Aircraft Engines Maintenance Costs and Reliability

An Appraisal of the Decision Process to Remove an Engine for a Shop Visit Aiming at Minimum Maintenance Unit Cost

Euclides da Conceição Pereira Batalha

This dissertation is submitted in partial submission for the

Degree of "Mestre em Estatística e Gestão da Informação"

by

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Abstract and Keywords

The decision to remove an aircraft engine for SV is not a deterministic process. The decision is taken under conditions ok risk or uncertainty and some subjectivity. In this document it is presented a case study using a decision tree to decide the best time to remove an engine with high FH since last SV. This case study and the answers from engine experts to a questionnaire about the decision process provide information that may assist to decide how to optimize engine time on-wing.

Keywords: Aircraft engine, Reliability, Maintenance cost, Optimizing time on-wing

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Resumo

A decisão de remover um motor de avião para efectuar manutenção em oficina (SV) não é um processo determinístico. A decisão é tomada em condições de risco ou incerteza e de certa subjectividade. Neste documento é apresentado o estudo de um caso, utilizando-se uma árvore de decisão para escolher a melhor altura para remover um motor para SV. Este estudo de caso em conjunto com as respostas dadas por especialistas de motores a um questionário sobre o processo de tomada de decisão forneceu informação que poderá ajudar a decidir como optimizar o tempo dos motores em asa.

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GLOSSARY OF TERMS

ACMI - Aircraft with Crew, Maintenance and Insurance

AD - Airworthiness Directives

AOG - Aircraft On Ground

AR&O - Aero Repair and Overhaul

CC - Combustor Chamber

CM - Condition Monitoring

CSN - Cycles Since New

CSSV - Cycles Since Last Shop Visit

CST – Case Study

DLCV - Date of Last Shop Visit

DBS –Diffuser and Burner Section

DOC - Direct Operating Cost

EASA - European Air Safety Agency,

ECM - Engine Condition Monitoring

EFHs - Engine Flight Hours

EGT - Exhaust Gas Turbine

EHM - Engine Health Monitoring

EMV - Expected Monetary Value

FAA - Federal Aviation Authority

FAR - Federal Aviation Regulation

FH - Flight Hours

FP - Fleet Planner

GDP - Gross Domestic Product

HPC - High Pressure Compressor

HPT - High Pressure Turbine

HSN - Hours Since New

HSSV - Hours Since Last Shop Visit

HT - Hard Time

IAE – International Aero Engines

IFSD - Engine in Flight Shutdown

LLP - Life Limited Part

.

LPC - Low Pressure Compressor

LPT - Low Pressure Turbine

LRU - Line Replacement Unit

MGB – Main Gearbox

MROs - Maintenance Repair and Overhaul Organisations

MTBF - Mean Time Between Failures

MTBR - Mean Time Between Removals

MTTF - Mean Time to Failure

N1 – Rotation Speed of the Low Pressure Shaft

NGV - Nozzle Guide Vanes

OC - On Condition

OEMs - Original Equipment manufacturers.

OHB - Overhaul Base

OPS - Overhaul Prediction and Scheduling

QUE – Questionnaire sent to engine experts

SLSV - Since Last Shop Visit

SV - Shop Visit

SVR - Shop Visit Rate

TNZ - Turbine Nozzle

TSN - Time Since New

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Chapter 1

1. INTRODUCTION

1.1. The Importance of Engine Maintenance Costs in the Airline Industry

Competent costs management is a key factor of success in any industry. In the airline business it is critical, when taking into consideration its very low profit margins and its long standing, unstable and poor economic performance.

Aircraft maintenance cost, not being the highest direct operating cost of the airline activity, is normally the biggest part of the controllable costs by management decisions and also the one with the widest range of controllability.

Engine maintenance is the highest maintenance cost, carrying with it the risk of unexpected high expenses in a single event, when an engine has to be removed for a shop visit (SV), to perform a repair, a performance restoration or a full overhaul; depending on the engine model and design characteristics, thrust power, technical condition and workscope definition, an SV may cost from less than 1 million to more than 10 million US dollars.

Engine maintenance cost management has a significant impact on the profitability and even survival of airlines, a business that over time has presented an intriguing and poor economic performance together with an intrinsic glamour that exercises a strong attraction for new investors.

For decades the airline industry has presented huge global losses, through competition, high risk due to uncontrollable external factors and low chance of success, as proven by thousands of premature bankruptcies. Despite this discouraging scenario, the capital-intensive airline business every year attracts a significant number of investors to start-up airlines that join the market, only to fail.

Characterised by rapid growth in demand and low or negative profitability, the airline business presents a paradox (Doganis, 2010, p. 5) – rapid demand growth should imply high profits, which does not happen in the airline industry.

The root cause of this apparent paradox arises from the strong and fast variations of the growth rates of demand in the air transport industry, which react very quickly and

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in an amplified manner, to variations in the macroeconomic climate, represented, for example, by the Gross Domestic Product (GDP). This high susceptibility of the air transport industry demand to changes of macroeconomic status causes, in a very short period of time, serious gaps between demand and capacity, i.e., large reductions in revenue are not compensated quickly enough by reductions in costs.

To be consistently successful in the airline business requires, at the very least, competent costs and revenue management, a flexible organisation with a high degree of "escapability of costs" (Doganis, 2010, p. 78), and excellent skills and tools for boosting sales and profit in times of macroeconomic decline and, consequently, low air transport demand.

An airline organisation with the characteristics described above and well established as an organic system, i.e., with easy and good communication and coordination across all the levels of the company, (Stoner, Freeman, & Gilbert, 1995, pp. 326-327), has the conditions to adjust its processes and activity quickly enough to achieve an adequate balance of capacity and demand and, hopefully, of costs and revenues, in order to respond effectively to macroeconomic changes.

The scheduled airline industry lost US$ 54.1 billion from 2000 until 2008. During that period, the total Tonne-Km performed (including passengers, freight and mail) increased on average by 4.7% per year, with a minimum growth rate of -3.9% in 2001 (after September 11) and a maximum growth rate of 12.6% in 2004; in 2009 the industry had an estimated loss of US$ 4.1 billion and a growth rate of -4.3%.

The poor economic performance of the airline business has been always an issue. After describing the scheduled airlines' losses of US$ 2.7 billion in 1990 and US$ 4 billion in 1991 and the poor profitability of the industry, Shearman (1992, p. 121) asked "Is the airline business inherently unprofitable?" The answer was "Certainly not!" and this may be accepted as true; however, to obtain success in the airline business, as some few exceptional airlines consistently have (e.g. Southwest Airlines in the USA and Ryanair in Europe), it is important to identify and fine tune by competent management, a certain number of key factors. One of these is engine maintenance costs and expenses, the subject of this document, that may be of interest not only to Power Plant Engineers and to Maintenance and Engineering Managers but also to General Directors and Board Members of airlines; it may also be of interest to Maintenance

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Repair and Overhaul organisations (MROs) and to aircraft and engine manufacturers (OEMs – original equipment manufacturers).

Aircraft engines operate mainly under the maintenance concept “On Condition” (OC), which means that, during most of the operating time, it is only mandatory to remove an engine from the aircraft if certain operating parameters, degradation indicators or physical damages are found to be outside established limits. To be precise, removal is also mandatory if, for example, any Life Limited Part (LLP) is at the end of its lifetime, so, rigorously speaking, engine is subject to control by all the primary maintenance concepts, as described in Chapter 2.

1.2. When to Remove an Engine from the Aircraft to Perform Maintenance

From experience, engineering sense and internal criteria specific to each organisation, Power Plant Development Engineers responsible for monitoring and managing engines’ airworthiness, normally decide to remove engines conservatively below any established operating limitation, to avoid the following risks:

i) Unexpected failure and, consequently, unscheduled removal, incurring: 1) additional direct maintenance costs due, for example, to replacing the engine outside the base of operations; 2) consequential costs due to flights delays or cancellations, aircraft replacement, meals, hotel accommodation and compensation to passengers; 3) intangible costs such as damage to airline reputation.

ii) Excessive degradation that may significantly increase the cost of the engine repair and performance restoration.

iii) Uncontrolled internal failure causing additional severe and expensive damage to the engine.

iv) High increase in fuel consumption as a result of performance degradation.

Ideally engine maintenance should be managed in order to achieve the minimum maintenance unit cost, in full compliance with safety requirements.

The cost of engine maintenance in a small airline (let us say with six to eight aircraft) would be about 40% of the total maintenance cost, which may represent between 10 and 20% of the total operating cost of the flight of a scheduled or full

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charter airline: this percentage depends heavily on the fuel price. Assuming that the total maintenance cost is 15% of the total operating cost, the engine maintenance cost would therefore represent 6% of the total operating cost. Under the assumption that engine maintenance cost has a controllability range of 30%, then good management may represent a contribution to profit of about 1.8%, a significant figure for an industry where a 3 to 4% profit margin is celebrated as good and rare.

Besides the inherent reliability and maintainability of the engine model, achieved by the initial design and subsequent improvements, engine maintenance cost depends on a certain number of factors, including:

- average stage length of each flight;
- percentage of engine derating (reduction of the maximum engine power) at take-off and climbing;
- good maintenance practices;
- definition of the shop visit (SV) workscope, including service bulletins' incorporation policy;
- selection of Maintenance, Repair and Overhaul (MRO) organisation and contract negotiation skills;
- adequate decisions about the time to remove an engine from the aircraft and send it for an SV, the subject of this document.

This project will assess the criteria used or recommended by airlines, MRO organisations and OEMs, to decide when to remove an engine for a SV, and the impact of this decision on the engine maintenance unit cost, which means the engine maintenance cost per hour flown.

Also assessed will be past decisions on the time to remove engines from aircraft, through the review of engine SV reports and damage findings, to evaluate what would be the unit maintenance cost of the engine if the engine had been removed several flights sooner or later than the actual time.

1.3. The Aim and Objectives of this Project

Practical constrains will limit the number of organisations that will provide information for this investigation; additionally some relevant proprietary information

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may not be disclosed by airlines or other corporations. Taking into account some limitations of the research methodology, such as no random sample of the companies selected for the questionnaire used here, the conclusions from the practices reported here shall not be generalised or assumed as best practice at this stage.

The recommendations on the rules and model to decide when to remove an engine to achieve a minimum unit cost may be a satisfactory tool for certain airlines but not for others, depending on individual characteristics and conditions such as fleet size, aircraft owned or under operating leases, internal maintenance capability, type of subcontracts for engine maintenance, engine age, type of aircraft operation, commercial services of the airline, etc.

It is also important to mention that in certain financial or contractual situations, airlines may decide to sacrifice engine maintenance unit cost in favour of minimising cash out in a specific period – removing an engine sooner or later than ideal or reducing the recommended workscope of the SV are examples of decisions to reduce expense at a certain time, even if in the long term the unit cost will be higher.

Kennet (1994) developed a plausible econometric structural model of aircraft engine maintenance and estimated the structural parameters, per engine type, separately for the airline regulated and deregulated eras. The validity of separating the sample of engine data was proved by likelihood ratio tests, confirming earlier studies that there were different engine maintenance behaviours, before and after deregulation. The results of the data analysis seem to indicate that airlines took action to optimise the scheduling of engine SVs, by keeping the engines longer on the wing after the deregulation of the airline business, which increased the competition in the industry.

The aim of this project is to define a methodology to establish the best time to remove an engine for a SV, in order to achieve the minimum maintenance unit cost, taking into account the reliability of the specific engine model, the trends of the engine monitoring parameters (such as exhaust gas turbine temperature (EGT), engine rotation speeds, fuel consumption, vibration in rotors, oil pressure), the physical status of the engine as determined by oil consumption, and visual and borescope inspections.

To achieve the aim of this work, the following objectives will be undertaken:

a) To investigate, by using questionnaires, what are the criteria, recommendations and practices of airlines, OEMs and MROs to decide when to remove an engine

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for a SV, and if and how they look for the minimum engine maintenance unit cost.

b) To evaluate a small number of past engine histories of SVs, using open, deep and detailed qualitative analysis (Patton, 1990, p. 14) to obtain an adequate understanding of:

   i) Reasons for the engine removal;

   ii) Damage findings in the SV and related causes;

   iii) Engine deterioration process and characteristics of damage propagation;

Assessment of the decision on the timing to remove an engine, taking into consideration minimum cost and the risk and consequential costs of unexpected failure and unscheduled engine removal;

   iv) Conclusions on best practices and criteria that could improve the past decisions of the time to remove an engine for a SV.

c) To define a set of rules and outline a statistical model to assist in deciding the best or a satisfactory time to remove an engine for a SV, aiming to minimise engine maintenance unit cost, which may provide a significant contribution to airline profit.

The object of engine manufacturers is to achieve, by design and production, high inherent reliability and maintainability, so that the engine should be able to stay in the wing as long as possible and be economically affordable.

One hypothesis to verify within this project is a common belief that maintenance unit cost always decreases if the engine stays in the wing as long as possible, within the limitations defined by manufacturers and civil aviation authorities and weighting the safety and economic risks of unscheduled in-service failure.

