An Assessment of
Operational Consequences of Failures to Support
Aircraft Scheduled Maintenance Program Development

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Abstract

A majority of the direct and indirect maintenance costs in the life cycle of aircraft stems from the consequences of decisions taken during the initial maintenance program development. In particular, the preventive and corrective maintenance requirements, which greatly influence both the system availability and life cycle cost, need to be defined in order to perform only those preventive actions that are absolutely necessary and cost-effective.

Reliability-Centered Maintenance (RCM) is a systematic methodology used to identify the preventive maintenance tasks that are necessary to realize the inherent reliability of equipment at the lowest possible cost. Developing a scheduled maintenance program by means of RCM consists of identifying those preventive tasks which are both applicable (technically feasible) and effective (worth doing). An applicable maintenance task must satisfy the requirements of the type of failure to restore the item's initial performance capability. To be effective, a preventive maintenance task must lead to a reduced risk (or expected loss) of the consequence classes to a level which is acceptable to the user.

In the design development phase, in order to identify the most cost effective solution, a design trade-off study is needed. This involves choosing the correct balance of the cost of consequences of failure and its correction, with their cost of prevention.

However, during initial aircraft maintenance program development, lack of a methodology that supports the assessment of the operational consequences of failures has made the cost-effectiveness analysis of maintenance tasks a challenging issue. This might reduce the accuracy of the analysis, which results in higher maintenance costs and may decreases the punctuality of operation, which ultimately increases the total aircraft life cycle cost.

The purpose of this study is to develop a methodology for identifying different operational consequences and associated costs caused by aircraft system failure, in order to facilitate and enhance the capability of taking correct and efficient decisions when analyzing the cost-effectiveness of maintenance tasks.

Some empirical studies of possible scenarios involving aircraft failures and their operational consequences for a commercial airline have been performed. Empirical data were extracted through document studies and interviews, guided by the application of an Event Tree Analysis (ETA). The analysis was performed together with experienced practitioners from both an aircraft manufacturer and commercial airlines, which contributed to a continuous verification of the outcomes of the study. Finally, the study has also estimated the associated cost of the identified operational consequences of failures. In order to quantify the operational consequences of failures, in the absence of adequate and reliable data, a methodology using pair-wise comparison technique has been applied to extract judgments of experts efficiently.

Keywords: Aircraft maintenance, RCM, MSG-3, Maintenance program, Cost effectiveness, Failure consequences, Event tree analysis, Pairwise comparison, Cost of delay.

Summary of content

1 - Introduction

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

1.1 Background

The airline business is large, integrated, automated, and complex, and providing a safe, reliable, and best in class service has become a strategic issue to meet customer requirements and to gain a global competitive advantage.

Over the past decades, significant improvements in airline safety have taken place (Boeing, Statistical summary, cited by Sachon & Pate, 2000). At the same time, the air travel in the United States increased from 95 million passenger in 1965 to 547 million passengers in 1995 (FAA safety statistics, sited by Sachon & Pate, 2000). Moreover, Al-Rais (2007) noted that by 2010 the number of business and leisure passengers worldwide will rise significantly to 2.3 billion people from 1.6 billion in 2007.

At the same time, passengers still expect an affordable service which is on schedule. Increased awareness, new generations of travelers and changing attitudes have led to change in demand. Punctuality has become one of the most significant factors for defining a passenger's satisfaction with an airline (Herinckx & Poubeau, 2000). This has made the on-time performance of an airline's schedule a key factor in maintaining the satisfaction of current customers and for attracting new ones (Institute of Air Transport, 2000). Therefore, airlines are continuously under pressure to improve their punctuality (i.e. on-time performance), setting ambitious and very challenging objectives (Herinckx & Poubeau, 2000). This requires management of different operational resources (e.g. crew and aircraft) to ensure the operational readiness and on-time performance of each flight in the planned schedule. However, flight schedules often suffer from irregularities, leading to unreliable services (Institute of Air Transport, 2000).

When dealing with these complex technical systems and extensive competition, the consequences of unreliable services become more critical and may include high cost of operation, loss of productivity, incidents, and exposure to accidents. It can also lead to annoyance, inconvenience, and a lasting customer dissatisfaction that can create serious problem regarding the company's marketplace position. This is crucial since a company can rapidly be branded as unreliable after providing poor service, whereas building up a reputation for reliable services takes a long time (Croarkin & Tobias, 2005). Therefore, air carriers are constantly trying to achieve high standards of safety and services at minimal cost (Sachon & Pate, 2000).

In fact, one of today's most important concerns for both manufacturers and airlines is how to provide a more reliable service, increase operational readiness, and manage the consequences of unreliability, which result from many different causes. These causes may be divided into two groups, external or internal to the aircraft, some of which are under the control of airlines and some are not. External causes may include: design of schedule buffer time, aircraft and crew rotation plan, information and communication

issues, maintenance management policies, etc. Internal causes to the aircraft are mainly due to the intrusion of sudden failures of aircraft systems, which decrease aircraft operational readiness and lead to aircraft being unavailable to deliver a normal and punctual scheduled service.

Research related to external causes, can be found in Sachon & Pate (2000). They propose a probabilistic risk analysis model, represented by an influence diagram, to quantify the effect of an airline maintenance policy on delays, cancellation, and in-flight safety. Their proposed model consists of three tiers: first, a set of management decision variables (e.g. the level of qualification of maintenance personnel); second, a ground model linking policy decisions and flight delays; and third, an in-flight model, linking policy decisions, maintenance quality, and flight safety.

Other research related to external causes can be found in Wu (2005), who explores the inherent delays of airline schedules resulting from limited buffer times and stochastic disruptions in airline operations. The results of this study show that airline schedules must consider the stochastic nature of daily operations. Schedules will become robust and reliable, only if buffer times are embedded and designed properly in airline schedules. Also Wu & Caves (2000) investigate the relationship between tight schedule punctuality and aircraft turnaround efficiency at airports, which are used in order to minimize system operational costs and meanwhile to maintain a required level of schedule punctuality. Their study shows the significance of a proper use of schedule buffer time in maintaining schedule punctuality performance. Abdelghany et al. (2004) present a model that projects flight delays and alerts for possible future breaks during irregular operation conditions. Again, Wu & Caves (2002), developed a cost minimization model to optimize the scheduling of aircraft rotation by balancing the use of schedule time, which was designed to control flight punctuality and delay costs. Moreover, Abdi & Sharma (2007) explore the development of a Network Control Centre information system in Emirates airlines. They conducted an environmental analysis and identified the factors affecting flight operations.

Considering internal causes in the aircraft, it has to be mentioned that, depending on the characteristics and significance of a system's function, its failure might impose operational restrictions, or require immediate action, e.g. correction of failure prior to further dispatch, and/or using abnormal or emergency procedures, which will interrupt normal operation of the aircraft as planned. Operational interruption can also cause cumulative problems, not only for the day of operations, but also for future planning, as it sometimes has reactionary domain effects.

An analysis of the delay causes and categories, grouped by IATA[1] codes, shows that Technical & Aircraft Equipment (i.e. internal causes of aircraft unreliability) was the most penalizing direct delay category in 2006, with a 10.2 % contribution to total delay causes (see Figure 2). However, this portion of operational interruptions, might have significant economical consequences, and needs more attention. Moreover, this is the portion that is within the manufacturers' and the airlines' responsibility and control (Herinckx & Poubeau, 2000).

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[1] International Air Transport Association
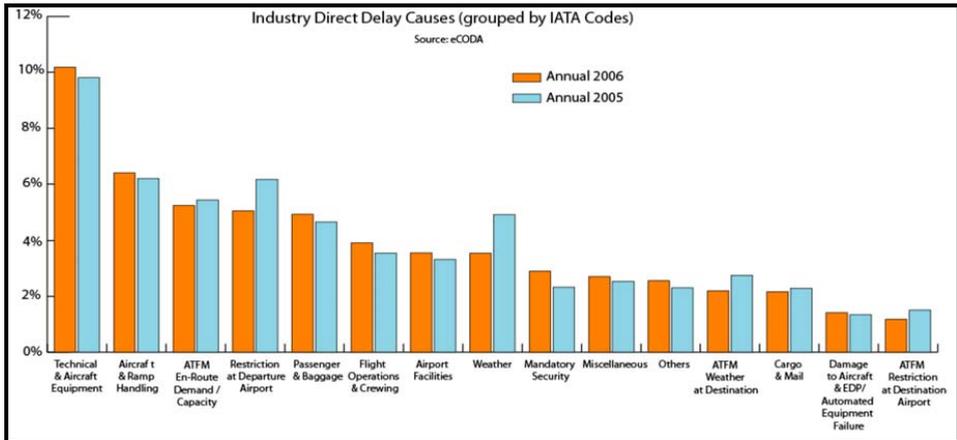
Figure 1: Industry Direct Delay Causes, grouped by IATA Codes.
(Source: EUROCONTROL - CODA Digest Annual 2006)

This is where the manufacturers can bring all their expertise and support for further improvement of aircraft on-time performance (Herinckx & Poubeau, 2000). The on-time performance of aircraft is also a function of aircraft operational readiness or availability performance.

The formal definition of availability performance is, "the ability of an item to be in a state to 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" (IEC, 2007). Blanchard (1992) 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".

Availability performance is a function of both reliability performance and maintainability performance, which both are inherent characteristics of the technical system (see Figure.2). However, availability performance is also influenced by the maintenance support performance, which is related to the organization providing maintenance (IEC 60300-3-11).
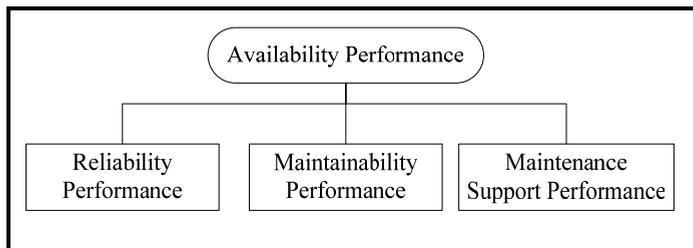
Figure 2. An illustration of relationship between availability performances and its associated factors. (IEV 191-02-03)

Maintenance support performance is defined by IEC (2007) 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 maintenance procedures, procurement of maintenance tools and facilities, logistic administration, documentation, and development and training programs for maintenance personnel (Barabady, 2007).

Many studies have been carried out on the different aspects of availability, reliability, and maintainability analysis. For example, reliability and risk analysis by Andrew & Moss (2002), reliability, maintenance and logistic support by Kumar et al. (2000), reliability modeling predictions and optimization by Blischke & Murthy (2000), maintainability, maintenance and reliability by Dhilion (2006), practical reliability engineering by O'Conner (2005), maintainability by Blanchard (1995), etc.

It has to be noted that the prime objective in the development of a system, within the constrains, specified by operation and maintenance requirement, is to be cost-effective. As depicted in Figure 3, system design attributes and system support elements impact on both the technical and economical sides of the cost effectiveness relationship. In addition, a major projected life cycle cost for a system stems from the consequences of decisions made during the early phases of design (Blanchard, 1995). Those decisions pertaining to the utilization of new technologies, the selection of components and materials, the identification of equipment packaging schemes and diagnostic routines, the selection of manufacturing process and maintenance support policies, etc, have a great impact on system effectiveness and life cycle cost (Blanchard, 1995).
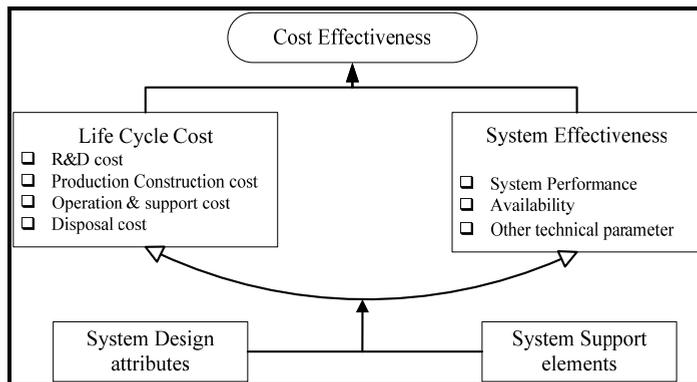
Figure 3: Element of system cost effectiveness (Blanchard, 1995).

In this context, the designer must take in to account the consequences of such interactions in order to achieve the predefined system effectiveness targets and minimize the cost, otherwise, the first factor will decrease and the second will increase, since the performance element is usually emphasized in comparison with other design parameters such as reliability, maintainability, and supportability. (D`Addio et al., 1998)

Hence, the development of a maintenance program, which primarily is dimensioning the required maintenance support performance, should be done as early as possible in system design, to influence necessary design changes to the technical system. Maintenance programs keep aircraft in safe, working order, ensure passenger comfort, preserve the airline's valuable physical assets i.e. aircraft, and ensure maximum utilization of the aircraft, by keeping it in excellent condition (Airline Handbook, 2000). Proper equipment maintenance and operation can assist in ensuring that the designed-in reliability performance is achieved, avoid failures, and reduce the cost (Barabady, 2007).

Considering availability issues, it has to be stressed that the aircraft costs its owner money every minute of every day, but makes money only when it is flying with freight and/or passengers. Hence, it is vital for the airline's financial success that aircraft are properly maintained (Airline Handbook, 2000). Therefore, it is expected that the aircraft will have to be in service as much as possible.

Maintenance accounts for approximately 11 percent of an airline's employees and 10-15 percent of its operating expenses (Airline Handbook, 2000). Furthermore, the operating costs over the life of equipment can be significantly influence by the effectiveness of the Preventive Maintenance that is performed (Kumar, 1990).Moreover, 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 program development. In particular, the preventive and corrective maintenance requirements, which highly influence both the system availability and life cycle cost, have to be defined in order to perform only the preventive actions, which are absolutely necessary and cost-effective (Savio, 1999).

Therefore, with increasing complexity and criticality of systems, the importance of developing an effective solution for technical failure management, during aircraft service life has increased. Hence, due to continuously increasing requirements related to safety, dependability, cost, and sustainability, significant improvements in the development of methodologies and in procedures for initial aircraft scheduled maintenance program development have taken place over the past decades.

Today, RCM is a systematic methodology used to identify the preventive maintenance tasks, necessary for realizing the inherent reliability of equipment at the lowest possible cost (Dhilion, 2006). The initial RCM methodology was developed by Nowlan and Heap in 1978. It contains systematic decision logic for identification of the Preventive Maintenance actions that are necessary to manage the failure modes that are causing functional failures in a given operating context. The objective of RCM is to define maintenance tasks that are applicable and effective with respect to the type of failure and its associated consequences. (Kumar, 1990; NAVAIR 00-25-403; MIL-STD-2173)

Ideally the role of these preventive maintenance policies is to cope with the failure process proactively to prevent the problems associated with the intrusion of failures so as to ensure safety and achieving inherent reliability of aircraft at the lowest possible cost in its service life. In fact the aim of such preventive maintenance program is to eliminate or reduce the consequences of failures to a level that is acceptable to the user (NAVAIR 00-25-403). The collection of these tasks forms part of the initial scheduled maintenance program of an aircraft.

In an RCM process, the consequences of every failure have to be analyzed. It should clearly separate hidden failures from evident failure, and distinguish events that have safety, environmental, operational, or economical consequences (Moubray, 1997). RCM uses an approach based on system level and function preservation (Smith & Hinchcliffe, 2004), and treats components differently in terms of relative importance according to the correlation between the equipment and system function.

RCM is a life cycle process not only for establishing, but for adjusting maintenance requirements for all levels of maintenance during the whole system life cycle. Therefore, the maintenance intervals are mainly defined based on actual equipment criticality and performance data. During the design phase RCM ensures that the PM tasks are based on the failure characteristics of the equipment and allows it to realize its inherent reliability. Therefore, only applicable and effective tasks are used to prevent failures; during the operational phase, as the equipment experiences changes (changes in mission, modification), RCM adjusts all of its PM requirements. (D`Addio et al., 1997)

Huge benefits can be derived by implementing RCM. These include higher safety and operating performance, better understanding of the failure modes, and reduction of operation and maintenance costs (Tsang, 1995). RCM principles play a fundamental role for both reducing operation and support cost and maintaining high level system effectiveness (D`Addio et al., 1998).

Since Nowlan and Heap's report (1978), the RCM methodology has been widely used by different industries, such as the military, nuclear power generation, offshore, oil and gas, maritime, solar receiving plant, grain terminal, coal mining and paper mills (Jones, 1995). As it has been refined, developed, and customized to a variety of specific requirements, different procedures and standards also have been produced such as: EPRI NP-4271, MIL-STD-2173, IEC-60300-3-11, SAE-JA1011 &12, etc.

The development of new-generation aircraft, new regulations and new damage tolerance rules for structures, which had a considerable influence on maintenance program development including the new premises for Nowlan and Heap's RCM methodology, provided the basis for the development of a new, improved "Airline/Manufacturer Maintenance Program Planning Document MSG-3", published by ATA in 1980. (Transport Canada, 2003)

MSG-3 was a combined effort by the manufacturers, regulatory authorities, operators, and ATA. The MSG-3 methodology implicitly incorporated the principles of RCM to justify task development, but stopped short of fully implementing reliability-centered maintenance criteria to audit and substantiate the initial tasks being defined (Transport Canada, 2003). In commercial aviation industries, increasing emphasis is now being placed on using the MSG-3 methodology.

MSG-3 classifies failure consequences into three groups: safety, operation and economical. Developing a preventive maintenance task in RCM and MSG-3 methodologies consists of determining which preventive tasks are both applicable (technically feasible) and effective (worth doing). An applicable maintenance task must satisfy the requirements of the type of failure to restore its initial performance capability (Rausand & Van, 1998). To be effective, a PM task must provide a reduced risk (or

expected loss) related to one or more of the consequence to a level which is acceptable to the user.

1.2 Statement of the problem

According to the RCM methodology, if the failure does not involve safety, the task should be cost effective, i.e. the cost of performing a PM task should be less than the cost of the prevented apprehensive failures (MIL-STD-2173). Though, for failures with operational consequences, the MSG-3 methodology requires that the task must reduce the risk of failure to an acceptable level (A330/A340 PPH, 2006). However, in order to assess the amount of risk reduction, the total associated operational losses due to failure also have to be determined in an MSG-3 analysis. Moreover, the term "risk of failure" pertains to the amount of losses resulting from a failure, which in respect to operation means the amount of losses resulting from the operational consequences of failures. Thus, the amount of risk or possible potential losses due to operational consequences of failures, should be assessed in both cases.

Depending on the situation in which a failure occurs during aircraft operation, the integration of the following criteria drives the ultimate state of operational situation and the deviation from its normal state, which leads to the possible operational consequences:

- the possibility of detection of loss of associated function by crew, in terms of evident or hidden failure and its detectability during normal operation of aircraft.
- the nature of the failure, in terms of adverse affect on operating capability, which might require an immediate corrective action, impose operational restriction, or in the worse case require using emergency or abnormal procedures.
- the possibility to dispatch the aircraft with an inoperative item, which is advised by Minimum Equipment List or Flight Operation Manual.
- the phase of the flight in which the failure may occur.
- and ultimately the pilot decision.

In fact the combination of these criteria determines the extent to which operational action is required to keep the aircraft in operation or to recover it to a normal operating state. This may include immediate maintenance action prior to dispatch when the aircraft is on the ground, or some sort of operational restrictions might need to be considered such as reduced flight altitude. It may also impose the use of emergency or abnormal procedures such as aborted take-off, in-flight turn-back, diversion, or touch-and-go, when the aircraft is airborne.

However, during initial maintenance program development of an aircraft, lack of a methodology to support assessment of the operational consequences of failures, and the associated financial losses, has made the cost-effectiveness analysis of maintenance tasks a challenging issue. This might reduce the accuracy of the analysis, which results in low operational readiness, higher downtime and maintenance cost and decreases the punctuality of operation, which ultimately increases the total aircraft life cycle cost.

