TÉCNICO LISBOA

Flight Data Tools Applied to Engine Health Monitoring

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Resumo

O crescente aumento de competitividade com o aparecimento das companhias aéreas do medio oriente e das companhias low-cost, a crescente preocupação com o impacto ambiental da aviação e a constante necessidade de realizar um operação segura requer cada vez mais uma maior otimização dos recursos por parte das companhias aéreas para que se possam manter sustentáveis. O departamento de Flight Data pode e deve desempenhar um papel importante pois é responsável pela recolha e fornecimento dos dados de operação para todos os outros departamentos da companhia, como o safety, manutenção e operações de voo. É importante que as companhias aéreas possam aferir o estado dos motores da sua frota. As ferramentas desenvolvidas durante a tese fornecem informação de uma forma interativa sobre os parâmetros que melhor representam o estado de degradação do motor, consumos de óleo e outro tipo de estudos estatísticos para um dado período. Foi criada uma base de dados que em conjunto que as rotinas desenvolvidas melhoraram significativamente os processos de processamento de dados e o esforço computacional. Todas as ferramentas foram desenvolvidas com o intuito de melhorar a avaliação da condição do estado motor, acompanhando sua natural degradação e identificando situações de falha de algum componente do motor. É esperado que o melhoramento na capacidade de avaliação do estado dos motores da frota leve a um melhoramento no planeamento e na eficiência da manutenção e consequentemente a uma diminuição dos custos.

Palavras-chave: Flight Data, Engine Condition Monitoring, Parametros de desempenho do motor, Consumo de ó leo.

Abstract

The increased competitiveness generated by the proliferation of low-cost airlines around the world and entry of airline companies of the middle east, the growing concerns regarding the environmental impact of aviation and the need to conduct a safe operation requires an exquisite optimization of resources for any airline company so they can still remain profitable. Flight data departments can and should play an important role as they provide critical information for the operation of many other departments such as maintenance, safety or performance. It is important that airlines are able to assess the condition of any engine of their fleet. The tools developed in the current dissertation can provide, in an interactive way, the plots of engine key performance parameters, oil consumption and some statistic studies over the specified period. It was also design and developed a database that greatly improved the data processing and computational effort. All the tools were developed to enhance the assessment of the engine condition by following its gradual degradation or by detecting some engine part fault. This improvement is expected to lead to an increase maintenance planning efficiency aiming contribute to the overall efficiency of the company and, consequently, an operation cost reduction.

Keywords: Flight Data, Engine Conditon monitoring, Engine Key Performance Parameters, Oil Consumption

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Nomenclature

Greek symbols

δ	Pressure correction factor.
δ_t	Pressure correction factor computed with the total pressure.
σ_p	Variance of parameter p.
θ	Temperature correction factor
θ_t	Temperature correction factor computed with the total temperature.

Roman symbols

N	Number of frames.
P_2	Pressure at inlet.
P_{02}	Total pressure at inlet.
QN	Quality Number.
T_2	Temperature at inlet.
t_a	Period of analysis.
T_{02}	Total air temperature at inlet.
Tol_i	Stability Criteria tolerance for parameter i.
$\overline{x_p}$	Mean value of parameter p.
k	Engine performance parameter.
k_f	Filtered engine performance parameter.
n	Number of samples.
s_p^2	Unbiased sample variance of parameter p.
x	Measured value.

Subscripts

$\triangle$ Parameter delta.

Superscripts

a θ correction exponent.

b δ correction exponent.

' Corrected.

Glossary

Baseline Function modelling the expected behaviour of a given engine under current ambient and thrust conditions.

Basic Conditions Set of boundaries that flight parameters must not violate in order to be eligible for stable frame conditions.

CAS Calculated Air Speed.

Cruise Cruise is the level portion of an aircraft's course where flight is most fuel efficient. It occurs between ascent and descent phases and is usually the majority of a journey.

CSV A comma-separated values (CSV) file stores tabular data (numbers and text) in plain-text form. Plain text means that the file is a sequence of characters, with no data that has to be interpreted as binary numbers. Each data cell is separated from rest by a comma.

ECM Engine Condition Monitoring

EGT Exhaust Gas Temperate.

EPR Engine Pressure Ratio.

FD Flight Data.

FDM Flight Data Monitoring.

FF Fuel Flow.

FOQA Flight Operations Quality Assurance.

HPTACC High Pressure Turbine Active Clearance Control.

HPTCC High Pressure Turbine Clearance Control.

IATA International Air Transport Association.

LPTCC Low Pressure Turbine Clearance Control.

MN Mach Number.

MOQA Maintenance Operations Quality Assurance.

N1 Low-pressure Fan Speed.

N2 High-pressure Fan Speed.

OEM Original Equipment Manufacturer.

outliers In statistics, an outlier is an observation point that is distant from other observations. An outlier may be due to variability in the measurement or it may indicate experimental error. This points are sometimes excluded from the data sets.

overhauled An article can be properly described as "overhauled" if, by using methods, techniques, and practices, the article has been disassembled, cleaned, inspected, repaired as necessary, and reassembled, and it has been tested in accordance with approved standards and technical data or in accordance with current standards and technical data.

P&W Pratt & Whitney.

Parameter Delta The Parameter Delta is a measure of the difference between a recorded parameter at its respective baseline.

QN Quality Number.

R R Statistical Software.

RALT Radio Altitude.

RPM Rotations Per Minute.

SAGEM Défense et Sécurité SAGEM - Groupe Safran.

SQL Structured Query Language.

Stability Criteria Defines the maximum variation allowed for a given parameter within a certain stable frame.

Stability Point Averaged values of key parameters corresponding to a period of stability during Cruise.

Stable Frame Period of time during a flight where all the Basic Conditions and Stability Criteria are met.

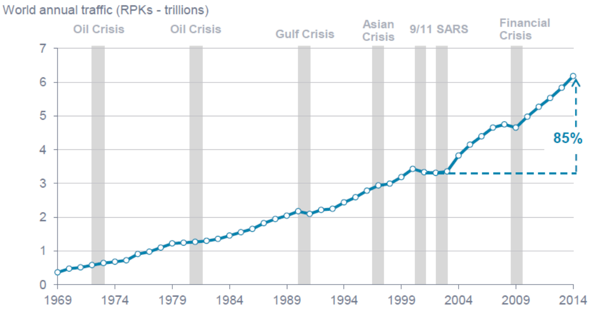
TAP Transportes Aéreos

Chapter 1

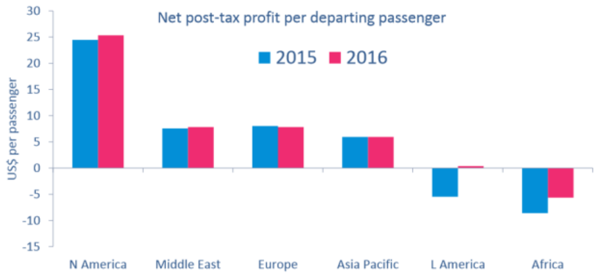
Introduction

1.1 Motivation

The constant growing of the airline industry since its early stages and its resilience to external shocks never changed the fact that the airlines always dealt with small profit margins this is well represented in figure 1.1."On average airlines will still make less than 10$ per passenger carried. The industry's profitability is better described as 'fragile' than 'sustainable'" said Tony Tyler, International Air Transport Association (IATA) Director General and CEO.



(a) World Annual Traffic[1]

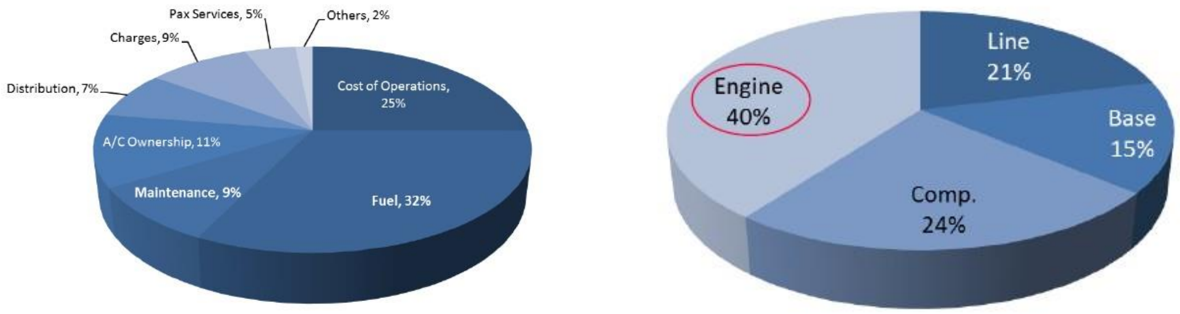


(b) Net post-tax profit per departing passenger[2]

Figure 1.1: Aviation Industry Outlook

According to IATA - Maintenance Cost Task Force (MCTF) recent reports[3] engine maintenance represent up to 40% of the direct maintenance cost (DMC) per year. In order to reduce the cost the industry has moved away from purely schedule maintenance practices and adopt on-condition maintenance. This was achieved by the development of diagnostic and monitoring methods. By continuously monitoring fleet's performance airlines assure that they are running in the most safe and efficient way possible and the appropriate counter measures for fault rectification can be taken at an early stage, increasing the time of the engine on wing. This time increase can be used for planning and determining the overhaul action needed.

In the past decade the business model of the airline companies has changed with the proliferation of low-cost airlines around the world and entry of airline companies of the middle east. Despite the noticeable difference between approach of these two new players, no one can deny that they have very interesting results. Not only this increased competitiveness but also growing concerns regarding the environmental impact of aviation and the need to conduct a safe operation requires an exquisite optimization of resources for any airline company so they can still remain profitable.The industry started by analyzing the total cost of the operation and concluding that even though maintenance is a small percentage of the total cost of an airline it is the one with the highest degree of controllability, Figure 1.2.



(a) Total Airlines Expenses (b) Direct Maintenance Costs by Segment

Figure 1.2: Airlines Expenses[3].

This kind of preventive approach has always been one of TAP Portugal policy[4]. The Flight Data Department (FDM) is responsible to collect the data from each flight and provide reports to Flight Operations Quality Assurance (FOQA) and Maintenance Operation Quality Assurance (MOQA). While FOQA analyse these reports to help standardize crew members procedures and identify undesirable behaviors, MOQA has the objective to identifying problems and failures in aircraft equipment. This straight collaboration leads to a safer and more economic operation.

Flight Data is also collected for subsequent analysis and production of Stable Cruise Reports that are sent to Flight Operations Technical Support department. This data is continuously analyzed in order to get the specific range degradation factor for each aircraft that is required to correctly calculate the operational flight plan for every flight.

The upgrades made in TAP Portugal fleet and ground station's software in the past decade allow the start of a new relation between FDM and TAP Maintenance and Engineering (TAP ME). FDM department is responsible for gathering and processing data from on-wing engine operation and For compiling statistical analysis that provides more comprehensive and accurate information for diagnostic purposes that are responsibility of TAP ME.

1.2 Objectives

The objective of this thesis is to design and develop within Fligth Data Department at TAP Portugal a multidisciplinary program that meet the needs of TAP Maintenance Engineering concerning engine health monitoring, oil consumption analyses and data tracking. This program should be able to monitor engine key performance parameters for different turbofan engine models and manufacturers, provide the total oil consumption and the oil consumption per hour for every flight of TAP Portugal fleet and keep record of any given installation or removal of an engine.

1.3 Thesis Outline

The current document is divided in seven chapters which are organized as follows:

- Chapter 1 states motivation behind the work developed as well as its objectives and an overview of the thesis outline.
- Chapter 2 discuss the general concepts behind turbofan engine, its parts and two of it's main systems: air system and oil system.
- Chapter 3 addresses the deterioration mechanisms that can affect any turbofan engine and introduces the method used to assess engine health.
- Chapter 4 describe some topics for engine condition monitoring and diagnosis, like data gathering, data process and diagnostic procedures.
- Chapter 5 is a description of the tools developed during the thesis project, namely the database, the engine health monitoring tool (Rehm), the oil tool (Roil), and the search tool (Rtracker).
- Chapter 6 presents some test cases and results that demonstrate the utility and potential of the program.
- Chapter 7 states the conclusions of the current thesis as well as suggestions for future improvements.

Chapter 2

Turbofan Engine

Engines are responsible for vital functions of the aircraft. The engine provides not only the thrust that is required for the aircraft to fly but also the pressurized air to feed the pneumatic system that drives the air conditioning system and wing anti-ice system for example. Different types of engines can be used by aircraft but modern airlines use turbofan engines because of their high thrust and appealing fuel efficiency [5].

Figure 2.1: Exemple of a Turbofan Engine: GE90-115B[6]

This chapter introduces and describes some of the systems that allow the engine to fulfil its role on the aircraft. Namely, the core engine that generates the thrust, the valves system which ensures the necessary cooling airflow and pressurized air for the pneumatic system and the oil system that keeps the temperature of the engine compartments and components within limits.

2.1 Air system

The main system of a turbofan engine is the air system. In this section some subsystems that are part of the air system will be addressed, namely, the engine core and valve system[7].

2.1.1 Engine Core

The engine core can be denominated as the propulsion system it comprehends all the engine parts that generates thrust required for the aircraft. Parts and operation of the engine core will be described. The air path for the engine core is well represented in the figure 2.2.