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Chapter 2

2. LITERATURE REVIEW

2.1. Primary Aircraft Maintenance Concepts

The aviation authorities, and in particular the Federal Aviation Authority (FAA), recognise three primary aircraft, component and engine (component or item) maintenance processes:

- Hard Time (HT) – certain tasks are mandatorily performed at fixed intervals;
- On Condition (OC) – the equipment, component or engine is checked periodically for its condition by means of inspections and/or the regular collection of data indicating its state or condition, being removed when one engine parameter exceeds certain established limits or when compared to trend patterns it shows a reduction of reliability and imminent failure;
- Condition Monitoring (CM) – the process of monitoring the airworthiness of the aircraft fleet and its maintenance performance; this process allows for the failure of the component and consists of collecting and analysing *ex post facto* (after the fact) data on the entire population of a component, using a reliability or performance evaluation programme to assess the behaviour of the unit and take corrective action to modify the equipment or maintenance programme, if and when necessary (BOEING, 1982, pp. 01-07).

HT and OC are *a priori* individual monitoring processes aimed at removing the component or unit before it fails, i.e., they are preventive maintenance processes. CM is not intended to prevent a failure, but to assess *ex post facto* the population behaviour.

A comprehensive CM/Reliability programme overlaps the three primary maintenance control processes, acting as a cover under which those processes are performed. It is a secondary maintenance control process used to assess the effectiveness of primary processes, the suitability of the HT and OC intervals, and may require modifications to the initial project, changing the primary control process or the time limits for removal or inspection (BOEING, 1982, pp. 01-07). The CM/Reliability programme collects information from flight hours and cycles (landings), pilot

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complaints, on-board aircraft equipment records, inspections and maintenance tests, shop findings and other data from aircraft operations for statistical analysis and technical evaluation in order to assess the performance and overall effectiveness of the maintenance programme and take corrective action (BOEING, 1982, pp. 01-09).

Aviation authorities require airlines to have CM/Reliability programmes to monitor their aircraft fleets, and in particular:

a) The FAA (Federal Aviation Authority)/USA, in the Federal Aviation Regulation (FAR) Part 121.373, requires:

> *Continuing analysis and surveillance.*
> *(a) Each certificate holder shall establish and maintain a system for the continuing analysis and surveillance of the performance and effectiveness of its inspection program and the program covering other maintenance, preventive maintenance, and alterations and for the correction of any deficiency in those programs, regardless of whether those programs are carried out by the certificate holder or by another person.*" (FAA, 1996, Sec 121.373).

b) The EASA (European Air Safety Agency), the regulating and supervisory authority for the EU and member countries, has established that:

> *(d) The maintenance programme shall contain details, including frequency, of all maintenance to be carried out, including any specific tasks linked to specific operations. The programme must include a reliability programme when the maintenance programme is based:*
> *1. on Maintenance Steering Group logic, or;*
> *2. mainly on condition monitoring.* (EASA, 2003, Part M M.A. 302).

In general, engines are subject to a consistent *lato sensu* On Condition programme or to be more precise, a Condition-Based Maintenance philosophy, that includes the designated Engine Condition Monitoring (ECM) or Engine Health Monitoring (EHM) programme, which constantly monitors the condition of a number of engine operating parameters (turbine gas temperature, speed of rotors, vibrations, oil pressure, etc.) to ensure engine removal before in-service failure.

Under the condition-based maintenance concept, gas turbine engines are in fact subject to control by the three primary maintenance processes, i.e. HT, OC and CM. GE/CFMI (2009) considers that those processes work hand in hand with one another and that they carry equal weight in a maintenance program. Most of time the engine removal time is dictated by the OC concept, but all three processes are equally important and their application priority depends only on the type of event that occurs first.

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In the Table 1 below is presented the use of the three primary maintenance processes to control engine operation and maintenance.

Primary Maintenance Processes	Method	Application Methodology	Action	Engine Examples
Hard Time (HT)	Preventive	Hour, Cycle or Calendar Limits	✓ Remove for SV: • Discard LLP • Overhaul • Other maintenance task	• Life Limited Parts: Turbine disks, Compressor disks, • AD (airworthiness directives)
On-Condition (OC)	Preventive	Inspect/Check/ Verify against standard: • Hardware • Performance parameters	✓ Check/correct defect: • replace component LRU • other line maintenance items; or ✓ Remove engine for SV	• Oil consumption • Turbine borescope inspection • EGT margin • Rotor vibration
Condition Monitoring	Predictive	ECM: Performance parameters trend/trend shifts evaluation	✓ Check/identify causes of trend shifts ✓ Correct defects ✓ Check parameters against limits	• Trend shift in Take-off EGT • Take-off EGT margin • Cruise Low Pressure rotor • Reliability data from OEM and operator

Table 1 - Engine primary maintenance processes

2.2. About Reliability and Bayesian Statistics

Kinnison (2004) considers two main approaches to the reliability concept in the airline industry: one is the overall airline dispatch reliability (and in particular the maintenance department dispatch reliability), represented by the percentage of on-time departures of scheduled flights; the other is concerned with the effectiveness of the maintenance programme, tracking maintenance problems, even if they do not cause

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departure delays. This second approach is more effective and complete for maintenance purposes and has a strong correlation with maintenance and engineering dispatch reliability and, consequently, with the overall airline dispatch reliability.

Reliability can be defined as "the probability of a given system performing its function satisfactorily over a certain period of time and under specified operating conditions." (Kapur & Lamberson, 2006, p. 13.2).

Reliability is a measure of the quality of a product and can have different meanings, depending on the characteristics of the product, its use and the viability or ability to be repaired after damage.

A method of determining reliability is through life testing whereby a batch of components or units is tested over an extended period of time and the failure times recorded. The test can be done either by i) Non-replacement, when an item fails it is not replaced and the test ends at a specified time (time-truncated) or at specified number of failures (sample-truncated); ii) Replacement, when an item fails it is replaced and the test continues indefinitely or stops by a specified rule; Sequential, in which the test is stopped when the batches being tested either achieve or fail to achieve the specified goal (Chatfield, 1983, pp. 319-320).

When life testing the reliability of a product or component, one of the important aspects to consider is censoring – the life testing data are censored when the failure time of a certain component is not precisely known, due either to the characteristics of the test, or to the test being interrupted, whether deliberately or not, or to fortuitous or other circumstances (Hamada, Wilson, Reese, & Martz, 2008, pp. 13-14).

In analytical terms, where T, the time to failure, is a random variable, reliability R (t) is defined as:

$$R(t) = \text{Probability } P(T > t) = \int_t^\infty f(\tau)d\tau = 1 - F(t) = 1 - \int_0^t f(\tau)d\tau$$

Where: $f(t)dt$ is the probability density function (representing the probability of instantaneous failure) and $F(t) = \int_0^t f(\tau)d\tau$ the cumulative distribution function (representing the probability of failure from time zero to time t).

Some of the indirect measures of reliability include:

a) Mean Time to Failure = MTTF = $\int_{-\infty}^{\infty} tf(t)dt$, a performance indicator calculated by the average number of hours operated per unit until failure –

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this method only takes into account the average life of the units that failed, as per Hamada et al. (2008, p. 8) and BOEING (1982, pp. 5-3).

b) Mean Time Between Failures

MTBF = $\frac{\text{Total Hours Operated by the unit (entire population) in the Period}}{\text{Number of failures of the unit in the Period}}$,

takes into account the hours operated by the unit (all units) in any given period, but only divides by the number of failures of the units that did fail.

c) Mean Time Between Removals

MTBR =

$$\frac{\text{Total Hours operated by the unit (entire population) in the Period}}{\text{Number of programmed and non−programmed removals of the unit in the Period}}$$

d) Failure rate or hazard function,

Hazard Function = h(t) = $\frac{f(t)}{R(t)}$, this is the conditional probability of instantaneous failure (i.e. in the interval t+dt), since there have not been any failures or the units have survived to time t.

Wu, Liu, Ding and Liu (2004) stress that "reliability and maintainability" are inherent properties of an aircraft (and engine) and they estimate that 70 to 85% of its lifetime cost is determined at the design stage. The authors refer to the "intrinsic reliability" or "ex works" that is conditioned by the characteristics and quality of the project (Assis, 2004).

Notwithstanding the maximum limits of reliability, and operational and economic performance established by the quality of the aircraft's or engine's project, it is obvious that good maintenance practices, good techniques for detecting anomalies, good condition monitoring, modifications for product improvement, associated with competent economic management, tend to maximise the availability of the equipment and minimise maintenance costs.

The reliability methodology based on Bayesian statistics appears to fit the needs of modelling and simulation to evaluate the decision of when to remove an engine from an aircraft and send it for a SV, which is the subject of this study.

The open, comprehensive and detailed qualitative analysis of historical data, (Patton, 1990, p. 14), may produce information to enhance statistical processing, using Bayesian methods.

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Assuming a mixing method of research, qualitative and quantitative data sets may be merged, connected or embedded to produce results (Plano Clark & Creswell, 2007).

Bayesian statistics are based on Bayes theorem:

$$P(A_i \mid B) = \frac{P(B \mid Ai)P(Ai)}{P(B)} = \frac{P(B \mid Ai)P(Ai)}{\sum_i (P(B \mid Ai)P(Ai)}$$

Where Ai is a partition A = {A_1, A_2 ... A_n) of the sample space considered, B is any event in the sample space, where P (A_i) > 0 and $A_i \cap A_j = \emptyset$.

The Bayesian method of reliability in conjunction with current computing power, enables flexibility for modelling and simulating situations in which, in addition to a priori knowledge, empirical results can be added to the mathematical model.

The model incorporates the concept of subjective probability or degree of credibility. Based on the above formula, an initial subjective probability (based on current knowledge), i.e. a certain degree of credibility, can be assigned to the input data or initial conjecture Ai, considered as "antecedents", "hypotheses" or "states". Subsequently, from the data gleaned from empirical research – analysis of historical data, operational occurrences, past experience, tests, observations – the *a priori* probabilities are modified, changing from $P(A_i)$ to $P(A_i \mid B)$, thus incorporating information from past experience represented by the data B (Paulino, Turkman, & Murteira, 2003).

As per Hamada al. (2008, pp. 27-36), overall Bayes' Theorem and for continuous distributions, is represented by

$$p(\theta|y) = \frac{f(y|\theta)p(\theta)}{\int f(y|\theta)p(\theta)dy}$$

Where $p(\theta|y)$ is the a posteriori distribution function, $p(\theta)$ the a priori distribution function, $f(y|\theta)$ the distribution function of the sample data of experience and $f(y|\theta)p(\theta)dy$ the marginal distribution (unconditioned) of data.

Having determined the a posteriori function, it is possible to define a predictive distribution, to project future or simulation values by integrating the sampling distribution over the *a posteriori* distribution.

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2.3. An Overview of the Jet Engine

The focus of this project is on the jet engine, the main method of propulsion of modern aircraft.

The first jet propulsion engine was patented by French engineer René Lorin in 1913; it was an athodyd engine, i.e. an aero-thermodynamic-duct, with no major rotating parts. This device, similar to what is now called the ram jet, was impossible to manufacture with the existing technology at that time (Rolls Royce Limited, 1973). In 1930, Frank Whittle patented a gas turbine to produce a propulsive jet, that 11 years later performed its maiden flight, providing the basis for propulsion of modern aircraft (Rolls Royce Limited, 1973).

There are several types of jet engine: ram jet, pulse jet, turbo ram jet, rocket, turbo-rocket and gas turbine. Modern commercial transport airplanes are equipped with turbo-propeller, turbojet and turbofan engines. Turbo jet engines are being replaced by the turbofan engine (Figure 1) which has the following characteristics:

i) Most of the engine inlet air, accelerated by the fan, does not go into the rest of the engine, i.e. the compressors, combustion chamber and turbines;
ii) A significant portion of the thrust is produced by the fan, a device with a working principle similar to a propeller;
iii) Due to the characteristics above, the turbo fan engine (especially the high by-pass turbo fan) is more efficient and less noisy than the turbojet engine.

