-study was performed through interviewing experts from one manufacturer and two airlines, and by sending the draft survey and questionnaire to three experts individually, to obtain some suggestions for improvement. Thereafter, a suitable team of experts working at different positions at the manufacturer and airlines was invited to assess the finalized questionnaire. When selecting the experts, emphasis was placed on the experience of the participants.

3.5 Reliability and validity

The reliability of a study demonstrates the extent to which the operations of the study, such as the data collection procedures, can be repeated by somebody else with the same results. High reliability may be seen as the absence of errors and biases in the study. With high reliability, it is possible for another researcher to arrive at the same results on condition that the same methodology is used. One condition for high reliability is that the methodology used for data collection is clearly described (Yin, 2003). In order to affect the reliability positively, the data collection and classification methodology has been described in the four appended papers and this chapter. Furthermore, the theoretical concepts used as support in the different studies are explained in each paper. These concepts serve as a basis for the pre-understanding of the different areas and are presented to guide other researchers. In addition, the analysis approach is described in each paper and the thesis in order to guide other researchers.

The validity of a study concerns whether the study investigates the phenomenon of interest or not. One approach to strengthening the validity is called triangulation, whereby multiple methodologies are applied for data collection (Yin, 2003). According to Neuman (2003) reliability is necessary for validity and is easier to achieve than validity. Although reliability is necessary in order to have a valid measure of a concept, it does not guarantee that a measure will be valid. It is not a sufficient condition for validity. Figure 3.2 illustrates the relationship between the concepts by using the analogy of a target.
In order to increase the reliability of this work the procedures and results related to conducted activities have been documented by the use of available information sources such as hard copy and digital databases. However, some of the data used in this research are confidential and classified, which limits the accessibility and repeatability for other researchers.

The reliability and validity of the work performed within this study were also continuously monitored and reviewed. The review was both internal by the research group at the Division of Operation and Maintenance Engineering at LTU, and external through regular presentation of the study progress and reports to the industrial partner.

In this study, the data and information have been collected either from peer-reviewed journals, refereed conference proceedings and reports or from company databases, which positively contributes to the research’s reliability and validity. Well-established models for reliability analysis of repairable items, as well as well-established multi-criteria decision making techniques, have been applied through organized and controlled approaches in different case studies, which also contribute positively to the reliability and validity of the research.

In this study, the theoretical findings have been verified through interviews with experienced practitioners and through some documents from their companies. In addition, colleagues of the author at Luleå University of Technology have given comments on the research design and worked with the appended papers at seminars, which strengthens the verification. The quality of the performed research work has also been judged by reviewers of scientific journals.

The aviation industry is highly regulated and an extensive process is required in order to apply any changes to the existing procedures and adopt new methodologies. Consequently, it would be time-consuming, to validate the findings of this research work. Hence, there is a need for further research activities in order to validate the results of this research.

### 3.6 The research process

An overview of the research process which was used to develop the proposed methodologies is presented in Figure 3.3. The different steps in the research process are described and discussed in the following.
Phase 1. Defining the research problems: The problems dealt with in the applied research documented in this thesis, were formulated in cooperation with two major European aircraft manufacturers. This contributed to understand what is needed in practice and what the requirements of usefulness are. Moreover, in order to address the research problem, the background and experience of the researcher with regard to the research domain were used. In this step, a preliminary literature study was performed to answer research question one, which relates to the issues, challenges, and potential areas of improvement in maintenance programme development within the MRB process, as well as risk analysis in general. The outcome of this literature study resulted in the formulation of four sharpened research questions (i.e. research questions two to five) and a sharpened research purpose. Thereafter, a tentative research methodology was constructed. The outcome of this phase is mainly summarized in the introduction of this thesis.

Phase 2. Specifying the research purpose: The stated research purpose was formulated according to the stated research problem and based on the stated requests of the manufacturers engaged in the study. Since there were interactions between the various steps, the research purpose was modified as new ideas and good reasoning were presented through other steps. Hence, the purpose of the research was not fixed but open to revision, and was subjected to continuous improvement.

Phase 3. Specifying the limitation and constraint conditions: Based on the available resources (such as time), and according to the research purpose, objectives and industrial interests, the scope and limitation of this study were defined. Based on the empirical
evidence, the research literature and some rational and logical reasoning gained from the other steps of the research, the limitation, and constraint conditions were changed.

**Phase 4. Identification of the alternative methodologies:** This step dealt with the need for further investigation of the alternative methodologies which were applicable to addressing the problems associated with the operational risk of failures, optimal maintenance interval assignment, and selection of the most effective maintenance task, and which were identified in the first and second steps. Creating appropriate alternative methodologies was a creative and explorative process that included considering the consequences of the various methodology choices.

**Phase 5. Construction of the methodology of our choice:** A further literature study related to the operational consequences of aircraft systems’ failures, risk analysis, expert judgments, and Multi-Criteria Decision Making methodologies was performed. In this stage, methodologies for event tree-based scenario development, a Cost Rate Function, and a survey were developed. The aim was to strive to develop the methodologies that would address the associated research questions and fulfil the purpose and objectives of the study according to the limitation and scope.

**Phase 6. Verification of the proposed methodology:** The aim of this step was to obtain an idea of the applicability, feasibility and effectiveness of the proposed methodology. The verification step was conducted with the collaboration of experts from both aircraft manufacturers and air carriers through an iterative process, by matching the developed methodologies to specific cases (hypothetical and real systems) on a small-scale. In addition, colleagues of the author at Luleå University of Technology gave comments on the research design and worked with the appended papers at seminars, which strengthens the verification.

**Phase 7. Evaluation of the proposed methodology:** In this process the weaknesses and gaps of the methodologies were identified through interviews with experienced practitioners, together with some documents from their companies, which contributed to improving the proposed methodologies. From these evaluations, conclusions were drawn regarding the applicability and effectiveness of the proposed methodologies in practice. This step played an important role for the continuous process of improving the proposed methodologies.

**Phase 8. Application of the proposed methodology:** Based on the evaluation phase, the suggested improvements were applied and the improved methodology was verified again to assure its applicability and effectiveness.
4 Summary of appended papers

This chapter provides a summary of the four appended papers in the thesis, and describes the contribution towards the research questions (see Table 4.1). Further information can be found in the appended papers.

<table>
<thead>
<tr>
<th>RQ 1</th>
<th>What are the potential areas of improvement in the scheduled maintenance development process using the MSG-3 methodology?</th>
<th>Paper I</th>
<th>Paper II</th>
<th>Paper III</th>
<th>Paper IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQ 2</td>
<td>How can the risk of an aircraft system’s failure be assessed?</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>RQ 3</td>
<td>How to determine the optimum Failure Finding Inspection interval?</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RQ 4</td>
<td>How to identify an optimum interval for a combination of Failure Finding Inspection and restoration tasks?</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RQ 5</td>
<td>How to select the most effective maintenance strategy?</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.1 Paper I


The purpose of this paper is to present issues and challenges of maintenance task development within the Maintenance Review Board (MRB) process and to find potential areas of improvement in the application of the MSG-3 methodology for aircraft systems.

The study is based on a constructive review that consists of two parts. The first part is a benchmarking between MSG-3 and other established and documented versions of RCM. The second part includes a discussion about methodologies and tools that can support different steps of the MSG-3 methodology within the framework of the MRB process.

The paper highlights the differences in approach between MSG-3 and RCM for scheduled maintenance programme development. The MSG-3 approach is closely related to the RCM...
methodology. The major difference between these two methodologies concerns the treatment of risk. For example, SAE RCM requires a consideration of both the consequences and the likelihood of failure in the identification of MSIs, while MSG-3 just considers the anticipated failure consequences. Furthermore, although the term “risk” is used within MSG-3 to address the applicability and effectiveness criteria, the risk treatment is not visible in the process and does not clearly indicate the acceptable level of risk. Another difference compared with SAE RCM, is that MSG-3 does not consider the environmental consequences of failures, and does not consider any operational consequences of hidden failures. Yet another difference compared with SAE RCM, is that MSG-3 does not consider the environmental consequences of failures, and does not consider any operational consequences of hidden failures. Yet another difference compared with SAE RCM, is that MSG-3 does not consider the environmental consequences of failures, and does not consider any operational consequences of hidden failures. Yet another difference compared with SAE RCM, is that MSG-3 does not consider the environmental consequences of failures, and does not consider any operational consequences of hidden failures. Yet another difference compared with SAE RCM, is that MSG-3 does not consider the environmental consequences of failures, and does not consider any operational consequences of hidden failures. Yet another difference compared with SAE RCM, is that MSG-3 does not consider the environmental consequences of failures, and does not consider any operational consequences of hidden failures. Moreover, in MSG-3 an “operational check” (i.e. failure -finding inspection) has priority over all other maintenance strategies. However, in every other RCM-documentation, an “operational check” is considered as a default action when other maintenance strategies are not applicable and effective. To this end, one potential area of improvement has been found as modifying the decision diagram to fulfill the fundamental assumptions of the task hierarchy, and the requirements of cost effectiveness.

Moreover, decisions regarding maintenance task development are mainly based on the logic of the Maintenance Steering Group (MSG-3) methodology and the analysts rely on experience of similar aircraft. In fact, the MSG-3 methodology provides a practical and structured approach to design a recommended scheduled maintenance programme which fulfils continued airworthiness requirements. However, from an air carrier’s point of view, there is no scientific foundation to justify that the maintenance programme derived from this approach is optimal, the most effective one, or business-oriented. Since the decisions that are made during the development of an initial scheduled maintenance programme strongly affect the aircraft’s safety, availability performance, and lifecycle cost, it is essential to acquire new supporting methodologies and refine the current use of expertise on the use of MSG-3, to increase the consistency of maintenance decisions. The major challenge when striving to achieve a more effective maintenance programme within the MRB process is to acquire supporting methodologies and tools for adequate risk analysis, for optimal interval assignments, and for selection of the most effective maintenance task.

4.2 Paper II


The purpose of this paper is to propose a systematic methodology guided by the application of an Event Tree Analysis (ETA) for identification and quantification of the different operational risks caused by aircraft system failures, to support decision making for maintenance task development.

The paper is based on empirical studies of possible scenarios of aircraft failure and deals with operational consequences in a commercial airline. Empirical data were extracted through document studies and interviews, guided by the application of an ETA. The analysis was performed together with experienced practitioners from both an aircraft manufacturer and a
number of commercial airlines. This contributed to a continuous verification of the outcomes of
the study.

The paper suggests a definition of operational consequences of failures in aircraft operation and
discusses different impacts of failure on the ground and in the air. It was found that the ultimate
state of the operational situation and the consequence of failure can be determined by four
criteria: 1) the phase of flight where the failure occurs, 2) the deferrability of failure, 3) whether
some sort of operational restriction is needed, or 4) whether the application of emergency or
abnormal procedures is required. Based on the possible combinations of events, 25 different
scenarios were identified which ultimately will lead to one or a combination of the following
classes of consequences: no operational consequence, airborne and/or ground delays, and
emergency or abnormal operation. Moreover, a methodology for estimating the associated cost
of consequences is explored. The application of the proposed event tree has been verified
through a case study on a hypothetical engine driven hydraulic pump of an aircraft hydraulic
system.

The constructed event tree provides an effective way to identify the operational risks of failures.
The results of this assessment can be used to determine the need for a failure management
strategy and, the amount of assessed risk provides a means to assess the intensity and type of
the maintenance action or to implement other actions, to make maintenance viable and
effective.

4.3 Paper III

Alireza, A. and Kumar, U. (2010), Cost-based risk analysis to identify inspection and
restoration intervals of hidden failures subject to aging. Accepted for publication in: IEEE
Transactions on Reliability.

The purpose of this paper is to develop a Cost Rate Function (CRF) model and graphical tools
to identify the optimum maintenance interval and frequencies for an aircraft’s repairable items
which are experiencing aging and whose failures are hidden.

The paper considers the two prevalent strategies, i.e. Failure Finding Inspection (FFI) and a
combination of FFI with restoration actions for both the non-safety effect and the safety effect
categories of hidden failures. The proposed CRF is simulated for different reliability and cost
parameters, to identify the optimum maintenance interval and frequencies for the two
strategies. Limiting values have been determined for the cases where the inspection interval, T,
and the number of inspection cycles, N, tend to infinity, and also when there are no undesired
consequences of failure, i.e. when the cost of an accident is equal to zero (CA,φ=0).

To facilitate the identification of the optimum inspection interval, an approximation formula
has been derived based on Vaurio’s (1997) approach, and the accuracy of approximation of that
approach has also been checked in that context. The deriving factors in the formula include the
time horizon or the operating time expected from the equipment, the cost of inspection and
downtime due to the inspection, the cost of an accident, and reliability factors. It has been found
that, while an increase in the accident cost tends to result in a lower interval, increasing the
inspection and downtime cost tends to result in higher intervals. Moreover, it has been noticed
that, while increased aging tends to lead to a lower interval, a higher scale parameter (α) tends
to lead to a higher interval.
The interval unavailability behaviour and Mean Fractional Dead Time (MFDT) are discussed for cases where the item is undergoing aging. A graphical tool has been introduced for maintenance task interval assignment and selection of the optimal strategy for the non-safety effect and the safety effect categories of hidden failure (i.e., with and without risk constraint). In the case of an operational limitation, when it is not possible to remove the item for restoration (when the item is aging), it has been shown that, by reducing the inspection interval, it is possible to postpone the inspection for a limited time, but with a higher cost.

The study shows that, depending on the failure data and cost parameters, a mixture of failure finding and restoration actions not only is effective in satisfying the risk limits, but may also lead to a more cost-effective solution than FFI alone. Hence, it would be beneficial to consider a combination of maintenance tasks during the formal maintenance task development, even for the non-safety effect category of hidden failure. In summary, the incorporation of an analytical methodology and supporting graphical tools has the potential to increase the accuracy of the maintenance decisions and make it possible to design a more effective maintenance task. This approach not only fulfils the airworthiness requirements, but also supports the decision making in identification of the most cost effective maintenance task.

4.4 Paper IV


The paper proposes a methodology for selection of the most effective maintenance strategy for non-safety category of failures in aircraft systems, using a combination of Multi-Criteria Decision Making (MCDM) methodologies.

The proposed decision making methodology includes two levels, i.e. the managerial level and the engineering level. The managerial level experts define the goals and the associated evaluating criteria, and also perform the pairwise comparison to assign the importance of the evaluating criteria. The AHP methodology is used to evaluate the importance of the appraisal criteria of a maintenance strategy. The engineering level experts select a failure mode, define applicable maintenance strategies, and assesses the effectiveness of each strategy after due consideration of the positive and negative consequences of choosing any one of the maintenance alternatives, according to the defined evaluating criteria. At this level the analyst performs a multi-criteria ranking of the alternatives using three methodologies, i.e. benefit-cost ratio, TOPSIS and VIKOR.

The proposed methodology provides a basis for consideration of three governing factors in decision making, which are “the rate of return”, “the total profit” or “the lowest investment”. When the preference is the rate of return, the benefit-cost ratio is suggested. For the total profit TOPSIS is applied. In cases where the manager has specific preferences, VIKOR can be adopted. The proposed methodology has been tested through a case study within the aviation context for an aircraft system. The alternative maintenance strategies considered in the paper include those offered by ATA MSG-3, but also the use of Prognostics and Health Management (PHM) provisions. The list of evaluating attributes was decided in consensus with field experts.
The results of the benefit-cost analysis show that the maintenance alternative “incorporation of PHM” has the maximum benefit-cost ratio, followed by the alternative “functional check”. The results of the TOPSIS analysis indicate that the maintenance alternative “incorporation of PHM” is the overwhelming choice, as indicated by the highest relative closeness value. The VIKOR index also ranks the alternative “incorporation of PHM” first, followed by “functional check”. The results of the three methodologies show that the alternative “incorporation of PHM” is found to be the most favourable choice, followed by “functional check”.

The study shows that using the proposed combination of the AHP, TOPSIS, and VIKOR methodologies is an applicable and effective way to implement a rigorous approach for identifying the most effective maintenance alternative.
5 Discussion and conclusions

This chapter discusses and draws conclusions from the results of the conducted research work. The structure of the chapter is based on the stated research objectives.

5.1 Potential areas of improvement in the scheduled maintenance development process

The first objective of the study has been stated as “Identify the potential areas of improvement in the maintenance programme development process”. This objective is linked with the first research question and is fulfilled mainly by the research presented in Paper I, and partly in Papers II, III and IV.

In Paper I, it has been found that, while MSG-3 is closely related to RCM, there are, however, some differences in their approach for analyzing maintenance tasks. One difference concerns their approach to analyzing the risk of failure. While SAE-JA1011 requires consideration of both the consequences and the likelihood of failures in the identification of Maintenance-Significant Items (MSIs), MSG-3 just considers the anticipated consequences of failure. The latter methodology of selecting MSIs does not consider the severity of the consequences on a more detailed level or the frequency of occurrence. Hence, this is a quick, but still conservative, collective engineering judgment process and not a complete risk-based assessment. The problem here is whether an item whose failure is unlikely to occur or an item whose risk of failure is already at an acceptable level should really be considered primarily as an MSI. In practice failure data about safety-critical systems do not exist specifically during the initial maintenance development. Hence, the decision defaults on the side of caution. Therefore, even unlikely failures should be prevented, due to the severity of even one failure, in order to fulfil the requirements of continued airworthiness made mandatory by authorities. This level of conservatism would be acceptable for the safety effect category of failures. However, it might not be applicable for the non-safety category of failures. In fact, the incorporation of appropriate methodologies and tools from the area of risk management and for elicitation of expert judgments provide a reasonably good basis for performing criticality analysis (see Paper I). Assessment of the need for a maintenance strategy should actually be based on risk assessment, which provides a basis for evaluating the effectiveness of the selected maintenance strategy. Moreover, risk assessment presents a basis for assessing how well a maintenance task can reduce the risk of failure to an acceptable level. Therefore, it can be concluded that incorporation of the risk approach as part of the MSG-3 core concept is vital to arrive at an effective maintenance programme.

Another difference is that MSG-3 does not consider the environmental consequences of failures, while other RCM-related standards take them into consideration, except for the original RCM publication provided by Nowlan and Heap (1978). The environmental issues relating to aircraft include air pollution (i.e. CO2 emission and fuel consumption) and noise pollution (i.e. aerodynamic noise, engine and other mechanical noise, and noise from aircraft systems). Both types of pollution are controlled and reduced by design efforts and regulation, rather than maintenance efforts. Moreover, there are tasks that are covered by national or international Advisory Circulars issued to control the level of pollution. Regarding the material release to the environment, i.e. the release of fuel and hydraulic fluid, these are considered primarily as a safety issue rather than an environmental issue. Moreover, there are strict design rules, which assure the prevention of leakage from couplings and attachments.
However, an adjustment may also be beneficial to address environmental problems, whenever this is applicable.

Moreover, MSG-3 does not consider any operational consequences of hidden failures. It should be mentioned that hidden failures within MSG-3 are analyzed as parts of multiple failures, and such failures on their own do not have any consequences. Here the aim of preventive maintenance is to assure the availability of hidden function necessary to avoid the effects of multiple failures on safety, operation, or economy. One can question why a multiple failure cannot have any operational effect within the MSG-3 framework. This is an area that needs to be clarified. Furthermore, MSG-3 does not take into account the effects of failure on operation costs (such as increased fuel consumption, and loss of the opportunity to use the maximum capacity of the aircraft as planned (see Paper II). Considering these costs is highly important from business point of view.

Yet another difference between MSG-3 and RCM arises in the priority given to the maintenance tasks. In MSG-3 the maintenance task “operational check” (i.e. failure finding inspection) has the highest priority over all the other maintenance strategies. In all other studied RCM-related standards, the “operational check”, i.e. failure finding inspection, is considered as a default action, carried out when other maintenance strategies (i.e. a functional check, restoration, and discard) are not applicable and effective in controlling the risk of multiple failures. In fact, the two key assumptions that form the preference hierarchy for failure management policies are that some policies are inherently more cost-effective than others and some are inherently more conservative than others. However, selecting the operational check as the first priority in the MSG-3 decision diagram does not seem to be consistent with these two assumptions. Hence, this may lead to selection of a less effective maintenance strategy among other applicable ones.

It has also been found that the MSG-3 methodology itself applies some restrictions which reduce the consistency of the maintenance task effectiveness analysis. For example, MSG-3 does not allow any cost-effectiveness analysis for failures with operational effects, and requires that the task should reduce the risk of failure to an acceptable level. Moreover, there is also an inconsistency concerning the strategies included in the decision diagram and the description of the MSG-3 process. While the “no scheduled maintenance” strategy is referred to in the document in the statement “no maintenance task is selected”, as a default strategy for failures with non-safety consequences, it is not included in the decision diagram.

Furthermore, the strategy of “combination of maintenance tasks” is considered as a pending redesign. In Paper III, it has been shown that depending on the failure data and cost parameters, in some cases the combination of Failure Finding Inspection (FFI) and restoration action, not only is effective in satisfying the risk limits, but may also lead to a more cost-effective solution than FFI alone. Hence it can be concluded that the use of a combination of tasks has potential to be used even for the non-safety effect category of hidden failure. In order to use the full capacity of all types of maintenance strategies, a rigorous approach in selection of maintenance task is suggested instead of decision diagram approach (see Paper IV). Hence, one potential area of improvement has been found as modifying the decision diagram to fulfil the fundamental assumptions of the task hierarchy, and the requirements of cost effectiveness.

The decision diagram is a tool that assists the analyst in selecting one of the applicable maintenance strategies. However, the analysis of maintenance tasks also needs to identify the
frequencies and intervals of task implementation. This requires adequate knowledge of the failure mechanisms, reliability methodologies and tools, and the utilization of modelling as a methodology for identifying the optimum frequency and interval. The current approach of assigning an interval for a selected maintenance task is mostly based on predefined intervals in the form of checks denoted by alphanumerical codes. In this process, the determination of the maintenance tasks’ intervals mainly relies on engineering experience, and the analysts who are engaged in the MRB process consult the experience gained from similar aircraft.

Obviously, without quantitative modelling support, the decisions made for maintenance task interval assignments are subjective and experience-based, which generally leads to conservative engineering judgments. The extreme formality of this process may lead to a higher maintenance frequency, which ultimately affects the aircraft availability performance and economy. Moreover, the role of maintenance is to sustain the aircraft operation, at the lowest possible cost. Therefore, it is vital to consider the costs associated with aircraft downtime due to maintenance, such as the cost of the aircraft’s lost production, in designing scheduled maintenance tasks and their intervals (see Paper III). The development of appropriate methodologies and supporting tools will enhance the current use of expertise on the use of MSG-3, which will increase the consistency and accuracy of maintenance decisions.

Hence, other potential areas of improvement are the introduction of supporting methodologies and tools for making correct and effective decisions on assigning an appropriate maintenance interval, and for selection of the most applicable maintenance alternative among applicable ones.

5.2 Systematic methodologies to support assessment of the risk of failures in aircraft systems

The second objective of this study was “to propose systematic methodologies that support assessment of the risk of failures in aircraft systems”. This objective is linked with the second research question and is fulfilled by the research presented in Papers II and III.

Paper II deals with the assessment of the operational risk of an aircraft system’s failures. An assessment of the operational risk of failures is needed to support decision making regarding maintenance investment as a risk reduction measure, for failures with operational consequences. Hence, in order to assess the effectiveness of the maintenance task, it should be possible to assess how well the maintenance task reduces the operational risk of failure. The fundamental step in developing a proper methodology is to clarify the definition of a failure with operational consequences. The paper suggests a definition for a failure with operational consequences as: a failure that might reduce the operating capability of the aircraft to meet the required functionality and performance requirements in the application in which the aircraft is operated.

Within the study, it was noted that the operational consequence of failures depends on the extent to which the failure affects the operating capability. It was also found that the ultimate state of the operational situation and the consequence of failure can be determined by four criteria: 1) the phase of flight where the failure occurs, 2) the deferrability of failure, 3) whether some sort of operational restriction is needed, and 4) whether the application of emergency or abnormal procedures is required (see Paper II).
In order to illustrate the integration and correlation of the parameters related to the operational risk of aircraft failure, Event Tree Analysis (ETA) was chosen as an appropriate methodology. The reason is that ETA can be applied to illustrate combinations of events (i.e. scenarios), gives a detailed picture of the possible operational consequences, and can be used for qualitative and quantitative consequence analyses (see Paper II). By using a qualitative approach, it was shown in Paper II how the combination of different events will create different scenarios, which in turn will determine the ultimate operational consequences. Based on the possible combinations of events, 25 different scenarios were identified which ultimately will lead to one or a combination of the following classes of consequences: no operational consequence, airborne and/or ground delays, and emergency or abnormal operation.

Out of the 25 different scenarios that were identified, there are six scenarios with no operational consequences. One of these scenarios is when a failure never occurs. The other five scenarios in which no operational consequences occur are when the failure’s associated maintenance is deferrable and there are no necessary operational or abnormal restrictions. There are also 14 event scenarios where the consequences are some sort of delay. Out of these, there are five scenarios where the operational consequences are manifested as only airborne delay. These five scenarios concern the occurrence of a failure that is related to deferrable maintenance, but requires some operational restrictions. It has to be noted that, in this study, the effect of failure which ultimately leads to increased fuel consumption or a lost opportunity to use the normal capacity of the aircraft as planned has not been taken into account. Hence, these consequences are not included among the ultimate consequences. However, for implementation of the proposed methodology, one could include these consequences without any major changes in the proposed methodology. Abnormal procedures resulting from operational consequences have also been found in four scenarios. All these scenarios concern failures with non-deferrable maintenance that have some sort of significant operational restrictions, and require emergency and abnormal procedures to be initiated by the flight crew.