In spite of all the work cited earlier, to the best of our knowledge, there are no studies available on the assessment of the operational consequences and the associated financial

losses of failures in aircraft systems. Hence, one major challenge still remains as how to develop a methodology that supports an assessment of the operational consequences and the associated economical losses of failures in aircraft systems, to support and enhance an efficient and accurate cost-effectiveness analysis of different maintenance tasks during the initial maintenance program development of an aircraft.

1.3 Purpose of the study

The purpose of this study is to develop a methodology for identifying different operational consequences and associated costs caused by aircraft system failure, in order to facilitate and enhance the capability of taking correct and efficient decisions when analyzing the cost-effectiveness of maintenance tasks.

1.4 Research questions

In order to fulfill the above stated purpose, the following research questions have been formulated:

1. What are the important reasons for the changes in the aircraft maintenance program development?
2. How can the possible operational consequences caused by occurrence of failures during aircraft operation be identified?
3. How can the cost of operational consequences of failures be assessed?

1.5 Objectives

The specific objectives of this study are to:

1. Describe the current state-of-the-art in trends of aircraft maintenance program development methodologies.
2. Propose a systematic methodology that supports the identification of the operational consequences of failures in aircraft system.
3. Propose a systematic methodology to estimate the cost of the operational consequences of aircraft system failures.

1.6 Scope of the study and delimitations

Based on the available resources such as time and research goals, the scope and limitation of this study are:

- system and power plant part of aircraft, according to MSG-3, and not structures, zonal and L/HIRF[3].
- failure effects that are classified as operational consequences and not safety or economical effects.
- technical system failures and not human errors.

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[3] Lightning/High intensity Radiated Field analysis procedure.

- the consequences of failures, which result into higher fuel consumption, or loss of opportunity to use the normal capacity of aircraft as planned have not been included in the proposed methodology.

The reason for the first limitation is that, according to MSG-3, aircraft scheduled maintenance analysis is divided in the four main groups: System power plant, Structure, Zonal and L/HIRF, each of these four groups follows a specific procedure.

The reason for the second limitation is that for safety and economical consequences, separate methodologies needs to be developed. Moreover, it is assumed that failures with economical consequences are only related to the cost of corrective maintenance.

Furthermore, one strong assumption of this study is that maintenance technicians and pilots who are directly involved in decision making, are aware of the procedures, and have enough training so that they do not introduce additional errors to the systems. This forms the reason for the third limitation.

The reason for the fourth limitation is that, sometimes, the occurrences of failures impose some operational restrictions, but proper implementation of procedures, ensures scheduled aircraft operation without any interruption. However, due to the restriction in aircraft operation, such as altitude restriction or reduced allowable load, failures ultimately result into economic losses such as higher fuel consumption or loss of opportunity to use the normal capacity of aircraft as planned. As these two consequences and other similar type, are more economical than operational, they have not been included in the proposed methodology.

2 - Research methodology

There are many different ways of doing research. In this chapter a brief introduction to different aspects of research methodology is presented together with the choices made in the present study.

2.1 Introduction

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 & Bogdan, 1984). Denzin & Lincon (1994) state that the term research methodology focuses on "the best means for gaining knowledge about the world".

2.2 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, descriptive, or explanatory (see Table 2.1). 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 & Rossman, 1999; Yin, 2003).

Table2.1. Different kinds of research proposals (Neuman, 2003)

Exploratory	Descriptive	Explanatory
- Become familiar with the basic facts, setting, and concerns.	- Provide a detailed, highly accurate picture.	- Test a theory's predictions or principle.
- Create a general mental picture of conditions.	- Locate new data that contradict past data.	- Elaborate and enrich a theory's explanation.
- Formulate and focus questions for future research.	- Create a set of categories or classify types.	- Extend a theory to new issues or topics.
- Generate new ideas, conjectures, or hypotheses.	- Clarify a sequence of steps or stages.	- Support or refuse an explanation or prediction.
- Determine the feasibility of conducting research.	- Document a causal process or mechanism.	- Link issues or topics with a general principle.

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 & 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.

2.2.1 Purpose of this study

The purpose of this study is to develop a methodology for identifying different operational consequences and associated costs caused by aircraft system failure, in order to facilitate and enhance the capability of taking correct and efficient decisions when analyzing the cost effectiveness of maintenance tasks.

Hence, to fulfill this purpose a combined exploratory, descriptive, and partly explanatory approach has been chosen. The first research question is related to motives for approaching the research as exploratory. These reasons are to generate knowledge and understanding about aircraft maintenance program development in general and the concept of RCM and MSG-3 more specifically. The knowledge gained from the explorative approach was used to formulate two sharper research questions and narrow down the purpose.

Hence, research questions Two and Three are more of a descriptive nature. The reason for choosing the descriptive approach is the identified need to describe how to model the operational consequences of failures during aircraft operation as well as how to assess the cost of operational consequences of failures in aircraft systems. The descriptive part is also intended to give valuable support to practitioners.

However, all three research questions also have some explanatory characteristics, e.g. regarding the relationships between drivers and trends in maintenance program development, the concepts of maintenance program development methodologies, the modeling of aircraft failure's operational consequences, and the assessment of the costs of these operational consequences.

2.3 Research approach

According to Alvesson & Sköldberg (1994), the research approach may be based on deduction, induction, or abduction. Another type of classification is where the approach is sub-divided into a qualitative or a quantitative approach.

The deductive approach strives to generate hypotheses, which are testable statements, based on existing theory. The results of a deductive study are derived by logical conclusions.

The inductive approach is based on empirical data and conclusions are drawn from the experience gained from the study.

Abduction may be considered a combination of deduction and induction. 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 & Sköldberg, 1994)

Research may also be divided into a qualitative or a quantitative approach. Quantitative information is conveyed by numbers and qualitative information is generally conveyed

by words. The quantitative approach emphasizes the measurement and analysis of causal relationships between different variables (Denzin & Lincoln, 1994). The qualitative approach aims at giving an explanation of causal relationships between different events and consequences (Miles & Huberman, 1994).

2.3.1 Applied research approach

The research process of the study presented in this thesis started with a deductive approach, initiated by a literature study aimed at identifying the need for further investigation of some aspects of aircraft maintenance program development. However, empirical irregularities also acted as input to the study. Thereafter, identified methodologies for the analysis of operational consequences and their costs were adapted, i.e. through operational scenarios and consequences together with expert judgments of the operational costs. The methodologies have been 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 applied research approach is similar to the abductive approach.

The research approach of the study presented in this thesis is mainly qualitative, but also supported by a quantitative approach. The qualitative approach aims at exploring drivers and trends in maintenance program development and the concepts of methodologies supporting maintenance program development with a focus on operational consequences and their costs. Furthermore, the approach also aims at describing different operational consequences of failures in aircraft systems. A quantitative approach is chosen to explore the costs of the operational consequences. However, the quantitative approach is not chosen to draw any statistical generalizations of the different operational consequences, but to illustrate the application of the proposed methodologies.

2.4 Data collection and analysis

Yin (2003) presents different ways of collecting data; see Table 2.2. In qualitative research, six sources of evidence for gathering information are typically used: participant observations, direct observations, interviews, documents, archival records, or physical art facts (Marshall & Rossman, 1999; Yin, 2003).

Data may also be divided into primary or secondary. 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)

Some advantages of secondary data are that they may be an easy, 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 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 for what reason (Yin, 2003). Data

analysis includes aspects of: examining, categorizing, tabulating, or recombining the evidence to address the propositions of a study (Yin, 2003).

Table 2.2 The selection of appropriate data collection methodologies for different research situations (Yin,2003).

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

2.4.1   Applied data collection and analysis

There are mainly two types of data that have been collected in the present study, i.e. theoretical and empirical data. Theoretical data were mainly collected to deal with research questions One, Two and Three. Empirical data were mainly collected in relation to research questions Two and Three, but to some extent also in relation to research questions 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.

Different databases have also been used to search for documents and research papers, e.g. Compendex, Scirus, Science Citation Index, Emerald, and Elsevier Science Direct.

Different keywords were formulated, such as: Reliability-Centered Maintenance (RCM), MSG-3, maintenance program, 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 heading 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 2.1.

Formation of different search words → Perform search in databases → First data reduction (reading headings) → Second data reduction (reading abstracts) → Third data reduction (reading articles) → Summary of results
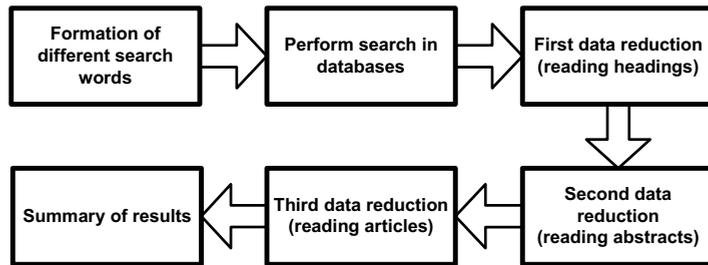
Figure 2.1. The data collection and analysis approach used for searching in different databases. The arrows represent the steps taken to reduce the amount of information, and to find relevant information.

Empirical data needed to investigate the operational consequences of failures in aircraft systems were collected using the three different approaches: archival records, interviews, and documents. The archival records consist of databases containing descriptions of operational consequences and historical data.

The interviews were conducted by selecting objects so as to represents a major part of the aviation sector, from airlines, Maintenance Repair Organizations (MRO), authorities, and manufacturers. The interviews were performed with experienced practitioners at both aircraft manufacturers and airlines. The documentation consists of different descriptions generated at the development of aircraft maintenance programs, as well as documents supporting the 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 program 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 the iterative process of interviews and the developed documents that acted as guidance during the interviews, e.g. the constructed event tree. Furthermore, the involved practitioners actively took part in the enhancement of the proposed methodologies, e.g. discussing, reading and making comments, and providing valuable and applicable documents and data. The practitioners mostly were 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 pair-wise approach to extract expert judgments regarding the cost of aircraft failure's operational consequences.

Mainly three different approaches have been applied in the data analysis. Firstly, theoretical findings related to the first research question have been ordered chronologically in the three phases of past, present, and future. Within each phase methodologies supporting aircraft maintenance program development were identified. In addition, drivers and trends for the evolution of these methodologies were identified.

Regarding research question Two, theoretical and empirical findings have been analyzed usin an Event Tree Analysis (ETA) approach. In this way different scenarios, from initiated failures to operational consequences, have been qualitatively mapped and partly quantified using empirical data.

The third analysis approach was the application of pair-wise comparison logic in order to quantify expert judgments regarding the cost of operational consequences, which is related to research question Three.

2.5 Reliability and validity

Reliability demonstrates that the operations of a 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 pre-understanding of the different areas to guide another researcher. In addition, the analysis approach is described in each paper and the thesis in order to guide other researchers.

Validity is concerned with whether the study investigates the phenomenon of interest or not. One approach to strengthen 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 2.2 illustrates the relationship between the concepts by using the analogy of a target. The bull's-eye represents a fit between a measure and the definition of the contract.

A Bull's-Eye = A Perfect Measure

| Low reliability and low validity | High reliability and low validity | High reliability and high validity |
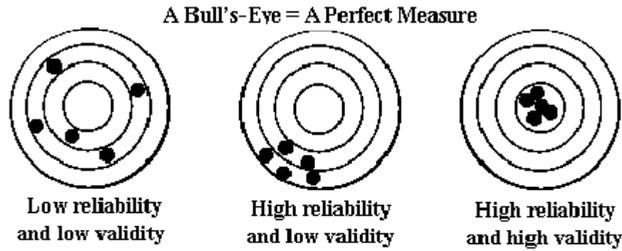
Figure 2.2 Illustration of relationship between reliability and validity
(Neuman, 2003).

In this study theoretical findings have been validated through interviews with experienced practitioners together with some documents from their companies. In addition, colleagues of the author at the Luleå University fo Technology gave comments on the research design and worked with the appended papers at seminars, which strengthens the validity.

2.6 The research process

The main activities of the applied research process are illustrated in Figure 2.3. This process can be seen as consisting of the four phases, Plan, Do, Study, and Act (Deming, 1993).

In the Plan phase, a preliminary literature study was performed to answer research question One, i.e. related to maintenance program development and RCM, but also risk analysis in general. The outcome of this literature study resulted in the formulation of two sharpened research questions (i.e. research questions Two and Three) 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.

The Do phase dealt with the need for further investigation of the operational consequences of failures and an assessment of their costs, which were identified in the Plan phase. Hence, a further literature study related to the operational consequences of aircraft failures, some specific risk analysis methodologies, and methodologies for extraction of expert judgments, was performed. An event tree and a survey were developed during this phase.

The Study phase focused mainly on the identification of the operational consequences of aircraft failures and an assessment of their costs. The data analysis models that were adapted in the Do phase were applied to analyze both theoretical and empirical findings. The outcomes of this phase are mainly summarized in the appended papers.

The research process presented in this thesis has resulted in the identification of aircraft failures' operational consequences and an assessment of their costs. The next step is to apply the proposed methodologies in the actual development of an aircraft maintenance program. Hence, suggestions for further research and reliability and validity issues can be found in the last chapters of this thesis and to some extent in the present chapter.
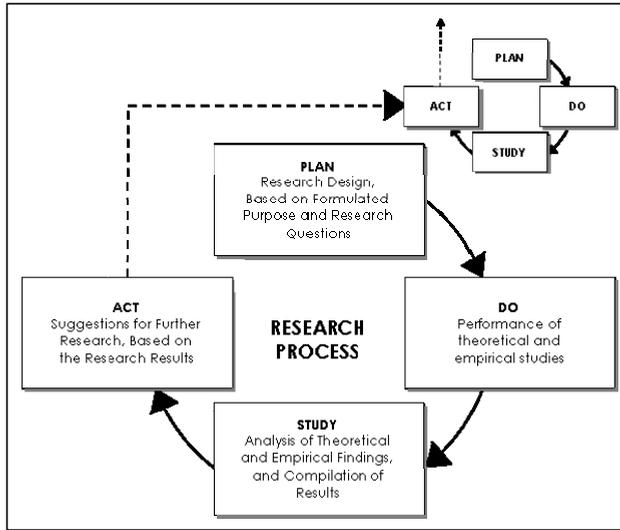
Figure 2.3. The main activities of the research process of the study presented in this thesis. The different phases follow the continuous improvement cycle. (Adopted from Söderholm, 2005)

3 - Summary of appended papers

This chapter summarizes the three appended papers and describes the relations between them. Further information can be found in the appended papers.

3.1 Paper I

Ahmadi A., Söderholm P., & Kumar U. (2007). An Overview of Trends in Aircraft Maintenance Program Development: Past, Present, and Future. In Proceedings of: *European Safety and Reliability Conference 2007 (ESREL 2007)*. June 25-27, Stavanger, Norway.

3.1.1   Purpose

The purpose of this paper is to describe the trends and important reasons for the changes in the aircraft maintenance program development in recent decades.

This paper is related to the study's first research question and objective. The research question is stated as: "What are the important reasons for the changes in the aircraft maintenance program development?". The objective is to describe the current state-of-the-art in trends of aircraft maintenance program development.

3.1.2   Study approach

The paper is based on a literature review covering the advancement of aircraft maintenance program development. The advancement is described in chronological order, i.e. roughly in the three phases of past, present, and future. In each phase the evolution of major supporting methodologies to aircraft maintenance program development, e.g. MSG and RCM, are linked to each other together with drivers and trends behind the evolution.

The major milestones and fundamental reasons for such development are also discussed and illustrated in relation to a flow diagram, which shows the logical and chronological order of the trends. Finally, the paper describes some possibilities and challenges of applying Information & Communication Technology (ICT) within the emerging approach of e-Maintenance, to improve the surveillance of aircraft maintenance program performance.

3.1.3   Findings

Two aspects have been critical drivers for the fundamental changes in maintenance concepts within the aviation industry. First the need for more reliable systems, which changed the industry's failure management approach from prevention of failures to preservation of system functions.

The second aspect was the need to control the potential losses and to be more effective, which urged the industry to use the system safety and risk management approach. This changed the focus from maintaining technical item characteristics on component level per se, to also consider consequences of item failure on system level.

3.1.4   Main conclusions

The study of trends shows that the changes of maintenance can be described in two different aspects. The first aspect is related to the failure management approach and the second aspect is related to the applied safety and risk management approach. (See Paper I)

The failure management approach changed from failure rectification, via failure prevention, to function preservation. The major driver for these changes was increasing availability requirements, specifically for the last change.

The safety and risk management approach changed from maintaining the technical characteristic of components, via failure mode identification per se, to the failure cause-consequence consideration. In fact, incorporating a risk management concept in the failure management strategies drove the changed focus from failure modes identification to a failure cause-consequences analysis. The major drivers for these changes were the need to control the potential losses and to be more effective.

Moreover, a scheduled maintenance program is considered as a living document and needs to be reviewed and refined to ensure that the aircraft and associated systems continue to fulfill the safety, cost effectiveness, and reliability goals. This continuous process requires organized information systems that provide a means to conduct surveillance of aircraft under actual operating conditions to sustain an efficient, safe, and cost-effective scheduled maintenance program.

This is where, the application of Information Communication Technology (ICT) is needed. e-Maintenance, which is an application of ICT, could be of great support for performing an effective and efficient surveillance of aircraft maintenance program performance in the near future.

3.1.5   Relation to other papers

The paper presents the evolution of aircraft maintenance program development, and identifies the current state-of-the-art regarding supporting methodologies. Hence, the paper acts as a foundation for the whole study, by making it possible to formulate sharper research questions that are related to the other papers.

3.2 Paper II

Ahmadi A. & Söderholm P. (2007). Assessment of operational consequences of aircraft's system failures: Using Event Tree Analysis. Accepted for publication in Proceedings of: *IEEE Aerospace Conference 2008 (Big Sky)*. March 1-8, Montana, USA.

3.2.1   Purpose

The purpose of this paper is to propose a systematic methodology to identify operational consequences of failures and associated costs in aircraft systems, to support the cost-effectiveness analysis of maintenance tasks when developing scheduled aircraft maintenance program.

The paper is mainly related to the second research question and objective of the study. The research question was stated as: "How can the possible operational consequences caused by occurrence of failures during aircraft operation be identified?". The objective was to propose a methodology that supports the identification of the operational consequences of failures in aircraft system. However the paper is also related to research question Three: "How can the cost of operational consequences of failures be assessed: and objective Three: "Propose a systematic methodology to estimate the cost of the operational consequences of aircraft system failures".

3.2.2   Study approach

The paper is based on empirical studies of possible scenarios from aircraft failure to operational consequences in a commercial airline. Empirical data were extracted through document studies and interviews, guided by the application of an Event Tree Analysis (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.

3.2.3   Findings

The main result presented in this paper is an event tree that qualitatively illustrates the different possible consequence scenarios which may happen if a failure occurs. Within the paper, a definition is suggested for the term "operational consequence". Furthermore, the six key parameters that will identify the ultimate operational situation and its associated consequences have been recognized. Moreover, a methodology to estimate the associated cost of consequences is explored.

3.2.4   Main conclusions

The constructed event tree is an effective way to assess the operational consequences of failures. If sufficient data are provided, the associated cost of operational consequence of failure could also be estimated. In order to quantify the ETA, historical data or expert judgments can be applied.

3.2.5   Relation to other papers

The paper presents a generic event tree that can act as a supporting tool to assess the operational consequences of aircraft system's failures. Hence, this tool can be applied within the MSG and RCM methodologies, which are described in Papers I and II. One way to quantify the operational consequences illustrated in the proposed event tree analysis is the efficient use of expert judgment, which is described in Paper III.

3.3 Paper III

Ahmadi A., Gupta S., & Kumar U. (2007). Assessment of the cost of operational consequences of failures in aircraft operation. *In Proceedings of: 3rd International Conference on Reliability and Safety. December 17-19, Udaipur, India.*

3.3.1   Purpose

The purpose of this paper is to show how to effectively utilize the knowledge of the field experts, which may serve as an effective database for assessing the cost of the operational consequences of failures, when there are no sufficient or reliable data. The paper is related to the third research question and objective of the study. The research question is stated as: "How can the cost of the operational consequences of failures be assessed?". The objective was to "propose a systematic methodology to estimate the cost of the operational consequences of aircraft system failures", when there is a lack of sufficient and reliable data.