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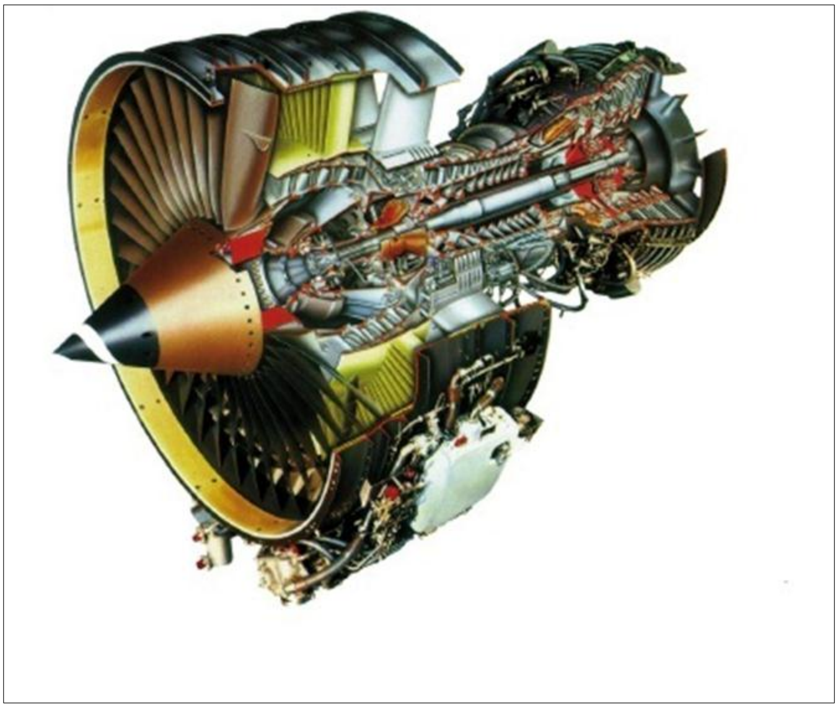

Figure 1 - Turbo fan engine CFM56 (source CFMI)

Using as an example a twin-spool (two shafts) turbo fan engine, the main modules of the CFM56 engine are as follows (Figure 2):

- Fan Module, comprising:
  - Fan
  - Booster or Low Pressure Compressor (LPC), where the inlet air from the fan is firstly compressed.
- High Pressure Compressor (HPC), where the air from the LPC suffers additional compression.
- Core Engine Module, comprising:

Combustor Chamber (CC), that receives high pressure air and fuel that are ignited by the igniters, resulting in very hot gas, which expands in the turbines and delivers the energy that makes the turbines spin and drive the fan and compressors;

  - High Pressure Turbine (HPT), which receives the very hot gas from the CC and drives the HPC.

Low Pressure Turbine (LPT), which receives hot gas from the HPT and drives the LPC and the fan; the gas from the LPT leaves the engine from the exhaust assembly, producing part of the thrust to move the aircraft;

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- Accessory Drive Module driven by the LPC, which drives:
    - several components that provide control and resources, such as fuel and oil, to the engine – for example fuel pump, fuel control unit and oil pump;
    - components that provide electrical, hydraulic and pneumatic power to several systems of the airplane – such as lights, navigation, landing gear and air conditioning.

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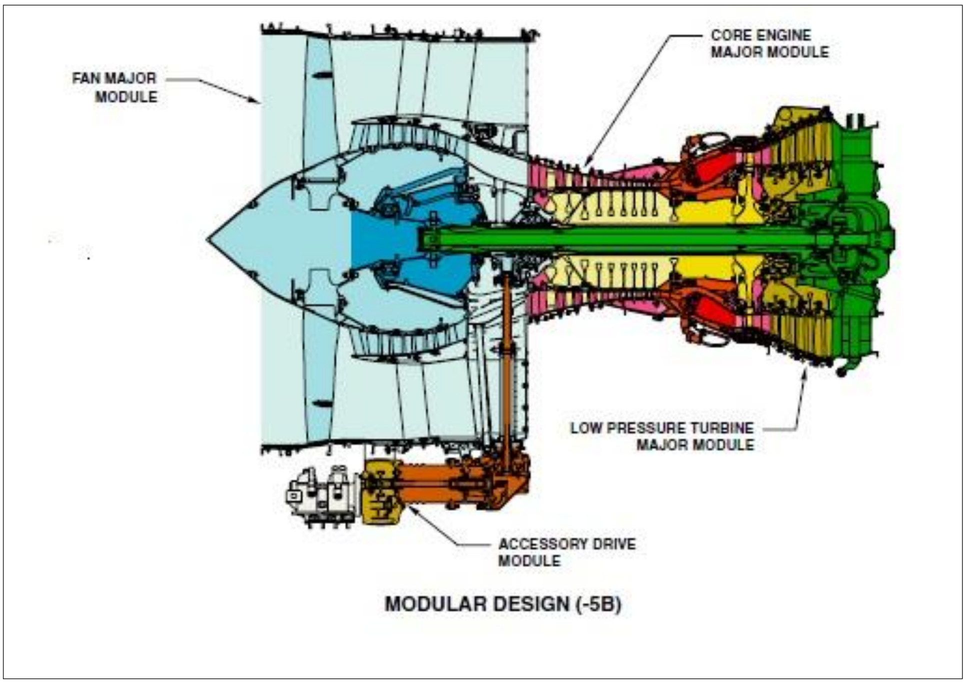
○ 

Figure 2 - Modules of the CFM 56 turbo fan engine (source CFMI)

Figure 3 below shows the two rotating systems of a twin spool engine: i) one shaft rotating at N1 speed with the LPT, LPC and Fan; ii) the other shaft rotating at N2 speed, with HPC and HPT.

Figure 4 illustrates the path of the air and the hot gas from the combustor chamber, as briefly described above.

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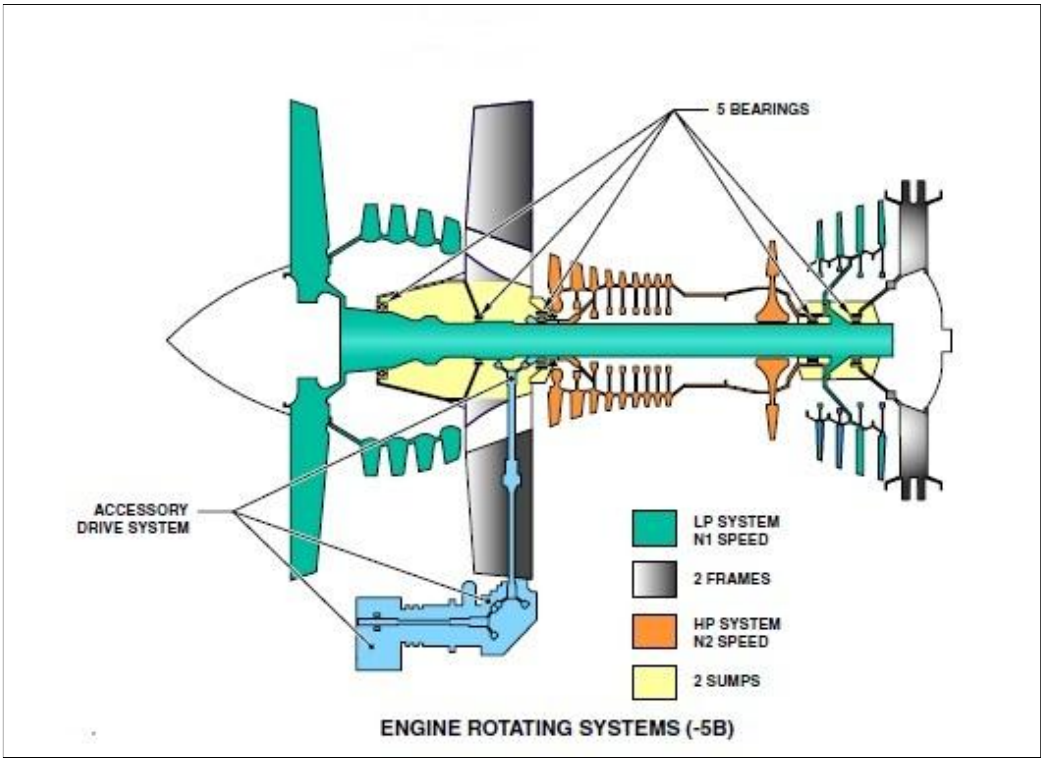

Figure 3 - The two rotating systems in a twin spool engine (source CFMI)

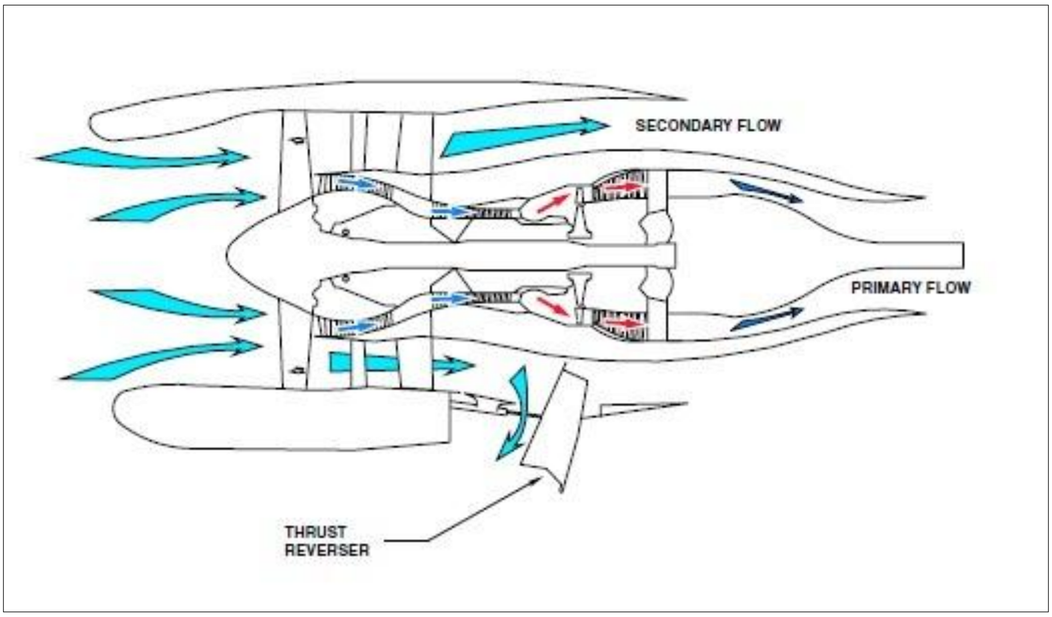

Figure 4 - The gas flow path in a turbo fan engine (source CFMI)

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2.4. Specific Academic literature Review on Engine Reliability and Costs

2.4.1. How relevant is the issue of optimising engine time on the wing?

When an aircraft becomes old or obsolete, because its technological and, concomitantly, its economic performance decays, the last remaining value stays with the engines; everything else is just like a can to be sold for the value of the weight of recyclable material. When airlines decide to discontinue the operation of one obsolete aircraft, engines may be sold to be used in other aircraft (likely to be obsolete also), as a less expensive alternative to the repair of replacement engines, or to be used for land power plants.

Kang, Ogaji, Pilidis and Kong (2008) consider that three components of aircraft Direct Operating Cost (DOC) can be directly attributed to engine performance, design and reliability: the cost of fuel, engine acquisition and engine maintenance. The authors state that for a typical wide body aircraft, those costs would be more than 40% of the DOC of the aircraft, split as follows: 55% for fuel, 30% for engine maintenance and 15% for engine acquisition.

The figures above represent a perspective in a certain calendar time and cannot be taken as an absolute truth. However, they provide a valid illustration of the importance of engines within aircraft operating cost. Actually a proportion of the cost depends on fuel price (i.e. crude oil price) and fuel consumption, and related cost depends not only on engine performance but is also highly dependent on the aerodynamic characteristics and structural efficiency of the aircraft.

The percentage of any cost component of the airline’s DOC depends significantly on the unit cost of fuel, meaning on the cost of a barrel of crude oil, which in recent decades has presented high variations. When the fuel price increases, the percentage of the other costs components on DOC decreases, and vice versa.

Modern aircraft are now built with more fibre reinforced plastics (composite materials) to reduce weight, advanced aerodynamic features (such as winglets/Boeing and sharklets/Airbus on the wing tips) to reduce drag, and in flight fuel transfer between tanks to optimise the aircraft’s centre of gravity and reduce drag. All these characteristics, together with engine performance, are relevant for aircraft fuel consumption and cost.

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Despite the above considerations, the engine related costs are very important in the airline activity.

Putting aside fuel consumption and other engine ownership costs that depend essentially on external factors with little controllability by the airline, engine maintenance cost is one of the most important parts of controllable DOC by management decision and has two main components:

a) On aircraft – includes inspection, servicing and defect correction tasks performed during line maintenance (between flights) and base maintenance (during periodic inspections) of the aircraft;
b) Off aircraft or SVs – extensive and time consuming work that may be an engine repair, a performance restoration or an overhaul, all of which are performed in engine shops.

As indicative figures, an aircraft manufacturer (Airbus S.A.S, n.d.) considers that On Aircraft (Line) Maintenance is 5% of ownership costs (10% of engine direct maintenance cost), and SVs account for 40% of ownership costs (80% of engine direct maintenance cost). In general engine ownership costs can be split as follows:

i) Acquisition 35%;
ii) Spares acquisition 15%;
iii) Shop Visits 30%;
iv) Life Limited Parts (Shop Visit) 10%;
v) Line (and base maintenance) 5%;
vi) Support 5%).

Actual proportions of On Aircraft and Off Aircraft vary significantly with engine models and airlines, but Off Aircraft (SV) maintenance is always much more expensive than On Aircraft maintenance.