In order to implement the proposed ETA-methodology and achieve valuable results, sufficient accurate data and information are needed as input to the analysis. This information mainly relates to the failure rate and the probability of occurrence of each event. Moreover, enough knowledge of the maintainability performances of the analyzed system, such as the Built-In Test (BIT) capability of the system, is essential. Other information that is needed concerns the aircraft operation and associated procedures and is given in formal documents such as the Minimum Equipment List, Flight Manual, Flight Crew Operating Manual, and Quick Reference Handbook (see Paper II). Furthermore, information about the maintenance support performance is necessary. Therefore, both the available data and the knowledge of the analyst who is implementing this methodology play an important role in achieving accurate results. This methodology can also be modified to be used for the safety effect category of failures.

Paper III discusses the interval unavailability behaviour and the Mean Fractional Dead Time (MFDT) of a hidden function, within inspection intervals when the item is experiencing aging. These assist in identification of the risk of a multiple failure. In the case of hidden failures with safety consequences, a maintenance task should reduce the risk of multiple failures to assure safe operation. A multiple failure is defined as “a combination of a hidden failure and a second failure or a demand that makes the hidden failure evident”. Since a demand occurs at random, it is essential that the item should be operative, i.e. available, upon demand. Hence, depending on the criticality and consequences of multiple failures and the demand rate, a specific level of availability of the hidden function is needed. Obviously, the probability of a
multiple failure can be reduced by reducing the unavailability of the hidden function. In order to define an effective Failure Finding Inspection (FFI) task to manage hidden failures, it is vital to identify how well a task with a defined interval reduces the unavailability of a hidden function to an acceptable level.

However, one conclusion is that, when there is aging, there is a positive correlation between the MFDT and the inspection interval. In fact, a larger inspection interval results in a higher MFDT. On the other hand, by assigning a higher inspection interval, the interval unavailability increases faster than with a lower inspection interval. Another conclusion is that the average interval unavailability increases in subsequent inspection cycles; i.e. the probability of multiple failure increases with the utilization time. Hence, it can also be concluded that the interval of an FFI plays a vital role for the degree of task effectiveness. This approach based on the MFDT is used in Paper III, for risk constraint optimization. The study shows that when the FFI strategy cannot satisfy the risk limits or when the associated costs are high, a strategy that combines FFI and restoration can be used to satisfy the risk limit and cost requirement.

Moreover, graphical tools based on the Mean Fractional Dead Time (MFDT), have been introduced in Paper III to identify the extent to which it is possible to postpone the discard or restoration of an item. In fact, due to operational restrictions, or a lack of resources, sometimes the operators cannot ground the aircraft and discard or restore an item as scheduled. In these cases, the operators are willing to postpone the discard or restoration task to the earliest possible opportunity so that their operation will not be affected. The postponement of a maintenance task for the non-safety effect type of hidden failure should be based on the economic consequences; whereas for hidden failures with safety consequences, the operator needs to provide adequate proof of safe operation for the authority concerned. It can be concluded that, by an adequate reduction in the FFI interval, it is possible to decrease the risk of multiple failure and postpone the discard or restoration of an item for a limited time, but at an increased cost (see Fig. 15 in Paper III).

5.3 A methodology for assignment of optimal inspection and restoration intervals

The third objective of this study was “to propose an appropriate methodology for identifying the optimum inspection and restoration intervals for both the non-safety and the safety effect category of hidden failures”. This objective is linked with the third and fourth research questions and is fulfilled by the research presented in Paper III.

In Paper III, a Cost Rate Function (CRF) is introduced to identify the optimum maintenance interval and frequencies for the two prevalent strategies, i.e. Failure Finding Inspection (FFI) and a combination of FFI and restoration actions, for both the non-safety effect and the safety effect categories of hidden failures.

In Paper III, As-Bad-As-Old (ABAO) inspection effectiveness and As-Good-As-New (AGAN) restoration effectiveness are considered. In the case of repair due to inspection findings, ABAO repair effectiveness is considered. Hence, after inspection and repair the item is returned to ABAO state. In fact, a repair resulting from findings during an inspection is a partial repair, and mostly concerns adjusting, lubricating or cleaning the item. Hence, the repair work performed on a failed item may be imperfect. The reason is that treating the parts of an item that are wearing out provides only a small additional capability for further operation, and does not renew the item or system. Therefore, in these cases the time periods
between successive failures are not necessarily independent. Moreover, in the initial maintenance development, the analyst uses previous experience of other similar equipment and aircraft, and the imperfect repair assumption is more rational and conservative since exact operational data on new items is not available. This conservative approach also addresses the requirements of the authority concerned.

Through simulation of the CRF, it has been found that, when there is aging and when the FFI strategy is used, the CRF is an increasing function of the number of inspection cycles, whereas, under the strategy of combining FFI and restoration actions, there are always a specific number of inspections (K) and a specific inspection interval (T) that result in an absolute minimum value of the CRF. The study shows that, depending on the failure data and cost parameters, in some cases a mixture of failure finding and restoration actions may be more cost-effective than FFI alone.

Limiting values have been determined for the cases where the inspection interval, T, and the number of inspection cycles, N, tend to infinity, considering different cost and reliability parameters. These values give the analysts an idea of the cost per unit of time in the long run, i.e. for the whole operational life of an item (see Paper III). It has also been found that, when the inspection interval tends to infinity (T→∞), the CRF limit will be equal to the cost of an accident, i.e. CA·φ. Another result is that, when there are no undesired consequences (i.e. CA·φ =0), the bigger inspection interval generates a lower CRF. On the other word, “run to failure” or “no scheduled FFI” is the best maintenance task option.

To facilitate the identification of the optimum inspection interval, an approximation formula has been derived based on Vaurio’s (1997) approach, and the accuracy of approximation of that approach has also been checked in that context. The deriving factors in the formula include the time horizon or the operating time expected from the equipment, the cost of inspection and downtime due to the inspection, the cost of an accident, and reliability factors. It has been found that, while an increase in the accident cost tends to result in a lower interval, increasing the inspection and downtime cost tends to result in higher intervals. Moreover, it has been noticed that, while increased aging tends to lead to a lower interval, a higher scale parameter (α) tends to lead to a higher interval (see Paper III).

However, the approach used in this study for risk constraint optimization is based on the mean fraction of time during which the item is not functioning within inspection intervals (MFDT) and the average interval unavailability behaviour within the restoration period. Paper III discusses the interval unavailability behaviour and MFDT within inspection intervals when the item is experiencing aging.

In order to reduce the complexity of the model and to make it practical for the analysts within the Maintenance Review Board (MRB), graphical tools have been introduced for maintenance task interval assignment and selection of the optimal strategy between the FFI option and the combination of FFI and restoration action option. The non-safety effect and the safety effect categories of hidden failure (i.e. with and without risk constraint) are discussed separately. The study shows that the CRF for FFI and, a combination of FFI and restoration actions is not sensitive around the optimum interval and frequency. Therefore, the analyst can, through utilizing the graphical tools, choose an appropriate interval in accordance with the predefined check packages (see Paper III).
It can be concluded that, depending on the failure data and cost parameters, in some cases the combination of FFI and restoration action strategy not only is effective in satisfying the risk limits, but can also lead to a more cost-effective solution than FFI alone. Hence, it would be beneficial to consider a combination of maintenance tasks during the formal maintenance task development, even for the non-safety effect category of hidden failure. It can also be concluded that, through the incorporation of adequate modelling support, the maintenance task interval assignment can be considerably enhanced and be based on a more scientific foundation. Thereby, not only are the safety requirements fulfilled, but a lower maintenance cost per flight hour is also obtained. This becomes more important when a fleet of aircraft is considered, and when taking into account the opportunity that is lost due to a non-optimized maintenance interval.

5.4 Methodologies for selection of the most effective maintenance strategy

The fourth objective of this study was “to propose appropriate methodologies for selection of the most effective maintenance strategy”. This objective is linked to the fifth research question and is fulfilled by the research presented in Papers III and IV.

The analytical and graphical approach presented in Paper III can be used to compare FFI and a combination of FFI and restoration actions, and to identify the most effective option when the evaluating criteria for effectiveness are cost and risk reduction. The study shows that, depending on the failure data and cost parameters, a mixture of failure finding and restoration actions can not only improve the availability of the hidden function of the item, but also may increase the cost-effectiveness of maintenance. Hence, it is reasonable to conclude that a combination of maintenance tasks should also be considered in a formal maintenance task development process for the non-safety effect category of failure. In fact, the results from this study show the necessity of considering all the applicable failure management strategies (i.e. taking a rigorous approach) in order to be able to find the most effective one.

Paper IV introduces a rigorous approach for selection of the most effective maintenance alternatives, for non-safety category of failures in aircraft systems, using a combination of Multi-Criteria Decision Making (MCDM) methodologies. The main steps included in the proposed methodology comprise the 1) formation of an expert team, 2) identification of the evaluating criteria that define the effectiveness of a maintenance task, 3) assigning the importance value of the evaluating criteria by the use of the AHP, 4) identification of the applicable maintenance alternatives, 5) ranking the maintenance alternatives by the use of benefit-cost analysis, TOPSIS (Technique for Order Preference by Similarities to Ideal Solution), and VIKOR methodologies, and 6) selection of the most effective one by the Maintenance Review Board (MRB).

The study considers \( m \) alternatives as \( m \) points in an \( n \)-dimensional space of \( n \) attributes/criterion. The proposed decision making methodology includes two levels, i.e. the managerial level, and the engineering level. The managerial level defines the goals and the associated evaluating criteria, and also assigns the importance of the evaluating criteria. In fact, any decision has several favourable and unfavourable concerns to consider. The favourable concerns are positive value and are called benefit, such as business enhancement, planning flexibility, and reduction in maintenance cost. The unfavourable ones are negative and are called costs, such as downtime due to maintenance and its associated costs. Each of these concerns contributes to the merit of decision and must be evaluated (rated) individually.
on a set of evaluating criteria. These criteria influence the decision into different degree and therefore have different importance. At managerial level, the importance of these criteria is decided through the use of AHP. The resulting importance value of the criteria is used for the whole analysis. This provides an overall view of the complex relationship of evaluating variables inherent in the decision making problem, and helps the decision maker in making judgments concerning the comparison of attributes and criteria that are homogenous and are on the same level of the decision hierarchy.

The engineering level selects a failure mode, defines applicable maintenance alternatives, and assesses the effectiveness of each alternative after due consideration of the positive and negative consequences of choosing any one of the maintenance alternatives, according to the defined evaluating criteria. Different units and scales are used for measuring these evaluating criteria. In order to ease out the effects of units and scales, normalization procedure is applied to the element of the performance appraisal matrix, which is framed from the responses of engineering level experts. At this level the analyst performs a multi-criteria ranking of the alternatives. The ranking of the applicable maintenance alternatives provides a basis for the MRB to select the most appropriate alternative. However, in this process the decision maker will be faced with numerous conflicting objectives. Sometimes a theoretically optimum maintenance strategy is not feasible for an operator, due to some strategic factors or restrictions. For example, a company may prefer to select a strategy that requires less investment, consumes less resource, and is less dependent on a sub-contractor; or the company may prefer a strategy that leads to the highest reduction of operational irregularities. Therefore, ranking of the alternatives at engineering level should be fact-based, in which the governing factors such as organizational preferences, internal and external restrictions, and national and international regulations, should be taken into account.

Following the proposed MCDM methodology presented in Paper IV, the analyst at engineering level performs a multi-criteria ranking of the alternatives using the three methodologies, i.e. benefit-cost ratio, TOPSIS and VIKOR, to meet these challenges. This methodology provides a basis for consideration of different decision governing factors in the ranking process, which may include the rate of return, the total profit per se, or the lowest investment. When the preference is the rate of return, the benefit-cost ratio is suggested. For the total profit TOPSIS is applied in which, the alternatives are ranked according to their distances from two cardinal points: the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS). In cases where the manager has specific preferences, such as “the alternative solution should preferably include the lowest investment needed in comparison with that of other maintenance alternatives”, VIKOR can be adopted. In VIKOR, the relative distance from the cardinal points is also taken into account. Finally, the analyst provides a ranking of the alternatives based on different points of view and the MRB can select one which suits the preferences well. In fact, the results out of the benefit-cost ratio, TOPSIS and VIKOR methodologies are complimentary which gives adequate support to the decision maker, in selecting the most effective maintenance alternative.

The proposed methodology has been tested through a case study within the aviation context for an aircraft system. The list of evaluating attributes was decided in consensus with field experts. The performance of the five maintenance alternatives was evaluated using 16 evaluating attributes divided into two groups, i.e. benefit and cost criteria. The alternative maintenance strategies considered in the paper include those offered by ATA MSG-3. (i.e. Operational/Visual Check, Inspection/Functional Check, Restoration, Discard, Combination of...
Strategies, Run to Failure and Redesign) and the use of Prognostics and Health Management (PHM) provisions.

The results of the benefit-cost analysis shows that the maintenance alternative “incorporation of PHM” has the maximum benefit-cost ratio (13.50), followed by the alternative “functional check” (2.21). The cost index value for the alternative “discard” is the maximum (0.342) and that for the alternative “incorporation of PHM” is the minimum (0.036). The benefit-cost ratio is highest (13.50) for the alternative “incorporation of PHM”, indicating that this alternative is the most rational choice, followed by “functional check” and “restoration”. The benefit-cost ratio for the remaining two alternatives is less than unity, indicating that they are not preferable alternatives. The results of the TOPSIS analysis indicate that the maintenance alternative “incorporation of PHM” is the overwhelming choice, as indicated by the highest relative closeness value (0.932). The alternative “functional check” is the second preferred choice, with a relative closeness value of (0.682), followed by “restoration” (0.505). The alternative “run-to-failure” is the least preferred choice. The VIKOR index also ranks the alternative “incorporation of PHM” first, followed by “functional check”.

The results show that the alternative “incorporation of PHM” was found to be the most favourable choice, followed by “functional check”, by all the three methodologies. The rest of the alternatives, i.e. “restoration”, “discard”, and “run to failure” have the same preferability as MSG-3 suggests. However, it is noticeable that the ranking index for PHM strongly proffers that alternative in comparison with other alternatives, which shows the necessity of including this alternative among the decision alternatives.

It has been found that using the methodology presented in the Paper IV, the relative advantage and disadvantage of each maintenance policy could be identified in consideration of different aspects, and that justification of the maintenance task selection will be more consistent and rationalized. These enhance the expert judgment process during the use of the MSG-3 methodology by the MRB, to assure the consistency and effectiveness of maintenance decisions. The study shows that using the combined AHP, benefit-cost ratio, TOPSIS, and VIKOR methodologies is an applicable and effective way to implement a rigorous approach for identifying the most effective maintenance alternative.

Summing up, in the move towards world-class competition, and according to the future market demand, it is vital for the air carriers to sustain and increase the capability of the air fleets to meet market demand, at lowest possible cost. Increasing the effectiveness of scheduled maintenance is seen as one of the most feasible solution to reach this ambitious and challenging objective. Moreover, proper decision on scheduled maintenance task development not only will enhance aircraft safety, but also increases its availability performance and cost effectiveness, which assist to meet air carriers’ business requirements. To this end, it is essential to acquire new supporting methodologies and refine the current use of expertise on the use of MSG-3, to increase the consistency of maintenance decisions. In summary, the incorporation of the proposed analytical methodologies for adequate risk analysis, for optimal interval assignments, and for selection of the most effective maintenance task, has the potential to increase the accuracy of the maintenance decisions and make it possible to design a more effective maintenance programme. This approach not only fulfils the airworthiness requirements, but also supports the decision making in identification of the most effective maintenance task.
5.5 Research contribution

The main contribution of this research work is identification and development of new decision support methodologies and tools for effective and efficient aircraft maintenance programme development. Some of the specific contributions can be listed as:

- Identification of issues and challenges, and some of the potential areas of improvement related to the implementation of Maintenance Steering Group (MSG)-3 methodology, for aircraft systems within the Maintenance Review Board (MRB) process.
- Differences and similarities between MSG-3 and Reliability-Centred Maintenance (RCM) procedures are identified.
- Development of an Event Tree Analysis (ETA) methodology for assessment of the operational risk of failures.
- Development of a Cost Rate Function (CRF) for identification of the interval and frequency of failure finding inspection (FFI) and; combination of FFI and restoration, for both the safety (a risk constraint optimization) and the non-safety effect categories of failures.
- Development of an approach to postponement of discard/restoration tasks related to hidden functions, which satisfies the risk limits.
- Development of a Multi-Criteria Decision Making (MCDM) methodology for selection of the most effective maintenance strategy.

5.6 Further research

During the progress of this research, several interesting new research ideas have emerged. However, it has not been possible to pursue all of these within the research presented in this thesis. Hence, in this section, some of these ideas are presented as suggestions for further research.

Extension of the proposed methodologies: The proposed ETA methodology could be enhanced by developing a dynamic ETA. An application of the proposed ETA could be extended to cover all types of failure consequences in the RCM and MSG-3 methodologies, such as safety and economic consequences. Moreover, the proposed Cost Rate Function (CRF) should be modified in which different level of maintenance effectiveness should be considered. Moreover, the CRF can be modified to cover possible errors due to maintenance actions, and common causes of failure. Furthermore, the proposed Multi-Criteria Decision Making should be augmented with the sensitivity analysis to check the robustness of the maintenance decisions, with the variation of the importance value of the evaluating criteria.

Integration of Prognostics & Health Management (PHM) and MSG-3: Increased aircraft operability requires a more proactive maintenance concept where most of the maintenance planning and preparation is carried out during uptime and where prognostics will be one of the key enablers. Better diagnostic capability and smarter maintenance can reduce the time required for both unscheduled and scheduled maintenance. Defining the requirements for PHM could be performed through a rigorous application of MSG-3 to acquire the capability of Condition-Based Maintenance, which could contribute to maintainability allocation in an effective way from a life cycle perspective. This would lead to an improved maintainability
performance of the system through the inclusion of new and innovative technologies for PHM. Hence, to fulfil these objectives, a methodology is needed that integrates PHM and MSG-3.

**Development of an e-Maintenance solution for management of the maintenance programme:** The maintenance programme is considered as a “living” document which should be continuously monitored during the operational phase, to identify deviations from established objectives. To this end, it is crucial to collect and analyze the large amount of operational data related to reliability, maintainability, and maintenance support. The information gained from these analyses provides a basis for making decisions. Collecting and analyzing operational data are time consuming, error-prone and costly processes. However, incorporation of an e-Maintenance solution would provide a platform for real-time data collection, analysis, and provision of decision alternatives. Therefore, a study is needed to explore the ways in which the application of information and communication technology could support both the development and the surveillance of a scheduled maintenance programme.

**Further incorporation of maintenance support performance in the scheduled maintenance development process:** In order to realize a higher level of achieved availability performance, the maintenance support organization and the resources that are required to support the system throughout its planned operational life should be considered in the scheduled maintenance task analysis. Such resources may include maintenance personnel quantities and skill levels, spares and repair parts and associated inventory requirements, tools and test equipment, transportation and handling requirements, facilities, technical data, computer software, and training requirements. Following this approach, the operational and business requirements of the air carriers could also be fulfilled, which would improve the aircraft operability and fleet performance.
References


On aircraft scheduled maintenance programme development

Alireza Ahmadi¹, Peter Söderholm² and Uday Kumar¹
Division of Operation and Maintenance Engineering
¹Luleå University of Technology, Sweden
²Swedish Transport Administration
alireza.ahmadi@ltu.se, peter.soderholm@trafikverket.se, uday.kumar@ltu.se

ABSTRACT

Paper category - Review paper

Purpose - The purpose of this paper is to present issues and challenges of scheduled maintenance task development within the Maintenance Review Board (MRB) process, and to find potential areas of improvement in the application of the MSG-3 methodology for aircraft systems.

Design/methodology/approach - The issues and challenges as well as potential areas of improvement have been identified through a constructive review that consists of two parts. The first part is a benchmarking between the Maintenance Steering Group (MSG-3) methodology and other established and documented versions of Reliability-Centred Maintenance (RCM). This benchmarking focuses on the MSG-3 methodology and compares it with some RCM standards to identify differences and thereby find ways to facilitate the application of MSG-3. The second part includes a discussion about methodologies and tools that can support different steps of the MSG-3 methodology within the framework of the MRB process.

Findings – The MSG-3 methodology is closely related to the RCM methodology, in which the anticipated consequences of failure are considered for risk evaluation. However, MSG-3 neither considers environmental effects of failures, nor operational consequences of hidden failures. Furthermore, in MSG-3, the operational check (failure finding inspection) is given priority before all other tasks, whereas in RCM, it is considered as a default action, where there is no other applicable and effective option. While RCM allows cost-effectiveness analysis for all failures that have no safety consequences, MSG-3 just allows it for failures with economic consequences. A maintenance programme that is established through the MRB process fulfils the requirements of continuous airworthiness, but there is no foundation to claim that it is the optimal or the most effective programme from an operator’s point of view. The major challenge when striving to achieve a more effective maintenance programme within the MRB process is to acquire supporting methodologies and tools for adequate risk analysis, for optimal interval assignments, and for selection of the most effective maintenance task.

Research limitations/implications - This study focuses on the system part of the aircraft and not on areas such as structure and zonal analysis. Moreover, the study focuses on an application of the MSG-3 methodology for task development, while aspects such as human factors, the MRB organization, communication etc. are not considered. These limitations give scopes for further research.

Practical implications - Since decisions that are made during the initial scheduled maintenance programme development strongly affects the aircraft’s lifecycle cost and availability
performance, it is essential to review the current practices and to identify ways to increase the efficiency and effectiveness of the maintenance programme.

**What is original/value of paper** - The paper presents a critical review of existing aircraft scheduled maintenance programme development methodologies, and demonstrates the differences between MSG-3 and other RCM methodologies.

**KEYWORDS:** MSG-3, Reliability-Centred Maintenance (RCM), Aircraft maintenance programme.

1. **Introduction**

The initial maintenance requirements of an aircraft are derived through two different processes. One is the Type Certification (TC) process (aircraft maintenance) and the other is the Maintenance Review Board (MRB) process. Maintenance requirements derived through the Type Certification (TC) process are intended to ensure that the design of the aircraft meets the defined safety standards. These requirements are compiled and structured into the Airworthiness Limitation Section (ALS). The ALS comprises Safe Life Airworthiness Limitation Items (the Life Limited Parts document), Damage Tolerant Airworthiness Limitation Items (the ALI document for Structure), the Certification Maintenance Requirements (CMR) document (Systems), the Ageing Systems Maintenance (ASM) document, and the Fuel Airworthiness Limitations (FAL) document. The ALS is the repository for stand-alone documents that are approved independently from each other.

Through the Maintenance Review Board (MRB) process, manufacturers, regulatory authorities, vendors, operators, and industry work together to develop the initial scheduled maintenance/inspection requirements for new aircraft and/or on-wing powerplants. The requirements that result from MRB evaluations are specified in an MRB Report (MRBR). The MRBR outlines the initial minimum scheduled maintenance/inspection requirements to be used in the development of an approved continuous airworthiness maintenance programme for the airframe, engines, and systems of a specific aircraft type. The MRBR is intended to be used as a basis for each operator’s development of its own continuous airworthiness maintenance programme, subject to the approval of its regulatory authority. After approval, the requirements outlined in the MRBR become a framework around which each air carrier develops its own individual maintenance programme. Fig. 1 illustrates the interfaces between the TC process, the MRB process, and the development of the approved maintenance programme of the air carrier (Transport Canada, 2003).

In the commercial aviation industry, increasing emphasis is now being placed on using the Maintenance Steering Group (MSG-3) methodology in the development of initial scheduled maintenance programmes published in an MRBR. The reason for this is that MSG-3 is a common means of compliance for the development of minimum scheduled maintenance requirements within the framework of the instructions for continued airworthiness promulgated by most of the regulatory authorities.

MSG-3 represents a combined effort by the manufacturers, regulatory authorities, operators, and the Air Transport Association (ATA) of the USA. The MSG-3 methodology implicitly incorporates the principles of Reliability-Centred Maintenance (RCM) to justify task development, but stops short of fully implementing RCM criteria to audit and substantiate the initial tasks being defined (Transport Canada, 2003). The working portions of MSG-3 are divided into four sections, i.e. system and power plant, including components and the
Auxiliary Power Unit (APU), aircraft structure, zonal inspection, and lightening/high intensity radiation field (MSG-3, 2007).

Since the decision made for developing an initial scheduled maintenance programme strongly affects the aircraft’s lifecycle cost and availability performance, it is essential to review the current practices, and to identify ways to increase the efficiency and effectiveness of the maintenance programme. Although there is a variety of publications that discuss the issues of RCM (see e.g. Bertling, 2002, Deshpande and Modak, 2002, Vatn et al., 1996; Sherwin, 1999; Savio, 1999 etc.), unfortunately, the development of a maintenance programme within the MRB process using MSG-3 seldom receives the attention of research projects (see e.g. Liu et al., 2006; Lienhardt et al., 2007, Hollick and Nelson, 1995, Lawrence, 1984).

The purpose of this paper is to present the issues and challenges of maintenance task development within the MRB process for aircraft’s systems, and to find the potential areas of improvement. The proposals have been identified through a constructive review that consists of two parts. The first part is a benchmarking between MSG-3 and other established and documented versions of RCM. This benchmarking focuses on the MSG-3 methodology and compares it with some RCM standards to identify differences and thereby find ways to facilitate the application of MSG-3. The second part includes a discussion about methodologies and tools that can support different steps of the MSG-3 methodology within the framework of the MRB process.
The rest of the paper is organized as follows. First, Section 2 provides a discussion about the conceptual framework of RCM as adapted in the MSG-3 methodology. Then, Section 3 includes a description of the operator's/manufacturer’s scheduled maintenance development, i.e., MSG-3. In Sections 4 to 7, a brief review of the development of maintenance tasks is provided, including Maintenance-Significant Item (MSI) selection, the MSI analysis process (identification of functions, functional failures, failure effects, and failure causes), and the selection of maintenance actions using decision logic. Finally, Section 8 ends the paper by outlining some conclusions and presenting a short discussion.