3.3.2   Study approach

The study is based on the identification of the cost of operational consequences by interviews and document studies. In order to quantify the operational consequences, expert judgments are extracted by an application of a constructed pair-wise methodology.

It uses the application of pair-wise comparison methodology to quantify and assess the cost of operational consequences of failures, in which quantifying the contribution of different factors and cost headings to the cost of operational impact is shown.

3.3.3   Findings

The pair-wise comparison methodology was considered valuable in order to collect individual expert judgments and compile them in an effective way.

3.3.4   Main conclusions

This study shows a methodology of calculating the cost of technical delay as an operational consequence of failures, using the expertise of field experts when there are no available or reliable data. This methodology can excel in the estimation of the cost of delay provided there is access to a good number of experts with a sound experience of the company's financial and maintenance issues. This methodology can help the managements of operating airlines to frame their maintenance policy by providing useful data on the cost of delay due to maintenance. This methodology can also be used to quantify the cost of other operational consequences of failures, rather than technical delay.

3.3.5   Relation to other Papers

The pair-wise comparison methodology applied in this paper can be used in order to extract required data, as input to the proposed ETA presented in Paper II.

4 - Discussion and conclusion

This chapter summarizes the findings of the present study, which are related to the stated research questions. Furthermore, some aspects of the findings will be discussed. Finally, some suggestions for further research will be presented. The area of discussion will be centered on the stated research objectives.

4.1 Discussion

4.1.1   Trends in aircraft maintenance program development

The first objective of this study was to describe the trends in aircraft maintenance program development in recent decades. This objective is linked to the first research question, which is answered by the research presented in Paper I.

During the literature review, it was found that the outcome of a FAA[4] study (1961), had given rise to the following five surprising discoveries, which resulted in revolutionary changes in maintenance concepts (see Paper I):

•   Scheduled overhauls had little or no effect on the overall reliability of a complex item unless it had a dominant failure mode.
•   There were many items for which there was no effective form of scheduled maintenance[5].
•   Many types of failures could not be prevented or effectively reduced by 'right-age' overhauls, no matter how intensively they were performed.
•   Cost reductions in maintenance could be achieved with no decrease in reliability.
•   The intrusive nature of the overhauls was itself a major cause of unreliability.

The introduction to the FAA study stated that: "... *in the past, a great deal of emphasis has been placed on the control of overhaul periods to provide a satisfactory level of reliability. After careful study, the Committee is convinced that: reliability and overhaul time control are not necessarily directly associated topics; therefore, these subjects are dealt with separately.*"

In fact, these five discoveries significantly influenced the maintenance concept, which resulted in the introduction of Condition-Based Maintenance (CBM) in addition to the traditional Time-Based Maintenance.

The study of trends also shows that the changes of maintenance can be describe from two different aspects. The first aspect is related to the failure management approach and the second aspect is related to the applied safety and risk management approach. (See Paper I)

The failure management approach changed from failure rectification, via failure prevention, to function preservation. These step changes represent three generation of

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[4] Federal Aviation Administration of America.
[5] Traditional time-based overhaul at that time.

failure management, the major driver for these changes was increasing availability requirements, specifically for the last change.

The safety and risk management approach changed from maintaining the technical characteristic of components, via failure mode identification per se, to the failure cause-consequence consideration. In fact, incorporating the risk management concept in failure management strategies drove the changed focus from failure mode identification to a failure cause-consequences analysis. The major drivers for these changes were the need to control the potential losses and to be more effective, which urged the industry to use the system safety and risk management approach more extensively. Some of the reasons for these changes, which are still present and increasing, are e.g.: item complexity, system dependence, competition, and failure consequences, but also increasingly stringent requirements related to: dependability, costs, airworthiness, sustainability, and safety.

To facilitate better management of risk, sufficient and trustable data are needed, which is still a challenge. One example is the challenge to determine a good estimation of the failure rate, which requires the collection of data from different operating context. Moreover, removal data sometimes do not necessarily imply a failure, or that subsequent test levels have difficulties in duplicating test results achieved at preceding test levels (i.e. no fault found events, see Söderholm, 2007). Another reason is that, even if there is a failure, it is not always possible to link the reported failure to the "functional failure" or "failure mode" identified in the RCM or MSG-3 analysis.

Moreover, during the early stages of developing a new aircraft maintenance program, the data used in initial analysis are limited and sometimes imprecise. Furthermore, the way in which the aircraft and associated systems are used will change with time. So, the decisions made for maintenance task applicability and effectiveness are mostly based on conservative engineering judgments. As the program experiences growth and mature, more precise data regarding system performance and operating environment will be available through operation. Thus the basis for the decisions made during the initial RCM and MSG-3 analysis may change with time. Therefore, review and refinement of the aircraft maintenance program is necessary to ensure that the aircraft and associated systems continue to fulfill the inherent reliability and safety requirements in a cost-effective way.

Therefore, the need of data for both, developing initial maintenance programs and continuous surveillance requires organized information systems that provide a means to conduct surveillance of aircraft under actual operating conditions to sustain an efficient, safe, and cost-effective scheduled maintenance program. In fact, the application of Information & Communication Technology (ICT), is of great support for data collection, classification, and analysis. One such application is the e-Maintenance approach in the development and surveillance of maintenance programs. The application of e-Maintenance is believed to effectively support both initial maintenance program development and its surveillance in the near future.

4.1.2 Propose a systematic methodology that supports the identification of the operational consequences of failures in aircraft systems.

The second objective of this study was to propose a systematic methodology that supports the assessment of the operational consequences of failures in aircraft systems. This objective, which is linked with the second research question, is fulfilled by the research presented in Paper II.

As presented in the paper, the assessment of operational consequences of failure and its associated costs is a great challenge due to a long list of uncertainties related to the large amount of influencing factors, inadequacy of service information and difficulties in understanding their influences.

In fact the first step towards developing a proper methodology is to clarify the definition of a failure with operational consequences. Within Paper II, the following definition is suggested for a failure with operational consequences:

"a failure 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 fact, when such a failure occurs, it affects the rate and quality of flight production to a different degree. In this study it is considered that the effect of this type of failure mostly affects the rate of production, hence, the quality of flight production has not been considered.

Through a related literature review and interviews with aircraft experts, it was found that the integration and correlation of different parameters drive the ultimate state of operational situation and the extent to which the rate and quality of flight production deviate from pre-defined ones. These parameters have been identified as (Paper II):

- the possibility of detecting loss of functions by operating crew, and its detectability during normal operation of aircraft,
- the nature of the failure, in terms of adverse affect on operating capability,
- the possibility of dispatching an aircraft with an inoperative item,
- the possibility of continuing a flight with an inoperative item,
- the phase of the flight where the failure may occur, and ultimately,
- the pilot decision.

In fact, the combination of these parameters determines the extent to which immediate maintenance action, some sort of operational restrictions, or the application of emergency or abnormal procedures is required.

In order to illustrate the integration and correlation of these parameters, the Event Tree Analysis (ETA) was chosen as an appropriate methodology. One major reason for this selection was that ETA can be applied to illustrate the combination of events (i.e. scenarios). Moreover, a scenario description, using the event trees, gives a detailed picture of the possible operational consequences of different failures in aircraft systems during

operation. Furthermore, ETA can be used for qualitative as well as quantitative consequence analyses. Hence, if sufficient data and information regarding failure frequency and the probability of occurrence of each event are available, the frequency of occurrence of each consequence scenario can be calculated. Otherwise, ETA can be conducted qualitatively, using "Yes-No" answers instead of assigning probability figures. (See Paper II)

The ETA presented in this study starts with the identification of the initiating events, i.e. the failure of interest for further analysis. For each failure, an event tree is constructed. Consequences of candidate failure are developed by considering the failure and success of two predefined criteria and their included alternative states. The analysis proceeds through all alternate paths, by considering each consequence as a new initiating event. (See Paper II)

Based on the above discussions, the parameters have been divided in two main criteria displayed in the event tree analysis as the:

- operational phase where failure occur,
- adverse effect of failure on operating capability.

For the first criterion, i.e. "operational phase", 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. either the failure occurs or not.

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

The first state, "deferability of failure" indicates whether the failure is deferrable or if it requires an immediate action, e.g. performing corrective maintenance, or to follow some specified operational procedures. This could be identified by consultation of the Minimum Equipment List (MEL), Flight Manual (FM), Flight Crew Operation Manual (FCOM) or Quick Reference Handbook (QRH). The second state, "the imposition of any operational restriction", describes the need to impose any operational restrictions, such as altitude restriction, which are mandated by procedures or by pilot decision. Finally, the third state including the full form of "using abnormal or emergency procedures", describes whether some emergency or abnormal operation is applied, which is mandated by procedures or by pilot decision.

Using a qualitative approach, it has been shown in Paper II how the combination of different events within the states of the two criteria will create different scenarios, which in turn will determine the ultimate operational consequences. Based on the possible combination of events, 25 different scenarios were identified, which ultimately will lead to one or a combination of the following classification 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 the failure never occurs. The

other five scenarios where 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 scenarios are related to the occurrence of a failure that is related to deferrable maintenance, but that requires some operational restrictions. It has to be noted that, in this study the effect of failure which ultimately leads to higher fuel consumption or loss of opportunity to use the normal capacity of aircraft as planned, has not been taken into account. Hence, it is not included as one of the ultimate consequences. However, for 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. All these scenarios are related to 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 illustrate the application of the proposed ETA, an Avionic Ventilation System (AVS) of a hypothetical twin–engine, single aisle aircraft has been selected. The associated data have been gathered and analyzed in consultation with practitioners. (See Paper II)

In order to enhance the implementation of the proposed ETA, one should consider the quality and adequacy of required information. Nowadays, it is still a challenge to determine a good estimation of the failure rate, since it requires the collection of data from the world fleet. The sorting process of collected data is also difficult. The reason is that removal data do not necessarily imply a failure, or that subsequent test levels have difficulty in duplicating test results achieved at preceding test levels (i.e. no fault found events). Another reason is that, even if there is a failure, it is not always possible to link the reported failure to the "functional failure" or "failure mode" identified in the MSG-3 analysis.

However, when there is a lack of historical data, expert judgments can be a good source of information. To support an effective extraction of the field experts knowledge, there are systematic methodologies available, e.g. pair wise comparison. This is further discussed in relation to the third objective (see also Papers II and III).

4.1.3 Propose a systematic methodology to estimate the cost of operational consequences of aircraft system failure

The third objective of this study was to propose a systematic methodology to estimate the cost of the operational consequences of failure during aircraft operation. This objective is linked to the third research question, which is fulfilled by research presented in Papers II and III.

In fact, the first step towards estimating the cost of the operational consequences of failures is to assess the different type of operational consequences, which may happen due to different operational scenarios. In Paper II, operational consequences of failures have been

classified as no operational consequence, airborne and/or ground delays, and/or performing emergency or abnormal operation.

The next step towards estimating the cost of the operational consequences of failures is to model different operational scenarios that may happen during operation. A methodology based on ETA has been presented in Paper II. Based on different operational scenarios, the analyst could assess what type of operational consequences or combination of consequences are applicable. For example, in scenario 1, there is no consequence and in scenario 7, a combination of consequences may happen, e.g. aborted take-off and ground delay at departure (see Paper II).

The next step towards estimating the cost of the operational consequences of failures is to quantify the rate at which each operational consequence scenario will occur.

In order to quantify the rate at which operational consequences occur, the frequency of failure (failure rate or intensity) should be multiplied by both the conditional probability of occurrence of this failure in the specific operational phase, and the conditional probability of adverse affect of the failure on the operational capability. This may be expressed as (Paper II):

$$
\begin{pmatrix}
\text{Rate of} \\
\text{occurrence of} \\
\text{each operational} \\
\text{consequence} \\
\text{scenario} \\
\text{(No/FH)}
\end{pmatrix}
=
\begin{pmatrix}
\text{Failure rate} \\
\\
\text{(No/FH)}
\end{pmatrix}
\text{X}
\begin{pmatrix}
\text{Conditional} \\
\text{probability of} \\
\text{states in} \\
\text{criterion 1} \\
\text{(\%)}
\end{pmatrix}
\text{X}
\begin{pmatrix}
\text{Conditional} \\
\text{probability of} \\
\text{states in} \\
\text{criterion 2} \\
\text{(\%)}
\end{pmatrix}
$$

Where, No. and FH stand for number of occurrence and Flight Hour.

The final step toward estimating the cost is to calculate the annual cost for each scenario per aircraft. Paper II supports this calculation as:

$$
\begin{pmatrix}
\text{Annual cost of} \\
\text{scenario} \\
\text{(\$/Aircraft/year)}
\end{pmatrix}
=
\begin{pmatrix}
\text{Rate of occurrence} \\
\text{of scenario} \\
\text{per FH}
\end{pmatrix}
\text{X}
\begin{pmatrix}
\text{Unit cost of} \\
\text{ground delay at} \\
\text{departure} \\
\text{per FH}
\end{pmatrix}
\text{X}
\begin{pmatrix}
\text{Duration} \\
\text{of delay} \\
\text{Hrs.}
\end{pmatrix}
\text{X}
\begin{pmatrix}
\text{Average annual} \\
\text{utilization} \\
\text{FH/year}
\end{pmatrix}
\text{X}
\begin{pmatrix}
\text{Quantity} \\
\text{Per} \\
\text{Aircraft} \\
\text{(QPA)}
\end{pmatrix}
$$

In order to illustrate the quantitative application of the proposed ETA, an Avionic Ventilation System (AVS) of a hypothetical twin–engine, single-aisle aircraft has been selected. (See Paper II)

As discussed in Paper II, the failure rate of "Skin air inlet valve fails to close at take off power setting" is $1.12e^{-5}$ per Flight Hour (FH), based on historical data. The conditional probability of states in criteria 1 (prior to take-off) is estimated to 100%, as the failure will be evident to the crew prior to take-off. The conditional probability of states in criteria 2 (non-deferrable, with no operational restriction) is estimated to 100%, as the failure is not

deferrable and it does not impose any operational restrictions (as the aircraft is not allowed to take-off with the failure present) according to the MEL. Hence, the rate of occurrence of scenario number 4 for AVS is: $(1.12e^{-5}$ per FH) X (100%) X (100%) $=1.12e^{-5}$ per FH.

Finally, the annual cost of scenario number 4, considering 3,000 FH of utilization per year, is estimated as: 14.14 $/aircraft/year.

In order to implement the proposed methodology and achieve valuable results, accurate and sufficient data and information are needed as input to the analysis. This information is mainly related to the failure rate, and the probability of occurrence of each event. Also, enough knowledge about maintainability performances of the analysed system, such as Built-in Test (BIT) capability of the system is essential. Other information that is needed is related to aircraft operation and associated procedures given in formal documents, such as MEL, FM, FCOM, QRH (see Paper II). Furthermore, information about the maintenance support performance is necessary. Therefore, both available data and the knowledge of the analyst who is performing this methodology play an important role in achieving accurate result.

It has to be stressed that in the real world, determining a good estimation of required data is still a challenge. This might be due to the lack of sufficient data, improper data collection methodology, etc. When there is a lack of historical data, expert judgments can be a good source of information. However, in reality, it is hard to expect a reasonable accurate numerical value from expert judgements as they are influenced by a large number of factors. In order to support an effective extraction of the field experts' knowledge, a methodology is presented in Paper III. The proposed methodology is based on pairwise comparison technique, suggested by Saaty, (1980).

The fundamental principle is that it is more difficult to evaluate *n* elements (where *n* > 2) simultaneously than to compare two such elements at a time. In pairwise comparison, experts compare the importance of two factors on a relatively subjective scale. In this way, a judgment matrix of importance is build up according to the relative importance given by the experts.

In Paper III, a specific case has been selected, i.e. when failure appears prior to dispatch and corrective action is required to rectify the failure prior to further dispatch. The operational consequence of this type of failure could be expressed as ground delay. In this case, the operational cost of a delayed aircraft increases from its normal operating cost primarily due to extra cost incurred for crew, passenger, aircraft, and ramp. In the proposed model presented in Paper III, this extra cost is considered as a measure of the financial effect of operational consequences.

In the presented model, the cost of technical delays has been expressed as a percentage of the crew-related planned operation expenses. Therefore, an effort was made to find the contribution of different cost headings towards the delay cost from the judgments of experts using a pair-wise comparison technique.

In an effort to rank the cost headings and their associated contribution to total delay costs, a multiple-choice questionnaire consisting of six questions was designed. Three field experts were chosen and were asked to mark their opinion on the questionnaire, to judge the

relative contribution of two delay cost headings that form the judgments matrix for the contribution of the different cost headings to the cost of delay, for a delay less than 15 minutes.

Out of the above four delay cost headings, crew-related expenses are mainly the predetermined overtime paid due to delay, and are almost fixed as a percentage of planned crew-related cost. Therefore, by calculating the overtime paid to the crew, the remaining three delay costs headings could be calculated with the help of values of the contribution matrix.

4.2 Conclusions

From the discussion related to the objectives and research questions presented in this thesis, the following conclusions can be made:

Available standards regarding both RCM and MSG-3 describe the steps required for implementation in general. However, the methodology for implementing some steps, such as cost effective analysis, has not been defined in details, and it is left to the user to develop a customized procedure to implement. One of the key issues which need specific attention is the assessment of operational consequences of failures and its associated financial losses during the cost effectiveness analysis of maintenance task. This is a complicated issue due to a large amount of influencing factors. Therefore a specific methodology needs to develop for this assessment, which definitely promotes more correct and more efficient decision-making.

ETA can be applied for the consequence analysis of a system's failure, where the integration of different factors creates different cause-consequence scenarios. The major reasons that make ETA an effective methodology are that it illustrate the combination of events, and gives a detailed picture of the possible operational consequences scenarios. It could also be used for qualitative as well as quantitative overall consequence analyses. Based on the outcome of the study, the proposed ETA has been found to be a valuable methodology for assessing both the rate at which consequence scenario happens and its associated costs within a specific period of time.

The accuracy and validity of maintenance tasks resulted from RCM or MSG-3 analysis depend directly on the quality and sufficiency of required data. This is vital for defining the most applicable and effective maintenance task and also for surveillance of maintenance program during aircraft operation. However, collecting real and quality data is still a challenge. The collection of data is difficult since removal data do not necessarily imply a failure. This is due to a lack of communication among airlines, suppliers, maintenance providers, etc., that result in the ineffective use of data. This will improve by a feed-forward and feed-back system that supports the adjustment and correction of data interpretation. Moreover, failure and removal data are not linked most of the time to repair and overhaul data. Furthermore, if there is a failure, it is not always possible to link the reported failure to the "functional failure" or "failure mode" identified in the RCM or MSG-3 analysis. An application of Information Communication Technologies (ICT) is needed as a common tool. e-Maintenance, which is an application of ICT supports fast, correct, efficient, and trustable data collection. It helps the analyst to obtain the right

information at the right time, and facilitates easy and fast decision making (Parida & Kumar, 2004).

When there is a lack of data, expert judgments can be used as a good source of information. However, the opinion of experts could be influenced by a number of factors such as improper conceptualization, mental fatigue; lack of adequate information that may reduce the consistency of their judgments. To support an effective extraction of the field experts knowledge, there are systematic methodologies available, e.g. pair-wise comparison. The study of this thesis shows that the proper implementation of pairwise comparison technique will generate good and appropriate results. However, the effective use of expert judgments also presupposes the development of procedures to be able to control the consistency of judgments.