Another important difference is that engine On Aircraft maintenance expenses occur almost uniformly along time and shop maintenance occurs in periods of about two to five years per operating engine, with expenses, for a wide body aircraft, that may vary from US$1 to 10 million; for example for a Boeing 767-300 aircraft, the cost of an SV is in the range of $2 to $3.5 million; for a Trent engine installed in a Boeing 777 it may cost $7 to $10 million.

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Kang et al. (2008) consider that an engine SV (unit) cost depends on Shop Visit Rate (SVR), i.e. the number of SVs per 1,000 engine flight hours (EFHs), the workscope of each SV pattern (the sequence of different workscopes) and the man hours and material spent in each SV. Despite the fact that manufacturers design engines to achieve a low SVR (i.e. long time on the wing) engine maintenance unit cost is not always a monotone function in relation to SVR or engine time on the wing.

The engine SV maintenance unit cost is the cost of the engine SVs divided by the engine flight hours operated by the engine between SVs.

Due to wear and material degradation, the total cost of an SV increases with increasing engine time on the wing. This is an obvious fact, therefore it is not possible to assume a priori that engine maintenance unit cost (engine maintenance cost per flight hour) will always decrease when engine time on the wing increases (i.e. when SVR decreases).

To decide when to remove an engine for an SV is not a deterministic problem. Since engines are maintained essentially under the concept “On Condition” and aircraft operators manage the engine to avoid the risk of unscheduled removal, the decision to remove the engine is done conservatively before engine condition monitoring parameters achieve allowed limits.

Engine time on the wing is not necessarily the most important factor in engine maintenance cost, but when an engine is installed on an aircraft, time on the wing is *quasi* the only factor that management may use to control engine maintenance cost, assuming that the airline is following the required and approved maintenance and operational practices.

Empirical research work done by Kennet (1993) and (1994) presented evidence, using two different methodologies, that after the airline business deregulation in the USA, airline managers changed maintenance behaviour towards optimising engine time on the wing to reduce costs in order to face the climate of stiff increased competition.

We may conclude that optimising engine time on the wing is relevant in managing airlines because it has a strong influence on maintenance costs, an important part of controllable DOC, by preventing over maintenance, provided there is an adequate monitoring of the ECM parameters, proper inspections on the physical status

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of the critical components and the reliability of the engine is taken into consideration to avoid the risk of in-service failure.

2.4.2. Methodologies regarding engine reliability and shop visit scheduling.

The design of engine components in the classical approach has been deterministic; in this method equations representing material and fluid characteristics establish the operating conditions of engine components, then by applying safety factors dictated by experience, the components' performance, life and reliability are determined (Zaretsky & Hendriks, 2002).

In actual conditions, there is significant variability in material, manufacturer processes and operating conditions that may not be adequately represented in the deterministic functions referred to above, resulting in high variances and very conservative safety factors.

Instead of using deterministic equations, it is valuable to use a probabilistic or stochastic approach that may assist to design for manufacturers and operational variations in accordance with an accepted or established risk.

Zaretsky & Hendriks (2002) used Weibull probability analysis to predict engine life and reliability, based on the linear damage rule (Palmgren-Langer-Miner**).**

$$\frac{1}{L_{sys}^{e}} = \frac{1}{L_1^{e1}} + \frac{1}{L_2^{e2}} \dots + \frac{1}{L_n^{e3}}$$

Where:

L_{sys} engine system life (all components)

L_1, ...,L_n cumulative life of each component

e engine system Weibull distribution slope or Weibull module

e_1, ...,e_2 Weibull slope of each engine component.

The method of Zaretsky & Hendriks (2002), applied with adequate statistical data from past operations, can be used by design engineers to predict the reliability of new engines; it can also be used by airlines to predict the life and reliability of their engines.

Wang & Jin (2010) presented an approach based on Weibull failure distribution to determine the optimal replacement times for turbine wheels, taking into account a trade-off analysis of safety risk and maintenance cost. In that research, the stochastic

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approach is considered to be adequate to determine the optimal replacement time, since significant uncertainty is assumed to exist in the turbine cumulative operating hours. This is a rare situation in a regulated airline environment, but the concept appears to have possible extensions to other operational characteristics, including at least the variations in manufacturer processes, maintenance programmes and procedures, average stage length and past engine workscopes.

MRO companies may provide engine maintenance services under two types of contract: time and material, or by flight hour. In the former, the customer is charged a posteriori an amount that includes cost of labour, material, life limited parts (LLPs) and subcontracted work spent in the engine SV. In contrast, in the latter, the customer is charged a priori an agreed fixed value by engine flight hour which depends on the engine's average flight length, i.e. the average flight hours (engine operating hours) per cycle or landing; that charge per flight hour increases when the average flight or stage length decreases, since thermal stress and other loads are higher when the engine is operating in a take-off (maximum power) regime.

Today, engine manufacturers have their own engine MROs to provide engine shop maintenance services to airlines and to other customers. The main engine manufacturers for airlines are General Electric, Rolls Royce, Pratt &Whitney, CFM, IAE and SNECMA.

Engine MROs operate in a very competitive arena and deal with a complex number of interrelated entities and parameters: i) airlines, MROs bases in different locations, material suppliers, logistics providers; ii) aircraft installed engines, spare engines; iii) flight hours, flight cycles, ECM parameters, borescope inspections, airworthiness directives (ADs); iv) commercial planning and operation, scheduled maintenance events, engine incidents; v) others.

In order to become competitive some engine MROs use computer applications for the prediction and scheduling of an engine SV.

It is a key requirement that engine MROs possess an effective tool for prediction, scheduling and to assist in deciding when to remove an engine for an SV in order to: i) plan shop maintenance slots; ii) optimise materials provisioning; iii) avoid aircraft on ground (AOG) due to lack of engine replacement; iv) ensure adequate capacity by service providers for subcontracted work; v) optimise engine time on the

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wing within an adequate trade-off with risk of in-service failure and consequential losses.

The last requirement (optimising time on the wing) is more important for the MRO when providing services under a contract with a fixed price by flight hour, since bad engine condition monitoring or a bad decision on timing to remove an engine for an SV would result in higher costs to be absorbed by the MRO during the long term life of this type of contract – 5, 10 or more years.

Higher than desirable maintenance costs may arise from:

i) engine removed before optimal time, resulting in over maintenance and consequently increased direct maintenance costs and finance costs;
ii) engine removed after time of optimal removal, with increased cost of labour and material in the SV, not compensated for by increased time on the wing;
iii) in-service engine failure (on the ground or in flight) that may implicate additional damage to the engine caused by internal failure of a component, logistics costs of engine replacement in an unplanned location, and commercial costs of passengers, cargo and reputation.

Stranjak et al. (2008) describe an agent-based simulation tool called "Overhaul Prediction and Scheduling" (OPS) to deal with the complexities faced by engine MROs to manage engine fleets. The project was developed in collaboration with the engine manufacturer and MRO Rolls-Royce. In the application of OPS, the stakeholders of the MRO (or Aero Repair and Overhaul – AR&O) are modelled as autonomous agents who negotiate to decide the best date to remove an engine to send it for an SV, taking into account the best compromise of cost, in-service failure risk and revenue.

The OPS agents are:

i) Fleet Manager – responsible for recording engine flight hours, cycles, ECM parameters and engine physical status;
ii) Fleet Planner (FP) – determines engine SV schedules;
iii) Overhaul Base (OHB) – responsible for capacity management of the MRO's engine overhaul base.

The FP Agent aims to keep the engine on the wing as long as possible, but not after the date that would exceed the risk or failure threshold. Through a scheduling

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algorithm that minimises costs, the FP Agent decides the priorities for scheduling engines for an SV, negotiating capacity with the OHB agent.

In the OPS application, engine removal must occur before the whole engine reliability is below an acceptable limit, which will be determined by the combination of failure risks of the engine components represented by the Weibull function with specific scale and shape parameters for each component.

In conclusion, academic work and sophisticated industry applications deal with the problems of prediction and scheduling time for engine SVs, using in many cases the Weibull distribution for reliability calculations and artificial intelligence algorithms. Taking into account the complexities of engine removal prediction and SV scheduling, the use of reliability methods, adequate algorithms and artificial intelligence approaches may provide fundamental assistance to engine managers to optimise the engine time on the wing and minimise the engine maintenance cost per flight hour.

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Chapter 3

3. METHODOLOGY AND STRATEGY

3.1. Methodology General Approach

To do an appraisal of the present procedures and to outline a methodology that objectively defines the best time to remove an engine and send it for a SV, aiming at the lowest maintenance cost per hour of operation, the working plan described below was adopted:

a) Literature review on engine reliability, maintainability, costs and other fields relevant for the project, including primary sources such as refereed journals, conference proceedings and research theses; secondary literature sources were also reviewed, such as text books, professional and trade journals, technical documentation from airlines, aircraft manufacturers, engine manufacturers, MROs and consultants.

b) Distribute questionnaires and conduct semi-structured interviews with engine experts from domestic and foreign aviation companies in order to collect and systematise information about the practices regarding engine reliability, removal decision, prediction and SV scheduling;

c) Collect qualitative (engine damage findings, behaviour and causes) and quantitative (operating hours and cycles, reliability and costs) information from airlines, manufacturers and engine repair and overhaul organisations (MROs) through surveys and visits;

d) Perform qualitative analysis and interpretation and quantitative evaluations.

Thus, the strategy to be adopted is essentially mixed.

Using qualitative methods to collect, select and analyse data – on a holistic basis of inductive, systemic and detailed analysis – a relatively small but information-rich data sample (information-rich cases – Patton, 1990, pp.145-183) will be evaluated and interpreted.

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Qualitative and quantitative data are collected and analysed, providing a better understanding of the subject under analysis; in the adopted methodology, during the appraisal process, it is intended that the two types of data will be merged, connected or embedded, to enhance results and conclusions (Creswell & Clark, 2007). Some data collected will be subject to statistical analysis and other quantitative methods to assist the decision process to remove an engine for an SV, with the aim at obtaining minimum engine maintenance unit cost.

It appears that the use of statistical and Bayesian reliability methods suits modelling objectives in deciding when to remove an engine for an SV. The use of this statistical approach may be particularly interesting, as an alternative to the classical frequentist statistical methods, in the case of small airlines where the sample space is small.

Bayesian reliability methods, due to the ease with which information beyond the information contained in experimental data can be included in the models, such as theories relevant to the study, the results of engineering tests, past experience with similar entities, generic reliability data and, particularly important in the case at hand, engineering sense (Hamada et al., 2008), may all be appropriate tools for data processing to determine, with adequate probability and reliability, the best time to remove the engine to obtain the minimum unit cost.

The potential for using Bayesian reliability in the field of engine SV prediction for minimum costs will be appraised in this study.

3.2. Application of the Methodology

To obtain data to achieve the objectives of this project, an operational plan was elaborated and followed, and is described in this section.

On-line Questionnaire

An on-line questionnaire (Appendix I) was prepared and sent, by convenience sample method (Hill & Hill, 2008), to engine experts or relevant staff of airlines, MROs, and engine and aircraft manufacturers – relevant people, in this context, are those who participate or have participated in the decision process to remove an engine for an SV.

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The objective was to obtain empirical data on the decision process to remove an engine for an SV, while still operating within manufacturer limits, by providing answers to the following questions:

i) Who decides?

ii) What departments participate in the decision process?

iii) What is the importance of engine maintenance unit cost in the decision process?

iv) What are the objective factors in the decision process?

v) How do objective factors change with the type of ownership of the aircraft?

vi) How do objective factors change with the kind of contract with the MRO?

vii) What are the criteria used to decide the time to remove an engine for an SV?

viii) What is the model or formal procedures used to decide when to remove an engine for an SV?

ix) How do the objective factors, criteria and decision procedures change with the size of airlines?

The questionnaire is divided into three parts: the first to characterise the organisation by size and number of aircraft, the second to ensure that the answers come from experts/relevant people for the project, and the third includes the questions to obtain the required data.

Evaluation of the documentation of past engine SVs

To obtain information about hours and cycles of operation until removal, causes for removal, damage findings during SVs, causes of damages.

Case Study – A formal process to decide the time to remove an engine for a shop visit

In this study it is described how the time to remove an engine for a SV was decided, in order to achieve the minimum engine maintenance cost per flight hour (FH), but taking into account the engine reliability to avoid the risk of failure and unscheduled removal. The decision was critical for the following reasons:

x) The engine had accumulated about 15,000 FH and 3000 cycles (landings) since the last SV, so it was operating at the highest limits of its reliability;

i) The engine condition monitoring (ECM) parameters were showing significant degradation and the take-off EGT margin in relation to allowable limits was accelerating towards zero;

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ii) If the engine were not removed soon, then the next suitable opportunity would be five months later, since the aircraft where the engine was installed had been wet leased in ACMI (Aircraft with Crew, Maintenance and Insurance) to another airline, to operate a very intense flight programme based in a foreign airport;

iii) Since the planned commercial operation was very intense, an engine failure and its unscheduled removal would cause serious damage to the flight programme, very high costs to replace the engine, loss of revenue and serious complaints from the customer airline.