2. Conceptual framework of RCM as used by MSG-3

Reliability-Centred Maintenance (RCM) is a well-structured, logical decision process used to identify the policies needed to manage failure modes that could cause the functional failure of any physical item in a given operating context. The RCM methodology is used to develop and optimize the preventive maintenance and inspection requirements of equipment in its operating context, to achieve its inherent reliability, where inherent reliability can be achieved by using an effective maintenance programme. The methodology is based on the assumption that the inherent reliability of the equipment is a function of design and the built quality (Nowlan and Heap, 1978, Moubray, 1997, Rausand, 1998, Dhillion, 2002, Smith and Hinchcliffe, 2004).

Figure 2 shows the chain from cause, via failure, to consequence in a typical engineering system, and includes an illustration of the role of system maintenance activities. The process of failure begins with a set of basic events, also known as “initiating events”, which perturb the system, i.e. cause it to change its operating state or configuration. If the initiating events (i.e. failure modes), as the initial cause of failures, cannot be managed at an early stage of their occurrence, they will lead to a number of “undesired events”, which is the outset of a possible undesired consequence. The consequences may include all the events causing any type of loss. The loss or unwanted consequence to be considered may include injury or loss of life, air and noise pollution, high repair costs, system or equipment loss, delay or flight cancellation etc. Barriers are used to prevent or mitigate the escalation of both basic events and undesired events to unwanted consequences or loss. A barrier is a measure taken to reduce the probability that an unwanted event or situation will occur, or to reduce the impact if they actually do occur. Barriers can be viewed as obstacles that perform the function of containing, removing, preventing, mitigating, controlling, or warning about the release of hazards (Modarres, 2006).

As shown in Fig. 2, in the leftmost block (“system function assurance”), maintenance acts as a preventive barrier in order to preserve the main functions of the system. In the middle block (“system protection assurance”), maintenance acts as a preventive barrier to preserve the function of a protective device, or to assure the availability of a protective function. Other barriers can also be incorporated into the system, i.e. training, audits, emergency procedures, insurance, etc.

RCM recognizes that the only reason for performing any kind of maintenance is not to avoid failures per se, but to avoid, or at least to reduce, the consequences of failure. Hence, the perception of RCM concentrates on the preservation of function instead of focusing on the hardware per se (Nowlan and Heap, 1978; Moubray, 1997, Kumar, 1990). By using an approach based on the system level and function preservation, RCM treats components differently in terms of relative importance according to the correlation between the equipment and the sys-
tem function. In fact, the probability of the consequences of undesired events, i.e. losses, and its magnitude depend to a great extent on the applicability and effectiveness of the barriers that are in place to avert the release of such consequences. Preventive maintenance acts as a preventive barrier whose aim is to eliminate the consequences of failure or reduce them to a level which is acceptable to the user. Maintenance helps to achieve this goal by an elimination of the failure completely, and, if this is impossible, by reducing the probability of the occurrence of failure (undesired events) or its consequences to an acceptable level.

In contrast to earlier methodologies supporting maintenance programme development, the RCM methodology is based on (see Ahmadi et al., 2007; Dhillon, 2002; Nowlan and Heap, 1978 for details):

- A system level and top-down approach for function identification, instead of a component level and bottom-up approach.
- A consequence-driven approach, to assure controls of the risk of failure.
- Function preservation instead of failure prevention, to assure the system function and the availability of protective devices,
- A task-oriented approach instead of a maintenance process-oriented approach to preparation of a maintenance programme.

Any RCM methodology shall ensure that all the following seven questions are answered satisfactorily in the order given below, to assure the success of the programme (SAE JA1011):

1. What are the functions and associated performance standards of the item in its present operating context (functions)?
2. In what ways does it fail to fulfill its functions (functional failures)?
3. What is the cause of each functional failure (failure modes)?
4. What happens when each failure occurs (failure effects)?
5. In what way does each failure matter (failure consequences)?
6. What can be done to prevent each failure (proactive tasks and tasks interval)?

7. What should be done if a suitable preventive task cannot be found (default actions)?

The RCM analysis may be carried out as a sequence of activities or steps, including study preparation, system selection and identification, functional failure analysis, critical item selection (significant item selection), data collection and analysis, Failure Mode Effect and Criticality Analysis (FMECA), selection of maintenance actions, determination of maintenance intervals, preventive maintenance comparison analysis, treatment of non-critical items, implementation and in-service data collection and updating (Rausand, 1998). Fig. 3 shows the RCM process, where task evaluation and task selection make up the RCM decision logic. It should be noted that RCM and similar methodologies are not a “silver bullet”, and need supporting methodologies and tools for successful implementation (see the discussion in Mokashi et al., 2002).

3. MSG-3: the operator’s/manufacturer’s scheduled maintenance development

MSG-3 is intended to facilitate the development of initial scheduled maintenance tasks and intervals for the purpose of developing an MRB report which will be acceptable to the regulatory authorities, the operators, and the manufacturers. MSG-3 outlines the general organization and decision process for determining the scheduled maintenance requirements initially projected for preserving the life of the aircraft and/or power plants, with the intent to maintain the inherent safety and reliability levels of the aircraft. The tasks and intervals developed become the basis for the first issue of each airline’s maintenance requirements, intended to govern its initial maintenance policy. As operating experience is accumulated, additional adjustments may be made by the operator to maintain efficient scheduled maintenance (MSG-3, 2007). As stated by MSG-3 (2007), the objectives of efficient scheduled maintenance of aircraft are to:

- ensure realization of the inherent safety and reliability levels of the aircraft;
- restore safety and reliability to their inherent levels when deterioration has occurred,
- obtain the information necessary for design improvement of those items whose inherent reliability proves to be inadequate;
- accomplish these goals at a minimum total cost, including maintenance costs and the costs of resulting failures.

MSG-3 implicitly incorporates the principles of RCM to justify task development. It involves a top-down, system-level, and consequence-driven approach in which maintenance task justification should be based on applicability and effectiveness criteria. The analysis steps include:

1. Maintenance-Significant Item (MSI) selection;
2. The MSI analysis process (identification of functions, functional failures, failure effects, and failure causes);
3. Selection of maintenance actions using decision logic (see Fig. 4), which includes:
   3.1 Evaluation of the failure consequence (level 1 analysis);
   3.2 Selection of the specific type of task(s) according to the failure consequence (level 2 analysis).
Fig. 4 shows the MRB process, with the MSG-3 decision logic marked by a dashed line. Since its original publication in 1980, MSG-3 has been revised several times, with the latest revision having been made in 2007. In the following sections, available failure management strategies and the maintenance task development process as offered by MSG-3 are discussed.

4. Available failure management strategies

The available failure management strategies offered by RCM consist of specific scheduled maintenance tasks selected on the basis of the actual reliability characteristics of the equipment which they are designed to protect, and they are performed at fixed, predetermined intervals. The objective of these tasks is to prevent deterioration of the inherent safety and reliability levels of the system. The four basic forms of preventive maintenance offered by RCM include (Nowlan and Heap, 1978; SAE JA1011, 1999; NAVAIR 00-25-403, 2005):

Scheduled on-condition inspection: Things done to apply the results of RCM to the maintenance program.

scheduled restoration (or rework or hard time restoration): a scheduled task used to detect a potential failure.
Scheduled discard (or hard time discard): a scheduled task that entails discarding an item at or before a specified age limit regardless of its condition at the time.

Scheduled failure-finding inspection: a scheduled task used to determine whether a specific hidden failure has occurred. The objective of a failure-finding inspection is to detect a functional failure that has already occurred, but is not evident to the operating crew during the performance of normal duties.

In some cases it may not be possible to find a single task which on its own is effective in reducing the risk of failure to a tolerably low level. In these cases it may be necessary to employ a “combination of tasks” such as “on-condition inspection” and “scheduled discard”. Each of these tasks must be applicable in its own right and in combination they must be effective (Defence Standard 02-45 (NES 45), 2000). These tasks are applicable to failure with safety consequences and, when applied, the probability of failure must be reduced to a tolerable level. In reality, a combination of tasks is rarely used. It is assumed, however, that in most instances this is a stoppage measure, pending redesign of the vulnerable part (Nowlan and Heap, 1978).

If no task is found to be applicable and effective, default strategies are introduced, which include:

- No scheduled maintenance (no preventive maintenance, run to failure)
- Redesign

When it is technically unfeasible to perform an effective scheduled maintenance task, and when a failure will not affect safety, or may entail only a minor economic penalty, the “no-scheduled-maintenance” or “run-to-failure” option will be accepted. Selection of the “no-scheduled-maintenance” option means that the consequence of failure is accepted. In cases where the failure has a safety effect and there is no form of effective scheduled maintenance task, “redesign” is mandatory. In other cases where the failure may produce a significant cost, a trade-off analysis identifies the desirability of redesign (Nowlan and Heap, 1978). In fact, the decision ordinarily depends on the seriousness of the consequences. Hence, if the consequences entail a major loss, the default action is redesign of the item to reduce the frequency of failures and their consequences.

MSG-3 considers the same failure management strategies as those used by RCM, but has made some modifications. For example, the term “on-condition inspection” has been changed to “inspection/functional check”. This was due to the fact that some maintenance engineers believe that “on-condition” means fit and forget or neglect to do anything until a failure occurs. The above interpretation of “on-condition” maintenance may cause operational surprises which could not only prove very costly, but also jeopardize the safety of an aircraft and its occupants (AWB 02-1, 2001). Hence, as a measure to prevent such an interpretation, MSG-3 changed the term. For the same reason, the term “failure-finding inspection” has been changed to “operational/visual inspection”. The maintenance strategies recommended by MSG-3 (2007) include:

- Lubrication/Servicing
- Operational/Visual Check (for hidden failures)
- Inspection/Functional Check
- Restoration
- Discard
- Combination of tasks (for safety effect)
- Redesign (for safety effect)

It is evident that no default strategy is considered and the “no-scheduled-maintenance” option is missing in the decision diagram. Nevertheless, MSG-3 guides the analysts by explaining that “where failure has no safety effect and no form of an applicable and effective scheduled maintenance task(s) has been found, no scheduled maintenance is allowed to be selected (no task has been generated)”. If no scheduled maintenance is an option, and the analysts can refer to that option, then this should be clearly apparent in the decision logic.

Moreover, it is noticeable that RCM and MSG-3 alone neither make full provision for the use of diagnostics and prognostics, nor support availability performance-based maintenance development. Today there is a growing demand from both military and commercial customers for improved aircraft operability and new enterprise models to support more sophisticated outsourcing and purchasing service agreements (Worsfold and Asseman, 2008). In fact, the prognostic and diagnostic capability of the system to predict the future health status and required maintenance actions is a key enabler of any availability- or performance-based programme. Therefore, a rigorous approach is needed that encourages consideration of all the applicable failure management strategies, and allows consideration of the provision of possible technologies, e.g. Condition-Based Maintenance (CBM) and Prognostics and Health Management (PHM), for cost-effective analysis (see the discussion in NAVAIR 00-25-403, 2005; Millar, 2008).

5. Maintenance-Significant Item (MSI) selection

Depending on the complexity of the end item, it may possess hundreds of functions. The importance of these functions ranges from “essential for operator safety” to “nice to have but can do without”. The perception of RCM and MSG-3 is that one should only consider those items whose functions are significant enough to warrant further analysis, i.e. Maintenance-Significant Items (MSIs), and apply the decision logic to them.

To this end, Nowlan and Heap (1978) state that the first step in the development of a scheduled maintenance programme is a quick, approximate, but conservative identification of a set of significant items. They define “significant item” as: “the item whose failure could affect operating safety or have major economic consequences”. The definition of major economic consequences includes a direct effect on operational capability or involves a failure mode with an unusually high repair cost. Hidden function items are also subjected to the same intensive analysis as significant items. The same methodology is suggested by NAVAIR 00-25-403, which, in addition, considers environmental issues.

Instead of these quick and very conservative processes, some of the standards suggest using a ranking methodology to recognize whether the impact of failure is sufficiently high to warrant further analysis. For example, IAEA-TECDOC-658 (1992) suggests that the identification of significant failures should be performed using the failure modes, the failure effects, the criticality of the function, the failure rate and the impact of the failure, with the criticality being based on a classification of the functional failure into one of three categories. The first category is used for functional failures that have negligible effects. The second category is used when the failure rate is acceptable. However, a functional failure with an acceptable failure rate has to be controlled. The third category is used when the failure rate must be kept under a given threshold, which means that a non-acceptable failure rate must be prevented.
Hence, this procedure classifies the severity of each failure effect according to the severity classification criteria established by the programme.

Some publications suggest that an FMECA should be performed and that the critical items should be selected based on the criticality of the function (see e.g. IAEA-TECDOC-658, 1992 for details). Some others suggest that one should first perform a screening to identify the critical items, and then apply FMEA to those items to reduce the workload, and to avoid wasting time and money (see e.g. Nowlan and Heap, 1978). However, some publications do not agree with the performance of such a screening (see e.g. Smith and Hinchcliffe, 2004). Rationally, depending on the characteristics of the equipment, the operational profile, and the requirements, in some cases it may be beneficial to focus on critical items; in other cases one should analyze all the items (see Rausand, 1998).

MSG-3 requires that the manufacturer should provide the initial list of MSIs, and obtain acceptance for the list from the Industry Steering Committee (ISC). MSG-3 uses a series of key questions to determine whether the function of the item is significant. The questions enquire whether the loss of function (failure) has an adverse effect on safety/emergencies, and a significant impact on operation or economy. Moreover, failures that are hidden, or unlikely to be detected by the operating crew, are subjected to the same intensive analysis. If the answer to any of these questions is “yes”, the item should be considered as significant. Hence, this selection is solely based on the anticipated consequences of failure. The selection does not consider the severity of the consequences on a more detailed level or the frequency of occurrence. Hence, this is a quick, but still conservative, collective engineering judgment process and not a complete risk-based assessment. The problem here is whether an item whose failure is unlikely to occur or an item whose risk of failure is already at an acceptable level should really be considered primarily as an MSI (Hollick and Nelson, 1995). In practice failure data about safety-critical systems do not exist, as they are guarded by design against the occurrence of failure. Hence, even unlikely failures should be prevented, due to the severity of even one failure, in order to fulfil the requirements of continued airworthiness made mandatory by authorities. Hence, even unlikely failures should be prevented, due to the severity of even one failure, in order to fulfill the requirements of continued airworthiness made mandatory by authorities. Still the question is raised for non-safety category of failure (i.e. operational and economic consequences). In fact, the difficulty is often that the appropriate information is not available, especially during the initial maintenance programme development phase, and the decision defaults on the side of caution. However, hiring the appropriate methodologies and tools to collect the experience of the field experts provides a reasonably good source of information for performing criticality analysis.

Other criteria that are important to consider in MSI analysis may include environmental issues, availability performance and whether the actual or predicted failure rate and consumption of resources are high. Moreover, special attention should also be given to the operation cost, a long lead time for spares, support equipment, equipment used for calibration tasks, low maintainability, items requiring a special maintenance crew or special training, and whether the item or a similar item on similar equipment has an existing scheduled maintenance task (see the discussion in e.g. MIL-STD-1629A, 1998, NAVAIR 00-25-403, 2005 and Rausand, 1998). In fact, a detailed description of criteria for MSI selection enhances the decision-making process, not only for the initial maintenance development, but also for further refinement by the operator.

Actually, the major projected lifecycle cost for a system stems from the consequences of decisions made during the early phases of design. Regarding availability performance, those decisions pertaining to the utilization of new technologies, the selection of components and
materials, the identification of diagnostic routines and prognostics, and the maintenance programme policies, etc. have a great impact on the system effectiveness and the lifecycle cost (Blanchard, 1995). Hence, it is essential to consider “the effect of the failure on availability performance”, while analyzing MSIs, to make it possible to influence necessary design changes in the technical system, unless the design is frozen. However, this needs be accomplished as early as possible in the system design phase, to make it possible to influence the design.

6. MSI analysis process (identification of functions, functional failures, failure effects, and failure causes)

RCM and MSG-3, as well as other general approaches to reliability and risk management, include the identification of hazards, the objects that could be harmed, and controls for reducing the frequency or consequence of unwanted events. The most important part of risk analysis is risk identification. Only those risks that have been identified can be managed in a systematic and conscious way (Njå and Nøkland, 2005). Hence, the consideration of risk as a criterion for selecting the maintenance policy is crucial (Arunraj and Maiti, 2010). To this end, RCM encompasses the well-known Failure Mode & Effects Analysis (FMEA) methodology. FMEA starts with making an end item breakdown into significant functional or hardware items, identifying system boundaries, and showing the relationships of components or functions with each other (MIL-STD-1629A, 1998). The FMEA defines the significant item(s) and establishes the cause-and-effect relationships among its/their function(s), functional failures(s) and failure mode(s), the end effects of the functional failures, and the consequences of failure(s), which aims at determining possible system states under the assumption of the presence of certain failures. This includes the determination of local effects, system effects, end effects and the failure detection methods (Conachey et al., 2003).

Some procedures also suggest conducting FMECA, i.e. performing a criticality analysis in addition to FMEA. The failure mode’s criticality is determined by the failure mode’s risk. This allows the comparison of each failure mode with all the other failure modes with respect to risk. The failure mode’s risk is determined by assessing the severity of the end effect(s) and the likelihood of the failure mode resulting in the end effect of the given severity. The results of the FMEA and risk assessment are used to determine the need for a failure management strategy and, if one is needed, the risk provides a means to assess the effectiveness of the failure management strategy (Conachey et al., 2003). Some of the other well-known inductive methodologies for risk identification include Preliminary Hazards Analysis (PHA), Hazard & Operability Studies (HAZOP), and Event Tree Analysis (ETA). The basic events are often identified and modelled by Fault Tree Analysis (FTA). If the failure rate and other necessary data are available for the basic events, the FTA will provide estimates of the frequency of occurrence of the various undesired events (Rausand and Vatn, 1998). The possible consequence chains starting from an undesired event are often identified and modelled by ETA. Depending on the type of failure, the outcome of the ETA will be a set of possible consequences, such as delay, a high repair cost, injury, or the loss of life. If the necessary input data are available for the barriers and physical models, the ETA will provide the frequencies or probabilities of the various consequences.

Prior to applying the MSG-3 logic diagram to an item, a preliminary work sheet will be completed which clearly defines the MSI and its function(s), functional failure(s), failure effect(s), and failure cause(s). In the MSG-3 procedure, the fundamentals of FMEA are implic-
ily incorporated in the analysis. However, in this adaptation, some changes have been made, in that the term “failure mode” has been changed to “failure cause” (i.e. why the functional failure occurs). Moreover, “failure effect”, which is defined by SAE JA1011 as “what happens when a functional failure occurs”, is defined by MSG-3 as “what is the result of a functional failure”. The latter is used to address the question of what the occurrence of failure means to the aircraft as a whole. In fact, these two definitions are slightly different.

Moreover, detailed analysis of the consequence of failure is not incorporated in the MSG-3 analysis. Issues such as “what the failure does to kill or injure someone, what it does to have an adverse affect on operation or production” are not addressed in the MSG-3 analysis, while SAE JA1011 requires them to be dealt with. The MSG-3 perception is that one should analyze the consequences of failure (i.e. the safety, operational and economic consequences) by using decision logic (see Fig. 5). Although decision logic is designed based on the consequences of failure, the detailed assessment of the consequence and associated risk of failure is not guided by decision logic. In fact, this sort of information includes a specific analysis and should be ready before the decision diagram is applied to each item to determine the need for a failure management strategy; and, if one is needed, this information provides a means to assess the effectiveness.

When analyzing the safety, operational, and economic consequences of failures, one major challenge is assessment of the operational risk of failures, and its associated costs. This is due to the long list of uncertainties related to the large amount of influencing factors, the inadequacy of service information, and difficulties in understanding the influences of the different factors. In fact, the integration and correlation of different parameters drive the ultimate state of the operational situation and the extent to which the rate and quality of flight production deviate from the predefined rate and quality.

Using some of the methodologies for risk analysis within the MRB process will support the MSG-3 analysis in arriving at a more reasonable decision. The difficulty is that, during the initial maintenance programme development, there is a lack of data (Hollick and Nelson, 1995; Liu et al., 2006). However, even if the real data is not available, the experience of experts can still be used as a valuable source of information to estimate the required data. In fact, this is not in contradiction with the conservative approach when the real data is not available. The risk can be assessed either quantitatively or qualitatively. For most RCM analyses, a simple risk matrix is used to assess the risk. To develop and use a risk matrix, consequence severity and likelihood (frequency) bins are established (Conachey et al., 2003), and they can be used in the MRB process to support the MSG-3 analysis.

7. Selection of maintenance actions using decision logic

In order to select the applicable and effective maintenance task, MSG-3 provides a decision diagram logic which includes two levels of analysis. The first level evaluates the type of failure and its consequences, i.e. evaluation of the failure consequences. The second level deals with the selection of an appropriate maintenance strategy according to the consequences of failure.

7.1 Level 1 analysis: evaluation of failure consequences

In order to determine if a preventive maintenance task can reduce the undesirable consequences to an acceptable level, it is necessary to know whether a single or a multiple failure
should be prevented. A multiple failure is defined as “a combination of a hidden failure and a secondary failure (or event) that makes the hidden failure evident”. Hence, the first step when classifying a failure is to determine if it is evident or hidden. A failure which, by itself, is obvious to the crew while they are performing their normal duties is classified as an evident failure. All evident failures are analyzed as single failures. Failures that are not evident to the operating crew while they are performing their normal duties are classified as hidden failures (Nowlan and Heap, 1978).

As standard design practice, if a failure has any operational consequences, it should be evident to the crew. Hence, single hidden failures are well analyzed within design practices to determine whether they have any effect on safety and operation. The classification of failures into hidden or evident failures is vital for the evaluation of protective devices, since their functions and failures are not apparent in isolation. Hidden failures that are analyzed as part of a multiple failure have no undesirable consequence when they occur on their own. In these cases, the objective of a preventive maintenance task is to prevent the consequences of multiple failures. When either evident or hidden failures occur, the user is concerned about the consequences of failure. In this context the term ‘consequence’ is defined in a very broad sense, including all the events causing any type of loss. The loss or unexpected consequence may comprise injury or loss of life, loss of a system or equipment, environmental deterioration, operation shutdown, delay, or a high maintenance cost.

RCM divides the consequences of failure into three major categories, i.e. “safety and environment”, “operational”, and “economic” consequences. RCM takes into account the following six failure effect categories for level-1 analysis: evident safety/environment effects, evident operational effects, evident economic effects, hidden safety effects, hidden operational effects and hidden economic effects (see e.g. Nowlan and Heap, 1998; NAVAIR 00-25-403, 2005; MIL-STD-2173, 1986; SAE JA1011, 1999; SAE JA1012, 2002; IAEA-TECDOC-658, 1992, Defence Standard 02-45 (NES 45), 2000, etc.).

Although all the RCM sources agree on these types of failure consequences, there are some differences in their decision diagram format. For example, Nowlan and Heap (1978) do not include any consequence category for hidden failure effects in the decision diagram. Moreover, NAVAIR 00-25-403 has merged the operational and economic categories together and reduced the decision path to four options. In contrast, Defence Standard 02-45 (NES 45) considers the full six types of failure effect categories as different paths in the decision logic. SAE JA1012 agrees on both later types of consequence category and leaves the user of the standard to decide the appropriate one. For comparison, MSG-3 follows a slightly different approach for the classification of failure effects. For example, MSG-3 does not consider all environmental issues and the operational consequence of hidden failures. Hence, the following five failure effect categories are provided:

i. Evident Safety
ii. Evident Operational
iii. Evident Economic
iv. Hidden Safety
v. Hidden Non-safety

Regarding the environmental consequences, SAE JA1012 states, “A failure mode or multiple failure has environmental consequences if it could breach any corporate, municipal, regional, national or international environmental standard or regulation which applies to the physical asset or system under consideration.” The major environmental issues in relation to aircraft
are air pollution (i.e. CO₂ emission and fuel consumption) and noise pollution (i.e. aerodynamic noise, engine and other mechanical noise, and noise from aircraft systems), and both types of pollution are controlled and minimized by design regulation, rather than maintenance efforts. Moreover, there are tasks that are covered by national or international Advisory Circulars issued to control the level of pollution. Although these tasks are included in the air carrier’s maintenance programme, they are not generated as part of the MSG-3 analysis. Most of these tasks are national or international requirements that differ from operator to operator. Regarding the material release to the environment, i.e. the release of fuel and hydraulic fluid, these are considered primarily as a safety issue rather than an environmental issue. Moreover, there are strict design rules which assure the prevention of leakage from lines, couplings and attachments. However, an adjustment may also be beneficial to addressing environmental problems, whenever this is applicable.

Regarding the operational effect of hidden failures, it should be mentioned that hidden failures within MSG-3 are analyzed as parts of multiple failures, and such failures on their own do not have any consequences. Here the aim of preventive maintenance is to assure the availability necessary to avoid the effects (consequences) of multiple failures on safety, operation, or economy. The question is whether there is “any hidden function that supports normal operation of a system” and that can have an effect on operation and production.

One can question why a multiple failure cannot have any operational effect within the MSG-3 framework. As mentioned previously, other standards, such as NAVAIR 00-25-403 and Defence Standard 02-45 (NES 45), consider that a multiple failure can have operational effects and they are included in the failure effect categories. NAVAIR 00-25-403 considers the economic and operational effects merged together as the non-safety category of hidden failure effects. Defence Standard 02-45 (NES 45) even separates the operational effect from the hidden effect in the decision logic process.

One major obstacle in the MSG-3 methodology is that it does not consider the effect of failure on production and its associated costs, and it focuses on operating capability per se. With a holistic view, the effectiveness of the maintenance programme is seen as its contribution to the both airworthiness enhancement and business of a company. In fact, by the proper selection of maintenance actions, the production quality and rate can be positively influenced (see the discussion in Alsyuf, 2007).