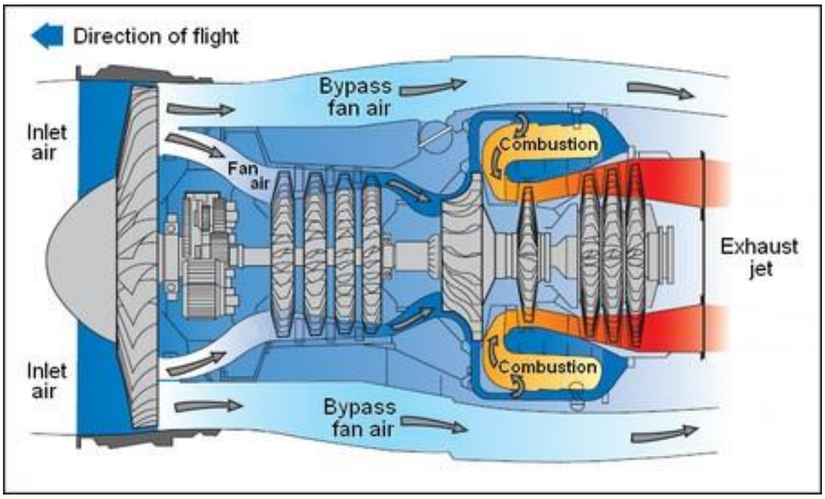


Figure 2.2: Air path on a Turbofan Engine[8]

The incoming air is captured by the engine inlet. Some of the incoming air passes through the fan and continues on into the core compressor and then to the combustion chamber, where it is mixed with fuel and combustion occurs. The hot exhaust mixture passes through the core and fan turbines and then out the nozzle. The rest of the incoming air passes through the fan and bypasses, or goes around the engine.

A turbofan net thrust has two components one from the core and the other from the fan since the air that goes through the fan has a velocity that is slightly increased from free stream. And is given by equation 2.1 [5].

$$T = \dot{m}_e * v_e - \dot{m}_o * v_o + \beta * \dot{m}_c * v_f \tag{2.1}$$

where T represents the thrust, $\dot{m}_e$ the exhaust air flow,$\dot{m}_o$ the fan air flow, v_e the exhaust air velocity,v_f the air fan velocity,v_o inlet air velocity.

The fuel flow rate for the engine core is changed only a small amount by the addition of the fan. a turbofan generates more thrust for nearly the same amount of fuel used by the core. This means that a turbofan is very fuel efficient.

All the engine air goes through the fan to be compressed and divided into two flows: primary flow or fan air and secondary flow or bypass fan air. The ratio between the secondary airflow and the primary flow is called the bypass ratio β and can be obtained using equation 2.2[5].

$$\beta = \frac{\dot{m}_f}{\dot{m}_c} \tag{2.2}$$

where $\dot{m}_c$ represents primary air flow and $\dot{m}_f$ bypass air flow. Lets assume if the BPR is 10:1 then it states that if 1 kg of air is obtained from the engine core then 10 kgs of air is obtained from the Bypass duct.

The total pressure ratio across the engine is referred to as engine pressure ratio EPR which is another important factor for this type of engine[9] and can be calculated using the equation 2.3.

$$EPR = \frac{P_n}{P_c} \tag{2.3}$$

P_c is the pressure at the face of the first stage of the compressor and P_n is the pressure at the nozzle.

Inlet

The inlet sits upstream of the compressor and, while the inlet does no work on the flow, inlet performance has a strong influence on engine net thrust. Inlets can have a variety of shapes and sizes with the specifics usually dictated by the speed of the aircraft. Since all airliners fly under subsonic conditions only subsonic inlets are addressed. For more information about other types on inlet please consult reference [5] and [10]

Figure 2.3: Example of the geometry of a subsonic inlet

For aircraft that cannot go faster than the speed of sound, a simple, straight, short inlet works quite well. On a typical subsonic inlet, the surface of the inlet from outside to inside is a continuous smooth curve with some thickness. The most upstream portion of the inlet is called the highlight, or the inlet lip. A subsonic aircraft has an inlet with a relatively thick lip.

An inlet must operate efficiently over the entire flight envelope of the aircraft. At very low aircraft speeds, or when just sitting on the runway, free stream air is pulled into the engine by the compressor. Inlets are also called intakes, which is a more accurate description of their function at low aircraft speeds. At high speeds, a good inlet will allow the aircraft to maneuver to high angles of attack and sideslip without disrupting flow to the compressor. The inlet is usually designed and tested by the airframe manufacturer because it is so important to overall aircraft operation. Nevertheless, the inlet operation is also important to engine performance so all engine manufacturers do their own tests.

There are several inlet performance indexes, different airframe manufacturers use different indices, but all of the indices are based on ratios of the local variation of pressure to the average pressure at the compressor face. The ratio of the average total pressure at the first compressor stage to the free stream total pressure.

Compressor

As shown in the figure , there are two main types of compressors: axial and centrifugal. In the figure 2.4, the compressor on the right is called an axial compressor because the flow through the compressor travels parallel to the axis of rotation. The compressor on the left is called a centrifugal compressor because the flow through this compressor is turned perpendicular to the axis of rotation.

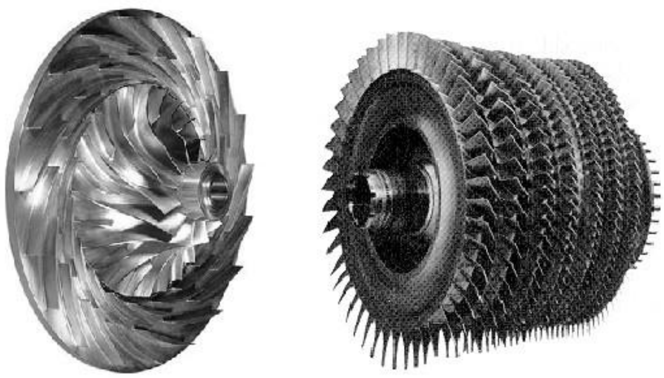


Figure 2.4: Different Types of Compressors adopted from [10]

Centrifugal compressors, which were used in the first jet engines, are still used on small turbojets and turbo shaft engines. Turbofan engines usually use axial compressors. An average, single-stage, centrifugal compressor can increase the pressure by a factor of 4. A similar average, single-stage axial compressor increases the pressure by only a factor of 1.2. But it is relatively easy to link together several stages and produce a multi-stage axial compressor. In the multi-stage compressor, the pressure is multiplied from row to row (8 stages at 1.2 per stage gives a factor of 4.3[10]). It is much more difficult to produce an efficient multi-stage centrifugal compressor because the flow has to be ducted back to the axis at each stage. Because the flow is turned perpendicular to the axis, an engine with a centrifugal compressor tends to be wider, having a greater cross-sectional area than a corresponding axial one. This creates additional undesirable aircraft drag. For these reasons, most high performance, high compression turbine engines use multi staged axial compressors. A centrifugal compressor is much simpler to use if only a moderate amount of compression is required.

In the axial compressor, the air flows parallel to the axis of rotation. The compressor is composed of several rows of air foil cascades. Some of the rows, called rotors, are connected to the central shaft and rotate at high speed. Other rows, called stators, are fixed and do not rotate. The job of the stators is to increase pressure and keep the flow from spiraling around the axis by bringing the flow back parallel to the axis. The overall efficiency of a multi-stage compressor is grater that the one for each stage.

Combustion chamber

The combustion chamber which can also be called burner sits between the last compressor stage and the first turbine. The combustion chamber for a turbofan engine can have three different configurations, figure 2.5.

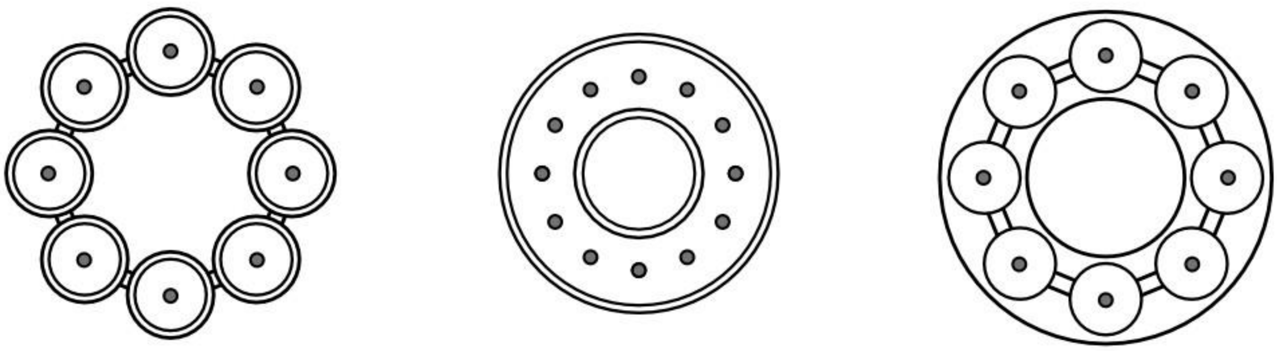


Figure 2.5: Configuration for Combustion Chamber adopted from[5]

- At the left of the figure 2.5 is the ”can” type design. This combustors are self-contained cylindrical combustion chambers. Each ”can” has its own fuel injector, igniter, liner, and casing. Multiple cans are arranged around the central axis of the engine. Can type combustors were most widely used in early gas turbine engines, due to their ease of design and testing (one can test a single can, rather than have to test the whole system) and are easy to maintain because each can can be removed separately rather than the whole combustion section. Most modern gas turbine engines, particularly for aircraft, do not use this design.

- At the center of the figure 2.5 is an annular combustor. The Annular combustors are most commonly used so most combustor research and development focuses on improving this type. There are no separate combustion zones in this design they have a continuous liner and casing in a ring (the annulus). There are many advantages to annular combustors, including more uniform combustion, shorter size (therefore lighter), and less surface area. Additionally, they tend to have very uniform exit temperatures and also have the lowest pressure drop of the three(on the order of 5%)[5][9].

- At the right of the figure 2.5 is the cannular combustor. Cannular combustors have discrete combustion zones contained in separate liners with their own fuel injectors. The combustion zones can also ”communicate” with each other via liner holes or connecting tubes that allow some air to flow circumferentially. The exit flow from the cannular combustor generally has a more uniform temperature profile, which is better for the turbine section. It also eliminates the need for each chamber to have its own igniter. Once the fire is lit in one or two cans, it can easily spread to and ignite the others. This type of combustor is also lighter than the can type, and has a lower pressure drop (on the order of 6%)[5][9].This design the individual cans are more easily designed, tested, and serviced than the annular design[10].

The details of mixing and burning the fuel are quite complex and require extensive testing for a new burner. Most of the time the combustion chamber can be simply considered as simply the place where combustion occurs and where the working fluid (air) temperature is raised with a slight decrease in pressure.

Turbine

All turbofan engines have a power turbine located after the combustion chamber to extract energy from the hot flow and turn the compressor.

The turbine, like the compressor, is composed of several rows of airfoil cascades. Some of the rows, called rotors, are connected to the central shaft and rotate at high speed. Other rows, called stators, are fixed and do not rotate.

Since the turbine extracts energy from the flow, the pressure decreases across the turbine. The pressure gradient helps keep the boundary layer flow attached to the surface of the turbine blades. Since the boundary layer is less likely to separate on a turbine blade than on a compressor blade (because there is no adverse longitudinal pressure gradient), the pressure drop across a single turbine stage can be much greater than the pressure increase across a corresponding compressor stage [11]. A single turbine stage can be used to drive multiple compressor stages.

nozzle

The nozzle performs two important tasks. It is shaped to accelerate the hot exhaust gas to produce thrust and sets the mass flow through the engine. There is nothing relevant to discuss regarding the nozzle, it is a mean to control hot exhaust gas flow.

Figure 2.6: Example of a co-annular nozzle for a Turbofan Engine

Turbofan engines often employ a co-annular nozzle shape. The core flow exits the center nozzle while the fan flow exits the annular nozzle. Mixing of the two flows provides some thrust enhancement and these nozzles also tend to be quieter than convergent nozzles. The nozzle can have a fixed geometry, but variable geometry provides efficient engine operation over a wider airflow range than a simple fixed nozzle.

2.1.2 Valve System

The air system of a turbofan engine serves various functions including providing damping of bearing forces supplying pressurized air for the pneumatic system through valve systems, cooling air for the different parts of the engine and guaranteeing optimal compressor performance during certain engine operating conditions. The air system is controlled by the Full Authority Digital Engine Control (FADEC) through Electronic Engine Control (EEC)[12].

The high pressurized air for the pneumatic system is mostly supplied by the high pressure (HP) compressors to the pneumatic system which then supplies the pressurized air to the wing anti-ice, air conditioning, water tank pressurization and hydraulic reservoir pressurization.The cooling air is supplied by fan air.Figure 2.7 system is a schematic representation of the air system for the CFM56-5B engine.