4.3 Further research

Based on the findings presented in this thesis, there are some opportunities for interesting further research, in order to support continuous improvements:

- The proposed ETA methodology could be enhanced by developing a specific procedure to guide the analyst. Moreover, developing a computerized tool will enhance implementation procedure.
- The application of the proposed ETA could be extended to cover all type of failure consequences in RCM and MSG-3 methodology such as safety and economical consequences. Moreover, it should be more developed to cover not only the system and power plant sections which are the focus of this study, but also for other parts such as structure.
- The terms "operational consequences" and "economical consequences" need to be more clarified, as sometimes it is difficult to differ between these two.
- The proposed pairwise comparison could be applied on a large scale, asking a variety of air operators to conduct a test to evaluate its applicability in that context.
- A study is needed to explore the ways in which application of ICT, specifically e-Maintenance could support both maintenance program development and surveillance programs.

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Appended Papers

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Paper I

An Overview of Trends in Aircraft Maintenance Program Development:
Past, Present, and Future.

An overview of trends in aircraft maintenance program development: Past, present, and future

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ABSTRACT: The purpose of this paper is to describe the trends in aircraft maintenance program development during the last 50 years, including the reasons for the aircraft industry to change its view of maintenance. The major milestones and fundamental reasons for such development are also discussed and illustrated in relation to a flow diagram, which shows the logical and chronological order of the trends. Finally, the paper describes some possibilities and challenges as regards applying Information & Communication Technology (ICT) within the emerging approach of e-Maintenance in order to enhance the surveillance of aircraft maintenance program performance.

1 INTRODUCTION

Before 1950, technical items were mostly simple, which made them reliable and easy to maintain. The maintenance concept were mostly based on the belief that failures were mostly caused by wear and tear and the common maintenance strategy was Corrective Maintenance. By the late 1950s, the second generation of maintenance started, with the introduction of more complex items, mostly due to lack of labor and high performance requirements. With increasing complexity and criticality of items, the importance of a preventive maintenance program for failure management increased. However, one of today's major challenges remains how to determine the success of such maintenance programs.

The first part of this paper provides some background to the airlines' problems during the 1960s, with a short discussion on efforts leading to the publication of the first systematic review of aircraft systems, known as the MSG-1 and the MSG-2 methodologies. Next, the efforts of United Airlines, which led to the Reliability-Centered Maintenance (RCM) methodology are described, outlining how the preventive maintenance concept was influenced by system level thinking. The effect of RCM on the MSG methodology, which resulted in the publication of MSG-3, will also be described. All these developments and trends are discussed with the help of a flow diagram, which illustrates the developments in a logical and chronological order.

Finally, the possibilities and challenges related to e-Maintenance for the surveillance of an aircraft maintenance program's performance is discussed as a future development.

2 EARLY MAINTENANCE STRATEGIES AND RELATED PROBLEMS

Prior to World War II, maintenance was a skill learned through experience and rarely based on scientific theories. The maintenance requirements were determined by a few experienced technicians with assistance from the Original Equipment Manufacturer (OEM). The items were quite simple, which made them reliable and easy to maintain. In those days, the common maintenance strategy was Corrective Maintenance, based on the belief that the failures were mostly caused by wear and tear. Hence, the maintenance was applied in order to restore the functional capability of failed items. This was a reactive approach to maintenance since the action was done after the failure had occurred. This period of maintenance is known as 'Pre World War II'. (Moubray, 1997)

By the late 1950s, or 'Post World War II', the second generation of maintenance started to evolve. Industry became more competitive and a lack of manpower, improved design standards, and new performance requirements led to increasingly complex and mechanized items. Therefore, the maintenance of items required more downtime and resources. Hence, maintenance costs were high and availability became another problem. These changes, together with penalties associated with loss of production, forced industry to consider how to prevent

the item from failing by applying Preventive Maintenance instead of relying on Corrective Maintenance.

In an effort to reduce the number of failures, industry concluded that, based on the accepted 'wear and tear' model of failure, every item had a 'fixed age' at which either complete overhaul or discard was necessary to ensure safety and operating reliability.

Based on these concepts, there was a widespread belief that all failures could be prevented by age-based overhaul. As a result, Time-Based Maintenance became the norm for Preventive Maintenance. This kind of approach motivated the indiscriminate use of overhaul or preventive replacement for all items included in a Preventive Maintenance program. (Tsang, 1995)

Consequently, the failure rate increased rapidly and maintenance costs grew accordingly. This prompted the airline industry to look for new preventive maintenance concepts. In addition, the Federal Aviation Administration (FAA) in the US was concerned that the reliability of some engines had not been improved by changing either the type or the frequency of overhaul. The available data indicated that although the frequency of some failures had been reduced, many more had remained unchanged or actually increased. These findings could not be explained by using the accepted model of failure. During this time, a new approach to maintenance evolved within the aircraft industry. Based on analysis of failure data, it was found that the probability of failure did not increase with operating age and the traditional time-based policies were found to be ineffective for controlling the failure rate of many items. (processonline, 2007)

During 1960, FAA was surprised that, notwithstanding many previous efforts, it was not possible for airlines to control the failure rate of a certain type of engine, by changing the scheduled overhaul policy. Moreover, due to congested continuous maintenance activities, fleet availability dropped significantly, causing operation and maintenance costs to increase rapidly without equivalent improvements in reliability. The reasons for the problems mentioned above can be summarized in the following nine areas:

1. Risk analysis was not considered in maintenance analysis. The objective of the maintenance activities was mostly to retain the technical characteristics of the items, rather than reduce or mitigate the consequences of item failures.
2. The objectives of preventive maintenance were not recognized. Consequently, the applicability and effectiveness criteria for maintenance tasks were not defined either.
3. The operating context was not considered in maintenance analysis. Therefore, one mainte-

nance program was applied to all aircraft fleets regardless of operating profile, weather, operator, etc. This approach was insufficient, since the operating context affects the failure characteristics and changes the failure rate. Hence, the maintenance task and its interval applicable to one operating context may not be applicable to another.
4. Maintenance was applied to control the degradation of functional performance and reliability of all items. It was believed that there was always an appropriate maintenance task to retain the inherent reliability or to restore the functional performance of the items. However, it is now known that, due to the nature of some failures, it might be impossible to retain or restore the item performance to the designated level. Hence, some of the maintenance tasks were inappropriate and contributed to anomalous maintenance effort and downtime without giving any benefits. It should be noted that inherent reliability is a function of design and cannot be improved without redesign or modification.
5. It was incorrectly assumed that all items had age-related failure characteristics and would benefit from age-based maintenance measures. Therefore, specific actions, mostly overhaul measures, were planned for every item. However, according to the reliability investigations conducted by United Airlines, no more than 11% of the items would benefit from a limited operating age or scheduled overhaul. Thus, for the remaining 89% of the items, these were inappropriate maintenance measures, which contributed to unnecessary maintenance efforts and non-beneficial downtime.
6. Prescribing hard-time actions for non-age-related failures had an adverse effect on the availability and reliability of the items, because it contradicted the actual failure characteristic and degradation processes. Therefore, serviceable items were unnecessarily removed from service and sent to shops for overhaul or other maintenance measures. This intrusive maintenance practice had a negative impact on manpower resources, spare parts, down time, total costs, and availability performance.
7. Since there is seldom any strong relationship between the items operating time and failure probability, many failure modes did not benefit from age-based shop visits. These failures were one of the main sources of unscheduled corrective maintenance, sudden aircraft unavailability, and disturbed operation. Even though many failure modes are not age-related, it is most often possible to identify and recognize the conditions that indicate an imminent functional failure. Hence, it is possible to apply On-Condition measures, i.e. scheduled inspections designed to detect a poten-

tial failure condition, in order to initiate preventive maintenance actions and thereby avoid the functional failure or its consequences. (Moubray, 1997)

8. All the items of systems were considered for maintenance regardless of the importance of their functions for system availability. Hence, limited maintenance budgets were not distributed in accordance with the importance of the items function for availability performance of the system.

9. Previous experience in the development of scheduled maintenance instructions had revealed that a program of effective maintenance measures could be developed through the use of logical analysis and decision-making processes. Hence, there was a need for a structured decision process to assess the maintenance requirements of the systems, and to develop an applicable and effective maintenance program.

In order to respond to the above-mentioned challenges and to find a proper solution, FAA formed a task force, including representatives from both FAA and American Airlines. The purpose was to evaluate the effectiveness of traditional time-based maintenance, investigate the capabilities of scheduled maintenance, and find the possible relationship between scheduled maintenance and reliability. These analyses gave rise to the following surprising discoveries (Kennedy, 2005; Equipment Links, 2007; processonline, 2007):

- Scheduled overhauls had little or no effect on the overall reliability of a complex item unless it had a dominant failure mode.
- There were many items for which there was no effective form of scheduled maintenance.
- Many types of failures could not be prevented or effectively reduced by 'right-age' overhauls, no matter how intensively they were performed.
- Cost reductions in maintenance could be achieved with no decrease in reliability.
- The intrusive nature of the overhauls was itself a major cause of unreliability.

The outcomes of the efforts mentioned above led to the first formal "FAA - Airlines Reliability Program" being issued in November 1961. The program was developed to improve the control of reliability through an analysis of the factors that affect reliability and to provide a set of actions to improve low reliability levels when necessary. As the propulsion system had been the area of greatest concern, and since power plant data was readily available for study, programs were developed for the propulsion system first. The introduction to that program stated that (Nowlan & Heap, 1978):

"…in the past, a great deal of emphasis has been placed on the control of overhaul periods to provide a satisfactory level of reliability. After careful study, the Committee is convinced that: reliability and overhaul time control are not necessarily directly associated topics; therefore, these subjects are dealt with separately."

3 THE FIRST STRUCTURED MAINTENANCE PROGRAM PROCEDURES: MSG-1 & MSG-2

United Airlines started a research program in 1965, to substantiate the outcomes of the FAA task force and to provide a generally applicable systematic review of the aircraft design. Hence, in the absence of operational experience, the best maintenance process should still be utilized through a structured logical decision tree. In June of 1967, T.D. Matteson and F.S. Nowlan presented a paper on the use of this methodology at an aircraft design and operations meeting of the American Institute of Aeronautics and Astronautics (AIAA). As a result, rudimentary decision logic was created and over the next few years, it was developed with the cooperation of airlines, manufacturers, and FAA. The methodology was used to develop the Boeing-747 initial maintenance program document. This document was published on 10 July 1968 by ATA under the title "Boeing-747 Maintenance Steering Group (MSG) Handbook: Maintenance Evaluation and Program Development (MSG-1)" (Nowlan & Heap, 1978). This was the first attempt at applying reliability-centered maintenance concepts when developing an aircraft maintenance program.

MSG-1 was a 'bottom-up' approach to the Boeing-747 systems, in which components were the highest level to be considered. Hence, MSG-1 focused on a component such as the Fuel Control Unit (FCU) in a system and analyzed which part of that component might fail. Then, it was determined what kind of maintenance action was required to prevent the failure. Through MSG-1, the potential maintenance measures for each maintenance strategy were selected and evaluated from criteria based on operating safety or essential hidden function protection. The remaining potential maintenance tasks were evaluated to determine if they were economically viable.

MSG-1 introduced three broad processes to classify the scheduled maintenance requirements, i.e. Hard Time (HT), On-Condition (OC), and Condition Monitoring (CM). OC requires an item to be periodically checked, or tested, against an appropriate physical standard to determine whether the item can continue in service or not (Nakata, 1984).

The efficacy of the systematic MSG-1 methodology applied to Boeing-747 was considered to justify a generic solution, which could be applied to other

new aircraft. This resulted in the publication of a second document by ATA in 1970 as MSG-2: "Airline manufacturer maintenance program planning document". This document was used to develop the maintenance programs for aircraft such as the L-1011 and DC-10. (Smith & Hinchcliffe, 2004)

The objective of the two MSG methodologies was to develop scheduled maintenance programs that assured maximum safety and reliability of the item, at the lowest possible cost. MSG-1 and MSG-2 both followed the same process, but MSG-2 was a generic document, and non-aircraft type-related (Nowlan & Heap, 1978) .

Subsequently, in 1972, United Airlines used the idea of MSG-2 under the US Department of Defense (DOD) contract to develop the P-3A and S-3A maintenance programs, and the F-4J program in 1974. (Smith & Hinchcliffe, 2004)

An enhanced document was also prepared in Europe, called EMSG-2. It was used to develop maintenance program requirements for such aircraft as the Airbus A-300 and Concorde.

MSG-2 and EMSG-2 continued to use a 'bottom-up' approach to aircraft systems and were 'maintenance process oriented', whereby the integrity of components in sub-systems was considered before those of the overall system

The most important advantage of MSG-1 and MSG-2 was the application of On-Condition (OC) maintenance, which made them unique. The introduction of OC began an era of new thinking. It was permissable to let an aircraft pass an immediate maintenance check with known deterioration, degradation or wear, and postpone the required maintenance action until the next earliest opportunity, as long as the appropriate physical standard and prescribed limitations were met. This approach helped the operators to have fleets that were more available and made planning more flexible. Moreover, since the cost of correcting potential failures is often far less than the cost of correcting functional failures, OC maintenance reduced the maintenance costs. Furthermore, OC maintenance strongly reduced the number of irrelevant scheduled overhauls, which was the main source of 'infant mortality' and unreliability. In addition, by avoiding premature removals of items that were still in a satisfactory condition, required spare part volumes were reduced.

Depending on the operating context of the asset, warning of incipient failure enables the users of an item to reduce or avoid consequences in a number of ways (Moubray, 1997):

1. Down time: corrective action can be planned at a time that does not disrupt operations.
2. Maintenance costs: the user may be able to take actions to eliminate the secondary damage, which would be caused by unanticipated fail-

ures. This would reduce the downtime and the maintenance costs associated with the failure.
3. Safety: warning of failure provides time to either shut down an item before the situation becomes dangerous, or to move people out of harm's way.

Today, OC tasks are well known because the inspected items are allowed to be left in service 'on condition' that they continue to meet specified performance standards (Moubray, 1997), until a potential failure is detected. For example, as many as 400 items that might have required scheduled overhaul prior to MSG-1/MSG-2/EMSG-2 were reduced to about 10 afterwards (ATE&M, 2001) .

In 1975, NAVAIR rewrote the MSG-2 procedures, to apply an 'analytical maintenance program' to naval aircraft and engine programs, which resulted in "NAVAIR Systems Command (NAVAIR 00-25-400)". This was applied to in-service naval aircraft and the manual was utilized to revise the preventive maintenance requirements for most of the Navy's in-service aircraft. (MIL-STD-2173)

The MSG-2 methodology revolutionized Navy procedures for developing preventive maintenance programs; but there were still aspects to consider for further development of both MSG-2 and NAVAIR 00-25- 400 documents. For example, they did not cover the procedures for developing inspections intervals and for refining the initial analysis. (MIL-STD-2173)

Moreover, the effectiveness criteria for different maintenance strategies and failure consequences were not considered and there was still a problem of balancing the requirements of cost and dependability. In addition, there was still pressure to decrease maintenance costs. In fact, the incentives to reduce the cost were changed from technical and engineering issues during design to economical issues and cost-effective maintenance during operation. As a result, the industry was expected to construct a framework that incorporated cost-effective maintenance strategies.

4 INTRODUCTION OF RELIABILITY-CENTERED MAINTENANCE

The US Department of Defense (DOD) sponsored United Airlines to write a comprehensive report, entitled "Reliability-Centered Maintenance (RCM)" (MIL-STD-2173). Stanley Nowlan and Howard Heap of United Airlines wrote this report in 1978 as the initial RCM Bible (DOD report AD-A0665791). The report gave a detailed rationale and analytical logic, which required a fundamental shift in the current methodology for maintenance program development (i.e. MSG-2).

RCM is a methodology that supports 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. These policies will reduce the risk of function loss and are: Preventive Maintenance, Predictive Maintenance, or Redesign. Hence, RCM can be considered as an overall risk management program, to effectively manage the risk of function losses through effective maintenance.

As one of the major elements in risk management is reliability, the RCM methodology is used to develop and optimize the preventive maintenance and inspection requirements of an item in its operating context to achieve its inherent reliability, where inherent reliability can be achieved by using an effective maintenance program.

Any RCM methodology shall ensure that all the following seven questions are answered satisfactory in the order given below (Rausand, 1998):

1. What are the functions and associated performance standards of the item in its present operating context (function)?
2. In what ways does it fail to fulfill its functions (functional failures)?
3. What are the causes of each functional failure (failure modes)?
4. What happens when each functional 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)?

In order to answer the questions above, RCM uses a structured decision diagram, and encompasses the well-known Failure Mode & Effects Analysis (FMEA) methodology to identify functions, functional failures, and failure modes of an item. Furthermore, FMEA classifies the severity of each failure effect according to severity classification criteria established by each program. Hence, the quality of the RCM analysis strongly depends on the quality of the FMEA execution.

The RCM logic requires an age exploration program for all maintenance tasks where reliable historical information is not available. It also requires an independent auditing of all performed analyses, see Nowlan & Heap (1978) and Moubray (1997). In contrast to earlier methodologies supporting maintenance program development (e.g. MSG-1 and MSG-2), the RCM methodology was based on:

- System level instead of component level.
- Top-down instead of bottom-up approach.
- Function preservation instead of failure prevention.
- Task-oriented instead of maintenance process oriented.
- Consequence-driven, where the consequences of failures are far more important than their technical characteristics.

In an RCM process, the consequences of every failure have to be analyzed. It should clearly separate hidden failures from evident failure modes, and distinguish events that have safety, environmental, operational and or economic consequences.

By using an approach based on system level and function preservation, RCM treats components differently in terms of relative importance according to the correlation between the equipment and system function. Huge benefits can be derived by implementing RCM. These achievements include higher safety and operating performance, better understanding of the failure modes, and reduction of operation and maintenance costs (Tsang, 1995). Figure 1 illustrates how the maintenance concept has changed in a
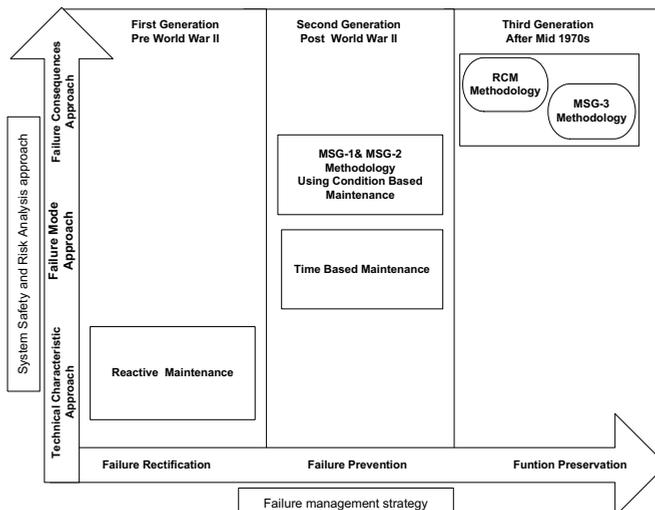

Figure 1: Changes and milestones in maintenance methodology development with regard to risk and failure management.

logical and chronological order.

Since Nowlan and Heap's report, RCM has been widely used by different industries, such as the nuclear and power generation industries, offshore oil and gas industries, and has been refined, developed, and customized to their specific requirements.

5 PUBLICATION OF MSG-3

A decade after MSG-2 was published and subsequent to Nowlan and Heap's report, US Association of Air Transport (ATA) formed another task force to review MSG-2 experience in 1979. In this review, it became obvious that there were some areas for improvement (Overman et al., 2003; ATA, 2005):

- The rigor of the decision logic.
- The clarity of the distinction between economics and safety.
- The adequacy of treatment of hidden functional failures.