### 7.2 Level 2 analysis: selection of a specific type of task(s) according to failure consequence

Among the available standards and procedures, two different approaches are used to select failure management policies. The first one uses a binary form of decision diagram (Yes/No answers), and assumes a preferred order in the selection of a failure management strategy, i.e. on-condition inspection first, restoration second, discard third, failure-finding inspection fourth, and a combination of tasks as the fifth one. Then come no scheduled maintenance and redesign as default strategies. SAE JA1012 has termed this as the “decision diagram approach”.

Nowlan and Heap (1978) state that the characteristics of the tasks themselves suggest a strong order of preference on the basis of their overall effectiveness as preventive measures. SAE JA1012 states that, in most of the RCM decision diagram approaches, there are two key assumptions which form the preference hierarchy for the failure management policies. The
first assumption is that some categories of failure management policies are inherently more cost-effective than others. The second assumption is that some are inherently more conservative than others. In the first approach, if one of the earlier tasks in the preference order is deemed to be applicable and effective, it is selected and the analysis continues with the next failure mode. Otherwise the second failure management strategy should be evaluated, and so on until the end of the decision diagram has been reached. It should also be borne in mind that the use of decision diagrams may introduce an element of sub-optimization to the failure management policy selection process, from the cost point of view (SAE JA1012, 2002).

The second approach is the “rigorous approach”, which encourages a consideration of all the applicable failure management strategies for a given failure mode and provides a comparison of methodologies to facilitate the selection of the most effective one among all the applicable options (SAE JA1012, 2002). This approach leads to a more detailed and thorough analysis than the decision diagram approach. However, decision diagrams are popular because they are quicker and cheaper to apply than the rigorous approach.

Most of the RCM literature follows the decision diagram (binary format) approach to select appropriate maintenance strategies (see e.g. SAE JA1012, 2002, Defence Standard 02-45 (NES 45), 2000). However, NAVAIR 00-25-403 incorporates a rigorous approach to select maintenance strategies, for all types of failure effect categories.

A combination of these two approaches is used by MSG-3 to form the decision logic diagram (see Fig. 5). For safety category failures, a rigorous approach is taken in which all possible avenues must be analyzed, and from this review the most effective task or a combination of tasks must be selected. In cases where there is no form of applicable and effective scheduled maintenance task (because any available task would be technically unfeasible or not worth doing), selecting “redesign” is mandatory to satisfy the applicability and effectiveness criteria. In the case of operational and economic consequences, a decision diagram approach (binary approach) is used.

One major difference between MSG-3 and other RCM literature is observed in the priority of tasks for the category of hidden failures, for which MSG-3 gives the operational/visual check (i.e. failure-finding inspection) the first priority in the hierarchy compared to other maintenance strategies. In fact, failure-finding inspection is a sort of default action, meaning that, when an applicable and effective maintenance strategy is not found, then the failure-finding inspection strategy should be considered to reduce the consequence of multiple failures. When an on-condition or restoration task is found to be applicable and effective, it is not rational to give priority to the failure-finding inspection strategy in the decision diagram. For the operational/visual check (i.e. failure-finding inspection) to be selected, the item must be one for which no other type of task is applicable and effective (see the discussion in Nowlan and Heap, 1978).

Moreover, one can question how a maintenance strategy can always be the most conservative and at the same time the most cost-effective option to be considered. In fact, in almost all the RCM standards, preference is given to on-condition maintenance. There is no doubt that on-condition maintenance has a great number of advantages, but this is a relative issue which depends on many key parameters. For example, if the failure is age-related and there is quite good knowledge of the failure data, most of the time a restoration or discard task (time-based maintenance) leads to a better and more effective maintenance strategy. However, when using the binary format, and there is an applicable and effective on-condition
task, it should be selected, which is not rational. The overall effectiveness of a maintenance task should be evaluated based on specific criteria. Examples include how much the task reduces operational irregularities and consequences, how much the item realizes its useful life, i.e. mature removal of the item, and how much it decreases the repair cost, the use of spares and material, facilities and tools, the man hours needed to support the repair process, and the maintenance downtime. Moreover, issues such as increased planning flexibility and adaptability to people are other concerns.

In the absence of adequate information, or if a MRB meeting is unable to reach a consensus for decision making, default replies are often used to answer the questions (Beno et al., 2005). For example, MSG-3 states, “Default logic is reflected in paths outside the safety effects areas by the arrangement of the task selection logic. In the absence of adequate information to answer “Yes” or “No” to questions in the second level, default logic dictates a “No” answer be given and the subsequent question be asked. As “No” answers are generated the only choice available is the next question, which in most cases provides a more conservative, stringent and/or costly task.” However, some publications do not agree with this methodology. For example, the SAE JA1012 standard states that “… most decisions have to be made in the absence of complete data. This can lead to a temptation to start relying excessively on “default logic,” in which decisions are made automatically if comprehensive data are not readily available. However the application of such logic can lead to incorrect decisions, especially in the assessment of consequences. In practice the view should be taken that, if the possible repercussions of too much uncertainty cannot be tolerated, then action should be taken to change the consequences of the failure mode rather than rely upon ‘default’ decisions.”

Although the procedures and decision logic provided by the MSG-3 methodology are well designed to guide the analysis, there are three major challenges in the task selection process within the MRB process. These challenges are: determination of the maintenance task interval, comparison of the maintenance strategies, and, finally, the applicability and effectiveness analyses. These challenges will be discussed in the following sections.

**Determination of maintenance interval**

As mentioned earlier, the current methodology used to determine maintenance tasks is mainly based on Maintenance Steering Group (MSG) logic, the analysts who are engaged in the MRB process consult experience of similar aircraft, and the methodology for determining maintenance tasks and intervals mainly relies on engineering experience (Liu et al., 2006). The analysts are free to assign specific intervals for each maintenance task. However, performing all the individual maintenance tasks at their own optimal intervals is not practical. The current methodology of assigning an interval for a selected maintenance task, within the MRB process, is mostly based on predefined intervals in the form of checks denoted by alphanumerical codes (e.g. A1 = at every 250 Flight Hours (FH), A2 = 500FH, B = 1000FH, C = 5000FH, or D = 10000FH), which should be specified in the procedures handbook.

Obviously, without quantitative modelling support, the decisions made for maintenance task interval assignments are subjective and experience-based, which generally leads to conservative engineering judgments. The extreme formality of this process may lead to a higher maintenance frequency, which ultimately affects the aircraft availability performance and economy. In fact, most new products are improved from old ones, while their structures, functions, working conditions, function failure and failure effects have certain similarities;
and some products have standard systems, and the analysts consult experience of similar aircraft. In order to enhance the decision on interval selection, it is suggested that one should use techniques such as Case-Based Reasoning, which solves a new problem by using or adapting solutions to old problems (see the discussion in Liu et al., 2006).

In fact, it is expected that, when the aircraft enters into service, real data will be collected and a more accurate and more optimal interval will be assigned. The lack of a methodology for identifying an optimum interval in the operation phase arises. This is especially true when the task development and selection are dealt with in a multi-objective decision-making process in which several elements, such as cost parameters, constrained conditions and other business considerations, e.g. fleet availability, are to be taken into account. Hence, there is a need to introduce an optimization-based decision support, to enhance the capability of taking correct and effective decisions for maintenance interval assignment (when data is available) in which both reliability and cost parameters are considered (e.g. the opportunity cost due to maintenance downtime). The analysis of maintenance tasks also needs to identify the frequencies and intervals of task implementation. This requires adequate knowledge about the failure mechanism, reliability and analysis methodologies, and the utilization of modelling support to identify the optimum frequency and interval.

**Preventive maintenance comparison analysis**

Following a decision diagram approach does not require to analyze all applicable options. In order to find the most effective option, one needs to follow a rigorous approach which allows consideration of all applicable maintenance options. In the case of a rigorous format of decision logic, the selection of an effective maintenance task among applicable ones is a challenging problem. In order to be able to make rational and justifiable tactical decisions concerning maintenance, one needs to have a clear idea of what the advantages and disadvantages of each maintenance policy are (Waeyenbergh and Pintelon, 2002). The assessments require knowledge of various factors which indicates the strengths and advantages of different maintenance strategies, according to the criteria that define the goal of maintenance. Due to a long list of contributory factors and attributes, the inadequacy and uncertainty of required information and numerical data, and also the lack of modelling of the cost and benefit factors’ interaction and influence, exact quantification of the cost-benefit analysis of alternatives and justification of the maintenance strategy selection are critical and complex tasks (Bevilacqua, 2000). In fact, management of the large number of tangible and intangible attributes that must be taken into account represents the main complexity of the problem (Bertolini and Bevilacqua, 2006). Since decision making in practice is often characterized by the need to satisfy multiple objectives, the formulation of multi-criteria decision models is another worthwhile topic of future research work in inspection problems (Tsang, 1995). To this end, the Multi-Criteria Decision Making (MCDM) approach has been proposed in the literature, and has gained impetus in the field of maintenance strategy selection in the provision of support in the decision-making process (see e.g. Almeida and Bohoris, 1995; Triantaphyllou et al., 1997; Bevilacqua and Braglia, 2000; Bertolini and Bevilacqua, 2006). Multi-Criteria Decision Analysis (MCDA) aims at highlighting these conflicts and deriving a way to achieve a compromise in a transparent process.

However, the role of maintenance is also changing towards a partnership of companies to achieve world-class competitiveness (Waeyenbergh and Pintelon, 2002). With a more holistic view in selecting maintenance strategies, it would be more beneficial and business-
oriented for air carriers to consider the total value added or benefit as a measure of the overall effectiveness that can be gained by an applicable maintenance strategy. On the other hand, the task selection process should aim to find the alternative(s) whose cost-value added (benefit) ratio is the lowest among the various applicable alternatives competing for a given amount of money. A rigorous approach is needed that encourages consideration of all the applicable failure management strategies (instead of just the binary format).

Applicability and effectiveness of the maintenance task

Regardless of the standard that is used to develop a scheduled maintenance programme, task justification should be based on the criteria that show whether the selected maintenance task is able to fulfill its objectives or not. Hence, maintenance task selection in RCM is based on overriding criteria, i.e. applicability (technical feasibility) and effectiveness (the extent to which the task is worth doing). Through a literature review it was found that SAE JA1011 is more organized, clear, fluent, and relevant, and contains a description and discussion that cover the requirements of other standards, handbooks etc. Hence, in the following the SAE standard is used as a reference for a discussion on the applicability and effectiveness criteria.

The applicability of a task depends on the reliability of the item (Rausand & Vatn, 1998), the item’s failure characteristics and the type of task (SAE JA1012, 2002, MIL-STD-2173, 1986, Nowlan & Heap, 1978). Hence, any discussion about the applicability criteria should be related to each type of failure management strategy as follows.

Scheduled on-condition inspection (MSG-3: inspection/functional check): There are mainly five criteria which an on-condition task must satisfy (SAE JA1012):

a. There shall exist a clearly defined potential failure.

b. There shall exist an identifiable interval between the potential failure and the functional failure (the P-F interval), or failure development period.

c. The task interval shall be less than the shortest likely P-F interval.

d. It shall be physically possible to perform the task at intervals less than the P-F interval.

e. The shortest time between the discovery of the potential failure and the occurrence of the functional failure (the P-F interval minus the task interval) shall be long enough for predetermined action to be taken to avoid, eliminate, or minimize the consequences of the failure mode.

MSG-3 summarizes the applicability criteria for an inspection/functional check as: “Reduced resistance to failure must be detectable, and there exists a reasonably consistent interval between a deterioration condition and functional failure.” This gives reasonable guidance with slightly different wording which fulfils the criteria mentioned by SAE JA1012 when discussing task interval selection criteria.

Scheduled discard: Any scheduled discard task shall satisfy the following criteria to be applicable (SAE JA1012):

1. There shall be a clearly defined (preferably a demonstrable) age at which there is an increase in the conditional probability of the failure mode under consideration.
2-A sufficiently large proportion of the occurrences of this failure mode shall occur after this age to reduce the probability of premature failure to a level that is tolerable to the owner or user of the asset.

MSG-3 defines the discard task as: “The removal from service of an item at a specified life limit.” It summarizes the applicability criteria for a discard task as: “The item must show functional degradation characteristics at an identifiable age and a large proportion of units must survive to that age.” MSG-3 also gives reasonable guidance with slightly different wording which fulfills the criteria mentioned by SAE JA1012 when discussing task interval selection criteria. However, the literature where MSG-3 is used is different from SAE JA1012. For example, instead of “shall”, the word “must” is used. This may dilute the sentences and may affect the interpretation of the criteria by the user. However, as far as the concept and the main framework are concerned, in the opinion of the present authors, the words “shall” and “must” convey the necessity to the same degree, and MSG-3 meets the requirements of SAE JA1011 stated above.

Scheduled restoration: A scheduled restoration task that is selected shall satisfy the following additional criteria (SAE JA1012):

1-There shall be a clearly defined (preferably a demonstrable) age at which there is an increase in the conditional probability of the failure mode under consideration.

2-A sufficiently large proportion of the occurrences of this failure mode shall occur after this age to reduce the probability of premature failure to a level that is tolerable to the owner or user of the asset.

3-The task shall restore the resistance to failure (condition) of the component to a level that is tolerable to the owner or user of the asset.

MSG-3 defines a restoration as “that work necessary to return the item to a specific standard”. It summarizes the applicability criteria for a scheduled restoration as: “The item must show functional degradation characteristics at an identifiable age, a large proportion of units must survive to that age, and it must be possible to restore the item to a specific standard of failure resistance.” This, in addition to the reasonable guidance given in the “Task interval selection criteria” section, fulfills the criteria mentioned by SAE JA1012.

Scheduled failure-finding inspection (MSG-3: operational/visual check): Any failure-finding task that is selected shall satisfy the following additional criteria (SAE JA1012):

1-The basis upon which the task interval is selected shall take into account the need to reduce the probability of the multiple failure of the associated protected system to a level that is tolerable to the owner or user of the asset.

2-The task shall confirm that all components covered by the failure mode description are functional.

3-The failure-finding task and associated interval selection process should take into account any probability that the task itself might leave the hidden function in a failed state.

4-It shall be physically possible to perform the task at the specified intervals.

MSG-3 defines an operational check as “a task to determine that an item is fulfilling its intended purpose” and as a task which “[does] not require quantitative tolerances”; and a visual check is defined as “an observation to determine that an item is fulfilling its intended
purpose”. It summarizes the applicability criteria for operational and visual checks as: “Identification of failure must be possible.” This, in addition to the reasonable guidance given in the “Task interval selection criteria” section, fulfils the criteria mentioned by SAE JA1012.

Normally, answering applicability questions is quite clear-cut. However, answering the question of whether the task fulfils the objective according to the effectiveness criteria is a more complex issue. The effectiveness of a task is a measure of the result of the fulfilment of the maintenance task objectives, which is dependent on the failure consequences (MIL-STD-2173, 1986; Nowlan & Heap, 1978). In other words, the maintenance task’s effectiveness is a measure of how well the task accomplishes the intended purpose and the extent to which it is worth doing (Rausand & Vatn, 1998). In general, a preventive maintenance task must reduce the expected loss to an acceptable level, to be effective (Rausand and Hoyland, 2004). Hence, the discussion about the effectiveness criteria of each type of failure management strategy should be related to each type of failure consequence. Regardless of the lubrication/servicing tasks which are provided by MSG-3, there are some differences, as described below:

**Evident safety and environmental consequences:** MSG-3 does not consider environmental issues. It requires that the task “must reduce the risk of failure to assure safe operation”; whereas SAE JA1011 requires that the task “must reduce the risk of failure to a tolerable level”. MSG-3 applies the wording “safe operation” to express the need for safety assurance. However, the question is how much “safe operation” is tolerable. Fischhoff et al. (1981) claim that risk is never acceptable unconditionally. In fact, the goal is to eliminate risk, but it would be naive to believe that this may be achieved completely; hence, we will always face the acceptable risk problem (Vatn, 1998).

Here the analyst should answer the challenging question of “which option has higher value as a risk reduction measure” for attaining an acceptable level of safety, i.e. safe operation. In fact, safety and risk management should also be based on the performance of cost-benefit analyses to support decision making for safety investments and implementation of risk-reducing measures, to attain a specific level of safety. Cost-benefit analysis is seen as a tool for obtaining efficient allocation of resources, by identifying which potential actions are worth undertaking and in what fashion they should be undertaken. Aven and Abrahamsen (2007) argue that by adopting the cost benefit method the total welfare will be optimized. There is a need for acquiring some cost-benefit models to evaluate alternatives competing for investment to achieve an acceptable level of safety.

**Evident operational consequences:** One major difference in defining effectiveness criteria between SAE JA1012 and MSG-3 appears in this failure effect category. While SAE JA1012 requires that “over a period of time, the failure management policy must cost less than the cost of the operational consequences plus repair costs”, MSG-3 dictates, “The task must reduce the risk of failure to an acceptable level.” In fact, the decision should be based on cost-benefit analyses performed to support decision making for maintenance investments and implementation as risk-reducing measures. Hence, the need for considering cost-effectiveness criteria for the evident operational consequences category of failure effects arises.

**Evident non-operational consequences (economic):** Both SAE JA1012 and MSG-3 consider the cost of maintenance, and require that “[the] task must be cost-effective”; i.e. the cost of the task must be less than the cost of the failure prevented/repairing the failure.
Hidden safety and environmental consequences: As mentioned before, MSG-3 does not consider environmental issues. SAE JA1012 generalizes the requirements of effectiveness criteria for all types of failure management policy, and requires that “the task must reduce the risk of the multiple failures to a tolerable level”. However, MSG-3 separates the effectiveness criteria of operational or visual checks (failure-finding inspection) from other types of tasks. MSG-3 requires that, for operational or visual checks, “[the] task must ensure adequate availability of the hidden function to reduce the risk of a multiple failure”, and does not consider any tolerable or acceptable levels. For other types of tasks, MSG-3 requires that “[the] task must reduce the risk of failure to assure safe operation”. The same discussion as that presented for “evident safety and environmental consequences” is applicable here.

Hidden operational consequences: Another major difference in defining effectiveness criteria between SAE JA1012 (and other publications) and MSG-3 appears in the definition of the effectiveness criteria for the operational consequences category of hidden failure effects. While SAE JA1012 considers this failure effect category, and requires that “over a period of time, the failure management policy must reduce the probability of multiple failure (and associated total costs) to an acceptable level”, MSG-3 does not consider any operational consequence for hidden failures. An explanation of why this type of failure consequence is not considered removes confusion among analysts.

Hidden non-operational consequences (economic): SAE JA1012 requires that “over a period of time, the failure management policy must reduce the probability of multiple failure (and associated total costs) to an acceptable level”, whereas MSG-3 requires that the task “must ensure adequate availability of the hidden function in order to avoid economic effects of multiple failures and must be cost effective”. Although both SAE JA1012 and MSG-3 use different wording, the content of both statements is almost the same. However, the expression used by MSG-3 seems to be clearer and relevant in its context.

8. Summary and concluding remarks

The paper presented the issues and challenges of implementing MSG-3 for maintenance task development within the MRB process. A benchmarking has been performed between the MSG-3 and the RCM methodologies, and identified the area that MSG-3 differs, and suggests ways to facilitate and enhance the application of MSG-3.

In fact, the MSG-3 can be seen as a sibling of RCM introduced by SAE JA1011. The major difference between these two methodologies concerns the treatment of risk. For example, SAE RCM requires a consideration of both the consequences and the likelihood of failure in the identification of MSIs, while MSG-3 just considers the anticipated failure consequences. Furthermore, although the term “risk” is used within MSG-3 to address the applicability and effectiveness criteria, the risk treatment is not visible in the process and does not clearly indicate the acceptable level of risk. Another difference compared with SAE RCM, is that MSG-3 does not consider the environmental consequences of failures, and does not consider any operational consequences of hidden failures. Yet another difference in MSG-3, compared with SAE RCM, arises in the decision logic diagram, in that “no scheduled maintenance” is not included in the decision diagram, even though it is referred to in the document as a possible strategy for failures with non-safety consequences, if it is effective. Moreover, in MSG-3 an “operational check” (i.e. failure-finding inspection) has priority over all other maintenance strategies. However, in every other RCM-documentation, an “operational
check” is considered as a default action when other maintenance strategies are not applicable and effective.

To this end, one potential area of improvement has been found as modifying the decision diagram to fulfil the fundamental assumptions of the task hierarchy, and the requirements of cost effectiveness. More over, based on the differences between MSG-3 and SAE RCM outlined above, it would be beneficial to provide a guideline which gives a clear idea of the steps and clarifies the differences. This guideline should include a description of risk in an aviation maintenance context and the introduction of some methodologies, tools and criteria that support the identification, analysis and evaluation of risk. One example of a valuable tool would be a risk matrix that includes risk criteria for acceptance with regard to both probabilities and consequences. This support would facilitate the decision-process and promote a standardization of the analysis.

The use of MSG-3 methodology by the MRB allows an analysis of the initial maintenance requirements of the aircraft systems, to fulfil the requirements of continued airworthiness in a systematic way. However, MSG-3, like RCM, is not a “silver bullet” on its own, and its use does not guarantee that the decisions are correct. In fact, the MSG-3 procedure is a general description of steps and requirements. Hence, the description is on a rather high level that mainly describes “what” to include in the analysis and not a detailed description of “how” to carry it out. In order to achieve a more correct decision, further support should be employed by MRB. Examples are support in the identification of MSIs (i.e. risk, as described earlier), the assignment of task intervals (i.e. optimization), and selection of the most effective strategy among the applicable ones (e.g. Multi-Criteria Decision Making, MCDM).

Much information is provided and valuable expertise is available within the MRB process. However, decisions regarding maintenance task development are mainly based on the logic of the Maintenance Steering Group (MSG) methodology and the analysts rely heavily on experience of similar aircraft. Since the decisions that are made during the development of an initial scheduled maintenance programme strongly affect the aircraft’s safety, availability performance, and lifecycle cost, it is essential to acquire new supporting methodologies and refine the current use of expertise on the use of MSG-3, to increase the consistency of maintenance decisions.

There is no doubt that the MSG-3 methodology gives a practical and structured approach to achieving a recommended maintenance strategy to fulfil the requirements of continued airworthiness. However, from the air carrier’s point of view, there exists no sound foundation for claiming that the maintenance strategy derived from this approach is in any sense optimal and business-oriented. For example, it is obvious that MSG-3 does not allow any optimization with regard to cost for failures with operational effects. Furthermore, neither the costs associated with downtime due to maintenance nor the costs associated with aircraft loss production are considered. However, these costs are highly important from an operator’s point of view, as their ultimate goal is to make profit. In order to achieve an optimum maintenance programme from an operator’s perspective, it is necessary to have appropriate support that enables a linkage of the maintenance decisions to the overall business objectives. To support a more holistic and business-oriented view and meet the dependability requirements of today, the following two criteria can be added to the company’s approved maintenance programme objectives:

• to ensure realization of the inherent operational capacity at the lowest possible cost; and
• to assure customer goodwill and satisfaction.

In general, the major challenge to arrive at a more effective maintenance program within the MRB process are found as acquiring supporting methodologies and tools for adequate risk analysis, optimal interval assignments, and selection of the most effective maintenance task. To deal with these challenges and to meet the air carrier’s requirements of today, it is necessary to introduce decision-support solutions which assist both MRB report and company-approved maintenance programme development.

9. References


Dhilion, B.S. (2006), Maintainability, maintenance and reliability for Engineers, Taylor & Francis, USA.


NAVAIR 00-25-403 (2005), Guideline for the Naval Aviation Reliability-Centered Maintenance Process, Naval air system command, USA.


Paper II

Operational Risk of Aircraft System Failure

Operational Risk of Aircraft System Failure

A. AHMADI*, U. KUMAR and P. SÖDERHOLM

Division of Operation and Maintenance Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden

(Received on April 17, 2009, revised November 03, 2009)

Abstract: The purpose of this paper is to describe a methodology based on Event Tree Analysis (ETA) for identification of the possible operational consequences of aircraft system failures and their associated costs. The developed methodology uses scenarios to explain the adverse effects of failure on an aircraft’s operating capability, by an integration and correlation of key parameters and events that are driving factors in causing the ultimate state of aircraft operation. The methodology was developed through studies of consequence scenarios and risk estimations where empirical data were extracted through document studies and interviews. The paper also demonstrates the application of the methodology through a case study of a hypothetical commercial aircraft.

Keywords: Event tree analysis (ETA), Operational risk, Failure consequences, Aircraft maintenance, Maintenance programme, Operation interruption, MSG-3.

1. Introduction

Assessment of the operational consequences of known, or suspected, technical failures of aircraft systems and their associated costs is an essential input for identification of the potential failure modes and their impact on aircraft operation, to enhance the capability of taking correct decisions for maintenance task development. It is also essential to identify possible design modification requirements, and to perform an analysis of the maintenance tasks’ applicability and effectiveness.

However, during the development of an initial maintenance programme for a new aircraft, the identification and quantification of the operational risk of aircraft system failure is a great challenge. This is due to a long list of uncertainties related to the large number of contributory factors, the inadequacy of in-service information, and a lack of understanding of the influence of failures.

The purpose of this paper is to describe a methodology guided by the application of an Event Tree Analysis (ETA), for identification and quantification of the different operational risks caused by aircraft system failure. The paper suggests a definition of operational consequences of failures in aircraft operation and discusses different impacts of failure on the ground and in the air. The paper introduces key parameters that are driving factors in determining the ultimate state of the operational situation when a failure occurs, and deals with the actions required if the failure has an adverse effect on the aircraft’s operating capability.
The paper presents an improved and extended version of Ahmadi and Söderholm [1] with focus on methodology for consequence scenario development and failure-cost calculations.

2. Operational risk of failures

Risk can generally be defined as “a potential of loss or injury resulting from exposure to a hazard or failure”. It is an expression of the probability and the consequences of an accidental event [2].

\[
\text{Risk} = \text{Frequency} \times \text{Magnitude}
\]

The most important part of risk analysis is risk identification. Only those risks that have been identified can be managed in a systematic and conscious way. However, identification is not enough. There is also a need for action, using risk evaluation to take the appropriate operational and maintenance decisions regarding risk reduction and control, thus ensuring that the system stays in a safe state, regarding both the technical and the organizational parts [3,4].