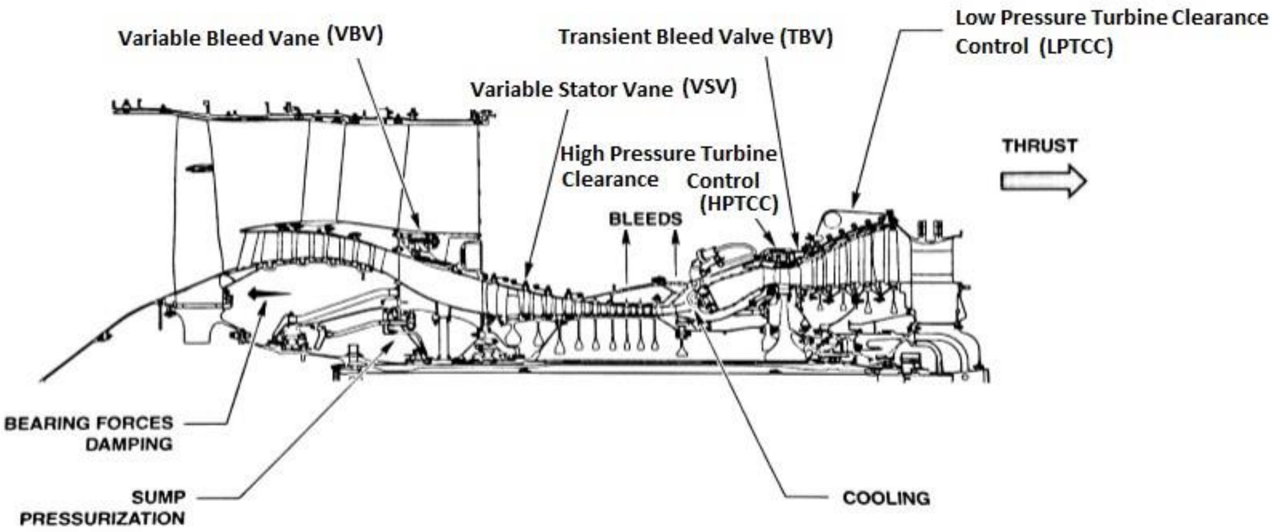


Figure 2.7: Air System for CFM56-5B [12]

The optimum compressor performance is achieved by controlling the primary air flow (the air that goes through the HP compressor) while preventing the compressor surge. Typically, the airflow control is made by a Variable Stator Vane (VSV) system and some bleed systems in the first stages of the HP compressor.

All the low and high pressure turbine areas are cooled during all flight phases, except during cruise, by the turbine vane and blade cooling system which controls the rate of the cooling airflow that is taken from the compressor to the high pressure turbine. The stages from where the air is bled from the primary flow depend on engine model and manufacturer. The nacelle compartment and the turbine case are cooled using the fan air[12].

The valve system bleed air from the primary airflow so it will affect the engine performance. The amount of air withdrawn from the primary flow is directly related to aircraft flight phase and outside atmospheric conditions during the engine operation. To generate the same amount of thrust the engine operating speed will be lower if all the valves are closed which means a increase in efficiency and therefore an enhance in performance (thrust). The effect of the bleed configuration on engine trend performance is discussed in [4] and [13]

The configuration of the engine's valve system can be inferred by the Pack Flow selection parameter [14] which is linked to the amount of high pressured air being drawn from the engine. This information is crucial since now the engine operating regime can be separated according to this parameter. Table 2.1

is an example of the A330 different bleed conditions and the associated pack flow.

Table 2.1: Bleed Logic for an A330-223

Cockpit Switch	AGS variable name	Value	Status
Engine Bleed Push-button Switch	ABLD_PB_POS (Engine 1)	0	OFF
		1	ON
	O_ABLD_PB_POS (Engine 2)	0	OFF
		1	ON
Pack Flow Selection Switch	BLD_MIN_PACK	1	Minimum
	BLD_NOM_PACK	1	Normal
	BLD_MAX_PACK	1	Maximum

2.2 Oil System

”The oil system can be considered the arterial system of an aircraft engine” said Eng. António Soares, Chief of Inspections and Quality of Aircraft for TAP Portugal. Cooling and lubrication is one of the most important aspects of the operation of any engine, especially when the temperatures and the shaft’s rotating speeds are very high.

The oil system and circuits can be different depending on the model or manufacturer. In the CFM56-5B

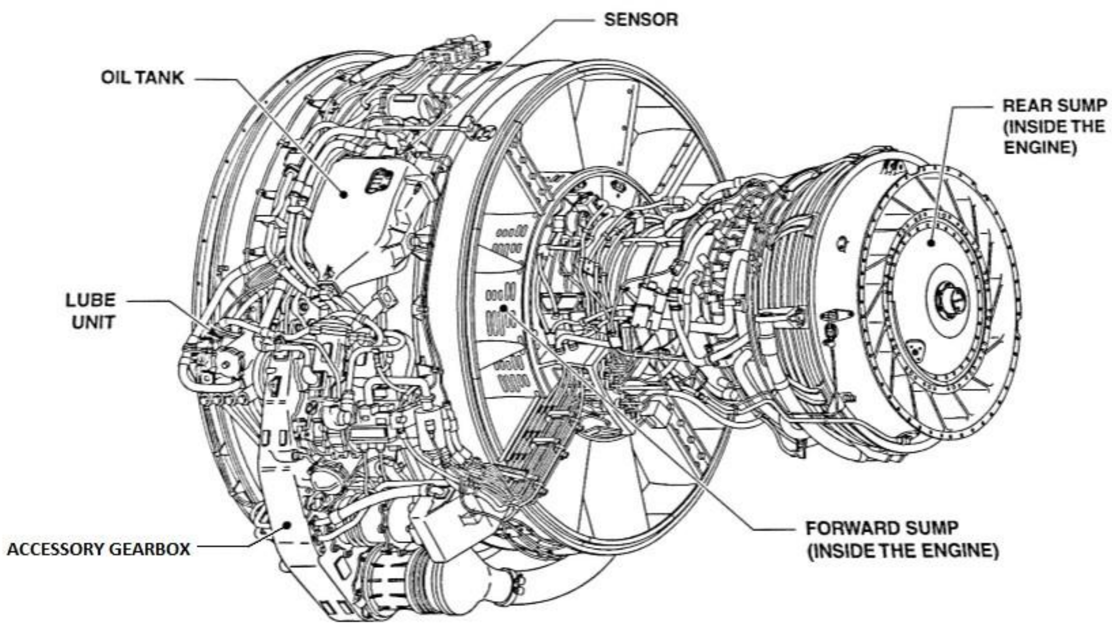


Figure 2.8: Oil System for CFM-5B adapted form [12]

engine, for example, the oil system comprises the temperature sensors, pressure sensors, as well as:

- The supply circuit that provides oil from the tank to the engine pump for lubrication of bearings and gears,

- The scavenge circuit provides the oil return to the tank through the lube unit and heat exchangers.
- The venting circuit ensures sealing of the sumps.

Figure 2.9 shows an example of the on board display of the oil system variables: This display can be accessed through engine page in the Electronic Centralized Aircraft Monitoring (ECAM).

Since the oil goes through a closed circuit an increase in oil temperature or a decrease in oil pressure

Figure 2.9: Oil System Ecam page[15]

can be a precursor of very serious engine faults or leaks in oil system that can lead to engine shut down in flight.

2.3 Conclusion

A turbofan engine is a masterpiece of engineering. The function of the engine in an aircraft is not restricted to generating the thrust required to keep the aircraft moving through the air but also supplying pressurized air for the cabin and other systems. The oil system does not take part in thrust generation but its role be neglected. The oil supplying the engine to support thousands of hours and cycles of operation. The engine performance can depend on the operating of the operating conditions since they dictate the quantity of air bled from the engine primary flow.

Chapter 3

Deterioration and Diagnosis of a Mechanical Condition On a Turbofan Engine

Any engine like every machine exhibits the effect of wear and tear over time, the degradation of one of the engine's parts can lead to a loss of performance or even failure. This chapter will briefly discuss the causes and the deterioration mechanism for some engine parts described in the previous chapter and a technique for assessment of the engine status or change in its condition by measuring and analyzing the trend of the engine's performance parameters without removing the engine from wing.

3.1 Deterioration Mechanisms of Engine Parts

The degradation is natural to these kind of machines where rotation is established in two balanced shafts, each one connected to its respective high-pressure or low-pressure compressor and turbine stages as all the movements of the parts produce erosion, worn bearings and seals and the general degradation of its internal components. Contributing to the degradation are also the thermodynamic cycles applied to the engine along the different modules that build up this machine.

The failure of a turbofan engine can happen mainly in two ways, by degradation or by object ingestion. Damage done to the engine by object ingestion is when foreign objects strike the flow path components. Foreign Object Damage (FOD) is defined as material (ice, birds, etc.) ingested into the engine from outside the engine envelope. Domestic Object Damage (DOD) is defined as objects from any other part of the engine itself [16]. Degradation considers damage done to the engine components by operation throughout time. An important source contributing to degradation is all the chemical and mechanical activity inside the engine. Different agents contribute to corrosion, oxidation, fouling and other contaminations.

3.1.1 Turbines and Compressors Deterioration

For turbines and compressors there are many different deterioration mechanisms[16] such as dirt build-up, fouling, erosion, oxidation, corrosion, foreign object damage, worn bearings, worn seals, excessive blade tip clearances, burned or warped turbine vanes or blades, partially or wholly missing blades or vanes, plugged fuel nozzles, cracked and warped combustion chamber, or a cracked rotor disc or blade.

Figure 3.1: Example of Turbine and Compressor deterioration [16]

All these effects are related to tip clearance increase, changes to air foil shape and surface quality, figure 3.1. The overall consequence being a decrease in turbine and compressor efficiency by reducing the swallowing and pumping capacity, respectively.

Turbines have to endure an environment more hostile than compressors. Sitting just downstream of the combustion chamber, the blades experience flow at high temperatures, requiring that turbine blades are actively cooled and made of special materials that can withstand the heat. With the high pressure change across the turbine the flow tends to leak around the tips of the blades, this phenomenon and the position on the engine of the turbines makes turbines blades more susceptible to deterioration.

3.1.2 Combustion System Deterioration

The combustion system is not likely to be the direct cause for performance deterioration but the chemical activity inside can be harmful for the engine. As hot combustion products pass through the first stage nozzle, they experience a drop in static temperature and some ashes may be deposited on the nozzle blades decreasing the nozzle area, but the combustion efficiency will not, usually decrease, except for severe cases of combustion chamber distress.

However, plugged nozzles failures will always result in distorted exhaust gas temperature (EGT) patterns. This is a result of the swirl effect through the turbine from the combustion chamber to the exhaust gas temperature-measuring plane.

3.2 Diagnosis of a mechanical condition

All the above causes and effects may be considered as faults. Generally speaking, a fault is a condition of a machine linked to a change of the form of its parts and of its way of operation, from what the machine was originally designed for and was achieved during its initial operation[17]. Some of the faults will become evident as vibration increases, by a change in lubrication oil temperature or by distortions in the temperature pattern or temperature profile along the engine. Diagnosis of a mechanical condition is the ability to infer about the condition of parts of the engine, without dismantling the engine or getting direct access to these parts[16].

Diagnostics does not require that the engine is either stopped or disassembled. Information is gathered while the engine is in operation.

3.2.1 Parameter Trend Monitoring

The performance assessment of an engine can be done by measuring and analysing the trend for some of the engine's performance parameters.

Parameter trend monitoring is vastly used by engine manufacturers [16],[18]. It is the process by which the recorded engine data is corrected and then compared to a baseline model of the engine. The difference, over time, between the measured performance and the expected performance based on the engines' baseline is the Parameter Delta. This Parameter Delta can be used to assess engine condition and therefore, in the best case scenario, produce a proper diagnostic.

According to [16], many techniques for inferring engine status or change in engine condition have been proposed and/or applied to various engine configurations with varying success.

Engine Key Performance Parameters

The parameters shown in table 3.1 are used to measure the engine performance and therefore are the most common ones used for engine condition monitoring. They are influenced by ambient conditions like temperature and pressure or even the bleed valve configuration as mentioned in section 2.1.2. Although

Table 3.1: Summary of parameters used in ECM

Parameter	Units
Exhaust gas temperature (EGT)	$^{\circ}C$
Fuel flow (FF)	kg/hr
Low-pressure fan speed (N1)	%
High-pressure rotor speed (N2)	%
Engine Pressure Ratio (EPR)	N/A
EGT Margin (EGTM)	N/A

the relevance of said parameters can change according to engine model and manufacturer[19]. The

EGT margin is the parameter that best represents the engine degradation state[17], it is at its maximum value when the engine is new or has just been overhauled.

Engine Parameters Corrections

In order to establish the possibility of diagnosing engine condition these parameters have to be corrected and the ambient conditions have to be accounted for, the classical parameters corrections described in [20] and [4] will be presented. This reference also states an empiric method that can be used to obtain said corrections.