Also in this study the decision taken is assessed, based on the actual facts that did occur in the following six months after the decision, including engine operation, removal, disassembly and inspection during the SV and estimates of the differential costs related to the option that was adopted.

In April 2011, the engineering department of one airline was requesting an approval to remove a PW4060 engine from an aircraft to send it for an SV. The approval from top management was mainly related to commercial and financial aspects: i) when would be the best time to remove the engine in order to minimise commercial impact and loss of revenue (opportunity costs); ii) the selection of the MRO and the associated cost to remove the engine for an SV; iii) the solution of the provider of a replacement engine on loan; iv) the engine MRO and the contractual conditions of the SV.

Regarding the above aspects, the most important economic and financial issue is the engine SV, which in this case would cost between $3 and $4 million. The engine loan, for a period of 70 to 90 days, would cost: i) between $2,000 and $3,000 as daily rent; ii) between $250 and $350 per Engine Flight Hour (EFH) and between $250 and $350 per engine flight cycle (or aircraft landing).

The reason for the engineering department to request the engine replacement was based on its technical status and pilots' reports:

i) The figures of the Engine Condition Monitoring (ECM) parameters were showing a reduction on margins towards the limits;

ii) Last borescope inspection of the engine core detected some significant defects in the High Pressure Turbine (HPT), one of them requesting "on watch"

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procedures i.e., periodic borescope inspection to be sure damage would not increase to dimensions and location that would exceed allowed limits.

iii) Pilots were reporting engine slow starting and instrument indications of relatively high engine temperature, fuel flow, rotation and vibration when compared with the other engine installed in the same aircraft; in addition, the fuel consumption difference was causing weight imbalance in the wing tanks so the pilots had to do fuel transfers in flight, although this is a common practice.

In the operational scenario described above, the common decision, without any cost evaluation, is to remove the engine and send it for an SV. In the present case, the airline decided to perform a systematic evaluation on the timing to remove the engine, as presented below.

The decision process includes:

i) Review of the engine status, including the workscope of the last SV;
ii) Technical assessment of the overall condition of the engine, including the ECM parameters;
iii) Technical assessment of the defects found during borescope inspections;
iv) Safety evaluation of the risk of the engine in-service failure and its consequences;
v) Evaluation of the economic impact of the risk of engine failure during the planned ACMI operation;
vi) Provided the safety risk is assessed as remote and concurrently the probability of in-service failure is very low, then a quantitative decision procedure may be used to decide either to keep the engine on the wing for more five months and 1,200 FH or to remove it for an SV.

In the tables below a summary of the status and technical condition of the engine at time of the decision to be taken is presented. In the text that follows, the safety, technical and economic evaluation of the option to keep the engine installed to operate more approximately 1,200 FH and 170 cycles are succinctly presented herein below.

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Engine Model	PW 4060 Manufacturer: Pratt & Whitney
Engine Serial Number	NNNNNN
Aircraft – Type	Boeing 767-300 ER
Registration	CS-XXX
Position Nr	2
Hours (Time) Since New (HSN or TSN)	51104
Cycles Since New (CSN)	10177
Date of Last Shop Visit (DLCV)	22JUN2005 Shop SRT
Hours Since Last Shop Visit (HSSV)	15598
Cycles Since Last Shop Visit (CSSV)	3235
Hour to Cycle Ratio Since Shop Visit	4:82

Table 2 - Engine Status - 17APR2011

Main Work Performed in the Last Shop Visit	
Component	Work
LPC	Repair;
Fan _____	Repair;
HPC	Overhaul;
DBS	Technical Performance Restoration;
TNZ	Technical Performance Restoration;
HPT	Overhaul;
MGB	Repair.

Table 3 - Main Work Performed in the Last Shop Visit

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ECM Parameters	ESN NNNN	Other engine
Cruise Delta EGT, ºC:	42.6	18
Cruise N1 Vibration:	1.7	0.4
Cruise N2 Vibration:	0	0
Take Off EGT Margin, ºC:	10	37.4
Delta WF (Fuel Consumption) %:	10	2
Oil Pressure_________:	220	190
Oil Temperature, ºC:	120	120

Table 4 - ECM Parameters ESN 724616 - 15SEP2011

Physical Status / Defects found through borescope inspection

i) HPT, 1st stage, 10 blades with coating missing

Risk evaluation

1) Safety risk: extremely remote

2) Economic: Blade damage – 10 blades x $11,500 = $ 115,000.

ii) HPT, Seal with missing material

Risk evaluation

1) Safety risk: extremely remote;

2) Economic: Fuel consumption increase; higher temperature in HPT, increase of core engine degradation.

iii) HPT first stage Nozzle Guide Vanes (NGV), with missing coating

Risk evaluation

1) Safety: Extremely remote;

2) Economic: Additional damage to NGV; no risk of unexpected failure.

iv) HPT, NGV, 1st stage with cracks near cooling holes

Technical Assessment

The crack near two rear rows of cooling holes is within limits, subject to borescope inspection every 250 cycles (landings) as per

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maintenance programme. If the crack increases up to 13.005 mm forward of the two rear cooling holes, with a width not exceeding 40.0005 mm, the engine is still within limits, but a borescope inspection is required every 150 cycles. If the crack exceeds the above limits, the engine must be removed immediately or, under certain limits, within five cycles.

Risk Analysis

1) Safety: Within the interval of 250 cycles between borescope inspections the risk of failure is remote or extremely remote.

2) Economic: i) In the next borescope inspection, the crack may be found to be outside the limits; this would disrupt the operation, based in a foreign country and continent, which was contracted by a valuable customer airline.

This operation was planned to start within two months and last for three months. The average aircraft activity was planned for about 14 hours per day, leaving little time to accommodate an unscheduled engine removal anywhere in the American or the European continents, which would require the urgent placing of a replacement engine at high logistics costs. The risk of this occurrence was assessed as very low, since:

i) By analytical methods, tests and field experience, manufacturers establish inspection intervals very conservatively, so that the probability of having a defect that would significantly reduce safety margins can be assumed as remote (say 10^{-7});

ii) Taking this into account, if the crack increased at a higher than expected rate, crack characteristics most probably would then require inspections every 150 cycles (landings) instead of 250 cycles.

Keeping the engine in operation would accelerate its deterioration and would increase SV cost; in particular it would increase HPT blades rates nozzle guide vanes (NGV) scrap rate, some of the most expensive engine items. A preliminary estimate of

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engine SV cost increase was made and is presented below in Table 5. Later on this estimate was reviewed and higher amount was used in the Results section of this document

Description	Qty	Price	% Scrap Rate Inc.	SV Cost increase
HPT 1st stage vanes	34	14,557	10	49,483
HPT 2nd stage vanes	21	23,525	0	0
HPT 1st stage blades	60	11,530	10	69,180
HPT 2nd stage blades	82	9,430	0	0
Other				50,000
Total (*)				168,674

Table 5 - Preliminary estimate of the cost increase of the engine SV

The decision process about removing the engine in April/May or in September, after about 5 months and 1,200 hours of operation (most of it in wet lease/ACMI for a customer airline) was formally conducted as “an act of selecting a preferred course of action among alternatives” (Dilworth, 1992).

The formal procedure for decision making took into account the required steps (Dilworth, 1992):

- “Recognition of the need for a decision” – to remove the engine now or in September;
- “Identification of objectives” – to achieve minimum engine maintenance cost per flight hour;
- “Search for reasonable alternatives” – in the present case, the alternatives about the time to remove the engine for SV were well defined;
- “Evaluation of alternatives” – the alternative events that could occur were evaluated, based on safety and economic risks;
- “Select the best alternative” – it would be selected the alternative that, through the evaluation performed, would result in the minimum engine maintenance cost per flight hour.

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The decision making functions in three types of environments (Levin, Rubin, Stinson, & Gardner, Jr, 1989):

i) Under conditions of certainty –only one event or state of nature exists, so there is absolute certainty about the future;

ii) Under conditions of uncertainty – there is more than one possible event or state of nature, but the decision maker has no knowledge about them;

iii) Under conditions of risk – as in ii) above, but the decision maker has the knowledge to assign probability values to the different states of nature.

In the present environment, the decision is under conditions of risk, so it was considered as adequate to use a decision matrix/decision tree under the following conditions:

i) The option to be selected would be the one in which the Expected Monetary Value (EMV) would result in the minimum estimated engine maintenance cost per flight hour;

ii) The calculation of EMVs would consider:

a. the engine conditional reliability to operate more 1,200 FH;

b. the costs that would be incurred in case of different situations of engine failure, that could happen in flight or on the ground, resulting from pilots' or maintenance reports or as result of findings outside limits that could be detected during the mandatory borescope inspection that was planned to be done during the subsequent 5 months of operation;

c. the estimated cost increase of the next SV as a result of keeping the engine in the aircraft operating more 1,200 FH;

d. the discounted estimated cost value of the engine SV, as a result of postponing the SV for five months.

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3.3. Conclusion

The literature review, about the approach to optimising engine time on aircraft, provides a good overview of theories and computer applications on the subject.

The questionnaire sent to engine experts and to relevant persons in the process of deciding when to remove an engine for an SV is a source of empirical data about actual practice in the industry.

The case study, related to an engine that was operating in the critical decision time for removal (more than 15,000 FH and 3000 cycles since last shop visit (SLSV)), presents a valuable opportunity for an in depth qualitative analysis of an information-rich case (Patton, 1990), since the condition of the engine may be evaluated as follows:

iv) On the wing, in the beginning and until the end of the period of operation under study, the status of the engine is analysed through pilots' and maintenance reports, borescope inspections, other maintenance checks and by the values of the engine condition monitoring parameters;

v) In the shop, at the end of the period under study, after the disassembly of the engine, during the table inspection, the parts of the engine are fully available for visual inspection and non-destructive tests;

vi) Comparisons of the engine's technical condition in different moments provide valuable information about the deterioration of the engine during the period under evaluation.

The analysis of the combination of the data collected, as referred to in this section, will provide a deep understanding of the methods to decide when to remove an engine for an SV, in order to minimise engine maintenance unit cost.

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Chapter 4

4. RESULTS

4.1. The Case Study – A Formal Process to Decide When to Remove an Engine for a Shop Visit

4.1.1. The decision process.

The decision maker has two options:

D1: To remove the engine “now” (i.e., immediately after the decision) and send it for a shop visit (SV);

D2: To remove the engine after five months from “now” and then it will operate on the aircraft more about 1,200 FH and 170 cycles (landings).

Decision D1 has only one possible event or state of nature:

E_1: With probability $p_1 = 1$, the engine will go for a SV at an estimated cost of SVC_0.

Decision D2 will generate the following events:

E_{21}: With probability p_{21}, the engine operates more five months and 1200 FH without failure and then is removed and sent for a SV at the estimated cost and saving as follows:

i) $SVC_5 = SVC_0 + \Delta SVC$, is the cost of the SV to be performed five months and 1,200 FH later than in the case of decision D1;

ii) ΔSVC is an estimated cost increase on SVC_0 after 1,200 FH of operation;

iii) $DSVC_0$ is the discounted cash flow saving over SVC_0, since the SV will be performed five months later;

E_{22}: With probability p_{22}, the engine fails in service after M months and T flight hours of operation; this event will generate two other possible events.

E_{221}: With conditional probability $p_{221} = P(E_{221}|E_{22})$ the engine failure occurs during a flight and the aircraft may have to divert to an alternative airport, so the operating airline would incur the following costs:

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i) -SVC_f the cost of the SV after failure in-flight and engine in flight shutdown (IFSD);

ii) CDC_f , contingency damage costs, to be included in $SVC_{f,}$ to cover the possibility of additional internal damage caused to the engine by the component that failed and originated the engine in-flight failure.

iii) LC_f the logistics costs to replace an engine outside the base, maybe in an alternate (alternative) airport, due to an in-flight failure and IFSD;

i) CL_f the loss of contribution (revenue – variable costs) during the period of AOG due to in-flight engine failure;

ii) $DSVC_f$ is the discounted cash flow saving over $SVC_{0,}$ since the SV will be performed M months later than in case of decision D1.

E_{222}: With conditional probability $p_{222,} = P(E_{222}|E_{22})$, the engine failure occurs on the ground, the engine is replaced and is sent for a SV, so the operating airline will incur the following costs:

i) SVC_g the cost of the SV after the failure on the ground;

ii) LC_g, the logistics costs to replace an engine outside the base due to in service failure;

iii) CL_g the loss of contribution (revenue – variable costs) during the period of AOG due to the engine failure on the ground;

iv) $DSVC_{g\ is}$ the discounted cash flow saving over $SVC_{0,}$ since the SV will be performed M months later than in case of decision D1.

4.1.2. Numbers Used in the Baseline Scenario of the Decision Matrix/Tree

a) Event E_1 – The engine is sent for an SV “now”:

SVC0 = \$3,000,000; despite being selected in accordance with the airline experience and the technical condition of the engine, this amount is essentially a cost baseline to compare the two options for the time to remove the engine for an SV. In this scenario the engine would be removed after 15,104 FH since the SV, so the engine maintenance unit cost would be \$198.62/FH.