To this end, Reliability Centred Maintenance (RCM) can be seen as a reliability and risk management methodology which seeks to identify the Maintenance Significant Items (MSI) and the applicable and effective preventive maintenance (PM) tasks. The applicability of PM tasks refers to the ability of those tasks to prevent or eliminate a failure, or at least reduce the probability of failure occurrence to an acceptable level, or reduce or mitigate the consequences of failure (the impact of failures). The PM task’s effectiveness is a measure of how well it accomplishes its purpose and the extent to which it is worth performing; i.e., whether or not it costs more than the failure(s) which it is intended to prevent [5,6,7].

The term consequence in this paper is defined in a very broad sense, and is used to mean all the events causing any type of loss, such as injury or loss of life, a high repair cost, the loss of a system, and delay or flight cancellation. Within civil aviation maintenance, the term “operational risk of failure” could be defined as “the possibility of losses arising due to aircraft technical failure, interrupting planned flight operation and making the aircraft mission incomplete”.

On the other hand, the term “operational risk of failure” can also convey the possibility of the occurrence of a failure with an operational effect, and how likely (or probable) such a consequence is. Hence, the first step in formal risk assessment is identification of the set of failure modes that may affect normal flight operation. For determining the failure modes and their effect, a functional block diagram or, as an alternative, the Failure Mode and Effects Analysis (FMEA) methodology can be used [2]. Then the analysis follows the following two steps (for each failure mode):

1. Consequence scenario development,
2. Risk estimation, which includes:
   a. Calculation of the rate of occurrence of possible consequence scenarios,
   b. Calculation of the expected (financial) loss due to the failure consequences.

3. Operational consequences of failures

In this paper, failure modes with possible operational consequences are defined as: “failure modes that might reduce the operating capability of the aircraft to meet the
intended functionality and performance requirements in the application in which the aircraft is operated”.

In general, failures affecting the aircraft’s flight altitudes, landing and flight distances, maximum take-off weight, and high drag coefficients, or failures affecting the routine use of the aircraft are also considered to have an adverse effect on the operating capability.

The effects of these failure modes interrupt the planned flight operations and interfere with the completion of the aircraft’s mission, and these operational interruptions are events by which the rate and quality of flight production are seriously affected. In aviation, the operational consequences can usually be expressed in terms of the inability to deliver services (e.g., to passengers) in a timely fashion.

These types of failures are potentially harmful to the normal scheduled operation of the aircraft, and could lead to consequences such as flight delays or cancellations, the additional cost of operational irregularities, and the cost of unplanned maintenance. When the operating capability is affected seriously, the flight crew might also have to refer to the crew check lists for abnormal occurrences or emergencies.

Failures with operational consequences may also cause different operational impact depending on whether the aircraft is on the ground or in the air. The impact on the ground may include delays related to flight dispatch, a ground turn-back (back to the gate), an aborted take-off, an aircraft substitution, and a flight cancellation. The impact in the air may include an in-flight turn-back, a diversion, a go-around, a touch-and-go landing, and re-routing. Hence, when such failures occur, they affect the rate and quality of flight production to different degrees. However, in the event of such a failure occurring, the correlation of many contributory factors can be used to recognize the ultimate state of an operation, and the extent to which the rate and quality of flight production have deviated from the pre-defined ones. Therefore, it is necessary first to identify the key contributory factors, and then to use a systematic methodology to illustrate the possible combinations of events, i.e., consequence scenarios.

4. Consequence scenario development

The goal is to identify the key parameters and events that contribute to the cause and effect relationship between the failure modes and the subsequent event progression. In fact, the integration and correlation of those parameters and events are a driving factor in causing the ultimate state of the operational situation and a factor determining the extent to which the rate and quality of flight production deviate. Through extensive studies of documents and interviews with experts, as well as the authors’ experience, the following key parameter has been recognized:

1. the nature of the failure, in terms of the adverse effects on the operating capability,
2. the possibility of the operating crew detecting the failure, during normal aircraft operation,
3. the phase of flight when the failure may occur,
4. the possibility of dispatching an aircraft with an inoperative item,
5. the possibility of continuing a flight with an inoperative item, and ultimately,
6. the pilot’s decision.

In fact, the combination of these six parameters determines 1) the extent to which operational action(s) is (are) required to keep the aircraft in operation, 2) the extent to which it is possible to postpone the maintenance action, or 3) whether or not it is necessary to restore the aircraft to its normal operating state immediately (see Figure 1).
In summary, the adverse effects of a failure on the operating capability may require the following actions which are proposed by the ATA MSG-3 document [8]:

- the correction of the failure prior to further dispatch; i.e., the failure needs immediate maintenance action,
- the use of an immediate operational procedure in flight, such as the activation or deactivation of a system,
- the imposition of operating restrictions such as a reduced flight altitude, and
- the use of abnormal or emergency procedures by the flight crew when the aircraft is airborne, e.g., an aborted take-off, an in-flight turn-back, a diversion, or a touch-and-go landing.

5. Proposed methodology for consequence scenario development

In order to illustrate the integration and correlation of the above-mentioned parameters and to develop possible consequence scenarios, Event Tree Analysis (ETA) was chosen as an appropriate methodology in this study.

One major reason for this selection is that ETA can be used to determine the likelihood and severity of a range of consequence scenarios, given different sequences of events. Moreover, ETA can be used for qualitative as well as quantitative reliability and risk analyses [9]. Hence, if sufficient data and information regarding the failure frequency and the probability of occurrence of each event are available, the frequency of occurrence of each consequence scenario can be calculated.

The ETA presented in this study starts with the identification of the initiating events (the first triggering event of the sequence), i.e., the failures of interest for further analysis. The consequences of the candidate failures are developed by considering the failure and success of two predefined main criteria and their included alternative states. The two main criteria displayed in the proposed event tree analysis are (see Figure 2):
1. The phase of flight operation when the failure occurs or is detectable. In this criterion five different states have been included, i.e., prior to take-off, take-off, climb, cruise, and approach and landing. In the real world, two different events may occur in each state; i.e., the failure either occurs or does not occur.

2. The adverse effect of the failure on the operating capability of the aircraft. In this second criterion, three different states have been included which indicate the extent to which the failure affects the operating capability of the aircraft, i.e., the deferability of the failure, the imposition of any operational restriction, or the use of abnormal or emergency procedures.

The first state of the second criterion, “the deferability of the failure”, indicates whether the failure is deferrable or if it requires an immediate action, e.g., performing corrective maintenance or following some specified operational procedures. Failures that are related to deferrable items are those that are non-critical with regard to aircraft safety; i.e., the aircraft can continue its normal flight with the failure present [10]. This can be identified through consultation of the Minimum Equipment List (MEL), the Flight Manual (FM), the Flight Crew Operation Manual (FCOM), or the Quick Reference Handbook (QRH). MEL advice is a Time-since-Fault repair strategy which involves a countdown being started towards the appropriate dispatch time. Once this countdown has reached zero, the fault must be repaired before further dispatch of the aircraft is allowed [11].

The second state of the second criterion, “the imposition of any operational restriction”, concerns the need to impose any operational restrictions, such as an altitude restriction, which are mandated by procedures or by a pilot decision. Finally, the third state of the second criterion, “the use of abnormal or emergency procedures”, refers to the application of some emergency or abnormal operation which is mandated by procedures or by a pilot decision. The analysis proceeds through all the alternative paths, by considering each consequence as a new initiating event (see Figure 2).

5.1 Results of the proposed ETA development

In Figure 3 it is shown how the combination of the occurrences of different events (Yes or No) within the states of the two criteria (the operational phase and the effect on the operating capability) will create different scenarios, which in turn will determine the ultimate operational consequences.

Based on the possible combination of events, 25 primary scenarios were identified which ultimately will lead to one or a combination of the following classes of consequences:

1. No operational consequence,
2. Ground delays (at departure and on arrival),
3. Airborne delays,
4. Emergency or abnormal operation, which may include:
   a. aborted take-off,
   b. in-flight turn-back, or
   c. diversion, go-around, and touch-and-go landing.
Out of the 25 different scenarios that were identified, there are six scenarios with no operational consequences. One of these scenarios is when a failure never occurs, i.e., scenario 25. The other five scenarios where no operational consequences occur are when the failure’s associated maintenance is deferrable and there are no necessary operational restrictions or abnormal procedures applied (see Figure 3 for scenarios 2, 6, 11, 16 and 21). There are also 14 event scenarios where the consequences are some sort of delay (i.e., scenarios 1, 3, 4, 5, 8, 9, 10, 13, 14, 15, 18, 19, 20, 23 and 24). Out of these scenarios, there are five where the operational consequences are manifested only as airborne delay (i.e., scenarios 1, 5, 10, 15, 20 and 23). These scenarios are connected to the occurrence of a failure which is related to deferrable maintenance, but which requires some operational restrictions. It has to be noted that this study has not taken into account the effect of failure which ultimately leads to higher fuel consumption or a loss of the ability to use the normal capacity of the aircraft as planned. Hence, these consequences are not included among the ultimate consequences. However, in future implementation of the proposed methodology, one could include them without any major changes in the proposed methodology. Abnormal procedures contributing to operational consequences have also been found in four scenarios (i.e., scenarios 7, 12, 17 and 22). All these scenarios are related to failures which need non-deferrable maintenance, which entail some sort of significant operational restriction, and which require emergency and abnormal procedures to be initiated by the flight crew. All of these events result in direct financial losses, such as additional costs related to the flight crew, the ramp and airport, the aircraft itself, and the passengers, and might lead to a loss of revenue if the failure effect leads to flight cancellation.

6. Risk estimation

The total operational risk is the sum of all the risks associated with the possible consequence scenarios in all the operational phases that have arisen from the proposed ETA. Hence, for a single component with a failure of type \( i \) and with \( n \) as the number of consequence scenarios, the total associated financial risk, \( R_{\text{Total}} \), can be calculated as:

\[
R_{\text{Total}} = \lambda \times \left[ \sum_{k=1}^{n} (P_i \cdot C_s) \right]
\]

(1)

where, \( R_{\text{Total}} \) = the expected financial risk of failure per flight hour (FH), \( \lambda \) = the rate of occurrence of failure per FH (a constant value), \( C_s \) = the cost of consequence scenario \( i \) (USD/consequence), and \( P_i \) = the probability of scenario \( i \). For a multi-consequence scenario, \( R_{\text{Total}} \) can be expressed as:
Consequently, the annual expected loss, i.e., the financial risk due to failure type \(i\), for the whole aircraft can be estimated as:

\[
R_{\text{Annual}} = R_{\text{total}} \times U \times N
\]

where \(U\) = the average annual utilization of the aircraft (FH/year), and \(N\) = the quantity per aircraft (QPA). This calculation can in turn easily be expanded for an aircraft fleet.

7. Verification of the proposed methodology

In order to verify the application of the proposed event tree, the example of a failure mode of an engine driven hydraulic pump (EDHP) of an aircraft hydraulic system has been selected. The example involves a hypothetical EDHP and aircraft, but it is still representative. The EDHP is used to provide a hydraulic pressure of 3500 ± 300 PSI for different systems, mainly the flight control, landing gears, and doors. The system has a highly redundant design with two EDHPs and two back-up electrically driven hydraulic pumps. One of the functional failures of the EDHP system can be defined as the “inability to provide the required hydraulic pressure” due to the failure mode “pump jammed”, with a failure rate of \(1.02 \times 10^{-4}\). If this failure occurs, a “low pressure” warning light turns on or a message appears on the cockpit display, so that the crew will be aware of the fault in any phase of flight. Hence, the failure is classified as an evident functional failure. Due to the high redundancy of the system, the failure does not have any direct adverse affect on safety. However, the failure will have a direct adverse effect on the operating capability. Therefore, according to the manufacturer’s advice and related regulations, the aircraft must be restored to its normal operating state by the maintenance crew immediately. Depending on the phase of flight during which the failure occurs, the failure situation may require the pilot to perform one of the following actions: a return to gate, an aborted take-off, an in-flight turn-back, or a diversion to another airport than the planned one. The outcome of the ETA for the hypothetical EDHP, the applicable values for each probability, and the average consequence cost, which has been gathered from expert opinions, are shown in Table 1, where \(P_1\) and \(P_2\) denote the probability of the first and second criteria in ETA, respectively. Using Equation 1 and Table 1, for a single EDHP, \(R_{\text{Total}}\) can be estimated as:

\[
R_{\text{Total}} = \frac{\lambda}{\text{Event USD Cost}} \times \text{Cost USD/Event} \times \text{As per Table 1:}
\]

\[
R_{\text{Total}} = \frac{1.02 \times 10^{-4}}{\text{(0.10),(0.35),(0.1),(0.2),(0.25)}} \times \begin{bmatrix} 8400 \\ 10300 \\ 11300 \\ 13500 \\ 8400 \end{bmatrix} = (1.05825 \text{USD/FH})
\]

Assuming 3,000 FH of utilization per year, the annual total consequence cost for the whole aircraft (two EDHPs, \(N = 2\)) can be estimated in accordance with Equation 2:

\[
R_{\text{Annual}} = R_{\text{Total}} \times U \times N = 1.05825 \times 3000 \times 2 = 6349.5 \text{ per Aircraft/Year}
\]
<table>
<thead>
<tr>
<th>Scenario No.</th>
<th>2: Effect of failure on operating capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Airborne delay</td>
</tr>
<tr>
<td>2</td>
<td>No operational impact</td>
</tr>
<tr>
<td>3</td>
<td>Airborne delay + Ground delay at departure</td>
</tr>
<tr>
<td>4</td>
<td>Ground delay at departure</td>
</tr>
<tr>
<td>5</td>
<td>Airborne delay</td>
</tr>
<tr>
<td>6</td>
<td>No operational impact</td>
</tr>
<tr>
<td>7</td>
<td>Aborted take-off + Ground delay at departure</td>
</tr>
<tr>
<td>8</td>
<td>Airborne delay</td>
</tr>
<tr>
<td>9</td>
<td>Ground delay on arrival</td>
</tr>
<tr>
<td>10</td>
<td>Airborne delay</td>
</tr>
<tr>
<td>11</td>
<td>No operational impact</td>
</tr>
<tr>
<td>12</td>
<td>In-flight turn-back + Ground delay on arrival</td>
</tr>
<tr>
<td>13</td>
<td>Airborne delay + Ground delay on arrival</td>
</tr>
<tr>
<td>14</td>
<td>Ground delay at arrival</td>
</tr>
<tr>
<td>15</td>
<td>Airborne delay</td>
</tr>
<tr>
<td>16</td>
<td>No operational impact</td>
</tr>
<tr>
<td>17</td>
<td>Diversion + Ground delay on arrival</td>
</tr>
<tr>
<td>18</td>
<td>Airborne delay + Ground delay on arrival</td>
</tr>
<tr>
<td>19</td>
<td>Ground delay on arrival</td>
</tr>
<tr>
<td>20</td>
<td>Airborne delay</td>
</tr>
<tr>
<td>21</td>
<td>No operational impact</td>
</tr>
<tr>
<td>22</td>
<td>Go around/Touch-and-Go/Aborted take-off + Ground delay on arrival</td>
</tr>
<tr>
<td>23</td>
<td>Airborne delay</td>
</tr>
<tr>
<td>24</td>
<td>Ground delay on arrival</td>
</tr>
<tr>
<td>25</td>
<td>No-operational impact</td>
</tr>
</tbody>
</table>

**Figure 3:** Proposed event tree for assessing the possible operational consequence scenarios caused by aircraft system failure.
Table 1: Probability and Cost Figures of Operational Consequences

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Phase of Flight</th>
<th>Probability of Scenario:</th>
<th>Candidate Failure Consequence(s)</th>
<th>Cost of event</th>
<th>Magnitude (Minutes)</th>
<th>Total cost of scenario (USD/event)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.4</td>
<td>Prior to take-off</td>
<td>0.10 1 0.10</td>
<td>Ground delay at departure</td>
<td>70 $/min.</td>
<td>120 min</td>
<td>8400</td>
</tr>
<tr>
<td>No.7</td>
<td>Take-off</td>
<td>0.35 1 0.35</td>
<td>Aborted take-off</td>
<td>1900 $/event</td>
<td>NA</td>
<td>10300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ground delay at departure</td>
<td>70 $/min.</td>
<td>120 min</td>
<td>8400</td>
</tr>
<tr>
<td>No.12</td>
<td>Climb</td>
<td>0.10 1 0.10</td>
<td>In-flight turn-back</td>
<td>2900 $/event</td>
<td>NA</td>
<td>11300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ground delay on arrival</td>
<td>70 $/min.</td>
<td>120 min</td>
<td>8400</td>
</tr>
<tr>
<td>No.17</td>
<td>Cruise</td>
<td>0.20 1 0.20</td>
<td>Diversion</td>
<td>5100 $/event</td>
<td>NA</td>
<td>13500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ground delay on arrival</td>
<td>70 $/min.</td>
<td>120 min</td>
<td>8400</td>
</tr>
<tr>
<td>No.22</td>
<td>Approach &amp; landing</td>
<td>0.25 1 0.25</td>
<td>Go-around</td>
<td>NA</td>
<td>N/A</td>
<td>8400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Touch &amp; go landing</td>
<td>NA</td>
<td>N/A</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Airborne delay</td>
<td>NA</td>
<td>N/A</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ground delay on arrival</td>
<td>70 $/min.</td>
<td>120 min</td>
<td>8400</td>
</tr>
</tbody>
</table>

8. Conclusions
The available standards regarding aircraft maintenance programme development (e.g., RCM) describe the steps required for their implementation on a general level. However, some steps, such as determining the risk of operational consequences of failures, which play a vital role in selecting an applicable and effective decision, have not been defined in detail. This paper aims at bridging this gap by outlining a proposed methodology for identification of the different operational consequences and associated costs of aircraft system failure due to technical interruption.

The paper describes the key parameters and events that contribute to the cause and effect relationship between a failure mode and the subsequent event progression. The description demonstrates how the integration and correlation of the key parameters and events determine the ultimate state of the operational situation.

In order to enhance the implementation of the proposed methodology, uncertainty analysis should be performed regarding the rate of occurrence of failure and all the ETA headings. Furthermore, the quality and adequacy of the required information should be considered. This information is mainly related to the failure rate, and the probability of occurrence of each event. Moreover, enough knowledge about the reliability and the maintainability performance of the analysed system is essential. Other information that is needed is related to the aircraft operation and associated procedures which are given in formal documents. Therefore, both the available data and the knowledge of the analyst who is performing the ETA play important roles in achieving accurate results.

References


Alireza Ahmadi is a Ph.D. candidate at the Division of Operation and Maintenance Engineering, Luleå University of Technology (LTU), Sweden. He has received his Licentiate degree in Operation and Maintenance Engineering in 2007. Alireza has more than 10 years of experience in civil aviation maintenance as licensed engineer, and production planning manager. His research topic is related to the application of RAMS to improve aircraft maintenance program development.

Uday Kumar is a Professor of Operation and Maintenance Engineering at Luleå University of Technology, Luleå, Sweden. His research and consulting efforts are mainly focused on enhancing the effectiveness and efficiency of maintenance process at both operational and strategic levels and visualizing the contribution of maintenance in an industrial organization. He has published more than 125 papers in peer reviewed international journals and chapters in books. He is reviewer and member of the Editorial Advisory Board of several international journals. His research interests are Maintenance Management and Engineering, Reliability and Maintainability Analysis, LCC, etc.

Peter Söderholm is an Assistant Professor at the Division of Operation and Maintenance Engineering, Luleå University of Technology (LTU). His research topics are risk, dependability, and application of Information & Communication Technology (ICT) within maintenance, mainly within aviation. He received his M.Sc. degree in 2001 in Mechanical Engineering and PhD in Operation and Maintenance Engineering in 2005, from LTU.
Ahmadi, A. and Kumar, U. (2010), Cost based risk analysis to identify inspection and restoration intervals of hidden failures subject to aging. Accepted for publication in: *IEEE Transaction on Reliability.*
Cost based risk analysis to identify inspection and restoration intervals of hidden failures subject to aging

Alireza Ahmadi and Uday Kumar

Abstract—This paper aims to develop a cost rate function (CRF) to identify the optimum interval and frequency of inspection and restoration of aircraft’s repairable components which are undergoing aging and whose failures are hidden, i.e. are detectable by inspection or upon demand. The paper considers two prevalent strategies, namely Failure Finding Inspection (FFI) and a combination of FFI with restoration actions (FFI+Res), for both the “non-safety effect” and the “safety effect” categories of hidden failures. As-bad-as-old (ABAO) inspection effectiveness and as-good-as-new (AGAN) restoration effectiveness are considered. In case of repair due to findings by inspection, as-bad-as-old repair effectiveness is considered.

The proposed method considers inspection and repair times, and takes into account the costs associated with inspection, repair and restoration, and the costs associated with a hidden function (as a result of an additional failure or second failure, i.e. a trigger event), or until a specific operational check, test or inspection is performed. Hidden failures are divided up into the “safety effect” and the “non-safety effect” categories. The failure of a hidden function in the “safety effect” category involves the possible loss of the equipment and/or its occupants, i.e. a possible accident. The failure of a hidden function in the “non-safety effect” category may entail possible economic consequences due to the undesired events caused by a multiple failure (e.g. operational interruption or delays, a higher maintenance cost, and secondary damage to the equipment). As a common practice in aviation maintenance, hidden failures

I. INTRODUCTION

One aspect of maintenance programme analysis is to develop tasks to preserve and assure the availability of hidden functions (or off-line functions). These types of functions are used intermittently or so infrequently that their failure will not be evident to the operating crew during the performance of normal duties [1]. Examples are the failure of a pressure relief valve, ram air turbine, fire detector, fire extinguisher or standby radio. Termination of the ability to perform a hidden function is called hidden failure.

Hidden failures are not known unless a demand is made on the hidden function (as a result of an additional failure or second failure, i.e. a trigger event), or until a specific operational check, test or inspection is performed. Hidden failures are divided up into the “safety effect” and the “non-safety effect” categories. The failure of a hidden function in the “safety effect” category involves the possible loss of the equipment and/or its occupants, i.e. a possible accident. The failure of a hidden function in the “non-safety effect” category may entail possible economic consequences due to the undesired events caused by a multiple failure (e.g. operational interruption or delays, a higher maintenance cost, and secondary damage to the equipment). As a common practice in aviation maintenance, hidden failures
are analyzed as part of a multiple failure and are considered as failures that do not have any undesirable consequence when they occur on their own. A multiple failure is defined as “a combination of a hidden failure and a second failure or a demand that makes the hidden failure evident”[1]. Since the arrival of a demand occurs at random, it is essential that the item should be operative, i.e. available, upon demand. Hence, depending on the criticality and consequences of multiple failures and the demand rate, a specific level of availability of the hidden function is needed. When the item is in a non-operational state when required to function, then it is termed unavailable [2]. Obviously, the probability of a multiple failure can be reduced by reducing the unavailability of the hidden function. For highly reliable systems it is often more appropriate to focus on unavailability rather than on availability [3]. If a hidden failure (undetected failure) occurs while the system is in a non-operating state, the system’s availability can be influenced by the frequency at which the system is inspected. If inspection finds the system inoperable, a maintenance action is required to repair it [4].

A common practice in aircraft maintenance programme development, ATA MSG-3 [5] is used to develop scheduled aircraft maintenance requirements. According to MSG-3, it is required to define a scheduled “failure finding inspection (FFI)” to detect the functional failure that has already occurred, but was not evident to the operating crew. FFI aims to assure the availability of a hidden function and to eliminate or reduce the probability of occurrence of multiple failures [5]. In some instances it may not be possible to find a single FFI task which on its own is effective in reducing the risk of failure to a tolerable level. In these cases it may be necessary to employ a combination of tasks such as FFI and scheduled restoration. Each of these tasks must be applicable in its own right and in combination they must be effective. In practice, a combination of tasks is rarely used, and is considered for failures with safety consequences, as a stopgap pending redesign [1]. However, as the present study shows, depending on the characteristics of the failure, the mode of maintenance execution and the cost parameter, selecting a combination of tasks may result in a more effective strategy even for the “non-safety effect” failure category. This may be due to the complexity of decision making and task interval development.

Hence, all the available maintenance opportunities should be analyzed and the ultimate decision should be based on cost-benefit analyses made to select the most cost-effective strategy among applicable options. These challenges can be addressed more accurately by quantitative models. Some studies relevant to the optimization of Failure Finding Inspection can be found through literatures. Some of the relevant literatures are presented in the following paragraphs.

Jardine [6] proposed a model considering AGAN inspection and repair effectiveness, and the known and constant inspection time (T_i) and repair time (T_r). The AGAN assumption for inspection and repair is reasonable when there is no trend in the data [7, 8]. In this case the average unavailability of the unit is the same in subsequent intervals.

Vaurio [9], [10] studied the time-dependent unavailability of standby units under ageing in a nuclear power plant, considering different inspection and repair effectiveness. A general formalism has been developed for selecting the economically optimal test and maintenance intervals, with replacement policy constraints. Furthermore, Vaurio [11] extended his previous studies and developed unavailability and cost models for normal operating units subject to hidden failure and periodically inspected and maintained, considering “like-old” tests and “like-new” repairs.

A common practice in aviation maintenance is to ground the aircraft, i.e. stop the flight operation, to perform maintenance. Grounding the aircraft also entails costs for the airline, and hence one needs to consider inspection and repair times and include their effect in the optimization model.

Rausand and Vatn [12] discussed the consequences of choosing a Weibull life distribution instead of an exponential distribution when calculating the unavailability of hidden functions for a surface-controlled subsurface safety valve in an offshore oil and gas production well. They used the Mean Fractional Dead Time (MFDT) concept to estimate the unavailability of hidden function within inspection intervals. They proposed age-based replacement policies to balance the risk and operational cost on the basis of calculations using a Weibull distribution in which attention was paid to the integration between the proposed replacement policies and the work entailed by the replacement policy constraints. They considered the component to be as-good-as-new after replacement and disregarded test and replacement time. Inflation and other financial effects were regarded as negligible.