Formulation

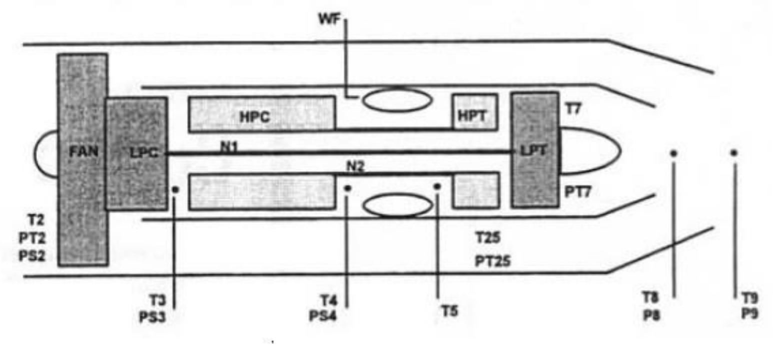


Figure 3.2: Schematic of a turbofan engine Engine [20]

Generally speaking for a given gas path parameter k, the equivalent corrected parameter will be represented by k'. Hence a change in the inlet conditions T_2 and P_2, will imply a change in any downstream gas path parameters k.The corrected parameter k' serves as a constant approximation to a value regardless of changes in inlet conditions, it represents the value that k would have at some fixed inlet condition. One can set the reference conditions freely, however, it is common to select standard day conditions[1]. IIt can be assumed without loss of generality that $k = f(T_2, P_2, k')$ thus following equations 3.1 and 3.2[4].

$$dk = \left(\frac{\partial k}{\partial T_2}\right) dT_2 + \left(\frac{\partial k}{\partial P_2}\right) dP_2 + \left(\frac{\partial k}{\partial k'}\right) dk' \tag{3.1}$$

$$\frac{dk}{k} = \left(\frac{\frac{\partial k}{k}}{\frac{\partial T_2}{T_2}}\right)_{\frac{P_2=const}{k'=const}} \frac{dT_2}{T_2} + \left(\frac{\frac{\partial k}{k}}{\frac{\partial P_2}{P_2}}\right)_{\frac{T_2=const}{k'=const}} \frac{dP_2}{P_2} + \left(\frac{\frac{\partial k}{k}}{\frac{\partial k'}{k'}}\right)_{\frac{P_2=const}{T_2=const}} \frac{dk'}{k'} \tag{3.2}$$

Assuming that the first two partial derivatives are constant (the third clearly is constant and equal to unity) and substituting them for coefficients “a” and “b”, respectively, we can simplify 3.1 and 3.2 as follows:

$$\frac{dk'}{k} \approx a\frac{dT_2}{T_2} + b\frac{dP_2}{P_2} + \frac{dk'}{k'} \tag{3.3}$$

[1] T_0 = 288.15 K, P_0 = 1013.25 hPa

If we now define two dimensionless parameters $\theta = T_2/T_0$ and $\delta = P_2/P_0$ it is possible to deduce an expression for k'.

$$\frac{dk'}{k} \approx a\frac{dT_2}{T_2} + b\frac{dP_2}{P_2} + \frac{dk'}{k'} \tag{3.4}$$

Equation 3.4 is the parameter correction expression in use for the rest of this document. Table 3.2 summarizes some of the common gas turbine parameter corrections and commonly used values for coefficients a and b.

Parameter	**a**	b	Corrected Parameter
Rotor Speed (N)	0.5	0	$N' = \frac{N}{\sqrt{\theta}}$
Fuel Flow (FF)	0.5	1	$FF' = \frac{FF}{\sqrt{\theta}\delta}$
Temperature (T)	1	0	$T' = \frac{T}{\theta}$
Pressure (P)	0	1	$P' = \frac{P}{\delta}$

Table 3.2: Summary of common gas turbine parameter corrections

3.2.2 Baseline Definition

This type of parameter trend monitoring needs a baseline for the engine that replicates the expected performance. Ideally, the engine should be new because it is when its performance is at is peak but is also possible to derive a baseline from data recorded in flight [4]

Since the objective is to have the most efficient engine as a reference, there is a need select the data recorded in flight where this criteria is met. It was already mentioned in section 3.2.1 that the delta EGT parameter is the major indicator of engine performance, and it can be used as a reference to choose the best period of time for baseline calculation. EGT margin is at its maximum after shop visits, best case scenario after the engine has been overhauled, and will decrease with each flight cycle, as seen in Figure 3.3

As mentioned previously the influence of the engine bleed status in engine performance can not be neglected. The pack flow selection is the parameter that characterizes the engine bleed configuration. Given this, different pack flow values it should have different associated baselines.

3.2.3 Delta Definition

The process of Trend Monitoring, implies the calculation of the parameter's Deltas. Trend Analysis corresponds to the evolution over time of the parameter's Deltas calculated from the difference between the corrected data extracted from the model. Figure 3.4 exemplifies how the calculation is done.

Depending on the parameter being analyzed, its delta can be expressed in the same units as the parameter or as a dimensionless ratio as seen in the following equations.

$$EGT(t) = EGT_{Stab.Point}(t) - EGT_{Baseline}(t)[^{\circ}C] \tag{3.5}$$

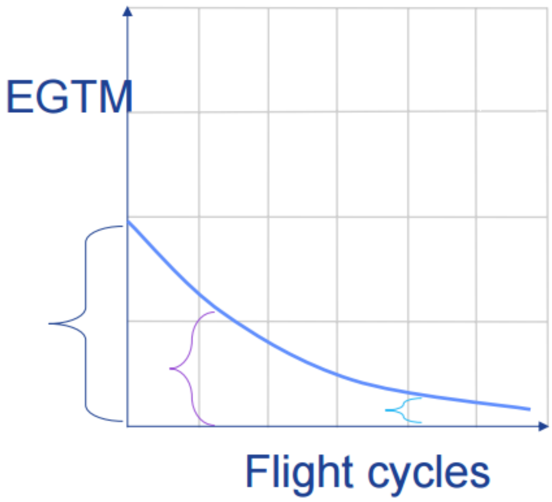


Figure 3.3: EGT Margin Decay [21]

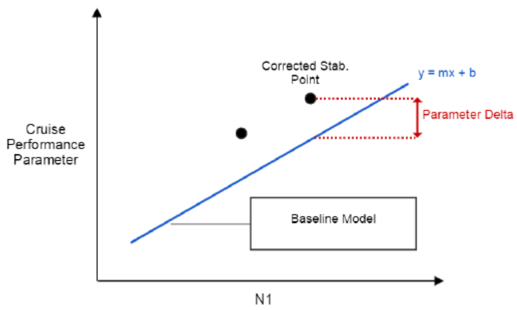


Figure 3.4: Schematic for engine performance parameter's Delta calculation [4].

$$\text{D } FF(t) = \frac{FF_{Stab.Point}(t) - FF_{Baseline}(t)}{FF_{Baseline}(t)} \tag{3.6}$$

$$\text{D } N2(t) = \frac{N2_{Stab.Point}(t) - N2_{Baseline}(t)}{N2_{Baseline}(t)} \tag{3.7}$$

3.2.4 Assessment of a mechanical condition

Parameter trend analysis rely on graphical interpretation of the trend of delta parameters in other to assess the condition of the engine. Some anomalies produce similar sudden shifts every time they manifest. This shifts, denominated by anomaly's fingerprints, are identified by the engine OEM and each engineś OEM supplies a document containing a register of the fingerprints of the most common anomalies. Figure shows an example of a fingerprint sheet for the a PW engine. Identifying the source, after the problem is detected, is a very hard task but when it can be done results in a direct reduction of time and cost because the appropriate maintenance actions can be taken more quickly and efficiently.

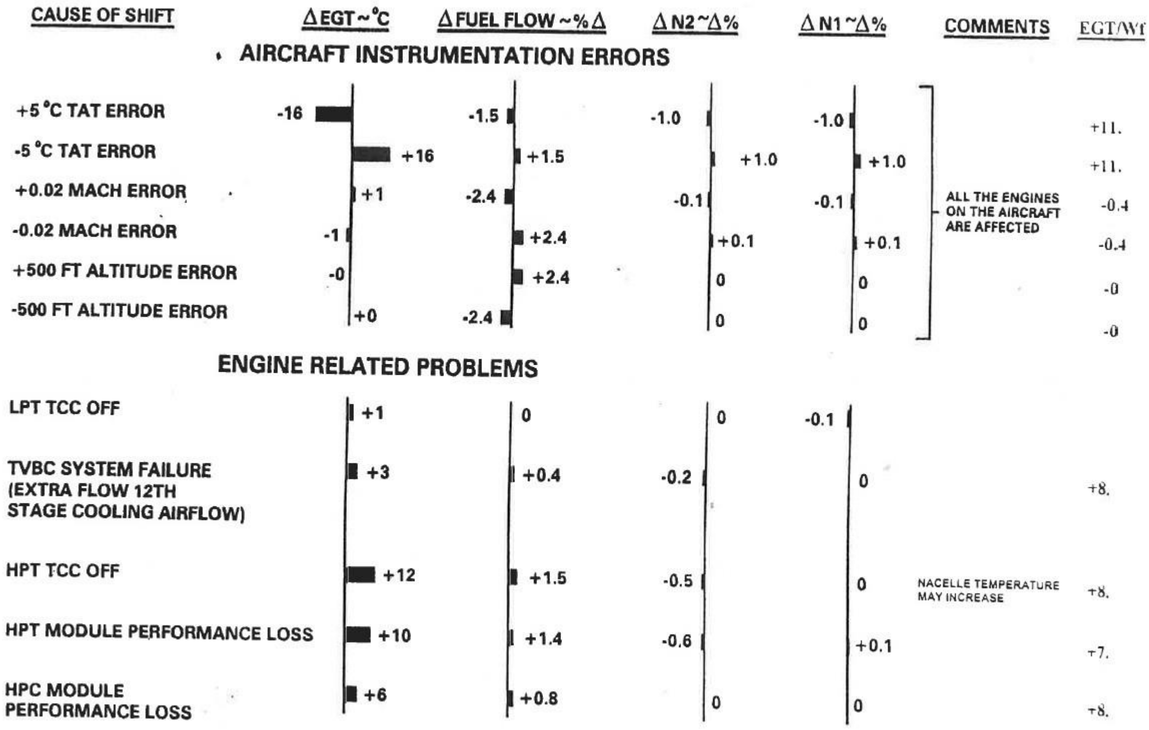


Figure 3.5: Typical PW4164/68 observed parameter shifts [4].

3.3 Conclusion

Engine performance is affected by the accumulation of cycles and external factors. For the engine to operate in the most efficient and safer way the use of techniques for assessment of the engine status or change in its conditions is required. This can be done by measuring and analyzing the trend of the engine's performance parameters.

Chapter 4

Engine Condition Monitoring and Diagnosis

Engine maintenance planning can be made more efficient by applying the method of diagnosis called Engine Conditions Monitoring which will be further discussed during this chapter. The performance of the fleet is one of the major concerns of any airline and it is intrinsically associated to the condition of its engines. There is no downside for a good performance engine, it is directly linked to lower fuel consumptions and lower emission of CO2, in general it is equivalent to financial benefits for the operator. An Engine Condition Monitoring and Diagnosis (ECMD) process will infer engine status or change in its condition while the engine is still in operation.

Many diagnostic methods are proposed and revised in [22] and [23] many variants of diagnosis with different features and complexity have been developed and reported in the open literature. Extensive reviews of existing methods provided by [16] All approaches consist in at least three stages:

- Measured data,
- A data processing model relating measured data with health parameters,
- diagnostic decision making procedure.

Accordingly the proposed methods are classified on the basis of the kind of the comprising elements as:

- Steady state or Transient,
- Physical or Mathematical,
- Conventional or Artificial intelligence method.

The tool developed, subject of the current thesis, is based on a steady-state with a mathematical approach with a convention decision making procedure for diagnostic proposes. This chapter will address said topics.

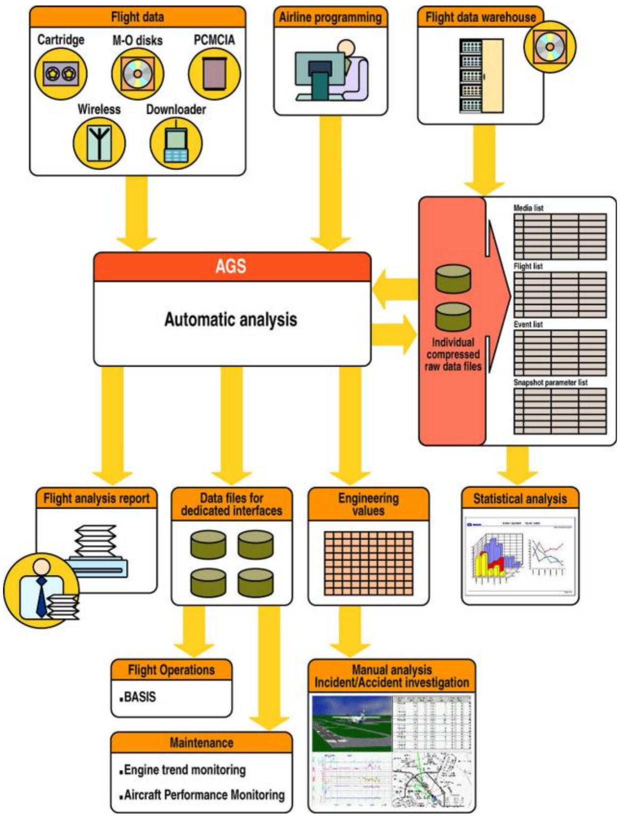
4.1 Data Acquisition

There are different approaches for engine health assessment, but they all should be based on data collected in-flight to make full use of engine condition monitoring (ECM) [17]. With the evolution of technology, modern commercial aircraft are equipped with systems able to automatically record data for monitoring purposes and are also able to store a larger number of parameters. Furthermore, a new set of parameters can be obtained through the use of more complex sensors that can even, for instance, measure inter-stage temperatures and pressures from the gas turbines.