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b) Event E_{21} – The engine will be removed after five months from now and will run in the aircraft more 1,200 FH.

SVC_5 = SVC_0 + ΔSVC = \$3,000,000 + \$168,674 x 1.3 = \$3,219,276 ,

where ΔSVC is the estimated SV cost increase caused by more than 1,200 FH of engine operation; based on the airline expert's opinion, it was decided to use the amount estimated in Chapter 2 augmented by 30%.

$DSVC_0 = SVC_0 – SVC_0 / (1+i (5/12))$ = \$3,000,000 - \$2,920,892 = \$79,108

where i = 6.5% is the assumed discount rate per year.

$p_{21} = 1- p_{22} = 1 – 0.03024 = 0.9698$, where p_{22} is the probability of engine failure, determined below.

c) Event E_{22}

$p_{22} = \lambda t e^{-\lambda t}$ = 0.026 x 1.2 $e^{\wedge -0.026 \text{ x} 1.2}$ = 0.03024

assuming, as acceptable for the decision process, that the engine failure rate is constant during the additional period of operation, so we have a Poisson process, where

λ = 0.026 is the basic unscheduled removal rate per 1,000 FH, reported in the Pratt and Whitney PW4000 Service Information Report (2009)

t = 1.2 thousand FH, the additional time of operation

e = 2.71828… is the neperian number.

d) Event E_{221}

p_{221} = IFSD rate x 1.2 $e^{-\text{IFSD rate x } 1.2}/p_{22}$ = 0.005 x 1.2 $e^{-0.005 \text{ x } 1.2}$/0.03024 = 0.1972

Assuming a constant IFSD rate during the additional period of operation and using the IFSD rate reported in the Pratt and Whitney PW4000 Service Information Report (2009).

$SVC_f = SVC_0 + T/1200 \text{ x } \Delta SVC + CDC_f$ = \$3,000,000 + 600 FH/1200 FH x \$168,674 x 1.3 + \$500,000 = \$3,609,638

$DSVC_f = M/5 \text{ x } dSVC_0$ = 2.5/5 x \$79,108 = \$39,554

LC_f = \$250,000

CL_f = 7 days x 14 FH x \$3,800 = \$ 372,400

Using the criterion of rationality – "all states of nature are assumed equally likely" (Levin et al., 1989) – it was assumed that the failure would occur in

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the middle of the planned period of operation (i.e. after M=2.5 months and 600 FH of operation).

From the expert opinion of the airline staff, CDC_f was assumed to be $500,000, as a robust figure.

Taking into account past experience and the routes to be operated, the LC_f cost was estimated at $250,000 for transportation of the removed and installed engines and for contracting a team with the necessary equipment to replace the engine, eventually in an alternate airport, where the aircraft had been forced to land.

The contribution loss CL_f was estimated on the assumption of seven days AOG to replace the engine. The operating airline would have an average daily contribution loss of 14 hours per day multiplied by $3800/FH, which is difference between the ACMI price per BH and the variable cost per BH, that in this case (aircraft wet lease) is just the aircraft maintenance variable cost.

e) Event E_{22}

$p_{222} = 1 – P_{221} = 1 – 0.1972 = 0.8028$.

$SVC_g = SVC_0 + T/1200 \times \Delta SVC$ = \$3,000,000 + 600 FH/1200 FH x \$168,674 x 1.3 = \$3,109,638

$DSVC_g = M/5 \times dSVC_0$ = 2.5/5 x \$79,108 = \$39,554

LC_g = \$100,000

If the engine failure would occur or be detected on the ground, the engine change would be done in one of the airports of the planned operation, so it was estimated, based on the airline experience, that the logistics cost LC_g would not exceed $100,000.

CL_g = 5 days x 14 FH x \$3,800 = \$266,000

For the engine failure on the ground it was estimated five days AOG to replace the engine.

The safety assessment and the technical evaluation of the engine condition, as described in the previous chapter, did not conclude that the engine could not be operating for more 1,200 FH and 170 cycles. So the decision, about removing the engine “now” (i.e., immediately after the decision) or after five months, depended on

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the economic evaluation, which was done using a decision tree/decision matrix, as presented below.

The best decision is the one that results in the minimum expected unit cost, i.e. the minimum expected engine maintenance cost per flight hour.

In Figure 5, two decision branches are presented in the decision tree: i) branch D1: remove now; ii) branch D2: remove after five months. The expected values are calculated at each node from right to left, multiplying the total cost of each event by the probability of the event and dividing by the FH operated by the engine. The calculations are described in the decision matrix.

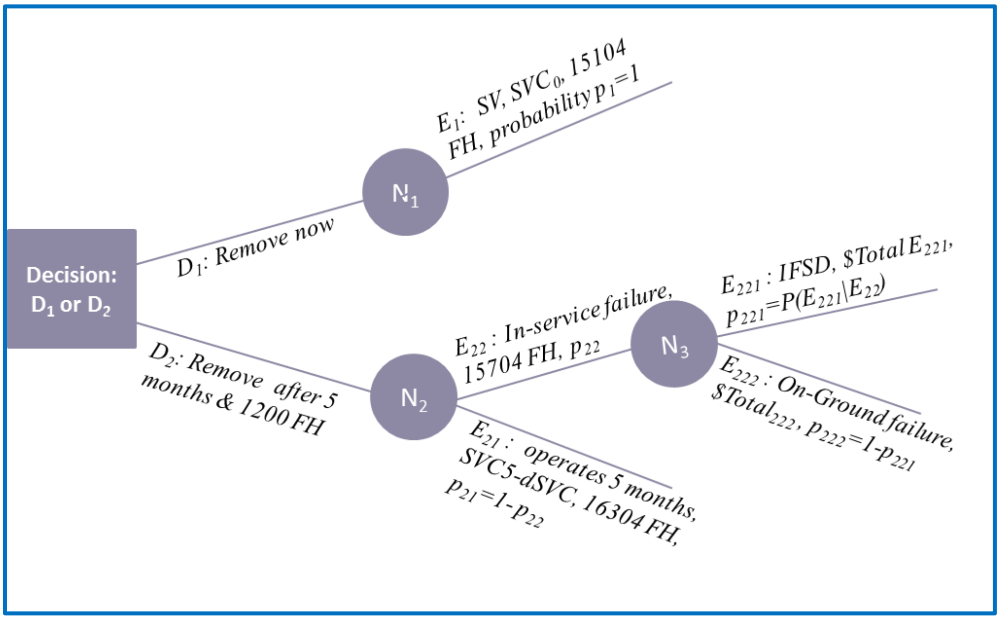

Figure 5 - Decision Tree for time to remove the engine for an SV

In the following pages four decision matrixes are presented, including the baseline scenario and tree simulations for sensitivity analysis.

In Table 6 below is presented the most likely scenario of estimated costs to replace the engine, in case of engine failure in-flight or on-ground during the five months of operation. This is the Baseline Scenario, which uses the values of costs, flight hours and probabilities that are described above.

In Table 7 a more pessimistic scenario is evaluated, assuming much higher costs to replace the engine in the case of failure during the planned period of operation – LC_f = \$500,000 and LC_g = \$250,00.

Another sensitivity analysis was performed by increasing the probability of engine failure; this simulation was performed to deal with the controversial assumption of the constant engine failure rate during the additional period of operation. The conclusions are presented as follows:

- In Table 8, using the Baseline Scenario, it was necessary to multiply by 7,24 the probability of engine failure p22 to obtain a break-even point, where the expected values are equal for both decision options, D1 = Remove Now or D2 = Remove After Five Months.

- In Table 9, using the Pessimistic Scenario, the break-even point was found by multiplying p22 by 5.76.

Taking into account the sensitivity analysis that was performed, the decision to keep the engine in operation was assessed as adequate.

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Decision	Nodes	Event	Cost		Probability		Flight Hours	Expected Value	Expect Value/FH
D2: Remove after 5 months	Node 3	E221 - In Flight Shut Down	SVC_f	$3,609,638					
			$DSVC_f$	-$39,554					
			LC_f	$250,000					
			CL_f	$372,400					
		Total E221		$4,192,484	p_{221}	0.1972	15,704	$826,823	$52.65
		E222 - On Ground failure	SVCg	$3,109,638					
			DSVCg	-$39,554					
			LCg	$100,000					
			CLg	$266,000					
		Total E222		$3,436,084	p_{222}	0.8028	15,704	$2,758,435	$175.65
		Total Node 3						$3,585,258	$228.30
	Node 2	E22 - In Service failure		$3,585,258	p_{22}	0.030242	15,704	$108,424	$6.90
		E21 - No failure	SVC_5	$3,219,276			16,304		
			DSVC	-$79,108					
		Total E21		$3,140,168	p_{21}	0.9698	16,304	$3,045,204	$186.78
		Total Decision 2						**$3,153,628**	**$193.68**
D1: Remove Now	Node 1	E1	SVC_0	$3,000,000	p_1	1	15,104	$3,000,000	$198.62
		Total Decision 1					**15,104**	**$3,000,000**	**$198.62**
		D1 - D2							**$4.94**

Table 6 - Decision matrix - time to remove the engine for SV–Baseline Scenario

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Decision	Nodes	Event	Cost		Probability		Flight Hours	Expected Value	Expect Value/FH
D2: Remove after 5 months	Node 3	E221 - In Flight Shut Down	SVC_f	\$3,609,638					
			$DSVC_f$	-\$39,554					
			LC_f	\$500,000					
			CL_f	\$372,400					
		Total E221		\$4,442,484	p_{221}	0.1972	15,704	\$876,126	\$55.79
		E222 - On Ground failure	SVCg	\$3,109,638					
			DSVCg	-\$39,554					
			LCg	\$200,000					
			CLg	\$266,000					
		Total E222		\$3,536,084	p_{222}	0.802785	15,704	\$2,838,714	\$180.76
		Total Node 3						\$3,714,840	\$236.55
	Node 2	E22 - In Service failure		\$3,714,840	p_{22}	0.030242	15,704	\$112,343	\$7.15
		E21 - No failure	SVC_5	\$3,219,276			16,304		
			DSVC	-\$79,108					
		Total E21		\$3,140,168	p_{21}	0.969758	16,304	\$3,045,204	\$186.78
		Total Decision 2						**\$3,157,547**	**\$193.93**
D1: Remove Now	Node 1	E1	SVC_0	\$3,000,000	p_1	1	15,104	\$3,000,000	\$198.62
		Total Decision 1						**\$3,000,000**	**\$198.62**
		D1 - D2							**\$4.69**

Table 7 - Decision matrix for the time to remove the engine – Replacement Cost Pessimistic Scenario

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Decision	Nodes	Event	Cost		Probability		Flight Hours	Expected Value	Expect Value/FH
D2: Remove after 5 months	Node 3	E221 - In Flight Shut Down	SVC_f	$3,609,638					
			$DSVC_f$	-$39,554					
			LC_f	$250,000					
			CL_f	$372,400					
		Total E221		$4,192,484	p_{221}	0.0272	15,704	$114,202	$7.27
		E222 - On Ground failure	SVCg	$3,109,638					
			DSVCg	-$39,554					
			LCg	$100,000					
			CLg	$266,000					
		Total E222		$3,436,084	p_{222}	0.97276	15,704	$3,342,486	$212.84
		Total Node 3						$3,456,688	$220.12
	Node 2	E22 - In Service failure		$3,456,688	p_{22}	0.218949	15,704	$756,839	$48.19
		E21 - No failure	SVC_5	$3,219,276			16,304		
			DSVC	-$79,108					
		Total E21		$3,140,168	p_{21}	0.78	16,304	$2,452,631	$150.43
		Total Decision 2						**$3,209,470**	**$198.63**
D1: Remove Now	Node 1	E1	SVC_0	$3,000,000	p_1	1	15,104	$3,000,000	$198.62
		Total Decision 1						**$3,000,000**	**$198.62**
		D1 - D2							**$0.00**

Table 8 - Decision matrix for the time to remove the engine - Baseline Scenario using P_{22} x 7,24

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Decision	Nodes	Event	Cost		Probability		Flight Hours	Expected Value	Expect Value/FH
D2: Remove after 5 months	Node 3	E221 - In Flight Shut Down	SVC_f	$3,609,638					
			$DSVC_f$	-$39,554					
			LC_f	$500,000					
			CL_f	$372,400					
		Total E221		$4,442,484	p_{221}	0.0342	15,704	$152,105	$9.69
		E222 - On Ground failure	SVCg	$3,109,638					
			DSVCg	-$39,554					
			LCg	$200,000					
			CLg	$266,000					
		Total E222		$3,536,084	p_{222}	0.965761	15,704	$3,415,013	$217.46
		Total Node 3						$3,567,118	$227.15
	Node 2	E22 - In Service failure		$3,567,118	p_{22}	0.174192	15,704	$621,362	$39.57
		E21 - No failure	SVC_5	$3,219,276			16,304		
			DSVC	-$79,108					
		Total E21		$3,140,168	p_{21}	0.825808	16,304	$2,593,177	$159.05
		Total Decision 2						**$3,214,539**	**$198.62**
D1: Remove Now	Node 1	E1	SVC_0	$3,000,000	p_1	1	15,104	$3,000,000	$198.62
		Total Decision 1						**$3,000,000**	**$198.62**
		D1 - D2							**$0.00**

Table 9 - Decision matrix for the time to remove the engine - Pessimistic Scenario using p_{22} x 5.76

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4.1.3. The Decision

Taking into account that the safety assessment and the technical evaluation of the engine condition did not conclude with any constrains on keeping the engine in operation for more 1,200 FH, subject to the prescribed maintenance tasks, including the periodic borescope inspections, the decision was based only on the economical appraisal.