Barroeta and Modarres [13] studied the optimal inspection policy for periodically tested repairable components undergoing an aging process, in combination with an overhaul after a certain number of inspections using a so-called cost rate function. They considered the condition of the components to be as-good-as-old after inspection/testing and repair and as-good-as-new after an overhaul, i.e. after a renewal process. They assume that the test and repair time may increase after every test cycle, and that the associated cost of overhaul and the possible loss due to the unavailability of the component (the cost of an accident) are constant. Inflation and other financial effects are negligible. However, risk limits were not considered.

More recently, Lienhardt et al. [14] also studied the problem of selecting a suitable failure finding maintenance strategy for a repairable aircraft system that is subject to hidden failures that do not have any operational consequences, i.e. do not interrupt aircraft operation when they occur, such as the failure of warning devices. They developed an optimization model based on the Markov model, considering the maintenance cost rate as an objective function and using the risk of corrective maintenance as the constraint function. They applied their model for a constant failure rate, i.e. exponential distribution of failure, or a random type of failure.

Since, in practice, performing all the individual maintenance tasks at their own optimal intervals is not practical, the method presented in this paper aims to provide an optimization-based decision support, to enhance the
capability of taking correct and effective decisions for maintenance interval assignment, in accordance with the predefined intervals in a form of check package e.g. the A1, A2, B, C, or D check packages, a common terminology used in aviation industry.

The method presented in this paper is based on the cost rate function (CRF) and identifies the optimum interval and frequency of inspection and restoration that minimize the cost per aircraft flight hour. It considers two prevalent strategies, namely Failure Finding Inspection (FDI) and a combination of FFI with restoration actions (FFI+Res), for both the “non-safety effect” and the “safety effect” categories of hidden failures.

The proposed method considers as-bad-as-old (ABAO) inspection and repairs (due to failures found by inspection) and as-good-as-new (AGAN) effectiveness for restoration actions. It considers inspection and repair times, and takes into account the costs associated with inspection, repair and restoration, the opportunity cost of the aircraft’s lost production due to inspection and repair time (maintenance downtime), and also the cost of accidents due to the occurrence of multiple failure, in order to arrive at the applicable and most cost-effective maintenance intervals.

In this study we use analytical and graphical methods to identify the optimum maintenance intervals and to decide which check package is the most appropriate option. However, the approximations and model presented by Vaurio [9] for the FFI strategy, which were found practical to apply for aircraft application with consideration of the opportunity cost of the aircraft’s lost production due to maintenance downtime. This adopted model is used for cross-checking with the results obtained by the graphical methods, and for validation in this context. Moreover, instead of the average time unavailability, which was used by Vaurio [9] for risk constraint optimization, the Mean Fractional Dead Time (MFDT) is used, which is proposed by Rausand and Vatn [12].

II. REPAIRABLE UNITS AND PROBABILISTIC MODELS

A repairable system is a system which, after failing to perform one or more of its functions satisfactorily, can be restored to fully satisfactory performance by any method other than replacement of the entire system [15]. The quality or effectiveness of the repair action is categorized as [15], [16], and [17]:

1) Perfect repair i.e. restoring the system to the original state, to a “like-new” condition,
2) Minimal repair, i.e. restoring the system to any “like-old” condition,
3) Normal repair, i.e. restoring the system to any condition between the conditions achieved by perfect and minimal repair.

In fact, based on the quality and effectiveness of the repair action, a repairable system may end up in one of the following five possible states after repair [15], [16], and [17]:

1) as good as new;
2) as bad as old;
3) better than old but worse than new;
4) better than new;
5) worse than old.

While perfect repair rejuvenates the unit to the original condition, i.e. to an as-good-as-new condition, minimal repair brings the unit to its previous state just before repair, i.e. an as-bad-as-old condition, and normal repair restores the unit to any condition between the conditions achieved by perfect and minimal repair, i.e. better than old but worse than new condition. However, states four and five may also happen. For example, if through a repair action a major modification takes place in the unit, it may end up in a condition better than new, and if a repair action causes some error or an incomplete repair is carried out, the unit may end up in a worse-than-old condition.

Failures occurring in repairable systems are the result of discrete events occurring over time. These situations are often called stochastic point processes [17]. The stochastic point process is used to model the reliability of repairable systems, and the analysis includes the homogeneous poisson process (HPP) renewal process (RP), and the non-homogeneous Poisson process (NHPP).

A renewal process is a counting process where the interoccurrence times are independent and identically distributed with an arbitrary life distribution [16]. Upon failure, the component is thus replaced or restored to an as-good-as-new condition.

The NHPP is often used to model repairable systems that are subject to a minimal repair. Typically, the number of discrete events may increase or decrease over time due to trends in the observed data. An essential condition of any point process is that the probability of events occurring in any period is independent of what has occurred in the preceding periods. Therefore, an HPP describes a sequence of independently and identically distributed (IID) exponential random variables. Conversely, an NHPP describes a sequence of random variables that are neither independently nor identically distributed. The NHPP differs from the HPP in that the rate of occurrences of failures varies with time rather than being a constant. The renewal process as well as the NHPP are generalizations of the HPP; both having the HPP as a special case [16].

To determine whether a process is an HPP or NHPP, one must perform a trend analysis and serial correlation test to determine whether an IID situation exists [7]. Recently the generalized renewal process (GRP) also is introduced to generalize the third point processes discussed above [16].

The failure of a component may be partial, and the repair work performed on a failed component may be imperfect. Therefore, the time periods between successive failures are not necessarily independent. This is a major source of trend in the failure rate. Furthermore, repairs made by adjusting, lubricating, or otherwise treating component parts that are wearing out provide only a small additional capability for further operation, and do not renew the component or system. These types of repair may result in a trend of increasing failure rates [17].

Experience shows that, for many of the aged repairable units, the IID assumption is contradicted in reality. Different approaches are introduced to model the probability of failure for a non-IID data set, and in the present study the power law process has been selected. The utilisation of a power
law process to describe the data set is not contradicted. For a test of the power law process, readers are referred to [7].

In this study, minimal repair is considered, and hence the unit returns to an "as-bad-as-old" state after inspection and repair actions. On the other hand, the component keeps the operating state, the system availability can be influenced by the frequency at which the system is inspected. Note that inspection, cannot improve reliability, but can only improve function availability [4].

According to Ebeling [4], Vaurio [9], and Rausand and Vatn [12], the function availability at time "t" within the Nth inspection cycle is equal to the conditional reliability i.e. R_0(t) (see Eq. 3), and respective function unavailability is corresponds to the conditional function probability i.e. F_0(t) (see Eq. 4).

Consequently, the average unavailability within the Nth inspection cycle with inspection at every "T" time, i.e. MFDT_{T,N}, is given by [10], [12]:

\[ \text{MFDT}_{T,N} = \frac{\int_0^T F_N(t) \, dt}{T} \]

Fig. 1 illustrates an example of the point and average interval unavailability behaviour of a typical hidden function in a period of operating time (e.g. 5500FH), when the function is tested at each "T" interval (e.g. 500FH). As is shown, when there is an aging effect, i.e. β>1, the MFDT increases in subsequent inspection cycles (see Fig. 1).

IV. PROPOSED ANALYTICAL MODEL

Fig. 2 shows the schematic description of a maintenance

![Figure 1: Variation of MFDT over time, for T=500FH, α=1200 and β=1.5](image-url)
event. The aircraft must be grounded to perform the inspection task after the accumulated “T” flight hours (FH). The first inspection is performed after “T” FH, and consequently the Nth inspection will be performed after “N.T” operating hours. The inspection task takes T_I hours and, in the case of a finding which leads to a repair, the repair takes T_r hours. Hence, an inspection cycle includes T, T_I and T_r. An expected operating time, “T_k”, is divided into K inspection cycles with the interval T, so that T_k=K.T.

In view of an operating time of T_k, we are interested in identifying the optimum maintenance task interval (T) and frequency (K) that will minimize the cost per flight hour, for both the “non-safety effect” and the “safety effect” failure category under the following two strategies:

- Failure Finding Inspection (FFI),
- A combination of FFI and restoration action (FFI+Res).

The analytical model presented in this paper is based on the following assumptions:

1) The failures are not evident to the operating crew and are only detectable by inspection or demand, and hence do not interrupt the aircraft operation when they occur.
2) The function of the proposed unit is not available during the inspection and repair time.
3) The failures are completely detectable by inspection/testing.
4) The component is functional after Inspection/repair, and restoration.
5) The failures associated with normal operation of the aircraft are considered in the unavailability and cost model. Inspection, repair, and restoration actions do not create failure by the nature of the tasks themselves and through the maintenance crew. Common-cause failures, originating in design and manufacturing, or caused during a demand challenge (initiating events), are not considered.

A common practice in aviation is to identify the maintenance tasks’ cost per operating flight hour. The following cost parameters are considered for cost modelling:

1) Direct cost of inspection task, C_i. This is considered as a deterministic value and constant in consecutive inspection cycles.
2) Direct cost of possible repair due to a finding, C_r. As the system is undergoing aging, the probability of failure will change in consecutive inspection cycles. Hence, the expected repair cost within the Nth inspection cycle can be estimated as C_r.F_T(T).
3) Cost of restoration, C_{res}. This is a constant and deterministic value which includes the direct cost of restoration and the respective indirect costs of shipping, man-hours, etc.
4) Cost of an accident, due to multiple failures, C_a. The expected value of C_a in the Nth inspection cycle depends on the expected time during which the function is not available between two inspections, “MFD_T(T),” and the demand rate for the unit, ϕ, i.e. “C_a. ϕ. MFD_T(T).” For the “safety effect” category of hidden failure, C_a refers to the cost of accidents, e.g. the possible loss of the equipment and/or its occupants, while for the “non-safety effect” category, C_a refers to the cost of undesired consequences of failure, e.g. a higher maintenance cost or secondary damage to the equipment, due to the occurrence of a multiple failure.
5) Opportunity cost of the aircraft’s lost production, C_{oc}. This cost is associated with the total aircraft downtime due to inspection and repair, i.e. T_I and T_r (constant values). As F_S(T) changes in consecutive inspection cycles, the expected value of the opportunity cost of the aircraft’s lost production can be estimated as C_{oc}[T_I + T_r.F_S(T)].

Summing up, CRF for the Nth inspection cycle under the FFI strategy can be expressed as:

$$CRF_N = C_i + C_r.F_T(T) + C_{res}[T_I + T_r.F_S(T)] + [C_a. ϕ. MFD_T(T)]$$

Consequently, the CRF for “K” series of inspection cycles and performing one restoration at T_k can be estimated as:

$$CRF_k = \frac{C_i + C_r.F_T(T) + C_{res}[T_I + T_r.F_S(T)] + [C_a. ϕ. MFD_T(T)]}{K}$$

A. Limiting values

If the number of inspections tends to infinity (K→∞), then the following value for CRF can be expected:
The practical approach is to identify the CRF for different values of T and K.

Moreover, comparing Fig. 3 and 4, it is evident that under the FFI+Res strategy, there are always a specific K and a specific T that result in an absolute minimum value of CRF.

It is evident from the figures that for all the values of CRF which are less than CRF (FFI), CRF (FFI+Res) is the same for all the values of T, and the CRF does not depend on the values of T and K.

When there are no undesired consequences, i.e. CA, then the CRF limit will be equal to the cost of an accident, i.e. “CA”. Else the CRF limit can always be found for all the values of T and K.

When the inspection interval tends to infinity, i.e. (K→∞), the limit CRF does not depend on T and K.

When there are no undesired consequences, i.e. CA=0, in the long run, the limit CRF tends to a value of Cf + Cc + Ci (Tf + Ti). For example, in Fig. 3 and 4, for T=1000, at K=1000 (i.e. T.K=1000000FH), the CRF will be equal to $0.19722$, which is very close to the corresponding “LIM CRF”, i.e. $0.2$, that is obtained from Eq. 9.

When the inspection interval tends to infinity (T→∞), then the CRF limit will be equal to the cost of an accident, i.e. “CA φ”.

An important conclusion is that the selection of values that result in the absolute minimum will decrease the CRF dramatically for the long-term operation of fleets of aircraft, as shown in Fig. 4.

B. Optimum interval

As seen in Fig. 3, for each number of inspection cycles, “K”, there will be an inspection interval, “T”, which may minimize the cost per unit of time.

However, to find the optimal inspection interval, a practical approach is to identify the CRF for different values of T versus the operating time, T0, which we are considering as the unit life. Then, considering an expected operating time, “T0”, (e.g. 20000FH), for the unit, it is possible to compare the CRF associated with different T values, and to select the optimal T among the results.

Some adjustment is needed for Eq. 8, so that CRF can be derived as a function of the inspection interval “T” and the operating time “T0” as follows:

1) In fact, the operating time “T0” is divided into K inspections with the interval T, so that T0 = K.T.
2) The following equations are valid under certain conditions for F0(T), as proved by Vaurio [9]:
comparison, considering the arbitrary values of \( \alpha = 10000 \) and \( \beta = 3 \). As is shown in the figures, up to \( T_K = 10000FH \) (the operating time), the estimation is fairly good, but afterwards the deviation is visible even in the graph. It should be noted that this estimation depends on the value of \( \alpha \) and \( \beta \). For larger \( \alpha \) and smaller \( \beta \) values, the \( H(T_K) \) and \( F(T) \) become more close and tend to lead to more accuracy in the estimation, while smaller \( \alpha \) and larger \( \beta \) values tend to lead to more deviation in the estimation. Moreover, selecting larger \( T \) values increases the inaccuracy in the estimation.

Likewise, using the method introduced by Vairro [9], by substituting Eq. 10 and 11 into Eq. 8, and denoting \( T_K \) as the optimum inspection interval, \( T_{op} \), that can minimize the CRF, by a fixed operating time, \( T_K \) (FH), can be found through this derivative:

\[
\frac{dC_{RFTK}}{dT} = 0
\]

This leads to:

\[
T_{op} = \left[ \frac{2T_K (C_i + C_{oc} T_i)}{C_{oc} \phi(T_H T_K)} \right]^{1/2}
\]

It is obvious that \( T_{op} \) does not depend on \( C_{Res} \), because considering a fixed \( T_K \) value means that we will perform the restoration task at \( T_K \) and this does not change the order of the optimal intervals for both the FFI and the FFI+Res strategies. Moreover, by increasing \( T_K \) the optimum inspection interval, \( T_{op} \), decreases, as \( H(T_K) \) changes faster than \( T_K \), and by decreasing \( T_K \), \( T_{op} \) increases. It is also obvious that, for any specific values of \( T_K \), there will be an inspection interval, \( "T" \), that will minimize the cost per unit of time for a specific operating time, \( T_K \). It is also evident that, as \( C_i \), \( C_{oc} \), or \( T_i \), increases, \( T_{op} \) tends to increase, meaning that the aircraft will have less ground time (see Fig. 5c).

V. TASK INTERVAL SELECTION FOR THE “NON-SAFETY EFFECT” CATEGORY OF HIDDEN FAILURE

In the case of the “non-safety effect” category of failure, MSG-3 [5] requires the introduction of a task to assure the availability of the hidden function necessary to avoid the economic consequences of multiple failures. It must also be cost-effective, meaning that the cost of the maintenance task should be less than the economic effect of the multiple failures.

A. FFI strategy for the “non-safety effect” category

Setting \( C_{Res} = 0 \) in Eq. 12, leads to the CRF\(_{T,K} \) for the FFI strategy only.
Fig. 6b shows that the CRF is not sensitive around the absolute $(T, K)$ changes faster than $T_k$, hence the CRF under the FFI strategy is increasing function of $T_k$ meaning that by increasing the operating time, CRF will increase.

In accordance with Eq. 13 and considering a target operating time of $T_k=20000FH$, with the selected values of $a=10000$, $\beta=3$, $C_a=1$, $C_b=10$, $C_c=100$, $C_{res}=100$, $T_0=0.2$ and $T_{op}=0.7$, the optimum inspection interval will be estimated to $T_{op}=387FH$, which leads to $CRF=60.209$ with $K=52$ [20000/387=51.67].

In Fig. 6a, $K$ and $T$ in Eq. 14 have been changed to illustrate the variation of CRF versus the operating time, $T_k$, for different values of the inspection interval $T$, based on the arbitrary values used in the previous example. Fig. 6b also shows the respective CRF of different inspection intervals shown in Fig. 6a, considering $T_k=20000FH$. As shown, for an operating time of $T_k=20000FH$ and the above selected values, the optimum inspection interval is "$T_{op}=450FH$", which leads to $CRF=60.2042$ with $K=44$ [20000/450=44.44]. The difference between the result obtained from Eq. 13 and that obtained from the graphical method is due to the overestimation of $H(T_k)$ in Eq. 13, which was discussed in the previous section. However, as Fig. 6b shows, the CRF is not sensitive around absolute $T_{op}$ (i.e. $450FH$), meaning that a range of inspection intervals, i.e. $T_{op}$ [350FH-600FH], is reasonably acceptable. Hence, the result obtained from Eq. 13 is quite satisfactory in a sense that it helps us to find the area of optimum inspection intervals.

In fact, the properties of $T_{op}$ [350FH-600FH] help us to decide which check package (e.g. $A_1=250FH$, $A_2=500FH$, $B=1000FH$, $C=5000FH$, or $D=10000FH$) is more appropriate for inclusions of the inspection and restoration tasks in the check. As these tasks will be performed along with the other tasks included in the check package, the related cost downtime will be reduced, which will also reduce the cost associated with the maintenance downtime and will ultimately reduce the CRF more.

Summing up, since the results show that the cost rate of performing FFI is less than the economic effect of failure, i.e. $\phi_iC_{res}=1USD$, the performance of this task is effective. Moreover, in accordance with the range of $T_{op}$ [350FH-600FH], including the task in the $A_2$ check package is reasonable; hence, the following task will be selected:

- Performing an inspection at every $A_2$ check, i.e. "$T=500FH$"

### B. FFI+Res strategy for the "non-safety effect" category

Setting the value for $C_{res}$ in Eq. 12 leads to the identification of CRF for the FFI+Res strategy. This gives the optimum inspection interval in a situation where we perform $K$ inspections and carry out one restoration at $T_k$. In trade-off analysis it is of interest to identify which combination of the inspection interval, $T$, and the numbers of inspection, $K$, generates the lowest CRF among all the combinations of $T$ and $K$.

In order to find the most optimum combination of $T$ and $K$, which generates the absolute minimum CRF, a joint optimization based on both $T$ and $K$ is needed. However, in order to simplify the task analysis process, we prefer to apply a graphical method to identify the most optimized combination of $T$ and $K$.

Fig. 7 shows the variation of CRF with the different numbers of inspections, $K$, for different $T$ values, based on the arbitrary values used in the previous section and considering $C_{res}=11000$. Likewise, Fig. 8 also shows CRF versus inspection intervals, $T$, for different numbers of inspection cycles. According to the figures, it is evident that, for any selected value of $T$, there are specific numbers of inspections, $K$, which in combination with a restoration task lead to a minimized CRF. However, as is shown, there are also combination of $T$ and $K$ that generate an absolute minimized CRF under the FFI+Res strategy. As shown in Fig 7, it is obvious that the CRF is not sensitive around the absolute optimum $K$.

Fig. 9 also shows the variation of CRF versus the operating time "$T_k$" for different inspection intervals, $T$, based on the arbitrary values used in the previous figures. According to the figures, selecting $T=950FH$ and a restoration after 10 inspections, i.e. at $T_k=9500FH$, leads to $CRF=60.1893$.

Fig. 10 shows the optimum values of CRF obtained from Fig. 8 versus the respective $T$ values. As the figure shows, the CRF is not sensitive around $T_{op}$. This means that, for planning purposes and task packaging, a range of $T_{op}$ [700FH-1150FH] with the respective values of $K$ can be considered when deciding which check package (e.g. $A_1=250FH$, $A_2=500FH$, $B=1000FH$, $C=5000FH$, or $D=10000FH$) is more appropriate for inclusion of the
inspection and restoration tasks. Table I shows the candidate options which are more appropriate in accordance with the check package options.

Summing up, the results gained under the FFI and FFI+Res strategies show that the cost rate of performing both strategies is less than the economic effect of failure, i.e. $\frac{q \cdot C_D}{1\text{USD}}$. Moreover, Option 5 is suitable for inclusion of the inspection task in the B check package and the restoration task in the D check package, as increasing the number of inspections by “1” does not affect CRF (see Fig. 8). Hence, the following tasks will be selected:

1) Performing an inspection at every B check, i.e. “$T=1000\text{FH}$” and,
2) Performing a restoration task at the D check, i.e. “$T=10000\text{FH}$”.

In fact, at the D check, the unit will be restored and the function will return to an as-good-as-new condition. However, the following issues should be considered in decision making:

1) The cost of holding a spare part for replacement and the possible cost for the unavailability of spares during inspection.
2) The possibility of performing restoration in-house and the investment cost involved.

Comparing all strategies, if the economic penalties are still high, then redesign may be considered as an option in cost-effectiveness analysis, to reduce or avoid the probability of multiple failures. The options for redesign may include the incorporation of alerting or warning devices, to make the failure evident to the operating crew, the inclusion of built-in tests or automated test capability to reduce the maintenance downtime, increasing the redundancy level, or incorporating some prognostic health management into the unit or the whole system.

VI. TASK INTERVAL SELECTION FOR THE “SAFETY EFFECT” CATEGORY OF HIDDEN FAILURE: A RISK-CONSTRAINED OPTIMIZATION

In the case of the “safety effect” category of failure, MSG-3 requires the introduction of a task to limit the probability of multiple failures, i.e. the task must ensure adequate availability of the hidden function to reduce the risk of a multiple failure. Moreover, the policies of Civil Aviation Authorities or airlines may set additional conditions to limit the risk of failure which applies further than cost consideration.

For example, major failure conditions must be no more frequent than improbable (remote) failure conditions to each airplane during its total life. Improbable (remote) failure conditions are those having a probability which is in the order of $1 \times 10^{-7}$ or less, but which is greater than $1 \times 10^{-5}$ [18].

The acceptable risk problem should be solved by combining the acceptance criteria with the so-called ALARP (as-low-as-reasonably-practicable) principle. The idea here is that the company should define values for unacceptable probabilities of certain undesired events. To verify ALARP,
different tools are being used, including cost-benefit analysis and cost-effectiveness analysis [12], [19].

Hence, risk analysis is needed to reveal whether the risk of failure is below the specified limit by using a selected inspection interval, “T”. Considering Rmax as the maximum allowable limit for the probability of multiple failures, then the optimization process needs to minimize the cost rate function under the following supplementary constraint:

\[ \phi \cdot \text{MFDT}_{ij}(T, K) \leq R_{\text{max}} \Rightarrow \text{MFDT}_{ij}(T, K) \leq \frac{R_{\text{max}}}{\phi} \]

Hence,

\[ 1 - e^{-\frac{\text{MFDT}_{ij}(T, K)}{\phi}} \leq \frac{R_{\text{max}}}{\phi} \tag{15} \]

Therefore, one needs to verify T that satisfies Eq. 15 for any candidate values of \( \phi, R_{\text{max}} \), and the expected operating time \( T_x \) (e.g. 20000FH). Considering a specific operating time \( T_x \) (e.g. 20000FH), one needs to verify values for T and K that satisfy Eq. 15, for any candidate values of \( \phi, R_{\text{max}} \).

Fig. 11 shows the variation of MFDT over time, for different values of T, with MFDT_{max}=0.15. As is shown, if the unit is expected to be operated for example \( T_x=20000FH \), different combination of T and K, can be selected which satisfies MFDT_{max} (e.g. \( T=150, K=133; T=250 \) and \( K=80; T=270 \) and \( K=74 \)). However, in interval selection, the combination which generates the lowest CRF should be selected.

A. FFI strategy for the “safety effect” category

Assuming a maximum limit for MFDT, the objective is to identify values for T and K, which generates the lowest possible CRF that satisfies (MFDT)_{max}, if the unit is going to be used for an expected operating time \( T_x \) (e.g. 20000FH).

Fig. 12 shows the CRF and the average interval unavailability behaviour (MFDT) versus operating time \( T_x \) for different values of T, based on the arbitrary values selected for Fig. 6, in which MFDT_{max} is set to 0.15.

It is obvious that the MFDT for T=450FH, which was selected for the “non-safety effect” category, exceeds the MFDT_{max} after \( T_x=15750FH \), i.e. after the 35th inspection, and the risk of multiple failure will then be higher than the allowable limit, meaning that T=350 is applicable only up to 15750FH. Hence, one needs to reduce T so much that the MFDT at \( T_x=20000FH \) does not exceed the value MFDT_{max}=0.15.

As Fig. 12 shows, selecting T=270FH follows the MFDT_{max}=0.15 limitation by \( T_x=20000FH \). In fact, this is the maximum inspection interval that we can use if the MFDT_{max} is to be followed. Following Fig. 12 and 6, it is evident that the CRF for T=270FH will be higher than that for T=450, but this is the lowest CRF which can be obtained under the FFI strategy and with the MFDT_{max}=0.15 constraint.

It should be noted that any extra reduction of the inspection interval, which would lead to unavailability below (MFDT)_{max} would lead to an increase in CRF. However, according to Fig. 12, changing the inspection interval to T=250, instead of T=270, makes it possible to include the inspection task in the A_i check package. In this case, the amount of increase in CRF is reasonable, as the task will be performed along with other tasks included in the check package, and this itself will reduce the associated cost of downtime. Hence, the following task will be selected:

- Performing an inspection at every A_i check, i.e. T=250FH.

B. FFI+Res strategy for the “safety effect” category

If under the FFI strategy, it is not possible to define a task that satisfies the risk limit or, the CRF is still higher than the acceptable level, by defined task, then it is necessary to take action to reduce the risk of multiple failure or cost per unit of time, below the allowable level. The next step is to...
evaluate whether the FFI+Res strategy is effective option.