Data retrieval is a key point for aircraft performance monitoring. The quality and the quantity of records will govern the reliability of performance monitoring to a great extent. There are typically two ways of retrieving data from an aircraft. The first one, consists of manually recording in-flight data, and the second one is based on an automatic recording of the data from the Flight Data Recorder (FDR) on board the aircraft.

The process and benefits behind the use of the FDR are extensively explained in [4]. For this study, the on-wing operation data used came from Digital AIDS (Aircraft Integrated Data System) Recorder. The data collected is then fed to Analysis Ground Station (AGS), figure 4.1 a tool developed with SAGEM which main function is to perform monitoring of flight data. Is through AGS that the FD department at TAP Portugal provide the reports for the other departments. AGS allows the export of the three distinct

Figure 4.1: AGS workstation [14]



formats. The CSV format was chosen which allows the the use of in-built functions of the R Statistical Software (R) for data processing. The function of data export from AGS has other features. The set and rate of recording parameters exported is customizable by the user.

4.2 Gas Path Analysis

The modelling of an engine is an essential part for ECM. Gas path analysis is one method to process measurement data. A computer engine model will reproduce the values of any thermodynamic quantity measured along the engine gas path, shown in chapter 2, since all the components follow predictable thermodynamic laws. Therefore, each component will behave in a predictable manner when operating under a given set of conditions.

By viewing the engine as system and defining an operation point it is possible to know the condition of the engine. This procedure is useful for diagnosing changes in component performance which may be linked to degradation.

4.2.1 Mathematical Model

Several approaches can be used for monitoring engine performance. The linear approximation or classical methods has proven to be successful for practical purposes and existing commercial systems [24] and [25], are based on it. It is also the method used for the ECM tool developed.

The classical approach is based on delta parameter calculation. The difference between the value of a parameter and the expected, reference, at a given engine point of operation is called Delta. For a turbofan engine the parameters used to perform health engine monitoring were already stated in chapter 2.

4.2.2 Operating Point

The operating point defines the state of operation of the engine for which the trend study will be conducted and it's defined by a set of variables. These variables are not only the key performance engine parameters but other parameters that help characterize the attitude of the aircraft.

Effort demanded from the engine varied throughout the flight. While the most demanding phase for an engine is the take-off, where sometimes there is a need to use the full throttle, the engine is at its design point when the aircraft is in cruise. This means that different stages of operation are associated with different thrust conditions and, consequently, different flight phases.

The FLIGHT PHASE parameter, available through AGS, is an easy way to identify the different flight phases and, consequently, different operating conditions[14]. With this in mind we can choose which flight phase might be better to conduct the studies.

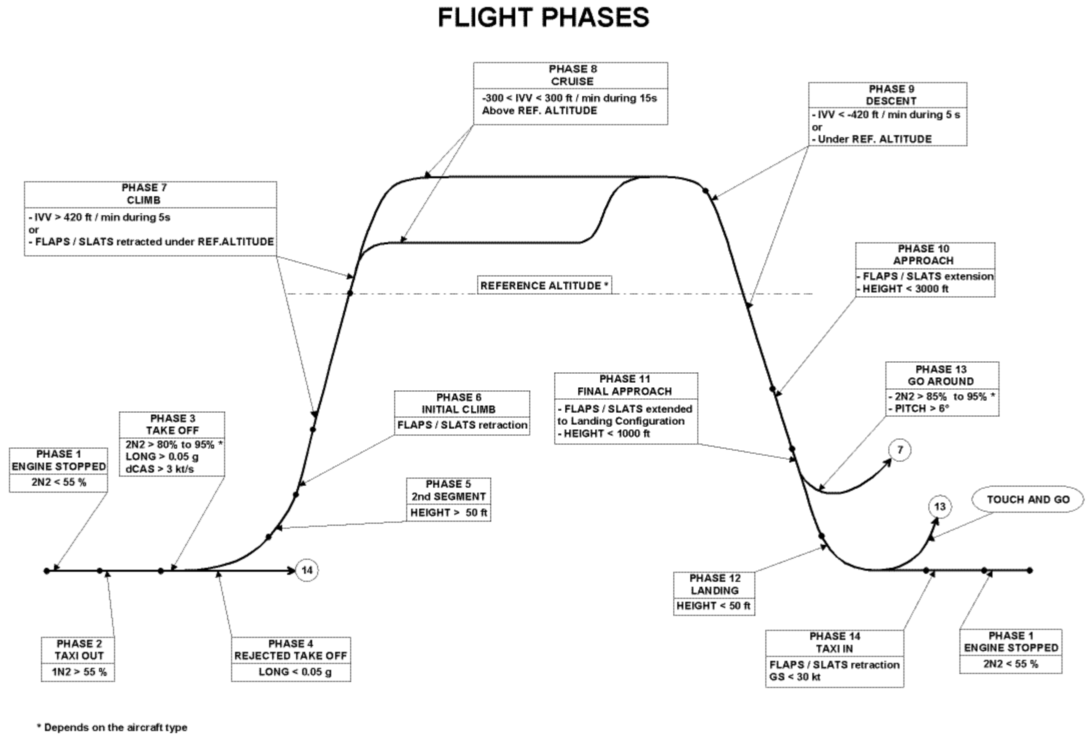


Figure 4.2: Sagem Flight Phases Identification[14]

Cruise Analysis

The trend analyses performed focus on cruise data. There are several reasons behind this decision. The data set available in cruise studies is significantly more populated than the corresponding Take-off one. During Take-off, the performance is not at steady-state conditions, as discussed in reference [26], while cruise operation is closer to quasi-steady state conditions. This is expected to be the case when large variations in ambient absolute humidity are expected, as for example when engines operate in different climate regions. On the other hand for altitudes above 6000m absolute humidity is negligible, according to ref [27]. In this context, the lack of humidity measurements is expected to add uncertainty only to the T/O data. During on-wing operation, relative humidity is not an available measurement. As discussed in Ref. [28], humidity effects may degrade the diagnostic information.

As in ref [29] it is mentioned that it is possible to identify stable cruise periods and stability points that are used to generate the ECM reports available in the ECAM on the ECM reports available in the ecam. These stability points are, in fact, the operating points for which the condition study of the engine will be provided The stability point, by definition, guarantees that the aircraft, and therefore the engine, is in ”steady-state condition”.

In order to ”calculate” a stability point some conditions need to be met during a certain period of time, usually set between 100 to 120 seconds, and the average of the values in that period is called a Stability Point. The set of conditions used to search for stable frames can be clustered in two groups:

- Basic conditions are associated with the aircraft attitude and bleed configuration,

Table 4.1: Basic Conditions Airbus A330-223

Logic Condition	**Parameters Values**
Nacelle Anti Ice Status Off	FNAI = 1
Wing Anti Ice Status Closed	WAO = 1, WAI = 1
20000ft < Altitude < 41100ft	20000ft < ALT_STD < 41100ft
0.6 < Mach Number < 0.96	0.6 < MACHR1 < 0.96
70 < Low-pressure Fan Speed < 120	70 < N1 < 120
Symmetrical Engine Bleed	EG_PRV_POS = O_ENGPRV_POS EG_HPV_POS = O_ENGHPV_POS
Cross Feed Valve Closed	XBV_POS2 = 0 Hz
APU Bleed Valve Closed	APUBV_O = 0

- Stability criteria are associated with the engine

Table 4.2: Stability Criteria Airbus A330-223

Parameter	**Description**	**Stab. Criteria**	**Recording Frequency**
IALT	Inertial Altitude	100 ft	1 Hz
GS	Ground Speed	5 kt	1 Hz
ROLL	Roll Angle	0.8°	2 Hz
TAT	Total Air Temperature	1.1°C	1 Hz
N2	High Press. Rotor Speed	1%	1 Hz
EGT	Engine Gas Temp.	22°C	1 Hz
GVRTI	Vertical Acceleration	0.05 G	8 Hz
MACHR	Mach Number	0.008	1 Hz
N1	Low Press. Fan Speed	1.8%	1 Hz
PT2	Inlet Pressure	0.05 PSIA	1 Hz
FF	Fuel Flow	200 kg/h	1 Hz
EPR	Engine Pressure Ratio	0.05	1 Hz
HPT	Selected HPTC Pos.	5%	1 Hz
LPT	Selected LPTC Pos.	5%	1 Hz

These criteria refer to the difference (or ratio depending on the parameter) between the maximum and minimum value recorded during the 100 second frame. Table 4.2 and Table 4.1 summarize the Stability Criteria and Basic Conditions currently in use in the A330-223. The basic condition parameters can be different depending on the type of aircraft as for example, the period in cruise for a low-range aircraft is different from a long-range. The stability criteria can be different depending on engine manufacturer and model.

The engines installed on an aircraft must be of the same manufacturer but the same aircraft model can be equipped by all the different manufacturers which is the case for A330 TAP fleet equipped with PW, RR and CFM engines. So for this case the same basic conditions are applied but the stability criteria can be different of those present in table 4.2

Parameter Filtering

No signal acquisition is free from noise and the aircraft's on-board systems are no exception. This implies outliers appear mixed with useful data and may be the cause of discarding an otherwise good frame. This effect is mitigated by a filtering process of the parameter readings before being integrated in the calculations for the stable frames search. Equation 4.1 is used to filter these readings[4].

$$k_{f}(n) = k(n-1) + \frac{t}{T}(k(n) - k(n-1)) \tag{4.1}$$

In the above equation $k(n)$ denotes the value of a given parameter k in the instant n and $k_{f}(n)$ its filtered value. The division t/T is a time constant defined by the manufacturer that is dependent on the sampling rate of each parameter. For the rest of this document the time constant T will be equal to $3/8$ and t will correspond to the sampling frequency of the parameter to filter.

4.3 Oil consumption analyses

The importance of the oil system in the normal function of the engine was already stated in chapter 2. It can be used as another variable to evaluate the engine performance. The oil consumption of an engine is also used to set the price when there is a need for renting or leasing an engine by an airline which are very common methods used by the operators when there is an unexpected shop visit or the need to monetize engines in hangar.

Typically, the oil quantity in the tank is made by an optical reading by the in-line technician with the aircraft on the ground before flight. The reading is made when there is no oil in the circuit and, therefore, all the oil is in the tank.
At TAP Portugal the process for reading the oil consumption is in charge of TAP Maintenance and Engineering and has a lot of room for improvement. The process consists of three steps:

- Optical reading of the oil quantity in the aircraft tank,
- If the quantity of oil in the tank is not between limits operating limits the line maintenance technician will fill the tank with the necessary quantity of oil. The oil is always delivered in one litre cans that can not necessarily match the quantity to fill the tank.
- The quantity of cans is posted on the informatics system.

Once the available field to post this information in the current software, is an integer it can only be posted a determined number of cans. The following situation can occur:

- The necessary oil quantity matches the number of cans posted in the software,
- The necessary oil quantity is less than the number of cans posted in the software,
- The necessary oil quantity is higher than the number of cans posted in the software,

Regarding the last two situations the oil consumption value provided by software is inaccurate since the value used for the oil consumption analysis does not match the reality. As an example, if it is necessary to fill the tank with one and a half litre, the posted value could be one or two cans which in any case would not be correct.

With the purpose of improving all the processes behind the oil consumption analyses, the Oil Tool, described further in this document, was developed in collaboration with TAP ME. This tool solved the inability to accurately estimate oil consumption, since now instead of counting cans of oil consumed the program generates statistics based on data recorded from the engine itself.

4.4 Diagnosis

In the past few years machine learning techniques have been used to produce a proper diagnosis and attempt to identify the origin of the engine flaw or loss of performance. The developed ECM tool still relies on the graphical interpretation of the results obtained. In this case the experience of the power plant engineering team is quite useful, since a more experienced engineer should be able to provide a more accurate interpretation of the data. An example from a output of a ECM analysis is presented in the figure 4.3.

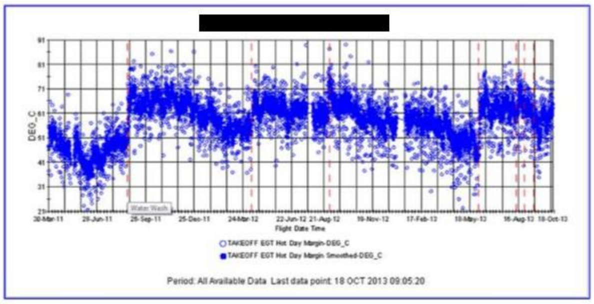


Figure 4.3: Plot from GE's analysis software adopted from [4]

4.5 Conclusion

Engine condition monitoring and diagnosis program can be classified by approach. Every method has its own limitations and advantages. Recognizing the limitation of your model is, in this case, more important because it is not only possible to adapt the method in use to surpass some of its intrinsic limitations but it also assists in avoiding wrong diagnostics or conclusions. Data gathering and processing is the most challenging topic in engine condition monitoring since inaccurate or untrustworthy data do not lead to a proper diagnostic. The tools developed have computer-controlled data-acquisition systems that permit on-line data acquisition and processing.