Based on the results of the decision tree evaluation, including the sensitivity analysis about increasing the probability of engine failure, it was decided to keep the engine installed in the aircraft for an additional five months to operate more 1,200 FH; besides the expected reduction on the unit maintenance costs a good incentive was the perspective of delaying for five months an expense in excess of $3 million.

4.1.4. The Engine Behaviour

During the five months of ACMI operation for the contracting airline (the Lessee or carrier airline), with the aircraft based in a foreign country airport, there were several technical problems that did cause delays and, in a few cases, complaints from the customer/contracting airline. None of the technical problems and complaints were related to the engine object of this case study; as a matter of fact, some technical problems were related with the other (low time) engine of the aircraft.

The engine performed as expected, passed the planned borescope inspection and, except for the pilots' reports about the operational parameters and the overall performance, mainly during start and climb, nothing relevant happened with the engine during the five months period of operation, in which more than 1,200 FH were accumulated.

A spread sheet that was prepared for comparing the ECM parameters at the beginning and at the end of the 5 months operation showed some increase in the degradation rate of the ECM parameters; this increase of the degradation rate was even more evident when comparing with the ECM parameters of the other engine installed in the same aircraft.

In the decision process to decide when to remove the engine for SV, the fuel consumption was not taken into consideration, because in the ACMI business the operator airline (the wet Lessor) is not responsible for the fuel cost, which is under the

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responsibility of the carrier airline (the wet Lessee), which is also responsible for the other variable cost, except maintenance.

In the study that was performed it was evaluated the effect on fuel consumption of an engine with high time of operation since last performance restoration SV. The results are illustrated in Figure 6, below, where are represented the fuel consumption of the aircraft with the engine that are being evaluated in this document (Target Aircraft) and another aircraft (Other Aircraft) equipped with low time engines that did performed at the same time very similar routes.

The aircraft with high time engines (Target Aircraft) had an average fuel consumption of 5,514 Kg/FH, 2.7% higher than the Other Aircraft that had a fuel consumption of 5,371 Kg/FH. It was estimated that the high time engine had fuel consumption in excess of 5% more than the other engines.

Taking into account that in 2011 the price of the aviation jet fuel, in most of the airports of the world is higher than $1 per Kg (in Lisbon is about $1.15 per Kg), it becomes evident that the fuel consumption may not be taken a priori as negligible in a decision process to remove an engine for SV, if the overall ownership costs are under consideration.

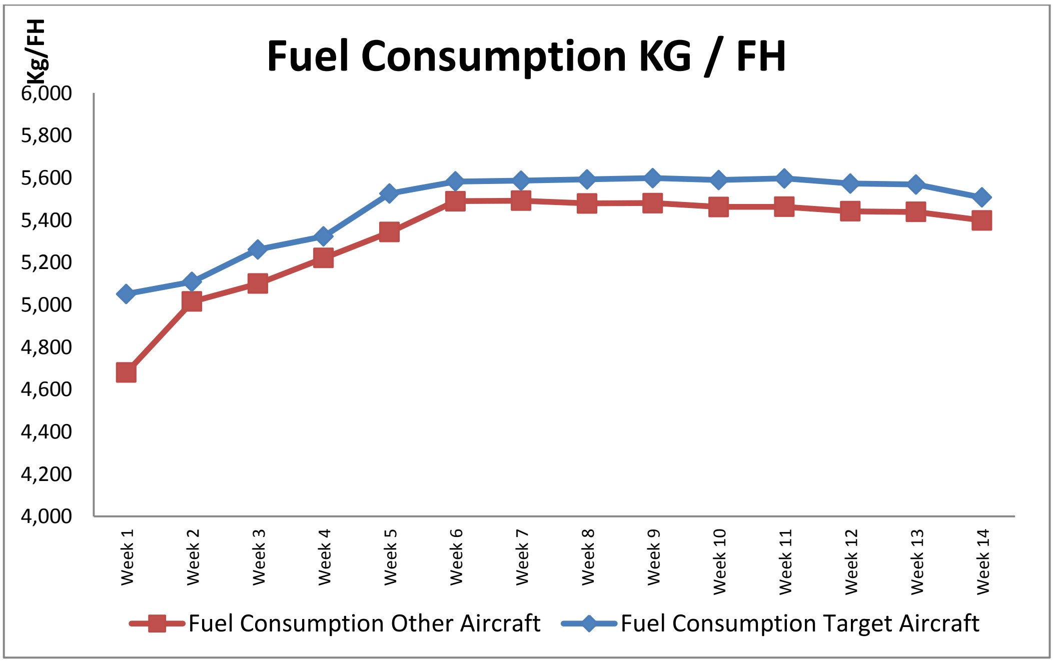

Figure 6 - Fuel Consumption of Target Aircraft (with one high time engine) versus Other Aircraft

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At the end of the ACMI contract, the engine was removed and sent for a shop visit (SV) in the MRO that was selected, from a final pre-selection of four, in a worldwide competition between companies in America, Asia and Europe.

ENGINE DETERIORATION

The progress of the physical status of certain critical areas of the engine, in the so called hot section (combustion chambers and turbines) was observed, by comparing selected images from the films of the engine borescope inspections performed in different occasions. The evaluation and understanding of the deterioration process is interesting, especially in this case of an engine with high time since last refurbishment in a SV.

As examples of the engine deterioration, the images that are presented here were selected from borescope inspections performed on the engine under study on the following dates:

a) 03SEP2010 - the engine accumulated TSN (Time Since New) = 49,680 flight hours, CSN (Cycles Since New) = 9825;
b) 28DEC2010 - TSN = 50,522 flight hours; CSN = 10,069 cycles;
c) 30SEPG2011 – TSN = 52,091; CSN 10316.

In Figure 7 it is shown in the combustion chamber the increase of burn spots and the growth of cracks, between 03SEP2010 and 30SEP2011; the image on the right shows the combustion chamber after the disassembly of the engine in the SV.

Figure 7 - Combustion chamber deterioration after 2411 FH and 491 CYC

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In Figure 8 it is shown the deterioration progress of a first stage blade of the HPT (a T1 blade), between 28DEC2010 and 30AUG2011; in the left side it is presented the blade that was disassembled in the SV. The ceramic coating of the T1 blade shows the deterioration resulting from high time in operation, exposing, in some areas, the parent material directly to hot gas, which increases the blade degradation rate. The T1 blade shown in the picture, which costs about $14,500, passed the preliminary inspection in the SV, so likely it will be repaired and installed again in the engine.

Figure 8 - Deterioration progress in a first stage blade of the HPT

In Figure 8 is shown the deterioration progress in a first stage nose guide vane (NGV) of HPT. It is evident the deterioration of the ceramic coating, there are areas of spalled surface material and it is evident the crack growth between the two borescope inspections. This NGV is the one that was under watch, as mentioned in the last chapter.

Figure 9 - Deterioration progress in first stage NGV of the HPT

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THE SHOP VISIT

In the shop the engine modules were separated, disassembled and a so-called table inspection was performed, where a detailed inspection of all the parts was made. The inspection revealed the normal wear and tear of an engine that had been in operation for more than 16,000 FH and about 3500 cycles since its last performance restoration SV, but nothing abnormal was found.

The HPT's first stage NGV that was a matter of special concern was confirmed to be still within limits, as per the last borescope inspection, and, despite its nasty aspect (Figure 10), it was not classified as scrap, so it was sent for repair and will be installed on the engine again.

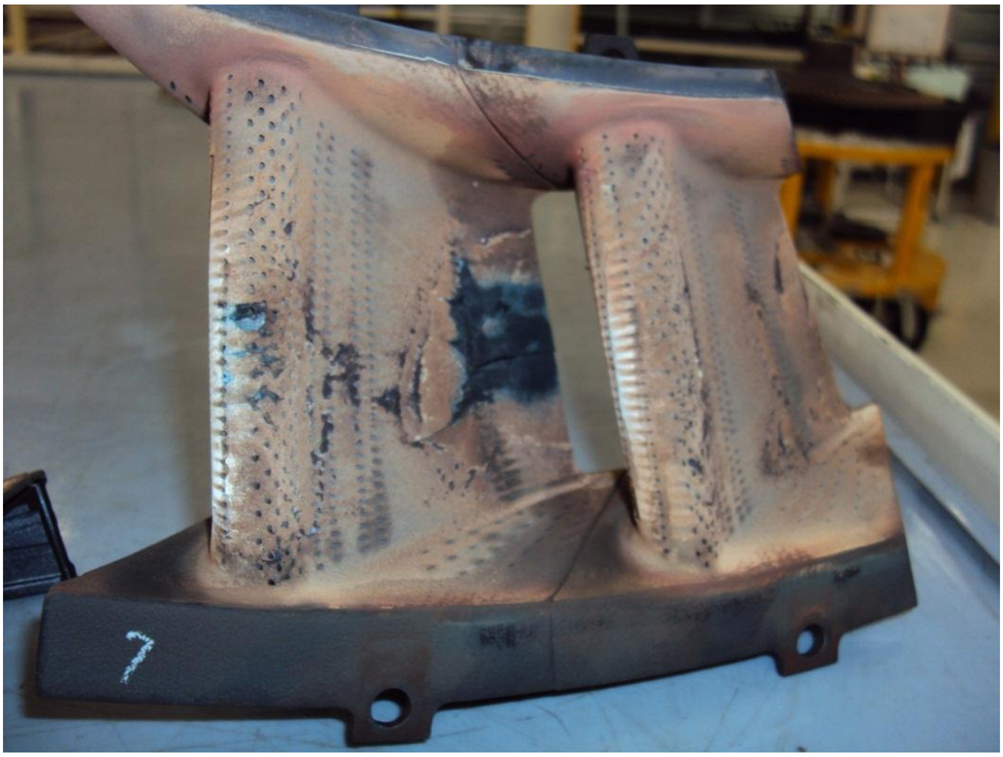

Figure 10 - Table Inspection´s photograph of the damaged HPT´s first stage NGV that was under surveillance

The final cost of the SV was not available at the time of the preparation of this document, but after the engine table inspection there is no indication that the

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assumptions about the cost increase of the SV, resulting from keeping the engine in operation for more approximately 1,200 FH, will be higher than estimated.

Taking the Baseline Scenario as a reference, if the decision taken in this case were to be repeated several times, it would result in an average saving of about US$5 per FH, i.e $80,000 per 16,000 FH of engine run.

In the present case, since no engine failure ocurred, the estimated total cost of the selected option is $3,140,168 for 16,304 FH resulting in a saving of $6/FH and a total saving of $98,179.

4.2. Results of the Questionnaire about the Decision Process to Remove an Engine for Shop Visit

As referred to in chapter 3, it was prepared an on-line questionnaire about the procedures and criteria used by airlines to decide the best time to remove an engine for SV. Engine experts and relevant people for the decision process of airlines, MROs and OEMs were invited to answer the questionnaire.

At the preparation of this document it was collected 18 answers from engine experts, working for relevant organizations in relation to this study. Despite the small size of the sample that is being analysed, Figure 11 and Figure 12 show the variety in size and activity of the organizations that did provide answers and the technical expertise and functional relevance of their staff that did participate:

- Airlines, MROs and OEM;
- Directors, managers and other engine specialists, with high expertise in engine maintenance; about 90% the engineers that did answer the questionnaire participate or did participate in decisions to remove engines for SV.