The same rule and discussion are applicable to the FFI+Res strategy as are applicable to the FFI strategy, to verify Eq. 15 for any candidate values of T and K, and thus obtain the allowable values. The objective is to identify the optimum “T” and “K” that have the lowest possible CRF that satisfies maximum allowable MFDT. The whole problem complex is illustrated in Fig. 13, where both CRF and MFDT with their respective limits are shown for different values of T, versus different values of N.

As illustrated, in accordance with MFDT_{max}=0.15, each inspection interval has a maximum utilization limit after which a restoration task should be performed to reduce the MFDT level. As the graph shows, taking T=950FH we are allowed to continue with the maximum K=12, i.e. up to T_K=11400FH with CRF=0.1940 (shown by the brown rectangular legend). This means that, in order to satisfy MFDT_{max}=0.15, we can conduct restoration after a maximum of 12 inspections. However, if we select K=10, not only the unavailability is still below MFDT_{max}, but also we can gain a lower CRF of 0.1893. Hence, the decision would be T=950 and K=10. As the graph shows, all the optimum combinations of T and K shown in Fig. 10 are still valid for selection, and hence the decision will be the same and as follows:

1) To perform an inspection at every B check, i.e. “T=1000FH” and
2) To perform a restoration task at the D check, i.e. “T=1000FH”.

In the case of an operational limit, when it is not possible to remove the component for restoration, we are allowed to postpone the restoration task until the next inspection, i.e. until N=11, meaning that an extra 1000FH is allowable, to use the component, to satisfy MFDT_{max}=0.15, and to meet the operational limit, but this results in a higher CRF.

If, in a specific case, the exact optimal values of T and K do not satisfy Eq. 15, then T, K or both parameters must be changed to reduce the MFDT_{T,K} below MFDT_{max}. This is shown in Fig. 14, where MFDT_{max} is set to 0.05 for the same condition as those illustrated in Fig. 13. As is evident, by reducing MFDT_{max}, the K_{op} decreases and CRF increases. In comparison with the case where MFDT_{max}=0.15, none of the optimal points meet the MFDT_{max}=0.05 requirements.

In general, if the (T, K) is the only minimum CRF, it is obvious that CRF increases gradually when T or K move away from optimum combination of (T and K)_{op}. Hence, by reducing K, we can reach an applicable combination of T and K (e.g. K=7 for T=950), but this results in a higher CRF.

Fig. 15 shows a situation where, with inspection at every T=1000FH, we have to perform a restoration task at T_K=6000FH. As the figure shows, reducing the inspection interval to T=500FH reduces the MFDT level, and we will have the possibility of postponing the task for an additional 2250FH. However, such a postponement would affect the CRF, and another trade-off analysis is needed to evaluate

| CRF vs number of inspection cycles for different values of T, under the FFI+Res strategy |

<table>
<thead>
<tr>
<th>Operating time (FH)</th>
<th>CRF</th>
<th>500FH</th>
<th>1000FH</th>
<th>1500FH</th>
<th>2000FH</th>
<th>2500FH</th>
<th>3000FH</th>
<th>3500FH</th>
<th>4000FH</th>
<th>4500FH</th>
<th>5000FH</th>
</tr>
</thead>
<tbody>
<tr>
<td>300FH</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>600FH</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.9</td>
<td>1.2</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>900FH</td>
<td>0.3</td>
<td>0.6</td>
<td>1.2</td>
<td>2.4</td>
<td>4.8</td>
<td>9.6</td>
<td>19.2</td>
<td>38.4</td>
<td>76.8</td>
<td>153.6</td>
<td>307.2</td>
</tr>
<tr>
<td>1200FH</td>
<td>0.4</td>
<td>0.8</td>
<td>1.6</td>
<td>3.2</td>
<td>6.4</td>
<td>12.8</td>
<td>25.6</td>
<td>51.2</td>
<td>102.4</td>
<td>204.8</td>
<td>409.6</td>
</tr>
</tbody>
</table>

| Options for task selection |

<table>
<thead>
<tr>
<th>Inspection Interval “T”</th>
<th>1050</th>
<th>1000</th>
<th>950</th>
<th>850</th>
<th>750</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum K</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Restoration time T_K</td>
<td>6650</td>
<td>6000</td>
<td>5500</td>
<td>5000</td>
<td>4500</td>
</tr>
<tr>
<td>CRF</td>
<td>0.211</td>
<td>0.207</td>
<td>0.207</td>
<td>0.217</td>
<td>0.217</td>
</tr>
</tbody>
</table>

C=5000FH, or D=10000FH). Making an adjustment to the T and N may also lead to values exceeding the MFDT_{max}. However, option 4, i.e. T=1000 and K=6, is well suited to task packaging. Summing up, the following tasks will be selected:

1) Performing an inspection at every B check, i.e. “T=1000FH” and
2) Performing a restoration task at “T=6000FH”.

In fact, it is not possible to include the restoration task permanently into a check package, but the planning engineers have the possibility of including the restoration task in the first B check after the C inspection, or even in the C check, depending on the situation and planning criteria.

In the case of an operational limit, when it is not possible to remove the component for restoration, we can still postpone the restoration task, by reducing the inspection interval to a value that reduces the MFDT below MFDT_{max}. Fig. 15 shows a situation where, with inspection at every T=1000FH, we have to perform a restoration task at T_K=6000FH. As the figure shows, reducing the inspection interval to T=500FH reduces the MFDT level, and we will have the possibility of postponing the task for an additional 2250FH. However, such a postponement would affect the CRF, and another trade-off analysis is needed to evaluate

| Table II: Options for task selection |

<table>
<thead>
<tr>
<th>Options</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspection Interval “T”</td>
<td>1050</td>
<td>1000</td>
<td>950</td>
<td>850</td>
<td>750</td>
</tr>
<tr>
<td>Maximum K</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Restoration time T_K</td>
<td>6650</td>
<td>6000</td>
<td>5500</td>
<td>5000</td>
<td>4500</td>
</tr>
<tr>
<td>CRF</td>
<td>0.211</td>
<td>0.207</td>
<td>0.207</td>
<td>0.217</td>
<td>0.217</td>
</tr>
</tbody>
</table>

Figure 14: Comparison of cost rate function versus MFDT for different values of T, under the FFI+Res strategy.

Figure 15: Possibility of inspection postponement in accordance with MFDT max.
whether this is acceptable or not.

VII. DISCUSSION AND CONCLUSION

A cost model has been developed to identify the optimum interval and frequency of inspection in the Failure Finding Inspection (FFI) strategy and the optimum interval and frequency of inspection and restoration in the strategy combining inspection with restoration after a specific number of inspections. In the model the opportunity cost of the aircraft’s lost production due to maintenance downtime is considered. Limiting values have been determined for the cases where inspection interval $T$ and number of inspection cycles $N$ tends to infinity and also when there are no undesired consequences of failure i.e. when the cost of accident is equal to zero ($C_{4000}$). These values give an idea to the analysts about the cost per unit of time, in a long run, i.e. a life cycle view.

The interval unavailability behaviour has been discussed and, using an example, maintenance task selection for the “non-safety effect” and the “safety effect” categories of hidden failure has been discussed, and the optimum inspection and restoration interval for both categories has been defined. Vaurio’s approach has been verified in the application of aircraft operation, and the accuracy of approximation of that approach has also been checked in that context.

The study shows that, depending on the failure data and cost parameters, a mixture of failure finding and restoration actions can not only increase the cost-effectiveness of maintenance, but also may improve the availability performance of the unit. Hence, a mixed strategy, i.e. a combination of maintenance tasks, should be considered in formal maintenance task development even for the “non-safety effect” category of failure.

In the case of an operational limitation, when it is not possible to remove the unit for restoration, it has been shown that even when the component undergoes aging, by reducing the inspection interval, it is possible to postpone the inspection for a limited time, of course with a higher cost.

As simulation is used with hypothetical data, further analysis needs to be performed with field data from real situations. The method can also be used for non-aged units. If data is available, the effectiveness of restoration action can also be considered in the model, by some adjustments.

Summing up, by the incorporation of adequate modelling support, the current methods of developing a maintenance task can be considerably enhanced and based on a surer scientific foundation. Thereby, not only are the safety requirements fulfilled, but a lower maintenance cost per flight hour is also obtained simultaneously. This becomes more interesting when we consider a fleet of aircraft, and the opportunity that is lost due to a non-optimized maintenance programme. By this approach, it is possible to recognize the real contribution of maintenance in the total operating cost and to evaluate whether performing redesign and including a monitoring system such as BIT, increasing the redundancy, or improving the system maintainability performance reasonably decrease the cost per flying hour and provide more available flight hours for the business. This approach makes the aircraft maintenance programme optimized, which makes the aircraft type attractive to the operators and contributes to the airline’s financial success.

REFERENCES


Alirezah Ahmadzada is a Ph.D candidate at the Division of Operation and Maintenance Engineering, Luleå University of Technology (LITU), Sweden. He has received his Licentiate degree in Operation and Maintenance Engineering in 2007. Alirezah has more than 10 years of experience in civil aviation maintenance as licensed engineer, and production planning manager. His research topic is related to the application of RAMS to improve aircraft maintenance program development.

Dr. Uday Ku mar is a Professor of Operation and Maintenance Engineering at Luleå University of Technology, Luleå, Sweden. His research and consulting efforts are mainly focused on enhancing the effectiveness and efficiency of maintenance process at both operational and strategic levels and visualizing the contribution of maintenance in an industrial organization. He has published more than 175 papers in peer reviewed international journals, proceedings of conferences, and chapters in books. He is reviewer and member of the Editorial Advisory Board of several international journals. His research interests are Maintenance Management and Engineering, Reliability and Maintainability Analysis, LCC, etc.
Paper IV

Selection of Maintenance Strategy for Aircraft Systems Using Multi-Criteria Decision Making Methodologies

Selection of Maintenance Strategy for Aircraft Systems Using Multi-Criteria Decision Making Methodologies

ALIREZA AHMADI1, SUPRAKASH GUPTA2, RAMIN KARIM1 and UDAY KUMAR1

1Division of Operation and Maintenance Engineering,
Lulea University of Technology, Lulea, SE-97187, Sweden
alireza.ahmadi@ltu.se, suprakash_gupta@yahoo.co.in, ramin.karim@ltu.se, uday.kumar@ltu.se

2Department of Mining Engineering, Institute of Technology,
Banaras Hindu University, Varanasi - 221005, India

This paper proposes the Multi-Criteria Decision Making (MCDM) methodology for selection of a maintenance strategy to assure the consistency and effectiveness of maintenance decisions. The methodology is based on an AHP-enhanced TOPSIS, VIKOR and benefit-cost ratio, in which the importance of the effectiveness appraisal criteria of a maintenance strategy is determined by the use of AHP. Furthermore, in the proposed methodology the different maintenance policies are ranked using the benefit-cost ratio, TOPSIS and VIKOR. The method provides a basis for consideration of different priority factors governing decisions, which may include the rate of return, total profit, or lowest investment. When the preference is the rate of return, the benefit-cost ratio is used, and for the total profit TOPSIS is applied. In cases where the decision maker has specific preferences, such as the lowest investment, VIKOR is adopted. The proposed method has been tested through a case study within the aviation context for an aircraft system. It has been found that using the methodology presented in the paper, the relative advantage and disadvantage of each maintenance strategy can be identified in consideration of different aspects, which contributes to the consistent and rationalized justification of the maintenance task selection. The study shows that application of the combined AHP, TOPSIS, and VIKOR methodologies is an applicable and effective way to implement a rigorous approach for identifying the most effective maintenance alternative.

Keywords: Aircraft maintenance, Multi-Criteria Decision Making, Maintenance strategy, AHP, TOPSIS, VIKOR, Benefit-cost ratio, Maintenance decision making. Maintenance effectiveness.

1. Introduction

Maintenance accounts for approximately 11 percent of an airline’s employees and 10-15 percent of its operating expenses. A large portion of the direct and indirect maintenance costs in the whole life cycle stems from the consequences of decisions made during the initial maintenance programme development. Since the decision made for developing the initial scheduled maintenance programme strongly affects the aircraft safety, availability performance, and lifecycle cost, it is essential to select the most effective maintenance options that assure system effectiveness. To this end, this paper suggests that, rather than use a decision diagram approach, one should use a rigorous approach which not only considers the maintenance strategies offered by ATA MSG-3, but also allows consideration of other available technologies such as Prognostic Health Management (PHM). However, to make rational and justifiable decisions concerning maintenance, one needs to have a clear idea of what the advantages and disadvantages of each maintenance strategy are. Moreover, in maintenance strategy formulation, Reliability, Availability, Maintainability and Safety (RAMS) characteristics and related consequences in system effectiveness should be taken into account. Every maintenance strategy has its inherent merits and demerits. To evaluate the appropriateness of a maintenance strategy, one must formulate a set of evaluating criteria that will adequately assess the effectiveness and efficiency of the maintenance strategy and the cost of implementing it. Moreover, these assessments require knowledge of various factors which indicate the strengths and preferability of maintenance strategies, according to the associated evaluating criteria.

Due to a long list of contributory factors and attributes, inadequacy and uncertainty in the required information, and lack of modelling support for tangible and intangible cost and benefit factors, justification of a maintenance alternative is a critical and complex task. However, the experiences of field experts provide an effective database supporting this estimation. In this process of decision making, the decision makers have to face making numerous
and conflicting evaluations. In fact, the management of the large number of tangible and intangible attributes that must be taken into account represents the main complexity of the problem. Since maintenance decision making is often characterized by the need to satisfy multiple objectives, the formulation of multi-criteria decision models is a worthwhile topic of future research work in inspection (maintenance) problems. To this end, the Multi-Criteria Decision Making (MCDM) approach has been proposed in the literature, and has gained impetus in the field of maintenance strategy selection to provide support in the decision making process. MCDM aims at highlighting conflicting evaluations and deriving a way to come to a compromise in a transparent process. Multi-criteria optimization is the process of determining the best feasible solution according to the established criteria (representing different effects). Al-Najjar et al. (2003) have proposed a fuzzy logic-based maintenance approach, setting failure causes as the criteria and ranking different maintenance approaches on the basis of their capability of detecting changes in the criteria, while Labib (2004) has used failure frequency and downtime as the criteria. Almeida and Bohoris (1995) discuss the application of decision making theory to maintenance with particular attention paid to multi-attribute utility theory. Triantaphyllou et al. (1997) suggest the use of the Analytical Hierarchy Process (AHP) for the selection of a maintenance strategy considering four maintenance criteria: cost, reparablebility, reliability, and availability. Kumar et al., (2010), introduced an AHP based method to assess the risk of rail defects. Bevilaqua and Braglia (2000) also used AHP for selecting the maintenance strategy for an Italian oil refinery based on four important criteria, namely cost, damages, applicability, and added value. Martorell et al. (2005) introduced an Integrated Multi-Criteria Decision Making (IMCDM) approach based on RAMS and cost criteria, to assess changes to the technical specification and maintenance-related parameters, with respect to the constraint conditions. They reviewed and emphasized the benefits of an IMCDM approach when tackling RAMS as a multi-objective optimization problem in a nuclear power plant. Bertolini and Bevilaqua (2006) presented an integrated AHP and goal programming (GP) approach to selecting the best maintenance policies for the maintenance of centrifugal pumps in an oil refinery. They took into account the failure occurrence, its severity, and its detectability as evaluating criteria and the budget and maintenance time as constraint conditions. Arunraj and Maiti (2010) use an AHP and GP approach in which the risk of equipment failure and cost of maintenance are considered as criteria for maintenance selection in a benzene extraction unit of a chemical plant. In addition, the Fussell–Vesely importance measure is utilized for measuring the risk contribution of different equipment.

AHP is a flexible approach and allows individuals or groups to shape ideas and define problems by making their own assumptions and deriving the desired solution from them. It takes into consideration the relative importance of factors in a system and enables people to rank the alternatives based on their goals. However, this method is often criticized for its inability to deal adequately with the uncertainty and imprecision associated with the mapping of the decision makers’ perception to crisp numbers. Moreover, most of the time, the choice of a maintenance alternative decision is governed by the preferences of the decision makers. In general, the preferences are guided mainly by three factors:

(a) Maximizing the total profit – aiming to increase business and investment, with no bar,
(b) Maximizing the benefit-cost ratio – looking for the maximum percentage of return, indicating rational investment restriction, and
(c) Minimizing the investment – aiming at the highest utilization of resources and an investment crunch.

In fact, practical problems are often characterized by several incommensurable and conflicting (competing) criteria, and there may be no solution satisfying all the criteria simultaneously. Therefore, the solution is a set of non-inferior solutions or a compromise solution according to the decision maker’s preferences. The TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) and VIKOR (ViseKriterijumska Optimizacija i Kompromisno Resenje, a Serbian term meaning Multi-criteria Optimization and Compromise Solution, see Section 4.) are MCDM methods which have been applied for solving many diverse real-world multi-attribute decision making problems. They are based on an aggregating function representing “closeness to the ideal, which originated in the compromise programming method”. Both TOPSIS and VIKOR are based on the calculation of distances from the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS). Chu et al. (2007) are in favour of using VIKOR when there are a larger number of decision makers, and otherwise they recommend the use of TOPSIS. Comparatively, the AHP method has a lesser distinguishing capability, whereas both VIKOR and TOPSIS are good at clarifying the differences between alternatives. Moreover, the core process of AHP is pairwise comparison, which is significantly restrained by human information processing capacity.
Selection of Maintenance Strategy for Aircraft Systems Using Multi-Criteria Decision Making Methodologies

processes are not restricted by human capacity restrictions and therefore can be easily accommodated with a large number of attributes and alternatives. Shyjith et al. (2008) have also given a combined AHP and TOPSIS-based maintenance strategy selection methodology for the process industry.

This paper proposes a methodology for the selection of a maintenance strategy for non-safety category of failure, based on an AHP-enhanced benefit-cost ratio, TOPSIS and VIKOR. The methodology enables determination of the importance of the effectiveness appraisal criteria of a maintenance strategy by the use of AHP. Furthermore, in the proposed methodology the different maintenance policies are ranked using the benefit-cost ratio, TOPSIS and VIKOR. The proposed method has been tested through a case study within the aviation context for an aircraft system. The rest of the article is organized as follows. In Sections 2, 3, 4 and 5, AHP, TOPSIS, VIKOR, and benefit-cost methods are discussed. In Section 6, the proposed methodology is described. In Section 7, the case study in the aviation sector is discussed and the paper ends with Section 8, which gives a discussion and conclusion.

2. Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) helps the analyst to organize the critical aspects of a problem into a hierarchical structure similar to a family tree. By reducing complex decisions to a series of simple comparisons and rankings and then synthesizing the results, AHP helps the analysts to provide a clear rationale for the importance of evaluating criteria.

AHP employs pairwise comparison in which experts compare the importance of two factors on a relatively subjective scale. In this way a judgment matrix of importance is built according to the relative importance given by the experts. Table 1 represents a pairwise comparison scale for the value rating of judgments and for deriving pairwise ratio scales. It includes reciprocals (\(a_{ij}=1/a_{ji}\)), which are equally often adopted for relative measurements or comparisons of factors. The geometric mean is the only averaging process that maintains the reciprocal relationship in the aggregate matrix. So, the weighted mean value for a group response is:

\[
\frac{1}{\sum_{k=1}^{n} w_k} \left( \prod_{k=1}^{n} w_k \cdot a_{ij} \right)^{1/n}
\]

where \(a_{ij}^k\) is the \(k^{th}\) expert’s paired comparison value, \(n\) is the number of experts, and \(w_k\) is the weight of the \(k^{th}\) expert. In this study, it was assumed that all the experts have equal expertise in their judgments and therefore \(w_k = 1\) \(\forall k\).

Some degree of inconsistency may be introduced concerning the judgments due to a lack of adequate information, improper conceptualization, and mental fatigue. The AHP technique also allows the analysts to reevaluate their judgments when the pairwise comparison matrix lacks consistency, as reflected by means of an inconsistency ratio. The judgments can be considered acceptable if and only if the inconsistency ratio is less than 0.123. If the obtained value of the inconsistency ratio is not within an acceptable range, the experts may be asked to modify their judgments in the hope of obtaining a modified and consistent matrix.

In this paper, the AHP analysis outcome is the global priority, i.e. the importance value \(w_j\) of the different evaluating criteria, which is elicited from the aggregated pairwise comparison matrix of the experts’ judgments. It is a vector, normalized to the unity, which allows identification of the importance of evaluating criteria with respect to the goal.

3. TOPSIS

The solution of a multi-attribute decision making (MADM) problem through TOPSIS is based on the simple logic that the best solution is furthest from negative ideal solution and preferably closest to the positive ideal solution. The alternatives are ranked by their distances from two cardinal points: the positive ideal solution (PIS) and the negative ideal solution (NIS). The different steps involved in TOPSIS are as follows:
Step 1: The core of TOPSIS is the appraisal (decision) matrix $D^k$ framed from the responses of the $k^{th}$ expert, $D^k = [x_{ij}^k]_{m \times n}$, where $i$ is the set of $m$ alternatives and $j$ is the set of $n$ appraising attributes used to evaluate the alternative set $i$. $x_{ij}^k$ is the score (appraisal rating) of the alternative $i$ for attribute $j$ given by expert $k$.

Step 2: The list of attributes in a real-world problem often contains conflicting, incommensurable, incompatible, unconformable, and unquantifiable attributes, which increases the complexity of MCDM problems. Therefore, it is mandatory to make the elements of the decision matrix unit-free to eliminate the scaling effect through normalization. This operation is performed column-wise to transform the attribute scores to a common norm or standard between 0 and 1 to allow the comparison of different attributes. The element $r_{ij}^k$ of the normalized appraisal (decision) matrix $(R^k)$ may be calculated using the expression for linear normalization to eliminate the effect of an evaluation unit for criteria, i.e.

$$r_{ij}^k = \left\{ \frac{x_{ij}^k - \min_{i} x_{ij}^k}{\max_{i} x_{ij}^k - \min_{i} x_{ij}^k} \right\}_{je.J} \left\{ \frac{x_{ij}^k - \min_{i} x_{ij}^k}{\max_{i} x_{ij}^k - \min_{i} x_{ij}^k} \right\}_{je.J}$$

where,

$$s_j^+ = \left\{ \max_{i} x_{ij}^k \right\}_{je.J} \left\{ \min_{i} x_{ij}^k \right\}_{je.J}$$

$$s_j^- = \left\{ \min_{i} x_{ij}^k \right\}_{je.J} \left\{ \max_{i} x_{ij}^k \right\}_{je.J}$$

Here $J$ is the set of benefit criteria and $J'$ is the set of cost criteria.

Step 3: Appraisal attributes have varying importance and they influence the decision as per their importance value. The importance of an attribute is evaluated through AHP. The importance of each attribute ($w_j$) is elicited from the pairwise comparison matrix of the experts’ judgments following the AHP methodology. The weight-normalized decision matrix $(V^k)$ is formulated by multiplying the elements of the normalized matrix $(R^k)$ by the corresponding weight ($w_j$) of the attributes, i.e.:

$$V^k = [v_{ij}^k]_{m \times n} = [w_j x_{ij}^k]_{m \times n}$$

Step 4: The aggregated decision matrix $(V)$ is formulated through the aggregation of all the experts’ decision matrices. The aggregated decision matrix $(V)$ is the group decision matrix. The geometric mean will combine the judgments of all the experts. The general formula for calculating the element of the aggregated decision matrix $(V)$ is:

$$v_{ij} = \left( \prod_{k=1}^{n} v_{ij}^k \right)^{1/n}$$

Step 5: The two cardinal points in the solution space are the positive ideal solution (PIS), composed of all the best criteria, and the negative ideal solution (NIS), composed of all the worst criteria. Therefore, PIS ($v^+$) contains all the highest scores of the benefit criteria and all the lowest scores of the cost criteria. NIS ($v^-$) contains all the lowest scores of the benefit criteria and all the highest scores of the cost criteria. The PIS and NIS of a group of experts are:

$$v^+ = \left\{ v_{ij}^+ \right\}_{j=1,2,\ldots,n} = \left\{ v_{1j}^+, v_{2j}^+, \ldots, v_{nj}^+ \right\} = \left\{ \max_{i} v_{ij} \right\}_{je.J} \left\{ \min_{i} v_{ij} \right\}_{je.J}$$

$$v^- = \left\{ v_{ij}^- \right\}_{j=1,2,\ldots,n} = \left\{ v_{1j}^-, v_{2j}^-, \ldots, v_{nj}^- \right\} = \left\{ \min_{i} v_{ij} \right\}_{je.J} \left\{ \max_{i} v_{ij} \right\}_{je.J}$$
Step 6: The decision alternatives are non-inferior solutions and at a distance from the cardinal points, i.e. PIS and NIS. The separation measure of the $i^{th}$ alternative from PIS is $D^+_i = \left( \sum_{j=1}^{n} (v^+_j - v^-_j)^p \right)^{1/p}$ and that from NIS is $D^-_i = \left( \sum_{j=1}^{n} (v^-_j - v^+_j)^p \right)^{1/p}$, where $p$ is an integer $\geq 1$. For $p=2$ the metric is a Euclidean distance.

Step 7: Ranking of the decision alternatives is performed on the basis of their relative closeness index $C_i^*$ in respect of the ideal solution. The relative closeness of the $i^{th}$ alternative with respect to PIS is calculated from the following expression:

$$C_i^* = \frac{D^+_i}{D^+_i + D^-_i}$$

where $0 \leq C_i^* \leq 1$. If the alternative solution is the positive ideal solution, then $C_i^*=1$. The alternatives are ranked according to the descending order of $C_i^*$ values.