The high fuel price increased the total operating cost of aircraft, and the pressure to decrease maintenance costs was still present. In addition, the development of new-generation aircraft, new regulations and new damage tolerance rules for structures, which had a heavy influence on maintenance program development including the new premises of Nowlan and Heap's RCM methodology, provided in the basis for the development of a new, improved "Airline/Manufacturer Maintenance Program Planning Document MSG-3", published by ATA in 1980. (Transport Canada, 2003; ATA, 2005)

This methodology was a combined effort by the manufacturers, regulatory authorities, operators, and ATA. The MSG-3 methodology implicitly incorporated the principles of RCM to justify task development, but stopped short of fully implementing reliability-centered maintenance criteria to audit and substantiate the initial tasks being defined (Transport Canada, 2003).

Since Nowlan and Heap's report served as the basis for MSG-3, it made major departures from MSG-2. Hence, MSG-3 involves a top-down, system-level, and consequence-driven approach, to classify failure effects in one of the failure consequences categories, see Figure 2. Since its original publication, MSG-3 has been revised five times. Revision 1 was issued in 1988 and revision 2 in 1993. MSG3-2001 and MSG-3.2002 were issued in 2001 and 2002 respectively and the latest revision was made in 2005. (ATA, 2005)

Method-ology	Characteristics
MSG-1 (1968)	• Bottom-up approach • Component level • Maintenance process oriented • Aircraft type-related (Boeing-747) • Using On-Condition and Condition-Based Maintenance
MSG-2 (1970)	• Same as MSG-1 • Generic document, non-aircraft typerelated
MSG-3 (1980)	• Generic document • Top-down approach • System level • Maintenance task oriented • Emphasis on structural inspection programs • More rigorous decision logic diagram • Distinction between safety and economy • Hidden functional failure treatment

Figure 2: Summary of some of the major conceptual differences and improvements between MSG-3 and previous versions of the methodology.

6 FURTHER DEVELOPMENTS OF RELIABILITY-CENTERED MAINTENANCE

One of the most valuable efforts to develop RCM methodologies was performed by the US Department of Defense (DOD), and was initiated by the AD-A066579 report published in 1978. This report was based on the principles of MSG-logic and was the foundation of the most modern RCM methodologies. Based on that report, DOD issued several documents related to RCM analysis; most notably, Military Handbook (MIL-HDBK) 266, "RCM Requirements for Naval Air-craft, Weapons Systems and Support Equipment" in 1981, which superseded NAVAIR 00-25-400 for all applications of RCM-decision logic. It also applied the principles of RCM (as covered by the DOD report and MSG-3) to Naval aircraft, weapons systems and support equipment. (Leverette et al., 2005)

In 1985, as another effort, US Air Force (USAF) issued MIL-STD-1843: "RCM Requirements for Aircraft, Engines and Equipment". This standard was similar to MSG-3, which was cancelled without replacement in 1995. In 1986, DOD issued MIL-STD-2173, "RCM Requirements for Naval Aircraft, Weapons Systems and Support Equipment" (MIL-STD-2173; Leverette et al., 2005).

In the early 1990s the DOD decided that new acquisitions should rely, as much as possible, on commercial or performance standards, instead of using Military Standards. As a result, a group called

"Reliability, Maintainability and Supportability (RMS) Partnership", began coordinating the efforts of various other organizations involved in developing related standards. Since no equivalent commercial standard existed at that time, the RMS Partnership requested the Society of Automotive Engineers (SAE) to lead the development of an RCM standard (Leverette et al., 2005).

The SAE RCM subcommittee initially consisted of representatives from the US Navy and some DOD contractors. As the group was supposed to find out more about the lessons learned through commercial industry efforts, John Moubray and some of his colleagues became involved in late 1997. With new participation and a clearer direction, the group was able to complete the SAE JA1011 standard in 1999.

7 AIRCRAFT MAINTENANCE PROGRAM SURVEILLANCE

The main objective of an aircraft maintenance program is to ensure that the aircraft meets and continues to meet the designed function to serve dependable and airworthy services. Hence, it is important for operators to determine any deviation from this objective and to assess the success of the program after bringing the aircraft into operation.

Today, it is known that an aircraft's reliability and safety will be strongly affected by its operating context, e.g. operator organization, humidity, temperature, utilization load, and so on. Hence, the original assumption of effectiveness criteria made during the design of the initial aircraft maintenance program will probably change and the surveillance of the aircraft maintenance program will be important. In order to manage this surveillance, the operators normally follow a defined surveillance program, which has been approved by the authorities.

In an ideal world, an applicable and effective maintenance program would ensure that there were no failure events between scheduled aircraft maintenance tasks. However, due to differences between design assumptions and actual operational conditions, each maintenance program must be adjusted to achieve this ideal situation. (Moubray, 1997)

According to official FAA research "Continuing Analysis and Surveillance System (CASS)" , an effective continuous airworthiness maintenance program should identify elements that are detrimental to the overall effectiveness of the air carrier's maintenance program, and correct any deficiencies before they become systematic problems. Therefore, the operators should develop indicators to determine possible deviations from defined objectives and to measure the effectiveness of an aircraft maintenance program. These objectives might be based on risks related to health, business, safety, environment, property, and on-time services.

According to MIL-STD-2173, 'effectiveness' is a measure of the result of the task objectives, which is dependent on the failure consequences. Therefore, the effectiveness of applicable tasks in preventing the failure consequences must be determined. Hence, for each failure consequence, it is possible to develop indicators according the effectiveness criteria as follows:

- Safety: the task must reduce the risk of failure to assure safe operation.
- Operation: the task must reduce the risk of failure to an acceptable level from an operational point of view, or remove the operational consequences.
- Economics: the task must be cost-effective.

In order to measure the performance of an aircraft maintenance program, actual operational and support data are necessary. This data can be obtained from sources such as aircraft inspections, pilot reports, air safety reports, scheduled maintenance findings, reliability programs, unscheduled maintenance actions, deferred maintenance actions, teardown reports, recorded flight data, and so on.

However, gathering data and converting it to information is very time-consuming. In addition, the effectiveness of these analyses will decrease with time. To mange these difficulties, e-Maintenance is one promising approach.

8 E-MAINTENANCE AND MAINTENANCE PROGRAM SURVEILLANCE

Information resources are critical to maintenance and maintenance support, for example to support surveillance of an aircraft maintenance program's performance. Hence, technological opportunities to improve the surveillance, such as innovative design features in the aircraft or its support system utilizing new technology applications can help to improve the maintenance program. The inclusion of developing technologies can also avoid early obsolescence and extend the useful life of the aircraft at the same time as availability performance and Life Cycle Costs (LCC) are improved. One example of new technology is Information & Communication Technology (ICT), which to an increasing degree is included in both the aircraft and its support system and that also integrates the two. The application of ICT within maintenance and maintenance support enables the emerging approach of e-Maintenance. (IEC 60300-3-14; Candell et al., 2007)

e-Maintenance is the application of ICT for remote maintenance (i.e. maintenance of an item performed without the maintenance personnel having physical access to the item) and for representing the physical world in an digital model aimed at supply-

ing tailored information such as decision support regarding appropriate maintenance activities for all stakeholders independent of time, geographical location, or organizational affinity. Hence, the e-Maintenance approach is not limited to the management of condition monitoring data, explicit technologies, or any specific support service solution. (Candell et al., 2007)

One important source of information that supports maintenance program surveillance is the maintenance database, which should be structured so that it facilitates the seamless transfer of data to other databases (e.g. the maintenance work order system) and analysis tools (e.g. RCM software) used by stakeholders involved in maintenance program development. However, it is also important that the maintenance database is kept under configuration control to ensure that it reflects the latest design standard of the aircraft and its indenture levels, to provide an audit trail and to ensure the integrity and consistent use of support data. The database should also be kept up-to-date to reflect changes in customers' use and requirements and thereby provide the guidance necessary for future maintenance program development. In this context, e-Maintenance facilitates the use of one single maintenance database that is shared by all involved stakeholders, which in turn decreases the risk of redundant, contradictory, and obsolete data (IEC 60300-3-14; Söderholm, 2007).

Another important source of information for maintenance program surveillance is the maintenance work order system, which is used to initiate, control and document specific maintenance tasks. As stated in the maintenance program, a maintenance task is either triggered by a predetermined time measure (e.g. calendar time, number of flights, or flight hours) or the item's actual condition. The work order is used to identify and plan required resources and to schedule execution of the work. Finally, it is used to record results, observations, and resources actually used, which all provide the basis for assessment and improvement of the aircraft maintenance program. An appropriate e-Maintenance solution should enable easy access to the maintenance work order system and also integration with other maintenance systems. (IEC 60300-3-14; Candell et al., 2007)

Another important part of an e-Maintenance solution, which also is valuable for maintenance program surveillance, is Built-in-Test (BIT) systems included in the aircraft. Using BIT systems it is possible to analyze the failures at the exact point in time when they occur at a specific indenture level of the aircraft during operation. Operational data that should be monitored and recorded include data on bus inputs, strain gauge and other dynamic data, propulsion parameters, BIT failure data, and environmental data. Continuous monitoring of the aircraft's condition helps to identify the nature of intermittent faults and the stresses imposed on an item during operation. Hence, it is possible to obtain an enhanced understanding of failures, failure modes, failure mechanism, and failure effects. However, in addition to digitally monitored parameters, relevant operator and maintainer observations, which cannot be digitally recorded, such as decisions based upon various circumstances, should also be recorded. All this data can act as input to the surveillance of the maintenance program's performance and update the engineering judgments made during initial aircraft maintenance program development. (Söderholm, 2007)

As described above, one important aspect of e-Maintenance is the combination of maintenance and ICT. Hence, it is necessary to have expertise in both areas in order to achieve a good e-Maintenance solution that satisfies the requirements for aircraft maintenance program surveillance. Thereby, maintenance and maintenance support may be seen as the problem domain to which selected and adapted ICT is used as a solution. (Candell et al., 2007)

Some of the obstacles related to e-Maintenance, which have to be overcome in order to achieve effective and efficient maintenance program surveillance, are (Karim & Söderholm, 2007):

- Heterogeneous organizations: there are different structures in the organizations involved in providing and receiving maintenance and maintenance support.
- Heterogeneous ICT-environments: there are differences in technology in systems that are normally used for different purposes, but are needed to exchange information in order to support maintenance program surveillance.
- Information integration strategy: it is necessary to have a strategy to integrate a number of different types of hardware and software in a seamless manner. The content type has an impact on the overall ICT strategy.
- Documentation and archiving strategies: it is essential to provide and manage documentation of different types. The context requires different types of strategies for storage, distribution, safety, security, accessibility, availability, reliability, archiving, and destruction.

One example of a civil aircraft with on-board technologies that support an e-Maintenance solution for aircraft maintenance program surveillance is the Boeing-787, which will be certified during 2008. The aircraft's on-board technologies will also be integrated with off-board technologies within the support system. Another similar example is the intelligent software Airman, which is provided by Airbus. This software can connect the different sources of maintenance information in a seamless manner and also provide tailored information to different stake-

holders. In military aviation, the Joint Strike Fighter (JSF) program is one example where on-board and off-board technologies are integrated in order to achieve an autonomic logistics system. Another military example is the Maintenance Work Station (MWS) efforts connected to the Swedish combat aircraft JAS 39 Gripen. These aircraft systems are examples where e-Maintenance will be very beneficial to aircraft maintenance program surveillance. The reason is that e-Maintenance enables measures supporting surveillance of aircraft maintenance program effectiveness to be more or less automatically collected, analyzed into indicators, and distributed to concerned stakeholders independent of the maintenance echelon.

9 CONCLUSIONS

This paper describes the trends in aircraft maintenance program development during the last 50 years, including milestones such as different versions of MSG and RCM.

Examples of fundamental changes described are: from failure correction to failure prevention; from time-based to condition-based maintenance, from bottom-up to top-down analysis; from component level to system level analysis; from technical characteristics to failure consequences; and from item rectification to function preservation.

Furthermore, the paper describes some of the reasons for these changes, e.g.: item complexity, system dependence, competition, and failure consequences, but also increasingly stringent requirements related to: dependability, costs, airworthiness, sustainability, and safety.

The paper ends with a description of challenges and possibilities related to e-Maintenance, which is believed to promote effective and efficient surveillance of an aircraft maintenance program in a near future.

10 ACKNOWLEDGEMENTS

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Paper II

Assessment of the operational consequences of aircraft failures:
Using Event Tree Analysis

Assessment of operational consequences of aircraft failures:

Using event tree analysis

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Abstract:

Purpose of paper

The purpose of this paper is to describe a methodology that supports an assessment of the operational consequences of failures in aircraft systems and its associated costs, in order to facilitate a correct and efficient decision-making during cost-effectiveness analysis of maintenance tasks within scheduled aircraft maintenance program development.

Study approach

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

Findings

The proposed methodology, which is based on ETA, is considered as a valuable support in the assessment of the operational consequences of failures within a MSG-3 framework.

Research implications

The proposed methodology focuses on assessing the operational consequences of failures and associated economical losses. Hence, in order to enable an estimation of the maintenance tasks' cost-effectiveness, the methodology should be further developed to include a cost assessment of the applicable maintenance tasks.

Practical implications

The proposed methodology could be adapted as a support to those involved in the development of aircraft maintenance program. The operational consequences and the probabilities of the proposed event tree can be quantified by the aid of historical data or expert judgment.

Value of paper

No other research paper or other available documentation dealing with the assessment of the cost of failures with operational consequences has been encountered by the authors. Hence, the proposed methodology fills this gap and provides a fulfillment of practitioners needs.

Introduction

An airline must ensure that customer requirements are fulfilled in order to gain a competitive advantage and stay in the market. Hence, providing the best in class and reliable services to customers has become a strategic issue. However, the airline business is large, complex, automated, and integrated, which mean that the consequences of failures are critical and include a high cost for system maintenance, loss of productivity, incidents, and exposure to accidents. It can also lead to annoyance, inconvenience and a lasting customer dissatisfaction that can play havoc with the responsible organization's marketplace position. Some of the above-mentioned consequences are due to unplanned corrective maintenance, which are potentially harmful to the normal schedule of the aircraft.

In fact, one of today's most important concerns among both manufacturers and airlines is how to provide a more reliable service and how to manage the consequences of unreliability, which results from many different causes, and which ultimately will results in aircraft unavailability.

One approach for achieving a good availability performance is to eliminate or minimize the probability of failures by designing the aircraft system with a high reliability performance. Another approach is to design the aircraft with a good maintainability performance, which means that it is easy to retain or restore the required functions of the aircraft and thereby reduce the consequences of failures. A third approach for affecting the availability performance of an aircraft is to have a good maintenance support performance, i.e. a maintenance organization that is both effective and efficient in retaining and restoring the required functions of the aircraft. (IEC, 2007)

The ability of the maintenance organization to upon demand provide the required resources to maintain the aircraft is related to the aircraft itself, the conditions under which it is used, and the maintenance policy. The maintenance policy describes the interrelationship between the echelons of the maintenance organization, the indenture levels of the aircraft, and the set of maintenance tasks to be applied on the aircraft. The set of maintenance tasks to be carried out on different indenture levels of the aircraft are stated in the scheduled maintenance program.

Preventive Maintenance (PM) tasks in a scheduled maintenance program are carried out according to prescribed criteria or at predetermined intervals. In fact, the role of PM tasks in a scheduled maintenance program, are to cope with the failure process proactively, to be sure of a safe and reliable operation of the asset at the lowest possible cost. PM avoids the problems associated with corrective maintenance so as eliminate waste and reduce asset life cycle costs. In general, the aim of any PM is to prevent or eliminate failure, to detect the onset of the failure or to discover hidden failure (Smith & Hinchcliffe, 2004; Tsang, 1995). Sometime complete failure prevention might not be feasible. In this case, the aim would be to reduce the risk of failure to an acceptable level for the user or to mitigate the consequences of failure. PM schemes are performed in the belief that they will improve component utilization.

In order to develop an effective and efficient scheduled maintenance program, Reliability-Centered Maintenance (RCM) was introduced within the American aviation industry in the 1970s. RCM is a systematic methodology used to identify the PM tasks necessary to realize the inherent reliability of equipment at lowest possible cost (Dhilion). The RCM methodology contains systematic decision logic for identification of the PM actions that are necessary to manage the failure modes that are causing functional failures in a given operating context. The

objective of RCM is to define maintenance tasks that are applicable and effective with respect to the type of failure and its associated consequences. (NAVAIR 403, MIL-STD-2173)

By the combined efforts of the aircraft manufacturers, regulatory authorities, operators, and the Air Transport Association of America (ATA), principles of RCM were implicitly incorporated into the MSG-3 methodology to justify task development (Transport Canada, 2003). In the commercial aviation industry, increasing emphasis is now being placed on using the MSG-3 methodology. The reason is that it is a common means of compliance to develop minimum scheduled maintenance requirements in the frame of the instructions for continued airworthiness promulgated by most of the regulatory authorities. In fact, MSG-3 is a methodology to implement the RCM philosophy in the aviation sectors.

According to RCM, if a failure does not have safety consequences[1], the corresponding maintenance task must be cost-effective. This means that the cost of performing the maintenance task must be less than the cost of the failure, i.e. the cost of operational loss and corresponding corrective maintenance (MIL-STD-2173).

Though, for failures with operational consequences, the MSG-3 methodology requires that the task must reduce the risk of failure to an acceptable level. However, in order to assess the amount of risk reduction, the total associated operational losses due to failure should be considered also in MSG-3 analysis. Therefore, assessment of expected operational consequences of the failure is an essential input for a cost-effective analysis.

However, during the development of an initial maintenance program for a new aircraft, the quantification, and assessment of the cost of operational consequences is a great challenge. This is due to a long list of uncertainties related to the large number of contributory factors, inadequacy of service information, and a lack of understanding about their influence.

Hence, the purpose of this paper is to describe a methodology that supports an assessment of the operational consequences of failures in aircraft systems and its associated costs, in order to facilitate a correct and efficient decision-making during cost-effectiveness analysis of maintenance tasks within scheduled the aircraft maintenance program development.

The role of failure consequences in maintenance task selection

Within RCM and consequently MSG-3, it is recognized that it is the failure consequence or failure effect (MSG3 terminology), and not the failure itself, that is the key issue for all maintenance decision. Hence, the purpose of any maintenance action is to eliminate or reduce the failure consequences to an acceptable level, and not to avoid the failures per se (Moubray, 1997; Nowlan & Heap, 1978).

Hence, regardless of the methodology that is used to design a maintenance program, the prime concern is whether the selected maintenance task is fulfilling its objectives or not. Moreover, designing to meet economical requirements and achieving competitive operation in both private and public sector organizations depends on prudently balancing what is technically feasible and what is economically acceptable (Sulivan et al., 2006). Thus, the selection of a maintenance task needs to be supported by overriding criteria to recognize the fulfillment of the maintenance task's objectives. In summary, the development of a scheduled maintenance

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[1] Evident operational/economic and hidden non-safety consequences.

programme consists of determining which maintenance tasks that are both applicable (technically feasible) and effective (worth doing).

A maintenance task is applicable if it eliminates a failure, reduces the probability of occurrence to an acceptable level (Hoch, 1990; cited by Rausand & Van, 1998). The effectiveness of a maintenance task is a measure of the fulfilment of the maintenance task objectives, which also is dependent on the failure consequences (MIL-STD-2173; Nowlan & Heap, 1978). In other words, the maintenance task's effectiveness is a measure of how well the task accomplishes the intended purpose and if it is worth doing (Hoch, 1990; cited by Rausand & Van, 1998).

According to Rausand & Hoyland (2004), to be effective a PM task must reduce an expected loss to an acceptable level. These losses may include injuries to people (e.g. flight crew and passengers), environmental impact (e.g. air and noise pollution), production losses (e.g. flight cancellation), and equipment damages (e.g. damaged hydraulic pump). Therefore, the consequences of failure determine the priority of the maintenance activities or design improvement required to prevent the failure (Nowlan & Heap, 1978). Following this concept, it is possible to identify the maintenance objectives more explicitly and consequently to devise the best possible task to correct the failure.

Types of failure and their consequences

The effect of failure depends directly on both the nature of the function that fails and the nature of the failure. Depending on the nature and state of failure, it may be recognized by the crew during normal operation, or remain unrecognized. Hence, the first issue to be ascertained when analyzing failures and their consequences is to determine if the failure is evident or not.