Chapter 5

Flight Tools Development

This chapter regards the development of flightRtools subject of the current thesis, figure 5.1. The main goal of the present master thesis is to develop a set of tools aiming to improve synergies inside the company with the creation of web-based applications. Some details about the software architecture will be discussed as well as the algorithms and database created.

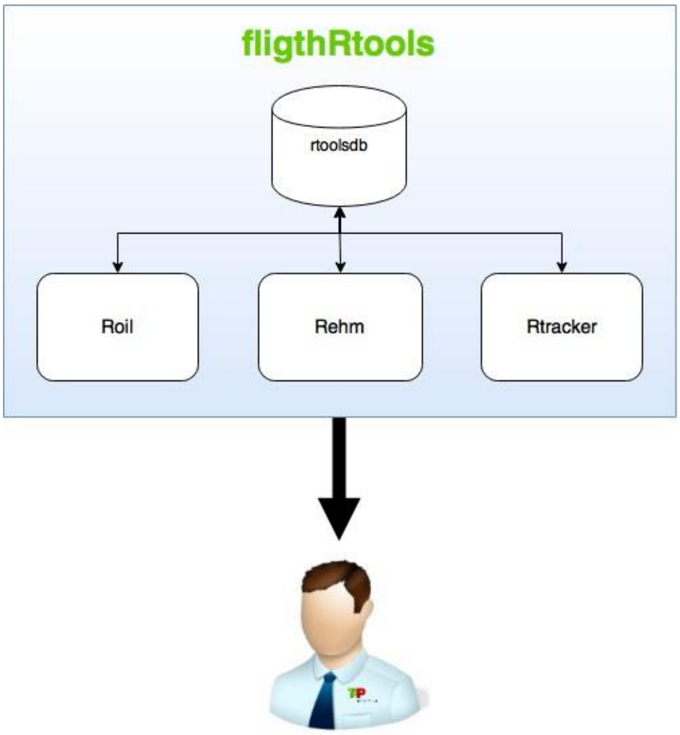


Figure 5.1: fligthRtools diagram

The tool can provide, in an interactive way, the plots of the delta parameter, oil consumption and some statistic studies over the specified period. Another feature of the program is the search option which allow searches to be made by aircraft, engine serial number or date. This was proven to be a major improvement over the available software. The login module added confidentiality to the data, a very serious matter to all airlines.

5.1 Database Set- up

By definition a database is a collection of data that is organized so that it can be easily accessed, managed and update. In order to storage all the data, collected and processed, used for all the tools, a relational database was designed. The structure of the database was modified several times along the development process with the purpose of creating the most flexible and generic program. This section will state the source of the data, the current structure of the database, the relations between the tables, and how the database is kept up to date.

5.1.1 Database Structure and Data

Currently the database comprises twelve tables, figure 5.2 Its easily noticed that this structure relies on four tables, the core of the database, since all tools, in a way or another, depend on information storage in them.

After the structure is established, it's necessary to populate the tables and update when necessary. It's

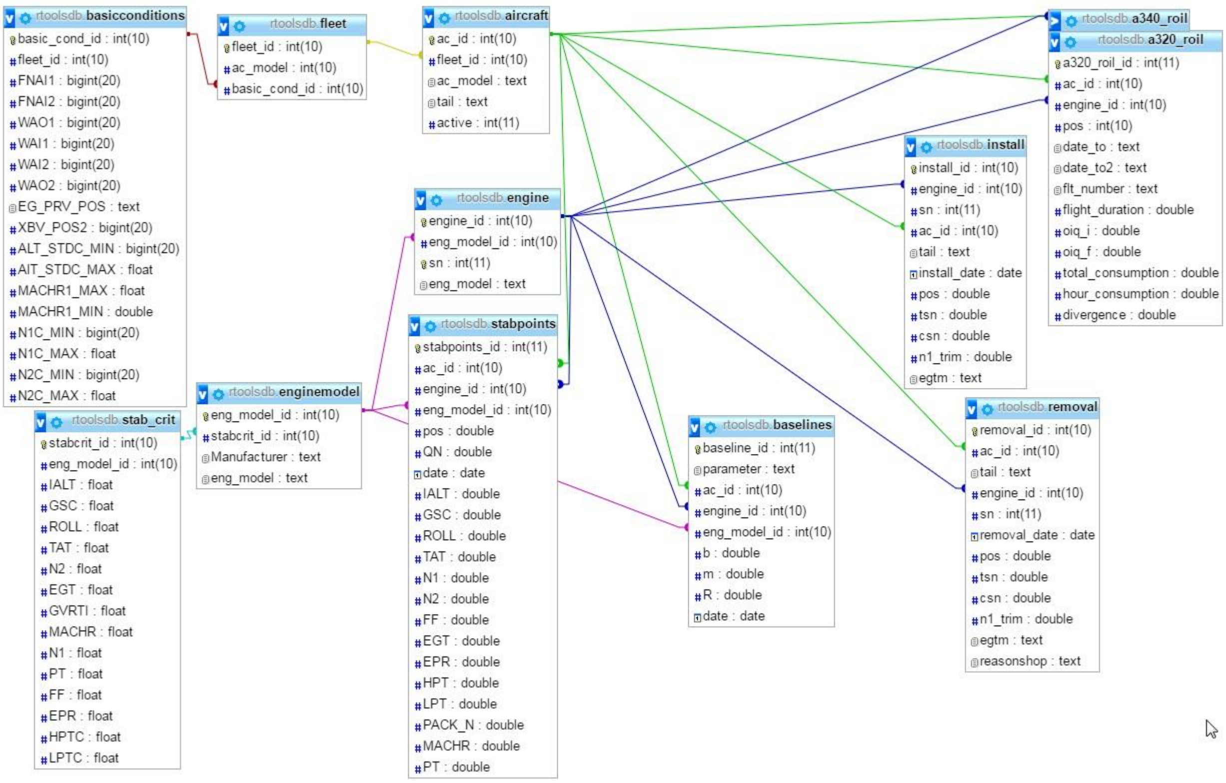


Figure 5.2: Database Structure and Relations

important to state the significance of the update process in any database, and this database is no exception. All the information that is presented to the final user, in this case a power plant engineer, is based on the database. Inconsistency in the results obtained may occur if there are any changes in the source of the data and an update routine is not started. The update routines also avoid the redundancy in the data which can lead to a much higher computational time spent when trying to access the database.

Some data of the database is provided by TAP Portugal ME via XLSX file. Those files are loaded into R Statics environment which will read and reorganize the data and, finally load and store the information on the database. The other sources are the R scripts that were created for the developed tools, described further in this chapter. Every time there is a modification on said XLSX files, a routine is launched to update the database.

5.1.2 Database Considerations

The structure and the relations of the database were already mentioned. In the figure 5.2 are displayed the table names and how many entries each table have.

Tabela	Registos	Tipo	Tamanho	Suspenso
a320_roil	87,822	InnoDB	15.5 MB	-
a340_roil	8,788	InnoDB	1.9 MB	-
aircraft	79	InnoDB	32 KB	-
baselines	30	InnoDB	80 KB	-
basicconditions	1	InnoDB	16 KB	-
engine	235	InnoDB	48 KB	-
enginemodel	37	InnoDB	48 KB	-
fleet	6	InnoDB	64 KB	-
install	477	InnoDB	112 KB	-
removal	458	InnoDB	128 KB	-
stabpoints	~889,733	InnoDB	245.8 MB	-
stab_crit	1	InnoDB	16 KB	-
12 tabelas	987,667	InnoDB	263.8 MB	0 Bytes

Figure 5.3: Rtools Database

Since the tables names are very suggestive is not difficult to deduce what is the subject of the data storage in any of the tables. The tables aircraft, engine, enginemodel, fleet, install and removal have the data of the XLSX provided by TAP ME and are the core of the data base since all the tools depends on the data storage and relation between in them. The a320_roil and A340_roil have the data that is specific for Roil tool while baselines, stabpoints, stab crit and basiccondition have the data for the Rehm tool. The install and removal tables and can be consulted via RTracter tool.

5.2 Rehm Tool

This tool was initially developed to monitor engine health parameters such has EGT FF, N2 of the TAP A330 fleet equipped with PW4168 engine [4]. This section will focus on the algorithm created to process the data and its interactions with the database. The EHM tool developed is much more complex. This tool is now capable of performing trend analyses for any aircraft-engine pair of an airline fleet. Its structure is represented in the figure 5.4. The Rehm Tool has a CSV file provided by AGS. The parameters that are exported for this tool are presented in the appendix A. One CSV file will represent one flight

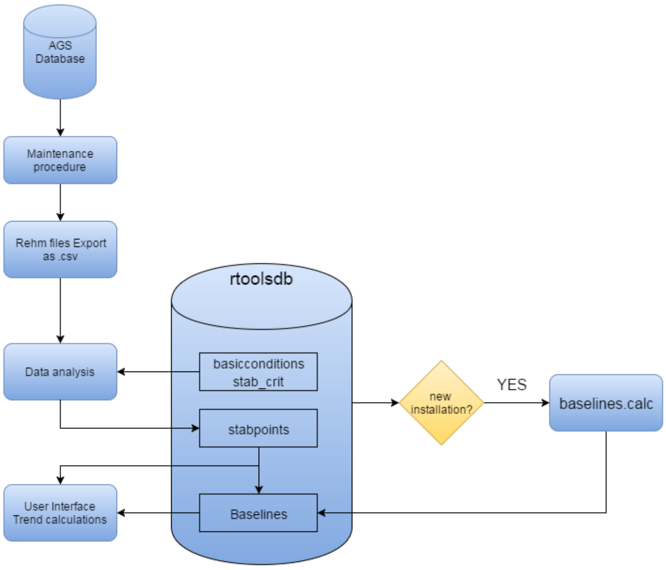


Figure 5.4: Rehm Structure

performed.

5.2.1 Rehm Data Processing

Data processing is one of the most challenging topics in EHM. There is a considerable amount of data that needs to be filtered and stored so as to have enough information to draw any conclusion.
The objective is to be able to process every flight of an airline on a daily basis. Let's assume that an airline company, on average, has 300 flights each day, the algorithm must be able to process the data of those flights on the same day. This way the information available is always up to date and allows the detection of abnormal parameter shifts with a minimum delay which leads to a much more efficient resolution.

All the data processing is made using built-in function of R Statistics. The architecture of the R script created to calculate is present in the diagram bellow. The CSV file is loaded to R environment. Only the parameters necessary for the EHM studies are loaded, appendix A. This detail is very important, with this AGS isn't mandatory to have a specific procedure to perform the EHM study. The figure 5.5 is a diagram of the the structure of script design and developed to calculate de stability points. The CSV file is loaded to R environment. Only the parameters necessary for the ehm studies are loaded, appendix A. This detail is very important, with this AGS doesn't have to do a specific procedure to perform the ehm study. The same CSV could be used for another studies it is only required to have the same export rate and parameters necessary.

The only information loaded that can identify the aircraft is the tail. At this point the database will provide

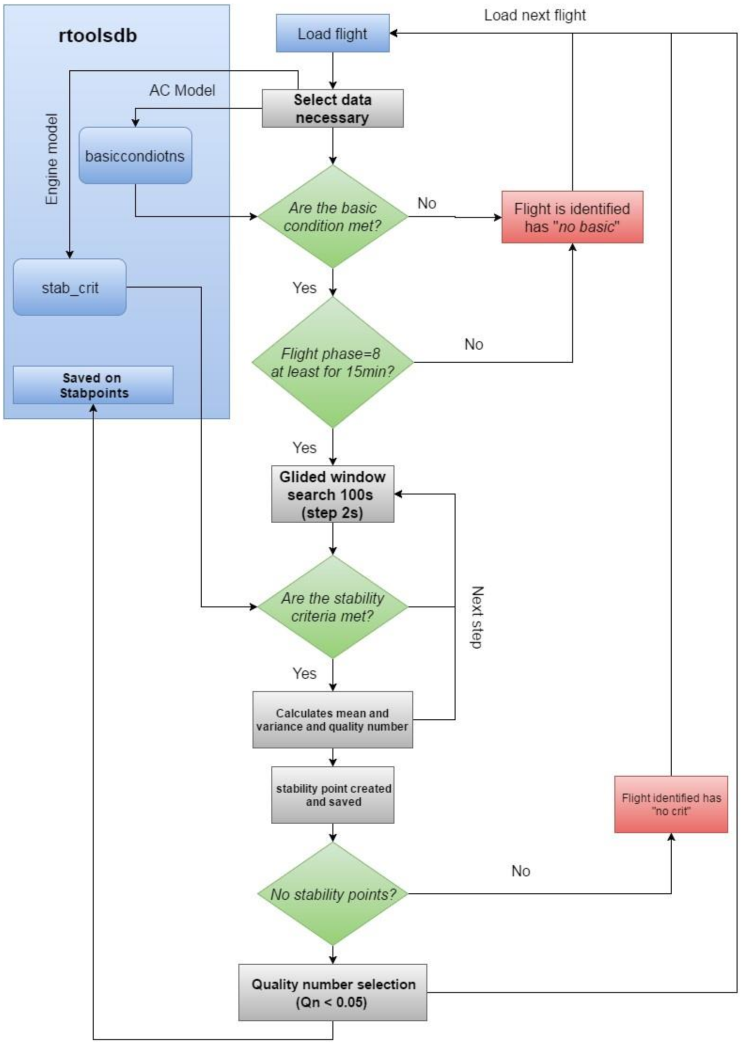


Figure 5.5: Stability Point Calculation Script

the information of the serial number, model and position of the engines aboard the aircraft, based on a query made to the database. Then another query is made to load the specific basic conditions and stability criteria of the aircraft and engine model. Which means it is only necessary to load into the database the proper basic conditions and stability criteria so the algorithm is capable of calculating the stability points of any aircraft or engine model.