4. VIKOR

VIKOR is a compromise decision making method in multi-criteria environments. This technique ranks the alternatives based on two measures: the utility measure (the weighted distance from the ideal solution) and the regret measure (the weighted distance from the negative-ideal solution). The VIKOR index for each alternative is calculated from these measures. The alternative with the least VIKOR index is the best alternative, as it has the maximum group utility and the least regret\textsuperscript{24, 25, 26}. This method includes the following steps, of which Step 1 and Step 2 are the same as the corresponding steps in TOPSIS.

Step 3: Two cardinal values of each criterion represent the best and the worst values. The association of the best criteria values gives the ideal solution (IS), while the set of all the worst values gives the anti-ideal solution (AIS)\textsuperscript{26}. Therefore, IS ($I_k^+$) contains all the highest scores of the benefit criteria and all the lowest scores of the cost criteria. AIS ($I_k^-$) contains all the lowest scores of the benefit criteria and all the highest scores of the cost criteria. The $I_k^+$ and $I_k^-$ of the $k^{th}$ expert are:

$$I_k^+ = \left( \frac{1}{n} \sum_{j=1}^{n} I_j^+ \right)_{k=1,2,\ldots,N} \quad I_k^- = \left( \frac{1}{n} \sum_{j=1}^{n} I_j^- \right)_{k=1,2,\ldots,N}$$

where $J$ is the set of benefit criteria and $J^c$ is the set of cost criteria.

Step 4: The utility measure ($S_i^k$) of the $i^{th}$ alternative is calculated from all the criteria values and their relative weights ($w_j$). The regret measure ($R_i^k$) of the $i^{th}$ alternative gives the most influential criterion and its corresponding values. The values of $S_i^k$ and $R_i^k$ are calculated using the expressions given below:

$$S_i^k = \sum_{j=1}^{n} w_j^{k'} \left( \frac{r_j^+ - r_j^k}{r_j^+ - r_j^-} \right)^{k^*}$$

where

$$R_i^k = \max_j \left[ w_j \left( \frac{r_j^+ - r_j^k}{r_j^+ - r_j^-} \right)^{k^*} \right]$$

Step 5: The group utility measure ($S_j$) and group regret measure ($R_j$) of an alternative are computed by the aggregation of all experts’ $S_i^k$ and $R_i^k$ values. The group measures for each alternative are calculated through the geometric mean of all the individual expert’s measures, as given below:

$$S_j = \left( \prod_{k=1}^{K} S_i^k \right)^{1/K} \quad R_j = \left( \prod_{k=1}^{K} R_i^k \right)^{1/K}$$

Step 6: The VIKOR index ($Q_j$) for the $i^{th}$ alternative is computed by the relation

$$Q_j = \frac{v S_j - S^*}{S^* - S^*} + (1-v) \frac{R_j - R^*}{R^* - R^*}$$
where $S^- = \min_i S_i$, $S^+ = \max_i S_i$, $R^- = \min_i R_i$ and $R^+ = \max_i R_i$ and $v$ is a weighting factor of the preferences for decision-making strategy. If the decision making is carried out on the basis of “consensus”, $v$ is 0.5, and $v$ is $>0.5$ when the “voting by majority” rule is followed. $v$ is $<0.5$ when the decision is made with a “veto”. Here the term $\frac{S_i - S^-}{S^+ - S^-}$ is the scaled distance from the ideal solution and measures the overall closeness of alternative $i$, and the second term $\frac{R_i - R^-}{R^+ - R^-}$ gives the scaled distance for the most influential criterion, indicating its closeness to the desired value.

Step 7: The ranking of the decision alternatives is performed by sorting the $(S_i)$, $(R_i)$, and $(Q_i)$ values in increasing order, which results in three ranking lists denoted as $S_i$, $R_i$, and $Q_i$.

Step 8: The proposed decision alternative $I_1$, having the lowest $Q_i$ value, will be a compromise solution if the following two conditions are satisfied.

C1: Alternative $I_1$ has an “acceptable advantage” when

\[ Q_{i[2]} - Q_{i[1]} \geq \frac{Q_{[m]} - Q_{[1]}}{m - 1} \]

C2: Alternative $I_1$ has an “acceptable stability in the decision-making process” when it possesses the best rank in terms of $S_i$ and/or $R_i$ values.

If either of these two conditions is not met, more than one alternative solution is proposed. Both alternatives $I_1$ and $I_2$ are proposed when only condition C2 is not met. Alternatives $I_1, I_2, ..., I_l$ are the proposed compromise solution set when condition C1 is not satisfied and $l$ is the maximum value as long as the following relation is satisfied.

\[ Q_{i[-]} - Q_{i[1]} < \frac{Q_{[m]} - Q_{[1]}}{m - 1} \]

Here the compromise solution sets are in closeness to each other.

5. Benefit-cost ratio

Any decision has several favourable and unfavourable concerns to consider. The favourable sure concerns are positive value and are called benefit, such as business enhancement, planning flexibility, and reduction in maintenance cost. The unfavourable ones are negative and are called costs, such as maintenance investment and its associated costs. Each of these concerns contributes to the merit of decision and must be evaluated (rated) individually on a set of evaluating criteria. These criteria are measured in different units and scales and have different importance. Here the importance of the evaluating criteria is assigned through AHP and a normalized performance appraisal matrix will ease out the effect of units and scaling. The methodology is as follows:

A performance appraisal matrix or aggregated decision matrix is framed following Step 1 to Step 4 described in Section 3.

Now the combined benefit index of the $i^{th}$ alternative is $\sum v_i j \in J$ and the combined cost index of the $i^{th}$ alternative is $\sum v_i j \in J$. Therefore, the rate of return, i.e. benefit-cost ratio, can be calculated by dividing the synthesized benefit value by the associated synthesized cost value for each alternative:

\[ \frac{\sum v_i j \in J}{\sum v_i j \in J} \]

The rate of return is an index to quantify the amount of gain or loss generated from a specific maintenance alternative, according to the specified evaluating criteria.
For the selection of a maintenance strategy, this paper proposes a methodology where the importance of the effectiveness appraisal criteria of the maintenance strategy is assigned by AHP and different maintenance policies are ranked using the three methods, i.e. the benefit-cost ratio, TOPSIS and VIKOR. The proposed decision making method includes two levels of an organization, i.e. the managerial level and the engineering level. The managerial level defines the goals and the associated evaluating criteria, and also performs the pairwise comparison to assign the importance of the evaluating criteria. The assignment of the importance value for the evaluating criteria, from a managerial point of view, is carried out by applying AHP. These importance values will be used for the whole analysis. The engineering level selects a failure mode, defines applicable maintenance alternatives and assesses the effectiveness of each alternative after due consideration of the positive and negative consequences of choosing any one of them from the standpoint of various evaluating criteria. At this level the analyst performs a multi-criteria ranking of the alternatives.

Compromise solutions are proposed based on the preferences of the decision makers. These preferences may be (a) the rate of return, (b) the total profit or (c) the lowest investment. When the preference is the rate of return, the benefit-cost ratio may be used, and for the total profit TOPSIS is appropriate. In cases where the manager has specific preferences, such as "the alternative solution should preferably include the lowest maintenance investment in comparison with that of other maintenance alternatives", VIKOR can be adopted.

Therefore, the ranking of the alternatives is carried out using the three methods, i.e. the benefit-cost ratio, TOPSIS and VIKOR. Finally, the analyst provides a ranking of the alternatives based on different points of view and the manager can select one that suits his preferences well.

### 6.1. The steps of the proposed methodology

The following steps form the proposed methodology, as shown in Fig. 1:

- **Step 1:** Building a hierarchical structure for both the benefit and cost criteria. By decomposing these criteria, an attempt is made to prioritize, simplify the problem, and come down from the goals to specific and easily controlled factors.

- **Step 2:** Calculating the weight of each evaluating criteria of each level from the pairwise comparison matrix, framed from the responses of managerial level experts, through the implementation of AHP. It is necessary to check the consistency of each matrix in this step and, if the consistency ratio exceeds 10%, the experts are asked to modify their judgments. Considering that the opinions of different experts are used for pairwise comparison, it is essential to calculate the mean weight for each sub-criterion.

- **Step 3:** At the engineering level, a failure mode should be selected, the applicable maintenance alternatives should be defined, and the effectiveness of each alternative should be assessed after due consideration of the positive and negative consequences of each maintenance alternative from the standpoint of various evaluating criteria.

- **Step 4:** At this level the analyst should rank the different alternatives by using the three mentioned methods.

- **Step 5:** Comparison of all the alternatives and their ranking by the three methods. The most consistent and justified task will be selected by the Maintenance Review Board (MRB). Thereafter, the analysis continues for the next failure mode.

### 6.2. Development of the hierarchical structure of the maintenance selection criteria

Structuring the problem into a hierarchy serves two purposes. First it provides an overall view of the complex relationship of variables inherent in the problem, and second, it helps the decision maker in making judgments concerning the comparison of elements that are homogenous and on the same level of the decision hierarchy.

Adopting a more holistic view in selecting maintenance strategies, it has been decided that it would be more beneficial and business-oriented to consider the benefit-cost ratio as a measure for the overall effectiveness that an applicable maintenance strategy can gain. The hierarchy developed in this study is a five-level tree in which the top level represents the goal of the analysis, i.e. “selection of the most effective maintenance strategy” (see Fig. 2).

Considering the role of maintenance as added value and contributor to the business enhancement, the evaluation criteria that will influence the main goal have been defined as **benefit** and **total cost**, which are included at the second level of the hierarchy. These criteria are then broken down into the sub-criteria which form the third and fourth level. Finally, the lowest level, i.e. the fifth level, comprises the alternative maintenance policies. The relevant factors (sub-criteria) defining the criterion of benefit are identified as business enhancement, planning flexibility, reduction in maintenance downtime, and procedural effectiveness. It has been decided that the business
enhancement factor itself should be evaluated based on the customer satisfaction, the reduced risk of operational irregularities, and the mature removal of the unit.

Moreover, planning flexibility should be evaluated based on the “warning of incipient failure” and the “failure deferral possibility”. Furthermore, it has been decided that the maintenance downtime factor itself should be evaluated based on the logistic delay time, administrative delay time, troubleshooting time, and active maintenance time. Finally, the procedural effectiveness should be evaluated based on the “reliability of the procedure” and “adoptability”. For the total cost incurred by the selected maintenance strategy, two factors (sub-criteria) have been selected, namely “investment” and “cost of maintenance”. The investment should be evaluated according to the requirements for specialists/training, facility and tools, hardware/software, and inventory/stock. Likewise, the associated cost of maintenance will be evaluated based on the cost of manpower and the cost of material. The alternative maintenance strategies considered in this study include those offered by ATA MSG-32, i.e. Operational/Visual Check, Inspection/Functional Check, Restoration, Discard, Combination of Strategies, Run to Failure and Redesign) and the use of Prognostics and Health Management (PHM) provisions.

7. Case study

Of confidential reasons, information related to company and the studied system has been masked. The company is European aircraft manufacturer and the component is part of the fuel system in an aircraft. Due to the high level of the redundancy, the failure of the studied component does not have any safety effect, and the major concern is the operational and economic consequences of failure. The performance of the five maintenance alternatives was evaluated using 16 evaluating attributes divided into two groups i.e. benefit and cost criteria (see Fig. 2). The list of evaluating attributes was decided in consensus with the subject matter experts. Through the discussion with the subject matter experts, it was decided that the criterion “customer satisfaction” could be evaluated through the criterion “reduced operational irregularities”. Hence the former criterion was removed from the analysis. It was decided also that, among the available maintenance strategies mentioned in Section 6.2, lubrication/servicing, a combination of strategies and redesign were not applicable for this study, and the rest were considered. The responses of the experts were analyzed and the maintenance alternatives were ranked using three methodologies: (i)
the benefit-cost ratio, (ii) TOPSIS and (iii) VIKOR.

7.1. Collection of judgments from experts

Two different sets of questionnaires were developed to collect the opinions of the participants. For pairwise comparison between the two criteria, benefit and total cost, on the second level of evaluating criteria, the following question was asked:

**Question A:** “To select the most effective maintenance strategy for the units/systems whose failure affects the normal operation of aircraft, we have identified two main criteria: 1) the benefit that the selected maintenance strategy creates and 2) the total cost under the specific maintenance strategy. In your opinion, with respect to the overall goal “selection of the most effective maintenance strategy”, which of these two criteria is of greater importance (or priority) in the selection of an appropriate maintenance strategy according to the following scale of importance?”

Likewise, a pairwise comparison was made between the criteria on the third and fourth levels of evaluating criteria. For example, for pairwise comparison among the four criteria of benefit on the third level, the following question was asked:

**Question B:** “The relevant factors defining the criteria of benefit are identified as the contribution to the business, increased planning flexibility, reduction in maintenance downtime, and enhancement of procedural effectiveness. In your opinion, with respect to sub-criterion 1, benefit, how important is sub-attribute 1 (business) when compared with sub-attribute 2 (planning flexibility)?” The question was repeated, after adaptation, for the other attributes.

The experts, on the basis of their knowledge and experience, gave their opinions in the multiple choice questionnaire that formed the basis of the pairwise comparison matrix for the given criteria. Then the verbal and qualitative responses were quantified and translated into a quantitative value/score by the use of a discrete 9-point scale (see Table 1). Using AHP the importance of all the 16 attributes was calculated from the judgment matrix of the individual experts and subsequently aggregated to obtain the group priority values as shown in Table 2. The experts chose to assign maximum importance to the “cost of manpower” (0.215), followed by “hardware/software” (0.180), among the cost criteria, and to “reduce risk of operational irregularities” (0.194), followed by “mature removal of unit” (0.113), among the benefit criteria. The managerial level experts assigned least importance to “adoptability” (0.04) among the benefit criteria and to “specialists/training” (0.18) among the cost criteria.

![Figure 2: Hierarchy of evaluating criteria](image-url)

<table>
<thead>
<tr>
<th>Evaluating Criterion</th>
<th>2nd Level Criterion</th>
<th>3rd Level Criterion</th>
<th>4th Level Criterion</th>
<th>5th Level Alternative Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal: Maintenance effectiveness</td>
<td>(Criteria 1) Benefit</td>
<td></td>
<td>Customer satisfaction</td>
<td>Run to failure</td>
</tr>
<tr>
<td></td>
<td>1-Business</td>
<td></td>
<td>Reduced risk of operational irregularities</td>
<td>Lubrication/Servicing</td>
</tr>
<tr>
<td></td>
<td>2-Planning flexibility</td>
<td></td>
<td>Warning of incipient failure</td>
<td>Operational check</td>
</tr>
<tr>
<td></td>
<td>3-Reduction in maintenance downtime</td>
<td></td>
<td>Failure deferred opportunity</td>
<td>Functional check</td>
</tr>
<tr>
<td></td>
<td>4-Procedural effectiveness</td>
<td></td>
<td>Logistics delay Time</td>
<td>Restoration</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Administrative delay Time</td>
<td>Discard</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Troubleshooting time</td>
<td>Incorporation of PHM</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Active maintenance Time</td>
<td>Redesign</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reliability of the procedure</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Adoptability</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Specialist/Training</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Facility and tools</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hardware/software</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Inventory/stock</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cost of manpower</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cost of material</td>
<td></td>
</tr>
<tr>
<td>(Criteria 2) Total Cost</td>
<td>1-Investment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2-Maintenance cost</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Hierarchy of evaluating criteria
7.2. Ranking of the alternatives

In order to collect the engineering level data to rank the alternatives, a second set of questionnaires was developed. The purpose was to collect engineering judgments regarding the ability of each maintenance alternative to achieve the ideal level of each evaluating criterion. For example, to identify the ability of maintenance alternatives to eliminate “the risk of operational irregularities”, the following question was asked:

*Question C:* “What score (0-100) do you assign to each maintenance strategy with respect to the criterion “reduced risk of operational irregularities”? The question inquires about the extent to which the alternative is capable of reducing the risk of operational irregularities. If it is capable of eliminating them completely, a score of 100 will be assigned, and if it is unable to contribute any reduction, a score of “0” will be assigned. If the expert is not sure about a specific score, he can assign his judgments in a range, e.g. 65-80.

The results of the TOPSIS calculation (see Table 3) show that the PHM alternative has the highest value for eight benefit criteria, whereas for the adoptability criterion it has the lowest value. At the same time it has the lowest value for four cost criteria. Therefore, for the majority of the criteria (12 out of 16), this alternative is close to PIS. In contrast, the alternative “run to failure” has the lowest value for all the ten benefit criteria and the highest value for one cost criterion, indicating its closeness to NIS.

Table 4 shows the weighted distance of each criterion from its ideal value by VIKOR, based on response of one of the experts. The PHM alternative has the least distance for nine benefit criteria and the highest distance for one cost criterion, showing its closeness to IS. However, for the alternative “run to failure”, this distance is the highest for all the ten benefit criteria and the lowest for two cost criteria, indicating its nearness to AIS.

Table 5 shows the results of the benefit-cost analysis. The maintenance alternative “incorporation of PHM” has the maximum benefit index (0.486), followed by the alternative “functional check” (0.385). The cost index value for the alternative “discard” is the maximum (0.342) and that for the alternative “incorporation of PHM” is the minimum (0.036). The benefit-cost ratio is highest (13.505) for the alternative “incorporation of PHM”, indicating that this alternative is the most rational choice, followed by “functional check” and “restoration”. The benefit-cost ratio for the remaining two alternatives is less than unity, indicating that they are not preferable alternatives.

The results of the TOPSIS analysis (see Table 6) indicate that the maintenance alternative “incorporation of PHM” is the overwhelming choice, as indicated by the highest relative closeness index (0.932). Therefore, this alternative is nearest to PIS and furthest from NIS. The alternative “functional check” is the second preferred choice, with a relative closeness index (0.682), followed by “restoration”. The alternative “run-to-failure” is the least preferred choice due to its closeness to NIS.

The aggregated results of the VIKOR analysis are tabulated in Table 7. Both the separation measures and the VIKOR index rank the alternative “incorporation of PHM” first, followed by “functional check”. All the three methods show that the alternative “incorporation of PHM” is the most favourable choice, followed by “functional check”. The criterion “hardware/software” is the most influential criterion for both of these alternatives, as it gives the highest value of the regret measure.

8. Discussion and conclusions

For selection of the maintenance tasks within the MRB process, this paper presents a rigorous approach in which all the applicable maintenance strategies plus the incorporation of PHM are considered for review. It suggests the use of the MCDM method to enhance the expert judgment process involved in the use of ATA MSG-3, to assure the consistency and effectiveness of maintenance decisions. The AHP method has been used to determine the importance of the maintenance effectiveness appraisal criteria of a maintenance strategy. This provides an overall view of the complex relationship between evaluating variables inherent in the decision making process, and helps the decision maker in making judgments in the comparison of attributes and criteria that are homogenous and are on the same level of the decision hierarchy.

The method provides a basis for consideration of different priority factors governing decisions, which may include (a) the benefit-cost ratio i.e. rate of return (b) the total profit or, (c) the lowest investment. When the preference is the rate of return, the benefit-cost ratio is used, and for the total profit TOPSIS is applied, as it governs by majority rule, neglecting the side-effects. In cases where the decision maker has specific preferences, such as “the alternative solution should preferably include the lowest investment needed in comparison with that of other maintenance alternatives”, VIKOR can be adopted, as it considers the smallest damages. Finally, the analyst provides a ranking of the alternatives based on different points of view and the Maintenance Review Board can select one that suits the preferences well.

The proposed methodology has been verified through a case study for an aircraft system. The list of evaluating attributes was decided in consensus with field experts. The performance of the five maintenance alternatives was
evaluated using 16 evaluating attributes. The results show that the alternative “incorporation of PHM” was found to be the most favourable choice, followed by “functional check”, by all the three methods. The rest of the alternatives, i.e. “restoration”, “discard”, and “run to failure” have the same preferability as MSG-3 has suggested. However, it is noticeable that the ranking index for PHM strongly proffers that alternative in comparison with other alternatives, which shows the necessity of including this alternative among the decision alternatives.

It has been found that using the methodology presented in the paper, the relative advantage and disadvantage of each maintenance strategy could be identified in consideration of different aspects, and that justification of the maintenance task selection will be more consistent and rationalized. The study shows that using the combined AHP, TOPSIS, and VIKOR methodologies is an applicable and effective way to implement a rigorous approach for identifying the most effective maintenance alternative.

Appendices:

Table 1: Judgment scores in AHP

<table>
<thead>
<tr>
<th>Judgment explanation</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>The two attributes are equally important.</td>
<td>1</td>
</tr>
<tr>
<td>One attribute is moderately more important than the other.</td>
<td>3 or (1/3)</td>
</tr>
<tr>
<td>One attribute is strongly more important than the other.</td>
<td>5 or (1/5)</td>
</tr>
<tr>
<td>One attribute is very strongly more important than the other.</td>
<td>7 or (1/7)</td>
</tr>
<tr>
<td>The evident greater importance of one attribute compared with the other is of the highest possible order (extremely more important).</td>
<td>9 or (1/9)</td>
</tr>
</tbody>
</table>

Note: 2, 4, 6, 8 can be used as intermediate judgment values between adjacent scale values.

Table 2: Results of AHP for calculation of weights of different evaluating criteria

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Criteria</th>
<th>Aggregated Weights of the criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cost of manpower</td>
<td>0.215</td>
</tr>
<tr>
<td>2</td>
<td>Reduced risk of operational irregularities</td>
<td>0.194</td>
</tr>
<tr>
<td>3</td>
<td>Hardware/software</td>
<td>0.180</td>
</tr>
<tr>
<td>4</td>
<td>Mature removal of unit</td>
<td>0.113</td>
</tr>
<tr>
<td>5</td>
<td>Troubleshooting time</td>
<td>0.056</td>
</tr>
<tr>
<td>6</td>
<td>Warning of incipient failure</td>
<td>0.035</td>
</tr>
<tr>
<td>7</td>
<td>Failure deferral possibility</td>
<td>0.035</td>
</tr>
<tr>
<td>8</td>
<td>Cost of material</td>
<td>0.035</td>
</tr>
<tr>
<td>9</td>
<td>Inventory/stock</td>
<td>0.030</td>
</tr>
<tr>
<td>10</td>
<td>Reliability of the procedure</td>
<td>0.030</td>
</tr>
<tr>
<td>11</td>
<td>Facility and tools</td>
<td>0.022</td>
</tr>
<tr>
<td>12</td>
<td>Active maintenance time</td>
<td>0.018</td>
</tr>
<tr>
<td>13</td>
<td>Specialists/Training</td>
<td>0.018</td>
</tr>
<tr>
<td>14</td>
<td>Logistic delay time</td>
<td>0.009</td>
</tr>
<tr>
<td>15</td>
<td>Administrative delay time</td>
<td>0.007</td>
</tr>
<tr>
<td>16</td>
<td>Adoptability</td>
<td>0.004</td>
</tr>
</tbody>
</table>
Table 3: Results of calculation by TOPSIS (aggregated decision matrix) for preferability of different maintenance alternatives

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Benefit value</th>
<th>Cost value</th>
<th>Benefit-cost ratio</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run to failure</td>
<td>0.000</td>
<td>0.276</td>
<td>0.000</td>
<td>5</td>
</tr>
<tr>
<td>Functional check</td>
<td>0.385</td>
<td>0.174</td>
<td>2.210</td>
<td>2</td>
</tr>
<tr>
<td>Restoration</td>
<td>0.287</td>
<td>0.253</td>
<td>1.135</td>
<td>3</td>
</tr>
<tr>
<td>Discard</td>
<td>0.282</td>
<td>0.342</td>
<td>0.825</td>
<td>4</td>
</tr>
<tr>
<td>Incorporation of PHM</td>
<td>0.486</td>
<td>0.036</td>
<td>13.505</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4: Results of calculation by VIKOR for preferability of different maintenance alternatives (based on response of one of the experts)

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Benefit value</th>
<th>Cost value</th>
<th>Benefit-cost ratio</th>
<th>Separation measures</th>
<th>Relative closeness index</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run to failure</td>
<td>0.194</td>
<td>0.113</td>
<td>0.035</td>
<td>0.035</td>
<td>0.056</td>
<td>5</td>
</tr>
<tr>
<td>Functional check</td>
<td>0.043</td>
<td>0.028</td>
<td>0.006</td>
<td>0.006</td>
<td>0.021</td>
<td>2</td>
</tr>
<tr>
<td>Restoration</td>
<td>0.086</td>
<td>0.057</td>
<td>0.020</td>
<td>0.020</td>
<td>0.021</td>
<td>3</td>
</tr>
<tr>
<td>Discard</td>
<td>0.065</td>
<td>0.071</td>
<td>0.024</td>
<td>0.024</td>
<td>0.021</td>
<td>4</td>
</tr>
<tr>
<td>Incorporation of PHM</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>1</td>
</tr>
</tbody>
</table>

References


6. A. Ahmadi and U. Kumar, Cost based risk analysis to identify inspection and restoration intervals of hidden failures subject to aging. Accepted for publication in: *IEEE Transaction on Reliability*, (2010).


**About the Authors**

Alireza Ahmadi is PhD candidate at the Division of Operation and Maintenance Engineering, Luleå University of Technology, Sweden. He has received his Licentiate degree in Operation and Maintenance Eng. in 2007. His research topic is related to the application of RAMS in aircraft maintenance development.
Suprakash Gupta is Associate Professor in the Department of Mining Engineering, Institute of Technology, Banaras Hindu University, India. His research interests are reliability analysis and maintenance optimization. He has published and reviewed a number of related papers.

Ramin Karim is Assistant Professor at Luleå University of Technology (LTU). He has a B.Sc. in Computer Science, and both a Licentiate of Engineering and a Ph.D. in Operation & Maintenance Engineering. He has worked within the Information & Communication Technology (ICT) area for 18 years, as architect, project manager, software designer, product owner, and developer. Karim is responsible for the research area eMaintenance at LTU, and has published more than 15 papers related to eMaintenance.

Uday Kumar is Professor and Head of the Division of Operation and Maintenance Engineering, Luleå University of Technology, Luleå, Sweden. His research interests are reliability analysis and maintenance engineering. He has authored, reviewed and edited a number of papers related to reliability and maintenance engineering.