The loss of an item's basic function may be evident, but in many cases the item will have secondary or other characteristic functions whose failure will not be evident to the operating crew. In fact, a failure that has a direct adverse affect on the operational capability, including critical failures, will always be evident to the operating crew. If the effect of a failure is not observable, this means that the loss of function has no immediate consequence.

Sometimes, a single failure results in an undesirable consequence. In other cases, a combination of several failures (i.e. a multiple failure) is required to result in undesirable consequences. Hence, 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. (NAVAIR)

Hence, the first step when classifying a failure is to determine if it is evident or hidden. A failure that, 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. On the other hand, a failure that is not evident to the crew while performing their normal duties is classified as a hidden failure. A combination of one hidden failure and another failure (or event) that makes the hidden failure evident is classified as a multiple failure (NAVAIR).

The classification of failures into hidden or evident 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 are those that have no undesirable consequence when

they occur on their own. In these cases, the objective of a PM task is to prevent the consequences of multiple failures.

When either evident or hidden failures occur, the user is concerned about how the failure affects safety, operations, or economics. Hence, the evident and hidden classes of failures are further divided into the following failure effect categories (IEC, 1999)[1]: evident safety, evident operational, evident economical, hidden safety, and hidden non-safety (economical/operational).

Failure modes having safety consequences involve possible loss of the equipment and its occupants. Operational consequences adversely affect the operating capability of system and involve an indirect financial loss due to operation repercussions. Failure modes having economical consequences do not prevent equipment operation and may involve the additional costs linked to aspects such as higher fuel consumption, quicker degradation of equipment, and more expensive corrective maintenance.

Evident failures that affect the safety or the operating capability have an immediate operational impact, since the aircraft cannot be dispatched until they have been corrected. The rectification of evident economical failures and hidden failures may be postponed, since necessary corrective maintenance can be deferred to a time and location that suits operation (Nowlan & Heap, 1978).

Failures having safety consequences definitely affect operation, which means that they also involve operational consequences. Since these failures involve possible loss of the equipment and its occupants, they ultimately cost money and thereby also have economical consequences. Hence, failures with safety consequences are a subset of those with operational consequences, which in turn are a subset of failures with economical consequences. Moreover, failures with operational consequences involve an indirect economical loss due to operational interruptions, such as delays or altitude restrictions (e.g. leading to higher fuel consumption), and the direct cost of maintenance. Hence, failures with operational consequences are a subset of the failures with economical consequences. In summary, since all failures with safety or operational consequences cost money, they are a subset of the failures with economical consequences. See Figure 1.

The classes and severity of failure consequences are illustrated in Figure 1. The closer to the center of the circles, the greater the severity of the failure. However, the criticality of the failure also depends on the frequency of occurrence, which is not illustrated in the figure. The treatment of failures depends on their consequences, which means that is necessary to identify the failure consequences. As common practice, the failure should be classified according to its most severe consequences. For example, a failure with both safety and operational consequences must be classified as a failure with safety consequences.

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[1] IEC standard is based largely on the tried and tested procedures in MSG-3, as expressed in IEC 60300-3-1, 1999.
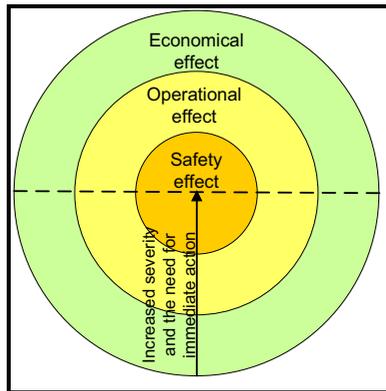
Figure 1: The severity of failure effects.

Operational consequences of failures

In this paper, failure modes with operational consequences is 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".

The effect of these failure modes interrupts the planned flight operations and interferes with the completion of the aircraft's mission, where operational interruption is an event by which the rate and quality of flight production is seriously affected. In scheduled airline operation the operational consequences can usually be expressed in terms of the inability to deliver services (e.g. to passengers) in a timely fashion.

These events are potentially harmful to the normal scheduled operation of the aircraft, which could lead to additional cost of operational irregularities, cost of unplanned maintenance, etc. Operational interruption can also cause cumulative problems, not only for the day of operations, but also for future planning, as it sometimes has reactionary domain effect.

In general, failures affecting aircraft flight altitudes, landing and flight distances, maximum take-off weight, high drag coefficients or the routine use of the aircraft are also considered to have an adverse effect on the operating capability. These events may lead to consequences such as, flight delays or cancellation. In some cases, the flight crew has to refer to the abnormal or the emergency crew check lists if the operating capability is affected. Hence, based on the different situations, the adverse effects of a failure on the operating capability may require actions including:

- The correction of failure prior to further dispatch.
- The use of immediate operational procedure in flight.
- The imposition of operating restriction.
- The use of abnormal or emergency procedure by the flight crew.

In general, the assessment of whether an aircraft is approved to continue its services with a specific type of failure detected requires a consultation of relevant documents, such as the

Minimum Equipment List (MEL), technical limitations and allowances, and the operation manual. These documents give some relevant information on how long the aircraft can fly with the existing failure, and what the imputed restrictions or necessary actions that must be fulfilled in order to permit the aircraft to remain in service. If the above mentioned documents allow the aircraft to remain in service and continue its normal operation with certain items inoperative (GO item), the failure will not have any operational consequence, since the correction of the failure can be deferred to an appropriate time.

There are also situations, where the MEL allows the aircraft to fly with certain items inoperative (GO IF item). However, this might require some action before departure, e.g. the activation of a system. This action will take time and might affect the flight. In some other cases, the aircraft might be operational with a failure present, but it will reduce the operational capability and induce some operational restrictions. It has to be noted that GO and GO IF items may introduce extra risk in case of additional failure in subsequent flights.

However, a failure that requires immediate correction (NO GO item) does not necessarily interrupt regular operation. For example, if a failure in an aircraft system can be rectified during the normal transit time at a line station, it causes no delay or cancellation of subsequent flights. In this situation the only economical consequence is the cost of corrective maintenance. This could be achieved by good reliability or maintainability characteristics, e.g. by equipment redundancy, accessibility, modular design, Line Replacement Units (LRU), or Built-in Test (BIT) systems that enhance the trouble shooting procedure and rectification, which reduces the maintenance downtime. Moreover, airlines' policy and procedures, training, availability of required resources, and level of maintenance practices highly contribute to decrease down time needed to rectify the failure during normal transit time.

Failures with operational consequences may cause different operational impact on ground or in the air. The impact on ground may include delays related to flight dispatch, ground turn-back (back to gate), aborted take-off, aircraft substitution, and flight cancellation. The impact in air may include, in-flight turn-back, diversion, go around, touch and go, and re-routing. All of these consequences result in direct financial losses, mostly due to the additional unexpected costs related to the:

- Flight crew, e.g. extra flight labor, substitution of crews by stand-by crews, crew overtime, and hotel.
- Ramp and airport, e.g. additional cost of ground equipment and gate staff overtime and airport fees.
- Aircraft itself, e.g. depreciation, associated fuel burnt cost, extra aircraft utilization and maintenance charges, navigation charges, and aircraft substitution.
- Passengers, e.g. penalties and compensations, rerouting of passengers, luggage complaints, hotel, refreshments, transportation, and possible loss of revenue if the interruption leads to flight cancellation.

These consequences also result in some indirect economical losses, mostly due to customer dissatisfaction, passenger ill-will, and loss of opportunity, i.e. the inability to use the aircraft as planned. Moreover, it sometimes has reactionary domain effects and could cause cumulative problems, not only for the day of operations, but also for future planning. All of the mentioned consequences involve economical losses in addition to the cost of the maintenance necessary to correct the failure.

The magnitude of the operational consequences of a particular failure mode depends mostly on the type and nature of the failure, the phase of flight operation in which the failure occurs (e.g. prior to dispatch, taxi, take off, climb, cruise, descent, approach, and landing), and the expected time duration for the rectification of the failure (e.g. less than 15 minutes, more than one hour, etc.). It also depends on the size and type of the aircraft, the management policy of the operating airline and its maintenance support system. Therefore, developing a universal model for assessing the cost of the operational consequences of a failure is difficult and includes large uncertainties.

## Current practices in aircraft line maintenance

Aircraft failures are classified according to deferrable or non-deferrable items. 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 (Sachon & Pate, 2000). If the time limited failure is not corrected within the allowed time, the aircraft is no longer in airworthy condition and thus can be grounded by national authority. Hence, airlines set goals for the allowed number and type of deferrals for each particular type of aircraft. Once a failure is corrected, it will be taken off the list of deferrals.

In general, if any failure happens on the ground i.e. prior to dispatch, the pilot reports the failure by means of a pilot report (pireps) in the aircraft technical logbook, which requests the maintenance engineers to correct the problems. Maintenance engineers perform a troubleshooting based on the reported pireps to fix the problem. In this case the assessment of whether a failure is deferrable or not, requires consultation of the Minimum Equipment List (MEL)[1]. The MEL grants allowances to fly with certain items inoperative (if the loss of function does not affect safety) and depending on the item, it may invoke additional limitations or time limits before maintenance must be performed. For example, if the radar is out, it is acceptable to take off as long as the radar will not be required for that flight. A close examination of the weather along the planned route will answer that question. Another example is the engine anti-ice system, which is not a particularly essential system in non-icing condition. .

If the MEL document allows the aircraft to remain in service with certain items inoperative (GO item only), and the pilot accepts to fly in this situation, the correction of the failure will be deferred to a proper time. Hence, the failure will not have any operational consequence, as the necessary maintenance will be postponed. GO IF items also may have operational consequence linked to MEL consultation and maintenance action like inhibition/flight preparation. Hence, the flight crew will initiate boarding procedures and the aircraft will take off.

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[1] A Minimum Equipment List (MEL) is an approved document created specifically to regulate the dispatch of an aircraft type with inoperative equipment. It establishes the aircraft equipment allowed to be inoperative under certain conditions for a specific type of aircraft with an acceptable level of safety. The MEL contains the conditions, limitations, and procedures required for operating the aircraft with these items inoperative.
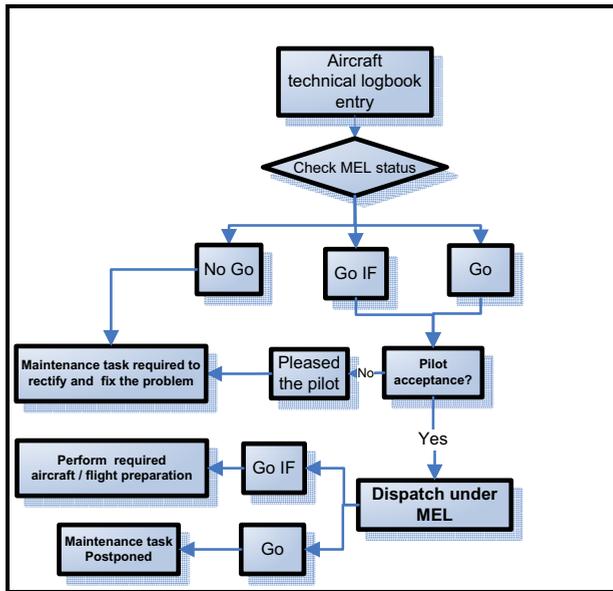
Figure 2: Unscheduled maintenance and MEL (Minimum Equipment List) consultation procedure

In some situation, the MEL allows deferring the required maintenance and the aircraft to fly with certain items inoperative (GO item), but it imposes some type of operational restrictions, such as reduced speed, altitude restriction or a restriction on the use of specific systems. In these cases, the aircraft may be operational with a certain types of failures, but its operational capability is reduced, which results in increased operating costs, primarily due to increased flying distance or fuel consumption.

There are situations, where the MEL allows the aircraft to fly with certain items inoperative, but it requires the maintenance crew to do some preliminary action, such as activation or deactivation of a system (GO IF). This takes time to implement and might affect the regularity of flight operation. In some other case, the aircraft might be operational with a certain type of failure present, but as its operational capability is reduced it requires some operational restriction. This might in turn result in additional operating costs, mostly due to high fuel consumption or increased flight time.

If the failure occurs while the aircraft is in flight, the assessment of whether necessary crew procedure is deferrable or not, requires a consultation of the Flight Manual (FM), Flight Crew Operationg Manual (FCOM), Quick Reference Handbook (QRH), and the pilot's experience.

Ultimately two different scenarios may occur if the failure is recognized in relation to a flight, i.e. either the failure has an effect on the operating capability or not. If the failure does not affect to the flight, the pilot normally reports the failure by means of a pilot report (pireps) in the aircraft technical logbook. When the aircraft arrives at the next airport, the maintenance engineers perform troubleshooting based on the reported pireps as mentioned above.

In some other cases, that failures affect the flight, requires the pilot to take some action with consultation of the FM, FCOM, QRH, or making use of its experience. In these cases, either some operational restriction may be necessary, or continued aircraft operation is prohibited

since the failure requires immediate maintenance, Depending on the phase of flight during which the failure occurs, the latter situation may require the pilot to perform: return to gate, aborted take off, in-flight turn back or diversion to another airport than the planned one. If the aircraft is in landing mode, the occurrence of a sudden failure in some systems may reduce the capability of the aircraft to complete the landing mission. Hence, in some situations the pilot may perform a"touch-and-go".

Study approach

A literature review was performed to find available methodologies and models that support the assessment of the cost of failures with operational consequences within the aviation industry. However, no systematic methodology or model for this purpose has been identified. Fortunately, there are systematic methodologies for reliability and risk management available, as well as some studies of the cost of airborne and ground delays of passenger aircraft.

In order to illustrate the operational consequences of aircraft failure, the Event Tree Analysis (ETA) was chosen as an appropriate methodology. One major reason for this selection was that the supporting tool, i.e. the event tree, can be applied in order to illustrate the combination of events leading to ultimate operational consequences.

Cause-consequence model of failures

The process of a failure begins with a set of basic events which are known as "initiating events" that perturb the system (Moderns, 2006). If the initiating event cannot be managed at an early stage of occurrence, it will lead to a number of so called "undesired events". (See Figure 3)

In RCM analysis, these events which are the initial cause of failure are known as failure modes and are defined as: "the specific physical condition or state that causes a particular functional failure". Failure modes represent the primary focus of the RCM analysis (NAVAIR 403). This might include human errors[1] (e.g. over loading of equipment), failures of a technical item (e.g. rupture of an O-ring), or maybe environmental impact (e.g. corrosion or unexpected high ambient temperature). For RCM purpose, undesired events are considered as failures. RCM further defines failure as: "any identifiable deviation from the original condition that is unsatisfactory to the user".

As Figure 3 shows, a failure is naturally the start of a possible undesired consequence. In this context the term consequence is defined in a very broad sense, including all events causing any type of loss. The loss or unexpected consequence to be considered may include injury or loss of life, air, and noise pollution, high repair cost, loss of system or equipment, delay or flight cancellation etc, see Figure 1.

RCM can be seen as a reliability and risk management methodology, since it aims at reducing the rate at which failures occur and faults are present, as well as reducing or mitigating possible consequences. Furthermore, RCM, as well as other general approaches to reliability and risk management, includes the identification of hazards, the objects that could be harmed, and also the current controls for reducing the frequency or consequence of unwanted events.

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[1] In MSG-3, human factor issues are not considered in the systems analysis as a cause for occurrence of a failure.

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, cf. the discussion in Njå & Nøkland (2005). There is also a need for action, using risk evaluation to take appropriate operation and maintenance decisions regarding risk reduction and control, thus ensuring that the system stays in a safe state, regarding both technical and organizational parts (Akersten, 2006).

In order to achieve above mentioned discussion, RCM analysis seeks to identify maintenance tasks that will prevent the consequences that result when failure modes are allowed to occur (NAVAIR 403). In this regard, one important support to the RCM analysis is the Failure Mode & Effects Analysis (FMEA) methodology, which aims at determining possible system states under the assumption of the presence of certain failures. Other well-known inductive methodologies for risk identification are Preliminary Hazards Analysis (PHA), Hazard & Operability Studies (HAZOP) and Event Tree Analysis (ETA).

The basic events are often identified and modeled by fault tree analysis. if 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 variouse undesired events, see Figure 3. (Rausand & Van, 1998)

The possible consequence chains starting from an undesired event are often identified and modeled by ETA; see Figure 3 (Rausand & Van, 1998). Depending on the type of failure, the outcome of the event tree analysis will be a set of possible consequences such as delay, high repair cost, or injury to the people or loss of life. If necessary input data are available, for the barriers, and physical models, the event tree analysis will provide frequencies or probabilities of the various consequences.
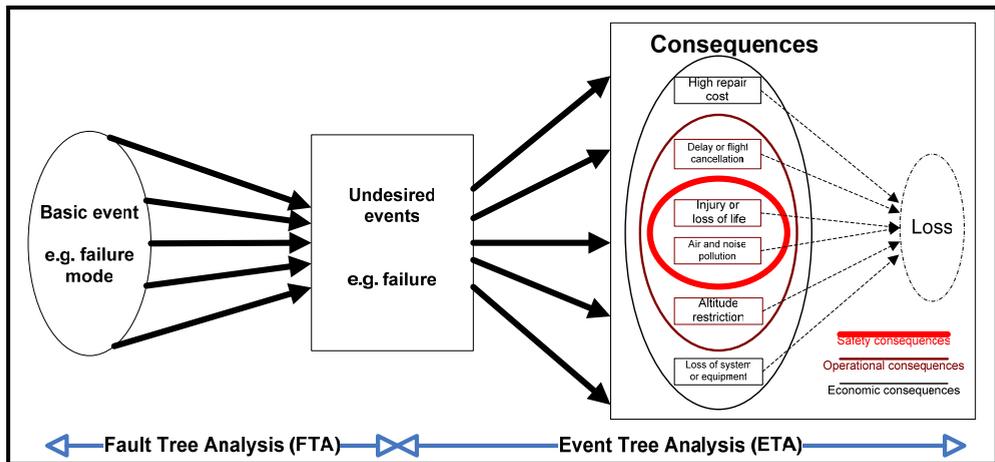

Figure 3 : Cause-consequence model of failure (adapted from: Rausand & Van, 1998).

Event tree analysis

ETA can be used for qualitative as well as quantitative reliability and risk analyses (Paté-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 an ETA in case where the successful operation of a system depends on an approximately chronological, but discrete, operation of its subsystems, e.g. 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 "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 on each subsystem being postulated. The first subsystem requirement appears initially, on top of the tree structure; in the event tree headings (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 60300-3-9). At a branch point, the upper branch of an event usually shows the success of the event and the lower branch its failure, hence, certain subsystems may not be necessary given the occurrence of some preceding events. 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 60300-3-9). 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, whether the overall system succeeds, fails, initially succeeds but fails at a later time, or something else.

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 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)

Proposed Event Tree Analysis (ETA)

Depending on the situation in which a failure occurs, the integration of the following criteria drives the ultimate state of the operational situation and the deviation from its normal state that leads to the possible operational consequences:

- the possibility of detection of loss of functions by operating crew, (in terms of evident or hidden failure) and its detectability during normal operation of aircraft,
- the nature of the failure, in terms of adverse affect on operating capability,
- the possibility to dispatch an aircraft with an inoperative,
- the possibility to continue a flight with an inoperative item,
- the phase of the flight in which the failure occurs, and
- the pilot decision.

In fact the combination of these criteria determines the extent to which operational action is required to keep the aircraft in operation or if needed to be restored to its normal operating state immediately.

This may include immediate maintenance action prior to dispatch, or it might be necessary to consider operational restrictions such as reduced flight altitude. It may also be necessary to follow emergency or abnormal procedures, such as aborted take-off, in flight turn-back, diversion, or touch-and-go, when aircraft is airborne.