In these first steps information is gathered so data processing and filtering can be made in the most efficient way.

Data Filtering

Like it was mentioned, data loaded into R comes from the whole flight, the first process consists in applying a filter, described in chapter 4 and make full use of some built-in R functions to reorganize the data and reduce computational time.

Search Method

The method chosen to search for the stable frames for the calculation of the stability point is Gliding Window Search method, as suggested in [4]. It implies overlapping the windows consecutively, taking a single window at time n and advancing it consecutively by i, getting N windows starting at $\{n;\ n+i;\ n+2i;\ n+3i;\ \ldots;\ n+Ni\}$, where N is given by equation 5.1.

$$N \leq \frac{t_a}{i},\ N \in \mathbb{N} \tag{5.1}$$

Note that t_a represents the period of time where analysis is being performed and expressed in the same time unit as i. Figure 5.6 exemplifies the difference between gliding window method and a fixed window

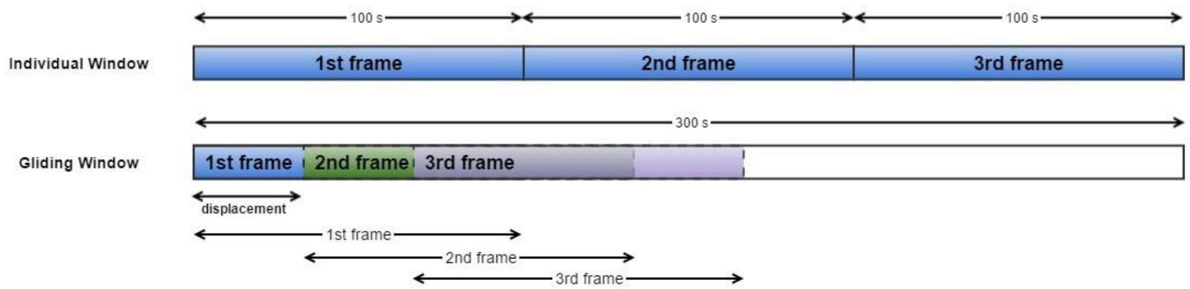


Figure 5.6: Fixed Window Vs GLidding Window search method [30]

After some testing was chosen a displacement of 4 seconds since it guaranties a satisfactory commitment between number of stable frames and computational effort.

Quality Number

Every stability point is associated with a Quality Number. The quality number is a method proposed in [24] used to identify and selecting the stability points that best represent what is happening to both the aircraft and its engines. It would also not be practical or efficient to store so many values per flight.

$$QN = W_a \frac{{s^2}_a}{Tol_a} + W_b \frac{{s^2}_b}{Tol_b} + \cdots + W_P \frac{{s^2}_p}{Tol_p} \tag{5.2}$$

W_i represents the weight factor for each parameter $p \in P$, P being the set of all analysed parameters, and Tol_i its tolerance according to the defined as in Table . The unbiased sample variance s^2 is calculated using equation 5.3.

$${s^2}_p = \frac{n}{n-1}{\sigma^2}_p = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2 \tag{5.3}$$

Note that n is the number of readings, or samples, in the observation window for a given parameter p and x_i a reading made at time i. The mean $\overline{x}$ can be obtained using the formula below:

$$x = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{5.4}$$

The variance gives a measure of the dispersion of the samples relative to the mean. The stability point will be of better quality when the overall variance of its parameters is lower. As stated before a stability point will then be the set of all calculated x_p, over the duration of a frame, with p belonging to the set of all analysed parameters P ,

Not all the stability points calculated are saved in the data base first is applied a filter by Quality number, qn less than 05, this value for the filtering was defined after a series of test in order to get best compromised between number of points and quality of points and size on the database. The stability points are saved in stabpoints table of the database.

5.2.2 Baseline Calculation

There diagram in the figure 5.7 is a representation of the script developed for the baseline calculation. Based in what was mentioned before in section 3.2.2 was set a period of 90 days after the engine is installed on wing, which mean that will be utilized flight data of three months of operation. With the

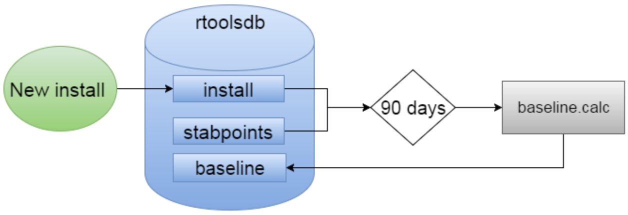


Figure 5.7: Baseline Script

information provided by TAP ME we were able to calculate several baselines for every parameter delta.

All the baseline that were calculated can be found in appendix B.It is important to note that only the baseline whit R coefficient closest to the unit will be used.

5.2.3 Data Smoothing

Health monitoring techniques benefit from having a data smoothing technique incorporated so trends can be easier to identify and in most optimistic scenarios have the ability to forecast engine failures. The Exponential moving forward was the chosen method as suggested in [17]. This method is vastly used when studying stock market tendencies. This method is calculated form the equation 5.5 listed below:

$$Y_{EMA}(n) = a * Y_{EMA}(n-1) + (1-a) * Y(n) \tag{5.5}$$

where is $Y_{EMA}(n)$ value of the exponential moving average at cycle n, a weighting factor can be selected in the Rehm Tool interface.

5.3 Roil Tool

Taking into account what was described in section 4.6 for the oil consumption studies an algorithm was developed that can automatically register the oil consumption for every flight and some statical studies for the operators fleet, in this case, TAP Portugal fleet.

By using the data provided by FDR of the aircraft it is impossible to verify the same condition on the time of the optical reading since there is no data recorded when the engines aren't running. To overcome this impossibility only the oil consumption is estimated instead of the oil quantity. Which means that, despite the difference in the conditions of the reading, the oil consumption values of the tool developed and method currently in use can be compared directly.

Based on empirical knowledge and some studies made prior to this development at TAP ME, it was defined a set condition for the values used for the estimation:

- The initial oil quantity is recorded 30 seconds prior to the beginning of the takeoff phase, it is expected that during this instant the oil levels are stable as the aircraft should be standing still facing the runway,
- The final oil quantity is recorded after the first engine shutdown. Furthermore, the oil quantity has to be constant during 3 seconds and the thrust levers must be at the IDLE position for the point to be extracted.

The difference between the final oil quantity and the initial oil quantity will be the oil consumption value used.

5.3.1 Roil Structure

As it was mention before, the tools works based on AGS procedures, R Statical files and batch files. The figure 5.8 resumes the entire Roil working network. The first step is exporting the oil data files from AGS, this is done through the maintenance procedure. This procedure runs as the flight data files are read by AGS on a daily basis.The table 5.1 will provide which parameters are used to extract the oil quantity points, the initial and final oil quantity points are extracted according to the conditions mentioned before: The outcome of the AGS procedure will be a single CSV file each day with the oil data for all the flights read during that specific day. The list of parameters exported to the .csv oil data files are listed in the following table 5.2: The second step is made through R Statical script which loads the CSV file into R environment then the data is organized and uploaded to the respective table of the database.The process used to update the database daily is through a Windows scheduled task. Will run a batch file

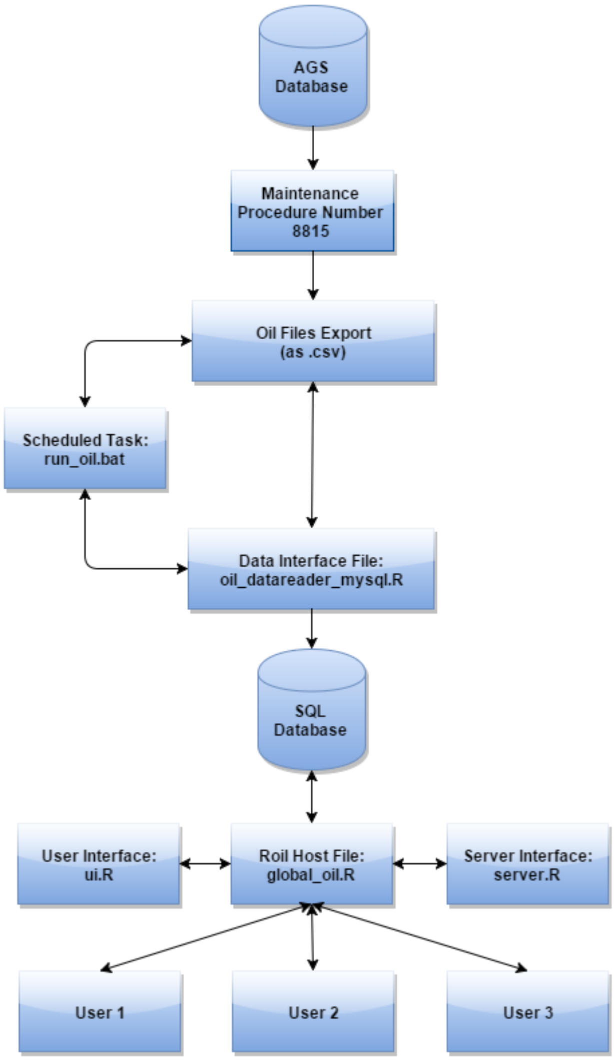


Figure 5.8: Roil Network

every day. This batch file calls R Statical a script that will search for an oil data file (.csv file) created on the same day as the task is running, if a CSV file is found then the R script will add all the new data to the database, otherwise no data is added.

5.3.2 Roil Additional Data

There is an additional set of information projected to provide statistical data regarding the oil consumption per hour. This additional set of information includes a histogram and a table with the number of observations (or points), mean value, standard deviation, maximum and minimum values of the current aircraft engine and date range selected.

Histogram

The red dashed line in the histogram corresponds to the mean value and the orange dashed lines correspond to the mean value minus or plus two times the standard deviation.The additional data about

Parameter	Description	Source	Resolution	Units
FLIGHT_PHASE	Flight Phase	Computed on Ground	NA	NA
FN1	Flight Number Part 1	Computed on Ground	NA	NA
FN2	Flight Number Part 2	Computed on Ground	NA	NA
DATE_TO	Date at Takeoff	Computed on Ground	NA	NA
TIME_TO	Time at Takeoff	Computed on Ground	NA	NA
T	Counter to Date Events	Computed on Ground	NA	NA
CUT	Message Cut if 1	Computed on Ground	NA	NA
AC_TAIL123	A/C Tail Word #1	FDIU/301/00	NA	NA
AC_TAIL456	A/C Tail Word #2	FDIU/302/00	NA	NA
AC_TAIL7	A/C Tail Word #3	FDIU/303/00	NA	NA
OIQ_1	Oil Quantity Engine #1	FWC-1/073/01	0.25	Quarts
OIQ_2	Oil Quantity Engine #2	FWC-1/073/10	0.25	Quarts
OIP_1	Oil Pressure Engine #1	FWC-1/317/01	2	PSI
OIP_2	Oil Pressure Engine #2	FWC-1/317/10	2	PSI
OIT_1	Oil Temperature Engine #1	FWC-1/316/01	0.5	DEGC
OIT_2	Oil Temperature Engine #2	FWC-1/316/10	0.5	DEGC
TLA1	Throttle Lever Angle Engine #1	ECU-1/133/01	0.04	DEG
TLA2	Throttle Lever Angle Engine #2	ECU-1/133/10	0.04	DEG
FF1	Fuel Mass Flow Rate Engine #1	ECU-1/244/01	0.227	Kg/h
FF2	Fuel Mass Flow Rate Engine #2	ECU-2/244/10	0.227	Kg/h
N11	N1 Low Rotor Speed Engine #1	ECU-1/346/01	0.03125	%RPM
N12	N1 Low Rotor Speed Engine #2	ECU-1/346/10	0.03125	%RPM

Table 5.1: List of parameters used to extract oil quantity points

the current selection on the menu is showed in a table.