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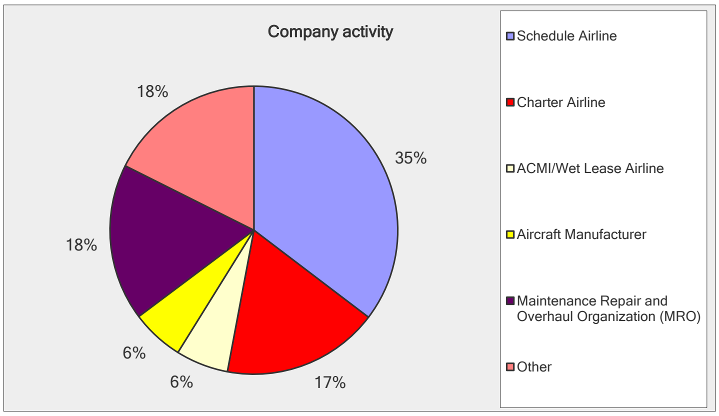

Figure 11 - Activity of the companies that did answer the questionnaire

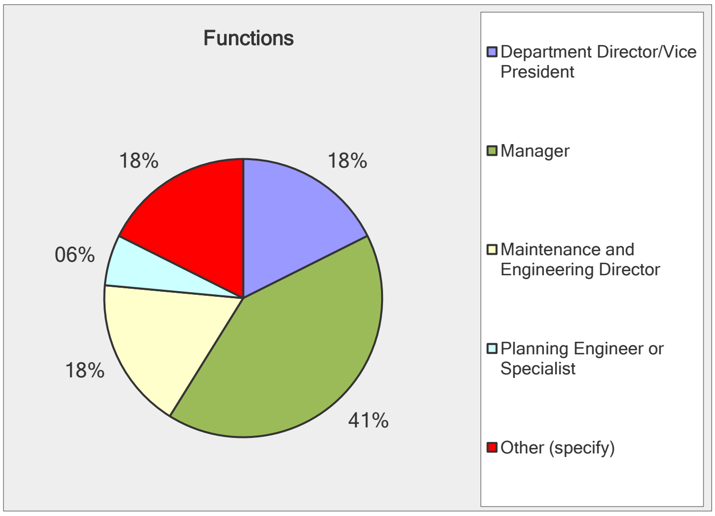

Figure 12 - Functions of the engine experts that did answer the questionnaire

The questionnaire was answered by high and medium rank engine experts from small, medium and large organizations.

Since the sample is small and was essentially obtained by convenience, the results cannot be generalized to all airlines, because there is no guarantee that it represents the universe (Hill & Hill, 2008, p. 50). Despite that weakness, the data and information that was collected is information rich and relevant, taking into account the variety and the expertise of the sources.

The questionnaire was analysed by selecting the relevant answers to understand the decision process to remove an engine for SV, when still operating within manufacturer defined limits, and to evaluate if and how the minimum engine maintenance unit cost is taken into consideration for that purpose.

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The questionnaire was prepared with 3 categories of questions and the answers were classified by the importance given by the engine experts to the related factors or dimensions of each category.

In Table 10 herein below are presented the main conclusions of the questionnaire, organized as follows:

a) In the first column it is described the key question, about the decision process to remove an engine for SV:

i. **Who Takes the Decision** – who and/or in what departments are the decision taken;

ii. **Decision Objective Factors** – what concerns and objectives are addressed to decide when to remove the engine for SV;

iii. **Decision Methods, Procedures and Tools** – what are the procedures, analytic methods and computer or manual tools that are used in the decision process.

b) In the second column are the 3 or 4 factors that got the highest scores from the engine experts;

c) In the third column are listed the factors that did get low scores from the answers of the engine experts, but, *a priori*, appear to be important in the decision process to minimize engine maintenance cost per flight hour or to optimize the decision process in a broad perspective of the engine ownership costs.

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PARTICIPATION	Strong Participation	Low or Null Participation
Who Takes the Decision	1rst Power Plant Engineer 2nd Engineering Manager 3rd Reliability Engineer	CFO/Finance Department Commercial Department Corporate Management

IMPORTANCE	High & Very High	Low
Decision Objective' Factors	1rst - Avoid In-Flight Shutdown 2nd - Maximize Safety 3rd Maximize Time On-Wing 4th - Minimize Engine Maintenance Cost/FH	• Minimize Fuel Cost *Note: Fuel consumption is not part of maintenance cost, but it is strongly correlated with maintenance practises (see Figure 6).*

Weight	High & Very High	Low
Decision Methods, Procedures and Tools	1rst Borescope Inspections 2nd ECM/EHM qualitative Evaluation 3rd ECM/EHM quantitative Evaluation 4th Descriptive rules	• MRO expert opinion • Reliability models • Computer models

Table 10 - Summary of the results of the questionnaire to engine experts

In addition to the score given by the engine experts to the closed questions, some of the participants added relevant comments about the decision process to remove an engine for SV. A summary of the most important comments are presented below.

A well-qualified engine expert from a big organization states clearly that in their decision process to remove an engine for SV they do not aim at minimum maintenance cost per FH. They have a target for engine run time, which is high compared with the industry average, and they keep the engine on the wing as long as possible, sometimes

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well above that target. The main drivers to remove the engine are: i) the results of the borescope inspections; ii) ECM trend monitoring; iii) reliability; iv) spares availability and v) financial and budgeting constrains. They use professional reliability procedures to assist on the decision process.

Another expert opinion does not state that they have not as an objective to minimize engine maintenance unit cost, but considers relevant the same engine removal drivers, as above; he includes an additional removal driver, the availability of slots in a suitable engine maintenance shop.

One expert mentions the importance of staggering the engines of the airline fleet, i. e. the need for planning the operation and the SVs to avoid the risk of having several SVs at same time, which could result in financial difficulties for the airline and shortage of replacement engines.

4.3. Results Consolidation

The case study, the questionnaire send to engine experts and the research that was done on the data of past SV provided valuable information for the understanding and improvement of the decision process to remove an engine for SV.

The case study provided a live situation, a specific information-rich extreme case, because the engine was operating in the critical interval of high time since last SV, with defects under watch and performing a very sensitive commercial operation. The decision process, the commercial operation, the degradation of the ECM parameters, the observation of engine parts deterioration and the comparison of fuel consumption on similar aircraft, all provided relevant information to this project.

The extensive research that was done on the files of past engine SV provided useful information about damage findings, material deterioration, SV costs and areas for improvement in On-Aircraft maintenance. The subject is complex, because it involves many variables, like engine type of operation, workscope of previous SVs, type of repairs and material used in previous SV and detailed information of the ECM parameters and borescope inspections at the time when the engines were removed. More research on the subject is required to assess past decisions about the time that chosen to remove the engine for SV. Despite that fact valuable information was collected for this project and for improvements on On-Aircraft engine maintenance.

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The answers from engine experts to the questionnaire provide information about the air transport industry approach to optimizing engine time on-wing. The opinion and the practices converge in some key factors, but there are also strong differences. About engine time on-wing there is a fundamental difference between two big organizations: i) one aims at keeping the engine on-wing as long as possible; ii) another organization removes the engine at first signs engine degradation that would increase fuel consumption and the cost of the SV.

The results of the case study, the questionnaire and the study of past shop visits are consolidated in the following sections, conclusions and recommendations.

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Chapter 5

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In the case study the decision maker used a certain number of key factors to select the better of the two options about when to remove the engine for SV.

In the answers to the questionnaire about the best time to remove an engine for SV, the engine experts expressed their opinion essentially about the same factors.

In the Table 11 is presented a combination of the results of the case study and the questionnaire. Selected factors are classified as High (H) or Low (L) as per their importance in the case study (CST) and in the answers to the questionnaire (QUE).

Key Questions	Entities/Factors	CST	QUE	Combination
Who Takes the Decision?	Corporate Management	H	L	H/L
	Power Plant Engineer	H	H	H
	Engineering Manager	H	H	H
	Reliability Engineer	L	H	L/H
Decision Objective Factors	Avoid IFSD	H	H	H
	Maximize Safety	L	H	L/H
	Time On-Wing	H	H	H
	Minimize Engine Maintenance Unit Cost	H	H/L	HH/L
	Avoid Unscheduled Removal	H	L	H/L
	Minimize Fuel Cost	L	L	L
	Financial /Budget constraints	H	H/L	HH/L
	Spare Engine Availability	H/L	H/L	H/L
	Engine Staggering	L	L	L
Decision Methods, Procedures and Tools	Borescope Inspection	H	H	H
	ECM/EHM qualitative evaluation	H	H	H
	ECM/EHM quantitative evaluation	H	H	H
	Descriptive rules/procedures	H	H/L	HH/L
	Reliability Calculation (professional)	H	L	H/L
	Decision Tree/Op. Research procedures	H	L	H/L
	Computer Decision Model	L	L	L
	MRO expert opinion	L	L	L
	Manufacturer expert opinion	H	L	H/L

Table 11 - Combination list of the key factors of the Case Study (CST) and of the Questionnaire (QUE)

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In the Table 11 a summary of the main conclusions of the study that is presented in this document. Instead of L or H, some factors were classified as L/H or H/L in the columns “CST” or “QUE”, to state that the importance of the factor is not well defined or is somewhere between L and H. In the “Combination” column is presented the combined result of “CST” and “QUE”.

The decisions about when to remove an engine for SV is normally taken in the engineering department, involving very specialised staff like power plant engineers, reliability engineers and the engineering manager. In airlines that have engine shops it is common that the management of the engine shop participates in the decision process. Despite the fact that an engine SV is very expensive, Finance Directors and senior corporate managers do not participate in the decision process.

Avoid IFSD, maximize safety and maximize time on-wing are the main objectives in the process to decide when to remove an engine for SV. In particular maximize time on-wing looks to be a preferred option of the engineers responsible for engine management, probably due to the following reasons: i) postpones the high expenses of a SV; ii) engine expert may believe that more time on-wing reduces maintenance costs.

In the case study safety was evaluated but was not considered a critical factor, because it was assumed that safety is assured by the strict compliance with the maintenance and operational procedures.

Despite some positive answers, the combination of the answers to different questions leads to the conclusion that, in most of the cases, to minimize the engine maintenance unit cost is not an explicit objective or a factor that is included in the procedure to decide engine time on-wing. There is more concern with financial and budget constraints.

The engine experts consider that the most important source of information to decide when to remove an engine for shop visit comes from the findings of the borescope inspection. This is clearly concluded from the answers to the questionnaire and it was also the main concern during the critical period of operation of the engine of the case study.

The answers to the questionnaire revealed that only a small percentage of the airlines of the sample doesn’t use any established procedure, like a set of rules or an

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analytic or computer decision tool to manage engine time on-wing; it is rare also the use of the statistic inference or prediction theory.

In the opinion of the engine experts that did answer the questionnaire, it would be desirable to use decision tree or other operation research techniques or models in the decision process for optimisation of engine time on-wing.

5.2. Recommendations

To decide when to remove an engine for SV is relevant for cost management and for the financial planning of the airlines because the expenses of a SV may vary from $1 to $10 million.

Based on the results of the research that was done in this project, some recommendations are presented below.

5.2.1. The recommended methodology to decide when to remove an engine for SV

1. For each engine organize and maintain a comprehensive data base that, besides the usual data of dates, hours, cycles, maintenance events, etc. would include:
    a. Historic information
        - Workscope of the past SVs;
        - ECM parameters before the past SVs;
        - Borescope images before the last SVs – relevant dated images with findings, deterioration progress;
        - Work performed in the past SVs including parts replacement history – new parts, repaired parts, types and numbers of repairs done in the past; number of repairs subsequent allowed repairs.
    b. Information about the engine current operation

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- systematic records of select images of the borescope inspections to monitor the material deterioration process in the critical areas of the engine;
- periodic records of the rate of variation of the ECM parameters;
- systematic records of images of engine items on watch, by borescope inspections or other inspections.

c. Establish a target of engine FH and cycles on wing
d. After engine installation on the aircraft do a forecast the cost of the next SV cost and SV cost/FH, based on the historic information of the fleet and of the specific engine
e. Monitor the estimates in c) and d) against the engine behaviour, status and technical condition that are monitored with the information in the data base.
f. Use a statistic model to predict engine reliability based on: i) the industry reliability information provided by the engine manufacturer; ii) airline engine reliability experience; iii) specific engine technical status and condition, based on visual and borescope inspections, ECM parameters, LLPs, ADs.
   The Bayesian reliability theory, using the Weibull as one of the distribution may be appropriate for this purpose – additional research is required to assess the effectiveness of this approach.
g. Combine or compare the results of reliability prediction with the target FH and cycles to evaluate regularly possible deviations and the impact on the estimated SV costs.
h. To decide when to remove an engine for shop visit use a quantitative model like a decision tree, to take the appropriate decision for each specific circumstance.

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5.2.2. The Decision Process

The high cost of SVs justifies that senior staff with corporate financial responsibilities participate in the decision process - even not being engine experts, they may provide important inputs related with the time value of the money and its availability.

The fuel cost should be considered as a factor to decide when to remove an engine for SV – its weight in the decision will depends on the circumstances.

5.2.3. Additional research

It is recommend additional research in the following areas:

- Research on the data of ECM parameters and on the other aircraft flight data monitoring data to improve predictive capability of defects and engine failures.
- Test the viability and evaluate the effectiveness of Bayesian statistics to predict engine reliability, with inputs airline own experience, specific engine condition and manufacturer general reliability data. The research should consider the individual reliability of the main modules of the engine.
- Research on the progress of the deterioration of the most expensive engine parts, as a function of calendar age, FH, cycles, operational environment, derating, work performed in past SVs, (including the condition of the repaired material installed) etc., to improve reliability prediction and the forecast of SV costs.
- Development of a computer based decision tool, using intelligent agents or other methods of artificial intelligence, including the results of the research and the recommended methodology described here above, to assist on the decisions to optimize engine time on-wing.

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