Based on the above discussions, two different types of criteria have been identified that are displayed in the proposed event tree the operational phase where failure occur and the effect of failure on operating capability. The first criterion includes the five different states that indicate the operational phase where the failure occurs prior to dispatch, take-off, climb, cruise, approach and landing. In each state, two different events may occur, either the failure occurs or not. A "Yes" means that the failure occurs during the operational phase, while "No" means that the failure does not occur during the specific operational phase.

The second criterion includes three different states, which indicate the extent to which the failure affects the operating capability of the aircraft. The first state indicates the situation where the failure requires some immediate action to be taken, e.g. performing corrective maintenance or to follow some specified operational procedures. Hence, "Yes" means that the failure does not have any immediate effect on the operating capability, i.e. required corrective maintenance could be deferred. However, "No" means that an immediate action is required, i.e. the required corrective maintenance or operational procedure is not deferrable.

The second state describes the need to impose any operational restrictions, which are mandated by procedures or by pilot decision. Hence, "No" means no operational restrictions, while a "Yes" means that some operational restrictions are necessary. Finally, the third state describes whether some emergency or abnormal operation is applied, which is mandated by procedures or by pilot decision. Here, "Yes" means that emergency or abnormal operation must be applied, while "No" means that an emergency or abnormal procedure is not necessary.

Both criteria are related to the failure and function characteristics, which are given as input to the ETA. One presumption is that only failure effects with possible operational or economic consequences (according to MSG-3) should be included in the analysis. The failure characteristics also include the rate of occurrence, which will affect the outcome of the analysis. The characteristics of the failure will also advice whether the occurrence of failure will be recognized by the crew or not. As standard design practice, if the failure has any operational consequences, it should be evident to the crew.

The combination of different events (Yes or No) within the states of the two criteria (operational phase and operating capability) will create different scenarios that in turn will determine the ultimate operational consequences. Based on the possible combination of events, 25 different scenarios were identified, which will lead to the following classification 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 the failure never occurs, i.e. scenario 25. The other five scenarios where no operational consequences occur are where the failure's associated maintenance is deferrable and there are no necessary operational or abnormal restrictions, i.e. scenarios 2, 6, 11, 16 and 21. Hence, the only difference between these five scenarios is the operational phase where the failure occurs.

There are 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 and 24. Out of these, there are five scenarios where the operational consequences are manifested as only airborne delay, i.e. scenarios 1, 5, 10, 15 and 20. These scenarios are related to the occurrence of a failure that is related to deferrable items but that requires some operational restrictions.

Abnormal procedures contribute to operational consequences in scenarios 7, 12, 17 and 22. All these scenarios are related to failures with non-deferrable items that have some sort of operational restrictions, and necessitates emergency and abnormal procedures by the flight crew. The main difference between the scenarios is the phase of flight where the failure occurs. In scenarios 7 and 12, the failure occurs prior to dispatch or during take off respectively. The two scenarios 17 (failure occurs during cruise) and 22 (failure occurs during approach and landing) result in diversion.

Also there are situations such as scenario 23, in which the aircraft is in landing mode, and the occurrence of a sudden failure in some systems may reduce the capability of the aircraft to complete the landing mission. Hence, the pilot may perform a "touch and go".

Delectability / Occurrence of failure during each phase of flight — Prior to dispatch | Take off | Climb | Cruise | Approach & landing

Effect of failure on operating capability — Deferrable | Impose operation restriction | Using abnormal procedure

Operational Consequences | **Scenarios No**

Operational Consequences	Scenarios No
Airborne delay	1
No operational impact	2
Airborne delay+ Ground delay at departure	3
Ground delay at departure	4
Airborne delay	5
No operational impact	6
Aborted take off + Ground delay at departure	7
Airborne delay	8
Ground delay at arrival	9
Airborne delay	10
No operational impact	11
In-flight turn back + ground delay at arrival	12
Airborne delay+ Ground delay at arrival	13
Ground delay at arrival	14
Airborne delay	15
No operational impact	16
Diversion	17
Airborne delay+ Ground delay at arrival	18
Ground delay at arrival	19
Airborne delay	20
No operational impact	21
Go Around/Touch and Go/Airborne delay + ground delay at arrival	22
Airborne delay	23
Ground delay at arrival	24
No failure	25

Figure 4: Proposed event tree for assessing the possible operational consequence scenarios caused by aircraft system failure.

Illustration of the proposed ETA

In order to illustrate the proposed ETA and to demonstrate the application of the constructed event tree, an Avionic Ventilation System (AVS) of a hypothetical twin–engine, single aisle aircraft has been selected. The associated data were gathered from particular airlines, and then altered for confidentiality reasons, to represent typical scenarios.

Avionic Ventilation System (AVS)

The AVS is used to cool different avionics equipment. AVS comprises different components, such as computer, blower, extract fan, sensors, filter, and valves. One of the most important functions of the AVS computer is to control the AVS system's valves (to open and close) and fans (to turn on or off). The skin air inlet valve is installed in the fuselage skin to provide an outdoor air supply gateway for AVS on the ground, see Figure 5. This valve is electrically operated, but can be manually overridden. When the aircraft is on the ground, the valve is fully open and in flight the valve is fully closed.
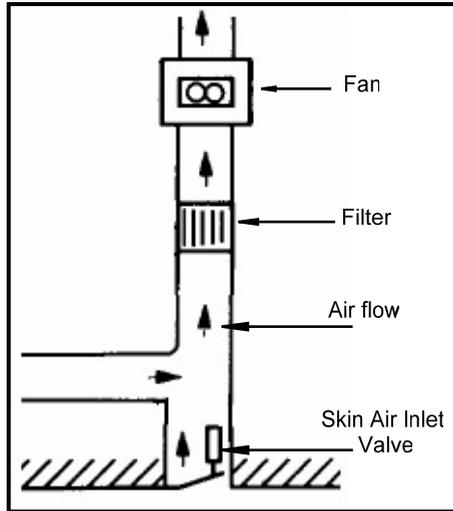

Figure 5: Skin air inlet valve schematic diagram.

One of the functional failures which might occur with an AVS system could be defined as "Skin Air Inlet Valve fails to close at take off power setting". Taking off with the Skin Air Inlet valve open (instead of closed), damages the avionics ventilation ducts, and may have a potential effects on both cabin pressurization, and degradation of avionics ventilation performance.

If the valve is not function properly at take-off power setting (prior to take-off), a warning message appears on the cockpit display unit so that, cockpit crew will be aware of the fault prior to take-off. Therefore, the conditional probability of detection of failure prior to take-off is 100% (See Figure 6)

This failure has no catastrophic or safety effect on the aircraft and its occupants. However, in order to avoid associated effect on cabin pressurization issues, and to protect damage to the system, the MEL advises that the valve should be closed manually on the ground and the related electrical connection should be isolated. This is an immediate action which is required to fly with an inoperative Skin Air Inlet Valve within a certain limited time, without any operational restrictions (see Figure 6). Therefore, the aircraft has to be returned to the ramp/gate so that the maintenance crew can perform these actions before further dispatch. Hence, this failure is classified as an evident failure with operational effect.

Based on the proposed ETA, the only possible scenario is number 4, which results in the operational consequence: "Ground delay at departure". (See Figure 6)

In order to quantify the rate at which operational consequences occur, the frequency of failure (failure rate or intensity) should be multiplied by both the conditional probability of occurrence of this failure in different operational phases (states 1.1 to 1.5), and the conditional probability of adverse affect of the failure on the operation capability (states 2.1 to 2.3). This may be expressed as in Equation 1:

$$\left(\begin{array}{c} \text{Rate of} \\ \text{occurrence of} \\ \text{each operational} \\ \text{consequence} \\ \text{scenario} \end{array} \right) = \left(\text{Failure rate} \right) \ \text{X} \ \left(\begin{array}{c} \text{Conditional} \\ \text{probability of} \\ \text{states in criteria} \\ 1 \end{array} \right) \ \text{X} \ \left(\begin{array}{c} \text{Conditional} \\ \text{probability of} \\ \text{states in criteria} \\ 2 \end{array} \right)$$

The failure rate of "Skin air inlet valve fails to close at take off power setting" is $1.12e^{-5}$ per Flight Hour (FH), based on historical data. The conditional probability of states in criteria 1 (prior to take off) is estimated at 100%, as the failure will be evident to the crew prior to take-off. The conditional probability of states in criteria 2 (non-deferrable, with no operational restriction) is estimated to 100%, as the failure is not deferrable and it does not impose any operational restrictions (as the aircraft is not allowed to take off with the failure present) according to the MEL. Hence, the rate of occurrence of scenario number 4 for AVS is: $(1.12e^{-5}$ per FH) X (100%) X (100%) $=1.12e^{-5}$ per FH

The outcome of the ETA on the hypothetical AVS system, and the applicable values for each probability, which has been gathered from historical data and expert opinions, is shown in Figure 6.
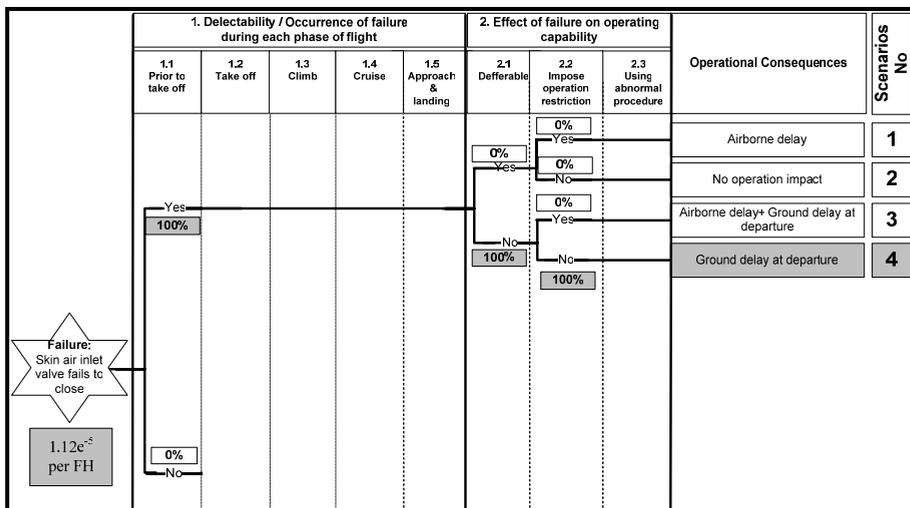

Figure 6: Proposed ETA on the hypothetical AVS system.

In order to estimate the cost of associated consequences, standard average cost can be used for different operational consequences, which normally are provided by the manufacturer or airlines. For this specific case, i.e. scenario number 4, the assumptions made are displayed in Table.1, as advised by experienced practitioners: $

<p align="center">**Tabel. 1:** Cost figures of some type of operational consequences[1]</p>

Consequences	Magnitude	Cost
Ground delay	Long: more than 30 min.	70 $/min.
	Short: less than 30 min.	30 $/min.
Airborne delay	Long: more than 30 min.	58 $/min.
	Short: less than 30 min.	28 $/min.

The annual total cost for each consequence scenario for whole aircraft could be estimated as follow:

$$
\begin{pmatrix} \text{Annual cost of} \\ \text{scenario} \\ \text{per aircraft} \\ \text{(\$/Aircraft/year)} \end{pmatrix} = \begin{pmatrix} \text{Rate of occurrence} \\ \text{of scenario} \\ \text{per FH} \end{pmatrix} \times \begin{pmatrix} \text{Unit cost of} \\ \text{ground delay at} \\ \text{departure} \\ \text{per FH} \end{pmatrix} \times \begin{pmatrix} \text{Duration} \\ \text{of delay} \end{pmatrix} \times \begin{pmatrix} \text{Average annual} \\ \text{utilization} \\ \text{FH/year} \end{pmatrix} \times \begin{pmatrix} \text{Quantity} \\ \text{Per} \\ \text{Aircraft} \\ \text{(QPA)} \end{pmatrix}
$$

Therefore, estimating the annual cost of scenario number 4, considering 3,000 FH of utilization per year, is calculated as:

$$
\begin{pmatrix} (1.12e^{-5} \text{ per FH}) \\ \times \\ (60\text{min}/60 = 1\text{hr delay time}) \\ \times \\ (70 \text{ \$/min} \times 60 \text{ min} = 420 \text{ \$/hr}) \\ \times \\ (3{,}000 \text{ FH/ year}) \\ \times \\ (\text{QPA:1}) \end{pmatrix} \approx \begin{matrix} 14.14 \\ \text{\$/aircraft/year} \end{matrix}
$$

Discussion

The scenario descriptions, using the event trees, give a detailed picture of the possible operational consequences of different failures in aircraft system during operation. Hence, the proposed methodology is considered as a valuable support in the assessment of the operational consequences of failures.

The proposed methodology could also be adapted as a support for cost effectiveness analysis of candidate maintenance tasks during the development of aircraft maintenance programs.

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[1] Given cost figures are just examples and should not be used in real calculations.

However, the analysis documentation also constitutes an important part of the knowledge base, which is also useful for design, operation, and maintenance of the aircraft.

In order to implement the proposed methodology and achieve valuable results, accurate and sufficient data and information are needed as input data for the analysis. This information is related to the technical system and its reliability (e.g. failure modes and their frequency of occurrence) and maintainability performances (e.g. Built-in Test Equipment, modularization, and Line Replicable Units). Other information that is needed is related to aircraft operation and associated procedures given in formal documents, such as the MEL, FM, FCOM, QRH. Also information about the maintenance support performance is necessary.

The operational consequences and the probabilities of different events included in the proposed event tree can be quantified by the aid of historical data or expert judgments. However, an exact quantification and assessment of the cost of operational consequences of failures is a challenge due to a long list of influencing factors and inadequacy of required information. One example is the challenge to determine a good estimation of the failure rate, which requires the collection of data from the world fleet. This collection of data is difficult since removal data do not necessarily imply a failure, or since subsequent test level has difficulties to duplicate test results achieved at preceding test levels (i.e. no fault found events). Another reason is that, even if there is a failure, it is not always possible to link the reported failure to the "functional failure" or "failure mode" identified in the MSG-3 analysis.

When there is a lack of historical data, expert judgments can be a good source of information. To support an effective extraction of the field experts' knowledge, there are systematic methodologies available, e.g. pair wise comparison.

Acknowledgements

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Paper III

Assessment of the cost of operational consequences of failures
in aircraft operation.

ASSESSMENT OF THE COST OF OPERATIONAL CONSEQUENCES OF FAILURES IN AIRCRAFT OPERATION

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Abstract

Maintenance decisions regarding aircraft require consideration of the operational impact of failures. The cost of the operational impact of failure is difficult to assess due to the influence of a large number of contributory factors. This study attempts to assess the cost of operational consequences of failures using the expertise of the field experts following a pairwise contribution technique. The study shows that the proposed model can be a tool to assess the cost of operational consequences of failures in aircraft operation, when there is not sufficient and reliable data.

Keywords: Operational impact, Failure consequence, Cost of delay, Pairwise comparison.

1. INTRODUCTION

An airline must ensure the safety and optimum service reliability of its fleets. This could be achieved by minimizing the intrusion of sudden technical failures and unplanned downtime leading to operational irregularities and interruptions in an aircraft's regular operation.

One way of mitigating or eliminating the effect of sudden failure is to cope with the failure process proactively, e.g. by performing scheduled maintenance. The maintenance task related to any failure with operational consequences is economically acceptable only if, over a period of time, the cost of preventive maintenance would be less than the combined cost of the operational consequences of failure and the related cost of corrective maintenance [1].

Therefore, preventive maintenance may be a viable alternative only if it is cost effective, i.e. the total cost of corrective maintenance including the cost of expected operational consequences of the failures and the cost of associated corrective maintenance task exceeds the cost of the proposed preventive maintenance task.

Failures with operational consequences may cause different operational interruptions that can be primarily divided into two main groups, i.e. ground or air interruptions [2]. All of these events result in direct financial losses, such as additional costs related to the flight crew, ramp and airport, the aircraft itself, passengers, and might lead to loss of revenue if the failure effect leads to flight cancellation.

These consequences may also result in some indirect financial losses, due to customer dissatisfaction, passenger ill-will, and loss of opportunity. All of the mentioned consequences involve revenue losses in addition to the cost of corrective maintenance. Most airlines recognize that the operational cost of a delayed aircraft is greater than the normal operating cost primarily due to extra costs incurred for crew, passengers, aircraft, and ramp. This extra cost serves as a measure of the economical aspect of failure effect on operation.

Exact quantification and assessment of the cost of operational consequences of failures is a challenge due to a long list of contributory factors, e.g. inadequacy in required information/data and lack in understanding regarding their nature of influence. However, the experience of field experts may provide an effective database towards this estimation.

This paper focuses on the study of the operational consequences of failures which lead to delay. In order to effectively utilize the knowledge of field experts in the assessment process, a pairwise comparison technique was adopted for quantifying the contribution of different factors to the operational cost of a delayed aircraft.

2. MODE, TYPE AND CONSEQUENCES OF FAILURES

Depending on the nature and state of a failure, it may be detected by the crew or remain undetectable. Hence, failures are broadly classified into two groups, i.e. evident and hidden failures. By definition, failure modes that are evident to the crew are termed evident failure and conversely failure modes not evident to the crew are known as hidden failures [3, 4].

Follow-up actions for failures depend on which mode they belong to i.e., whether the failures are evident or hidden to the operating crew. In respect to the type of failure, the user also is concerned about its impact on safety, operations, and economics as detailed in the following section [5]:

- o Evident safety– Includes evident failures that produce an immediate adverse effect on safety.
- o Evident operational– Includes evident failures that produce adverse effects on operations.
- o Evident economic– Includes evident failures that produce adverse effects on economics.
- o Hidden safety – Includes hidden failures that produce an adverse effect on safety.
- o Hidden non safety-Includes hidden failures that produce adverse effects on operations and/or economics.

Figure I details a failure classification on the basis of extent and time of "failure consequence". An evident failure may have immediate impact on the aircraft's regular operation, but hidden failures have no immediate effect on operation as their consequences are delayed.

Based on the definition, failure modes having safety consequences involve possible loss of the equipment and its occupants. Failure modes having operational consequences, involve indirect financial losses due to operational irregularities and direct cost of repair, and the failure modes having economic consequences involve the direct cost of repair only. [3]

Correction of failures, immediate or deferred, consumes time, human resources, and material. Hence all failures have financial consequences. Failures of aircraft that cannot be repaired within the available time (transit time) have operational consequences mainly due to delay to the next flight operation.
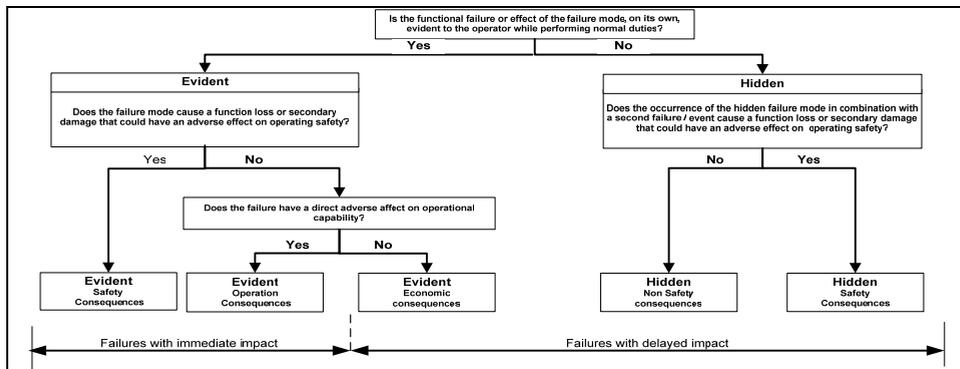

Figure. I: Classification of failures

3. MAINTENANCE SELECTION AND FAILURE CONSEQUENCE

Ideally the role of Preventive Maintenance (PM) is to cope with the failure process proactively and to ensure a safe and reliable operation of the aircraft at the lowest possible cost. PM reduces the problems associated with the occurrence of sudden failures so as to eliminate waste and to reduce aircraft Life Cycle Costs (LCC). In general, the aim of any PM schedule is to prevent failure, to detect the onset of the failure or to detect hidden failure [6]. Complete failure prevention might not always be feasible and then PM aims at the reduction of failure probability to an acceptable level or to mitigate the consequences of failure.

In order to develop initial scheduled maintenance tasks, Reliability-Centered Maintenance (RCM) and consequently, MSG-3 (Maintenance Steering Group methodology) have been introduced. RCM and MSG-3 are well-structured logical decision processes, used to identify the policies that must be implemented to manage the different failure modes causing functional failure in a given operating context. These methodologies rank the criticality of failure modes and provide guidelines for the selection of appropriate PM tasks that are most effective in preserving system function. [7, 3]

RCM and MSG-3 recognize that the consequences of failure are the key to all maintenance decisions rather than the failure itself. So the emphasis in any maintenance action lies on the avoidance or reduction of the consequences of failures to an acceptable level [7, 3], not on the avoidance of failures per se. Therefore, the consequences of failure determine the priority of the maintenance activities or design improvement required to prevent its consequences [3]. Following this concept, it is possible to identify the maintenance objectives more explicitly and consequently to devise the best possible way to rectify the problems.

Regardless of the methodology that one follows to frame a maintenance program, the prime concern is whether, the selected maintenance task is fulfilling its objectives or not. Therefore, maintenance task selection needs to have overriding criteria to recognize the fulfillment of these objectives. Selected maintenance tasks must satisfy the requirements of the type of failure to restore its initial performance and capability, i.e. a maintenance task is employed only when it eliminates a failure or reduces the probability of its occurrence to an acceptable level or reduces the impact of failure [4].

According to MIL-STD-2173, effectiveness is a measure of the result of the task objectives in terms of the failure consequences. Therefore, after choosing an applicable task, the effectiveness of the task in preventing the failure consequences must be determined.

Financial consideration is a must in maintenance task selection as the contribution of any activity to a business is measured ultimately in financial terms. According to the RCM and MSG-3 methodologies, if the failure does not involve safety, the task must be cost effective, i.e. the cost of a proposed applicable maintenance task should be less than the cost of prevented apprehensive failures.

Hence, the analysis of cost effectiveness of a PM task warrants the estimation of both the imputed cost assigned to the proposed PM task and expected operational consequence of the failure. Only then it is possible to compare both costs and find the most cost-effective task to chose.

4. ASSESSMENT OF OPERATIONAL CONSEQUENCES OF FAILURES

Failure modes interfering with the completion of the aircraft mission are known as failures with operational consequences [5]. In other words, a corrective action to a failure that disrupts planned flight operations is classified as an operational consequence. These failures cause various operational interruptions that may be divided into two main categories [2]:
  o Ground interruption
  o Air interruption

Ground interruption includes delay in flight dispatch, ground turn back, aborted take off, aircraft substitution, and flight cancellation. Air interruption includes in-flight turn back, diversion, go around, touch and go, and re-routing, or some operational restriction such as altitude restriction.

Three approaches have been developed in the aviation industry to manage operational interruptions and minimize the technical delays of possible failures [8, 9]:
  o Redundancy
  o Modular design and Line Replacement Units (LRU)
  o Identifying minimum aircraft dispatch requirements stated in Minimum Equipment List (MEL).

Item redundancy is a common engineering solution for the problems associated with high degree of reliability requirement. If one unit fails, the standby unit is available to take over the function. LRUs are those items that can be quickly removed and replaced so that, the aircraft can returns into service without any technical delay [9]. MEL also allows the aircraft to continue its service with certain items inoperative provided the loss of function does not affect the safety and operational capability of the flight.

Based on the gravity of the situation, the adverse effects of a failure on operating capability may require any one of the following actions [10]:
  o Correction of the failure prior to further dispatch.
  o The imposition of operating restrictions.
  o Flight crew uses abnormal or emergency procedure.

The assessment of whether or not a failure meets one of the above-mentioned criteria requires reference to the Minimum Equipment List (MEL), Flight Manual (FM), Flight Crew Operation Manual (FCOM), Quick Reference Handbook (QRH), the pilot's experience and technical limitations and allowances. As an example, MEL document give some relevant information on how long the aircraft can fly with an item inoperative and what necessary actions must be taken to permit the aircraft to remain in service.

The magnitude of the operational consequences of a particular failure mode mostly depends on the type and nature of the failure, phase of flight operation i.e. when the failure occurs (e.g. prior to dispatch, taxi, take off, climb, cruise, decent, approach, and landing) and the expected time duration for the rectification of the failure (less than 15 minute, more than one hour, etc.). Depending on the occurrence of the above mentioned factors, different scenarios for operational consequences might arise. For instance, if a non-deferrable failure happens in climb, and the final decision is diversion to the base airport, the flight will introduce airborne delay cost due to preparation to divert, and a ground delay cost due to the additional ground time needed for failure rectification.

In general, the operational consequences of any failure finally influence the profit and loss of the airlines directly or indirectly.

It has to be mentioned that failures that require immediate correction do not necessarily have operational consequences. For example, if a failed item on an aircraft can be replaced or repaired during the normal transit time, at a line station, then it causes no delay or cancellation of subsequent flights and the only economical consequences is the cost of corrective maintenance. In contrast, the aircraft may be operational with certain types of failures, but its operational capability might be reduced, resulting in increased operating cost due to high fuel consumption, longer flight time etc.

However, in all cases, the total cost of an operational failure includes the economic loss resulting from the failure as well as the cost of correcting it. If a failure has no operational consequences, the cost of corrective maintenance is still incurred and is the only cost. The cost of operational consequence of a failure also depends on the size and type of the aircraft, the management policy of the operating airline and its maintenance support system. Therefore, the magnitude of operational consequences will vary from one operating context to another. Hence, developing a universal model for assessing the cost of operational consequence of failure is difficult.

In the following section, we shall discuss a specific hypothetical case where failure appears prior to dispatch and corrective action is required to rectify the failure prior to further dispatch leading to flight delay.

5. PROPOSED METHODOLOGY

Maintenance actions consume time and resources and have direct financial impact. A delay occurs if the time needed for maintenance plus the time elapsed before maintenance starts is longer than the layover [11]. In fact, maintenance which lasts more than the planned available time causes a delay also to the next schedule of the aircraft, which results in direct or indirect financial losses for the airlines. These losses are mainly due to the cost of delay in operation and are considered in this study as financial aspect of delay due to technical failure.

For the most part airlines recognize that crew, ramp, aircraft and passenger related costs, contribute the lion's share to their respective delay costs [2]. Therefore, we have split up delay costs into the above four cost headings.

The profit and loss account reflects the economic status of any business. A business makes profit when the collected revenue exceeds the related expenses and there are two parts to this for any airline: (a) planned expenses and (b) unplanned expenses. The cost of the operational consequences of failure falls into the category of unplanned expenses.

In this paper, the cost of technical delays (as a consequence of aircraft technical failure) has been expressed in percentage of the crew-related planned operation expenses. An effort was made to find the contribution of different cost headings towards the delay cost from the judgments of experts following a pairwise comparison technique. This technique was originally suggested by T. L, Saaty (1980) and has played an important role in the decision making process for engineering, business and management.

In this study the experts were asked to judge the relative contribution of two delay cost headings that form the judgment matrix regarding the contribution of the different cost headings into the cost of operational delay.

Out of the above four delay cost headings, crew related expenses are mainly the predetermined overtime paid due to delay, and are almost fixed as a percentage of planned crew related cost. Therefore, by calculating the overtime paid to the crew, the remaining three delay costs headings could be calculated with the help of values of contribution matrix. In the following section, the algorithm for the proposed model is discussed.

5.1. Algorithm for the proposed methodology

Step 1: Collect information from the airline regarding the planned operational expenses per flight hour and the maximum profit per flight hour, when there are no operational irregularities and a normal situation prevails. The operational impact is lowest or negligible in this case. Express maximum profit in percentage of planned operational expenses. Also, collect data from the airline regarding the maximum loss per flight hour for the highest operational irregularities in the worst scenario. Here, the operational impact is the highest and the cost of operation impact overrides the profit margin. The operation of the flight become uneconomical and the business runs at a loss. Express maximum loss in percentage of planned operational expenses. A typical example of the operational impact of failure on the economy of the organization is explained in Figure II.

Step 2: Calculate the range of the cost of operational impact in percentage of planned expenses using the information from Step 1. Divide the range into the term set of operation impact such as, negligible, very low, low, moderate, high, very high.

Step 3: Select a group of experts from the operating airlines and collect their opinion of pairwise comparison regarding the contribution of the four cost headings towards delay cost with varying size and type of the aircraft as well as delay duration.

Step 4: Calculate and rank the priority values of different cost headings following the responses of the experts as exhibited in their respective pairwise comparison matrices. The experts are asked to modify their judgments whenever the consistency ratio exceeds the acceptable range of 10%.

Step 5: Calculate the crew related delay cost using the information collected in Step 1.

Step 6: Calculate the delay cost using the priority matrix values of Step 4 and sum up all the delay costs to estimate the total delay cost and determine where it falls in the linguistic term set developed at Step 2. This will guide management in framing an appropriate maintenance policy.
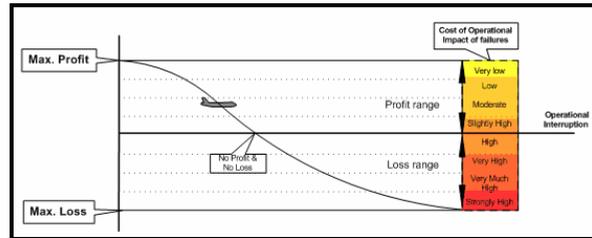

Figure.II: A typical qualitative example of effect of delay on economy.

5.2. *Pairwise comparison matrix*

It is hard to expect a reasonable numerical value for the percentage contribution of each of the four cost headings into the total delay cost from experts as they are influenced by a large number of factors. Many of these factors are subjective in nature. However, it is comparatively easier to compare the relative importance of two factors at a time, as is done in the pairwise comparison approach pioneered by Saaty (1980). This approach is based on the fundamental principle that it is more difficult to evaluate n elements (where $n > 2$) simultaneously than to compare two such elements at a time. In pairwise comparison experts compare the importance of two factors on a relatively subjective scale. In this way a judgment matrix of importance is build up according to the relative importance given by the experts. Table I represents a pairwise comparison scale for value rating of judgements and for deriving pairwise ratio scales. Table I includes reciprocals, which are equally often adopted for relative measurements or comparisons of factors. A total of $\dfrac{n(n-1)}{2}$ judgements are required for comparing n factors.

Table I Pairwise comparison scale

	Verbal judgement
1	Elements are equally preferred
3 or (1/3)	One is moderately preferred to the other
5 or (1/5)	One is strongly preferred to the other
7 or (1/7)	One is very strongly preferred to the other
9 or (1/9)	One is extremely preferred to the other
Note: (2, 4, 6, 8: intermediate judgemental values between adjacent scale values)	

6. METHOD OF COLLECTION OF JUDGEMENTS FROM DIFFERENT EXPERTS

To perform the pairwise comparison, a suitable team of experts at different positions in the organization are invited. We suggest that level of experience is a major factor when choosing the respondents. A multiple choice questionnaire consisting of six questions regarding the relative importance of one cost heading over the other to

the total delay cost, as shown in a sample questionnaire in appendix A was prepared. Three field experts were chosen and were asked to mark their opinion on the multiple choice response sheets for a delay less than 15 minutes.

6.1. Measuring inconsistency in judgements

Human judgements are the basis of the pairwise comparison approach. Some degree of inconsistency may be introduced in pairwise comparisons as a result of a number of factors, such as:
- o lack of adequate information;
- o improper conceptualisation;
- o mental fatigue.

The difference $\lambda_{max} - n$, (where, λ_{max} is the largest eigen value and n is the number of comparisons) can be employed as a measure of inconsistency. For perfect consistency the difference ($\lambda_{max} - n$) will be zero. But instead of using this directly, Saaty (1980), defined a Consistency Index (CI) calculated as:

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (1)$$

The closer this CI is to zero, the better the overall consistency in the judgements.

Simulation of a large number of randomly generated pairwise comparisons for different sizes of matrices carried out by Saaty, with regard to calculations of the average CIs, resulted in what he defines as the Random Index (RI). The values of such standard CIs (or RIs) are presented in Table II [12]. The significance of the values of RI is that the ratio of the CI for a particular set of judgements to the RI of the same size of matrix (such as given in Table II) indicates a measure of the inconsistency ratio or consistency ratio (CR) for the matrix of judgements, i.e. a measure of inconsistency in judgements. A perfectly consistent judgement will yield a CI of zero (0), the CR will also be zero. Usually, a value of CR between 0 and 0.10 (i.e. 10 percent of what would be the outcome from random judgements) is acceptable [13]. If the obtained value of RI is not within an acceptable range, the experts may be asked to modify their judgements in the hope of getting a modified consistent matrix.

The CR of the judgement matrices of all the experts was calculated. Depending on the value of the CR some experts were asked to modify their judgements. The final judgement of the three experts are presented in Appendix B and the CR values of their judgement matrices for delays less than 15 minutes are tabulated in Table III.

6.2. Aggregating judgements of different experts

Each expert generates their pairwise comparison matrix for the set cost headings. As pointed out by Aczel et al, (1983), the same pairwise comparison for each expert can be aggregated into a group comparison by taking the geometric mean of all comparisons. The geometric mean is the only averaging process that maintains the reciprocal relationship ($a_{ij} = \frac{1}{a_{ij}}$) in the aggregate matrix. The general formula for calculating a geometric mean for a group response is:

Weighted mean value of a_{ij}: $\qquad a_{ij} = \left(\prod_{k=1}^{n} w_k \bullet a_{ij} \right)^{1/\sum_{k=1}^{n} w_k} \qquad (2)$

Where a_{ij} is each expert's paired comparison value, n is the number of expert, and w_k is the weight of the kth expert. In this study we have assumed that all the experts have equal expertise in their judgements and therefore $w_k = 1$ for all k. The individual and overall judgement matrixes are given in Appendix B. The contribution of the four cost headings to the total cost of delay is given in Table IV, the priority vector of the pairwise comparison matrix.

Table II: RI of many randomly generated pairwise comparison matrices of size n	
Size of matrix (n)	Random index (RI)
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

Table II: RI of many randomly generated pairwise comparison matrices of size n

Table III: Final CR values of the judgement matrices for delays less than 15 min	
Expert	CR value
No. 1	0.01
No. 2	0.0037
No. 3	0.0175
Aggregate	0.0002

Table III: Final CR values of the judgement matrices for delays less than 15 min

7. RESULTS AND DISCUSSION

To illustrate the application of the proposed model, a hypothetical single-aisle, twin-engine and short range aircraft has been selected, and the opinions of the field experts were collected and aggregated (see Appendix B). The results given in Table IV show that for a delay up to 15 minutes the extra cost incurred for the passenger is the maximum and is more than the half of the total cost of delay in this hypothetical case. The additional cost for the overtime of crews amounted to almost one third while the extra cost for ramp is only 10.8%. Additional cost for operation of aircraft contributes the least to the total cost of delay. The financial effect of delay is explained in Figure II. This clearly shows the financial impact of delay categorically helps management in decision making. Table IV lists the contributions of the four delay cost headings with their amount of contribution in percentage of cost of operation. The basis of these calculations is:

- o The cost of operation per flight hour = 3500.0 €.
- o Maximum profit = 525.0 €.
- o Maximum loss = 7000.0 €.
- o Cost of crew overtime per hour = 517.0 €.

The calculated value of total cost of delay is 26.46 € per minute, which is 45.36% of the cost of operation.

Table IV: The contribution of the delay's four cost headings

Cost Heads	Contribution to total cost of delay	Cost per minute of delay
Aircraft related cost	5.96%	1.58 €
Ramp related cost	10.81%	2.86 €
Crew related cost	32.56%	8.62 €
Passenger related cost	50.67%	13.41 €
Total	100.00%	26.46 €

8. CONCLUSIONS

This study shows a methodology of calculation of the cost of delay using the expertise of field experts when there is no available or reliable data. This methodology can excel in the estimation of the cost of delay provided there is access to a good number of experts with a sound experience of the company's economy and maintenance issues. This methodology can help the management of operating airlines to frame their maintenance policy by providing useful data regarding the cost of delay due to maintenance. The applicability of the methodology is universal for the type and size of the aircraft and the duration and type of delay.

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Appendix A

Questioner I:

Pairwise comparison of delay cost heads for a single-aisle, twin-engine aircraft type with medium flight range
A) For delay less than 15 minutes:

1. Compare the cost of overtime paid to the crew for delay less than 15 min. with the additional cost of ramp for this delay period.

Over time paid to the crew	Very much more	Much more	More	Slightly more	Equal	Slightly less	less	Much less	Very much less	Additional cost of Ramp
	☐	☐	☐	☐	☐	☐	☐	☐	☐	

2. Compare the cost of overtime paid to the crew for delay less than 15 min. with the additional passenger-related cost for this delay period.

Over time paid to the crew	Very much more	Much more	More	Slightly more	Equal	Slightly less	less	Much less	Very much less	Additional cost of Passenger
	☐	☐	☐	☐	☐	☐	☐	☐	☐	

3. Compare the cost of overtime paid to the crew for delay less than 15 min. with the additional aircraft-related cost for this delay period.

Over time paid to the crew	Very much more	Much more	More	Slightly more	Equal	Slightly less	less	Much less	Very much less	Additional cost of aircraft
	☐	☐	☐	☐	☐	☐	☐	☐	☐	

4. Compare the additional cost of ramp for delay less than 15 min. with the additional passenger-related cost for this delay period.

Additional cost of Ramp	Very much more	Much more	More	Slightly more	Equal	Slightly less	less	Much less	Very much less	Additional cost of passenger
	☐	☐	☐	☐	☐	☐	☐	☐	☐	

5. Compare the additional cost of ramp for delay less than 15 min. with the additional aircraft-related cost for this delay period.

Additional cost of Ramp	Very much more	Much more	More	Slightly more	Equal	Slightly less	less	Much less	Very much less	Additional cost of aircraft
	☐	☐	☐	☐	☐	☐	☐	☐	☐	

6. Compare the additional cost of passenger for delay less than 15 min. with the additional aircraft-related cost for this delay period.

Additional cost of passenger	Very much more	Much more	More	Slightly more	Equal	Slightly less	less	Much less	Very much less	Additional cost of aircraft
	☐	☐	☐	☐	☐	☐	☐	☐	☐	

Appendix B:

Expert No. 1 judgement matrix

COST	Overtime Crew	Cost of Ramp	Cost of Pax	Cost of Aircraft
Overtime of Crew	1	3	1/2	5
Cost of Ramp	1/3	1	1/7	2
Cost of Pax	2	7	1	9
Cost of Aircraft	1/5	1/2	1/9	1

Expert No. 2 judgement matrix

COST	Overtime Crew	Cost of Ramp	Cost of Pax	Cost of Aircraft
Overtime of Crew	1	3	1	7
Cost of Ramp	1/3	1	1/3	3
Cost of Pax	1	3	1	9
Cost of Aircraft	1/7	1/3	1/9	1

Expert No. 3 judgement matrix

COST	Overtime Crew	Cost of Ramp	Cost of Pax	Cost of Aircraft
Overtime of Crew	1	3	1/2	5
Cost of Ramp	1/3	1	1/5	1
Cost of Pax	2	5	1	7
Cost of Aircraft	1/5	1	1/7	1

Overall aggregated judgement matrix

COST	Overtime Crew	Cost of Ramp	Cost of Pax	Cost of Aircraft
Overtime of Crew	1.00	3.00	0.63	5.59
Cost of Ramp	0.33	1.00	0.21	1.82
Cost of Pax	1.59	4.72	1.00	8.28
Cost of Aircraft	0.18	0.55	0.12	1.00