Additional Info on the Oil Consumption per Hour (Raw Points Only):

n	mean	sd	min	max
50.00	0.31	0.12	0.08	0.67

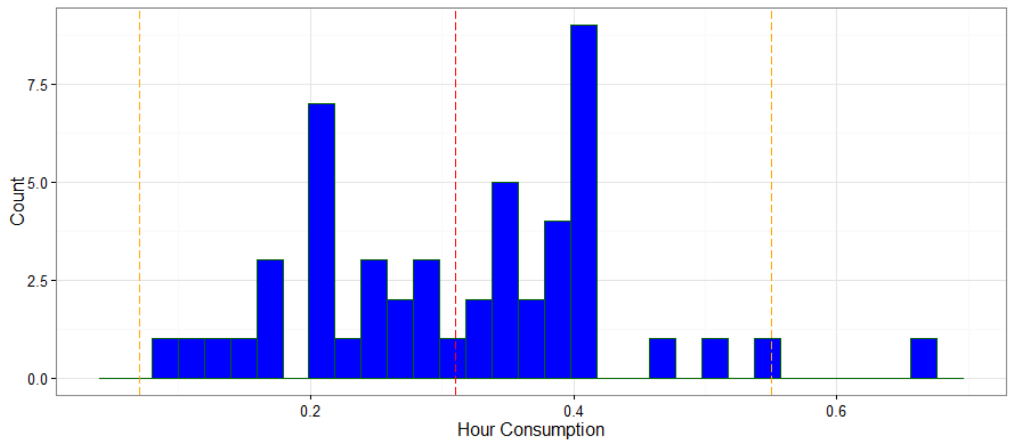


Figure 5.9: Additional statistical data

Engine Divergence

The engine divergence can be viewed by clicking the respective button in the main menu. It returns a plot with symmetric divergence points, which are calculated with the oil consumption per hour points according to:

$$Engine\,1\,Divergence = Engine\,1\,Point - (Engine\,1\,Point + Engine\,2\,Point)/2 \qquad (5.6)$$

Parameter	Description	Source	Resolution	Units
DATE_TO	Date at Takeoff	Computed on Ground	NA	NA
TIME_TO	Time at Takeoff	Computed on Ground	NA	NA
AC_TAIL123	A/C Tail Word #1	FDIU/301/00	NA	NA
AC_TAIL456	A/C Tail Word #2	FDIU/302/00	NA	NA
AC_TAIL7	A/C Tail Word #3	FDIU/303/00	NA	NA
FN1	Flight Number Part 1	Computed on Ground	NA	NA
FN2	Flight Number Part 2	Computed on Ground	NA	NA
time_flight	Flight Duration	Computed on Ground	0.1	mins
oiq1_i	Oil Quantity Engine #1 (initial)	FWC-1/073/01	0.25	Quarts
oiq2_i	Oil Quantity Engine #2 (initial)	FWC-1/073/10	0.25	Quarts
oip1_i	Oil Pressure Engine #1 (initial)	FWC-1/317/01	2	PSI
oip2_i	Oil Pressure Engine #2 (initial)	FWC-1/317/10	2	PSI
oit1_i	Oil Temperature Engine #1 (initial)	FWC-1/316/01	0.5	DEGC
oit2_i	Oil Temperature Engine #2 (initial)	FWC-1/316/10	0.5	DEGC
oiq1_f	Oil Quantity Engine #1 (final)	FWC-1/073/01	0.25	Quarts
oiq2_f	Oil Quantity Engine #2 (final)	FWC-1/073/10	0.25	Quarts
oip1_f	Oil Pressure Engine #1 (final)	FWC-1/317/01	2	PSI
oip2_f	Oil Pressure Engine #2 (final)	FWC-1/317/10	2	PSI
oit1_f	Oil Temperature Engine #1 (final)	FWC-1/316/01	0.5	DEGC
oit2_f	Oil Temperature Engine #2 (final)	FWC-1/316/10	0.5	DEGC

Table 5.2: List of parameters exported to oil data files

$$Engine2\,Divergence = Engine2\,Point - (Engine2\,Point + Engine1\,Point)/2 \qquad (5.7)$$

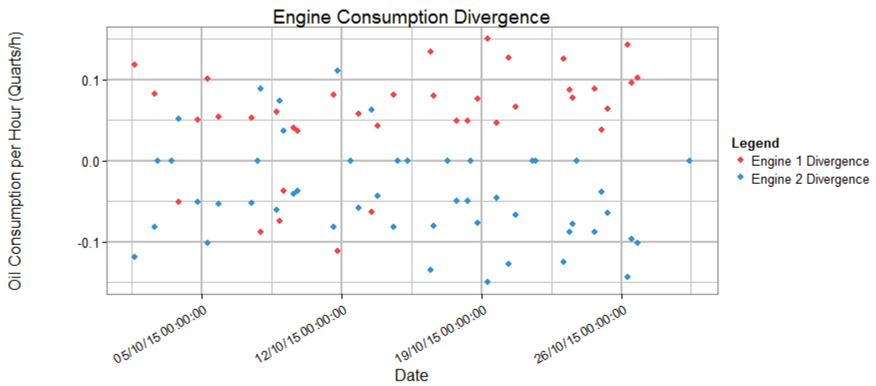


Figure 5.10: Engine divergence

Data Smoothing

Another important feature is the capability of adding smoothing lines to the total oil consumption, oil consumption per hour and engine divergence plots. These smoothing lines are obtained through a polynomial fit determined by numerical predictors. The method used is the loess method which finds β coefficients through a polynomial fit with local x values that will miniize the following mathematical expression 5.8:

$$n^{-1}\sum_{i=1}^{n} W_{ki}(x)(y_i - \sum_{j=0}^{p}\beta_j x^j)^2 \qquad (5.8)$$

Where W_{ki} are weights calculated iteratively and usually p = 1. The final result will be a function such as:

$$y = g(x) + E \tag{5.9}$$

Where $g(x)$ is a polynomial with an error variable represented by E which depends on the number of iterations and points used. The user is allowed to choose the smoothing span parameter, this parameter is roughly the proportion of raw points displayed in the plot that will be used in calculating each smoothed point. The smoothing span parameter must be within the interval $]0, 1]$ and the higher it gets the smoother will be the final result obtained.

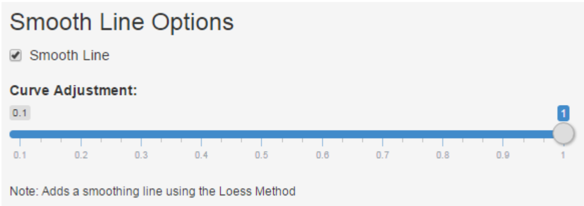


Figure 5.11: Smoothing adjustment

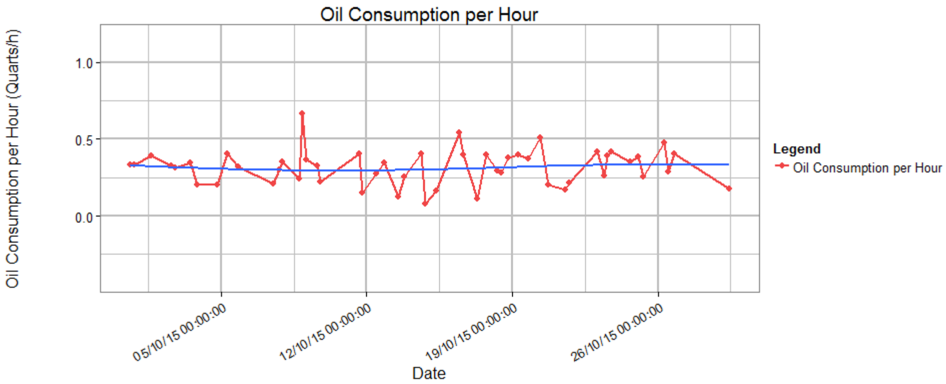


Figure 5.12: Example of a smoothing line

5.4 R Tracker

Another tool developed is the Rtracker. This tool is an easy way to access the history of the installations and removals of the engines of the TAP Portugal fleet. Information about the engine (engine serial number (engine SN), wing position, time since new (tsn), cycles since new (csn), N1 configuration(N1 trim), exhaust gas temperature margin(EGTM)), on the time of the removal or install of the engine is presented to the user, figure 5.13 is the illustrates the output of the Rtracter Tool.

This tool is a complement to the other two. It provides more detailed information about the engine just

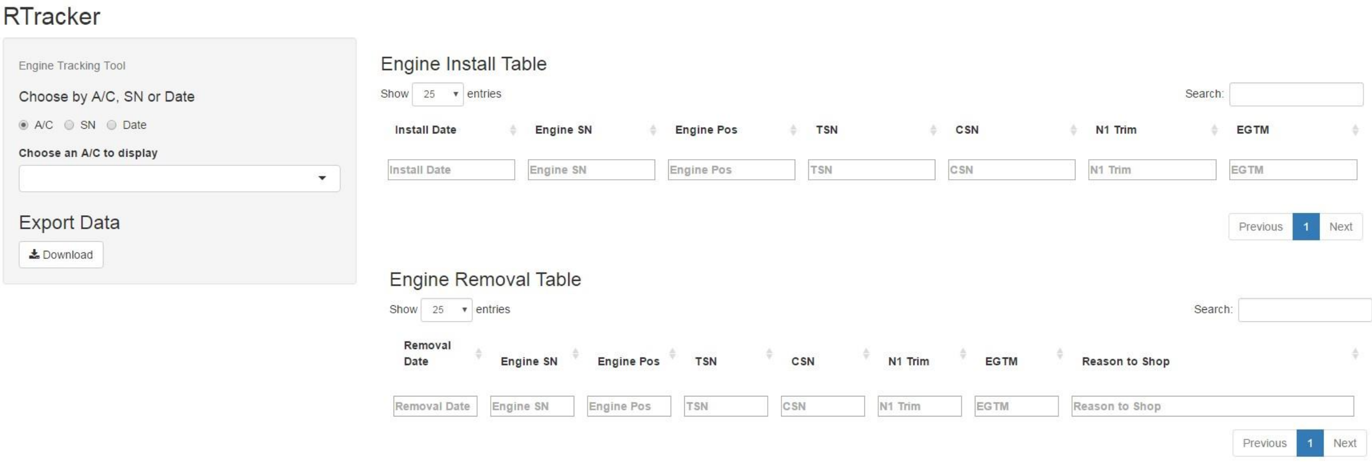


Figure 5.13: Rtracker Tables

a ”click way”. For example, when analyzing a specific engine through Rehm if it is detected some undesired behavior, it is possible by consulting, the same engine, in Rtracker which aircraft, when, why and how many times the engine was removed from wing. Sometimes this information can help draw conclusions about the current state of the engine.

5.5 User Interface

In this section, will be described how the user interface of the program works and his features. Starting by the login page and remembering that confidentiality of the flight data is a concern for the operator, in this case TAP Portugal.

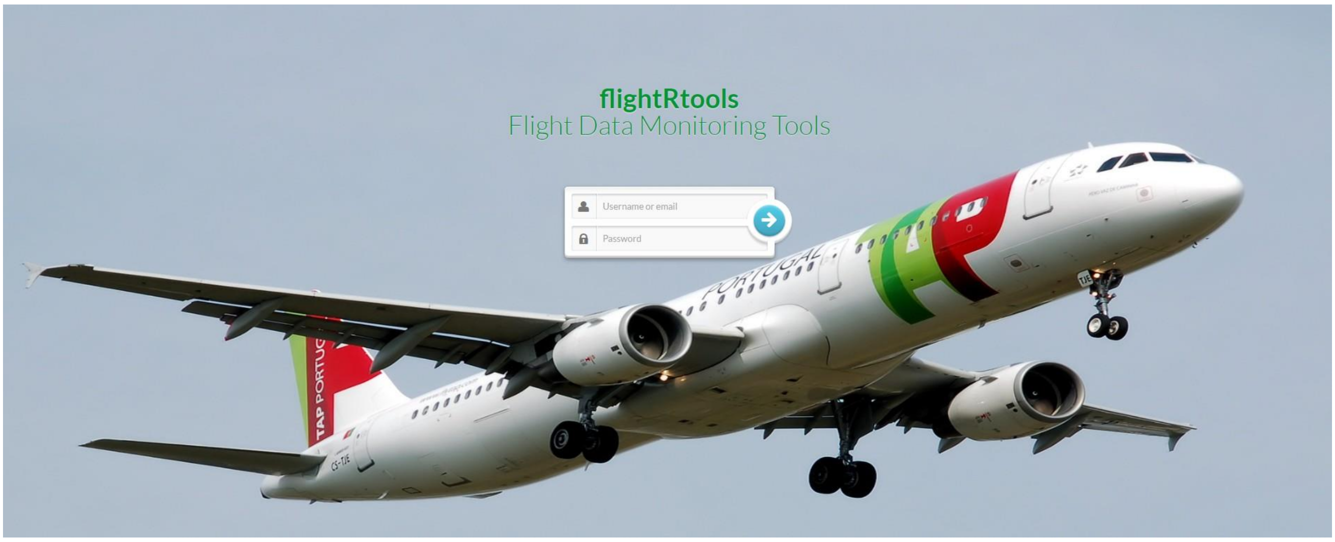


Figure 5.14: fligthRtools Login Page

Said that, was created a login page where a register has to be done. This restrict the access to the information to the people who actually need it.The login is guaranteed via database was created a database to manage the user's accounts and access. the figure 5.14 shows the login page that can be accessed via at TAP Portugal.

All the tools have similarities in the options menus. Which are the search option previously, that can de done for aircraft tail, engine serial number or data, has shown in figure 5.15

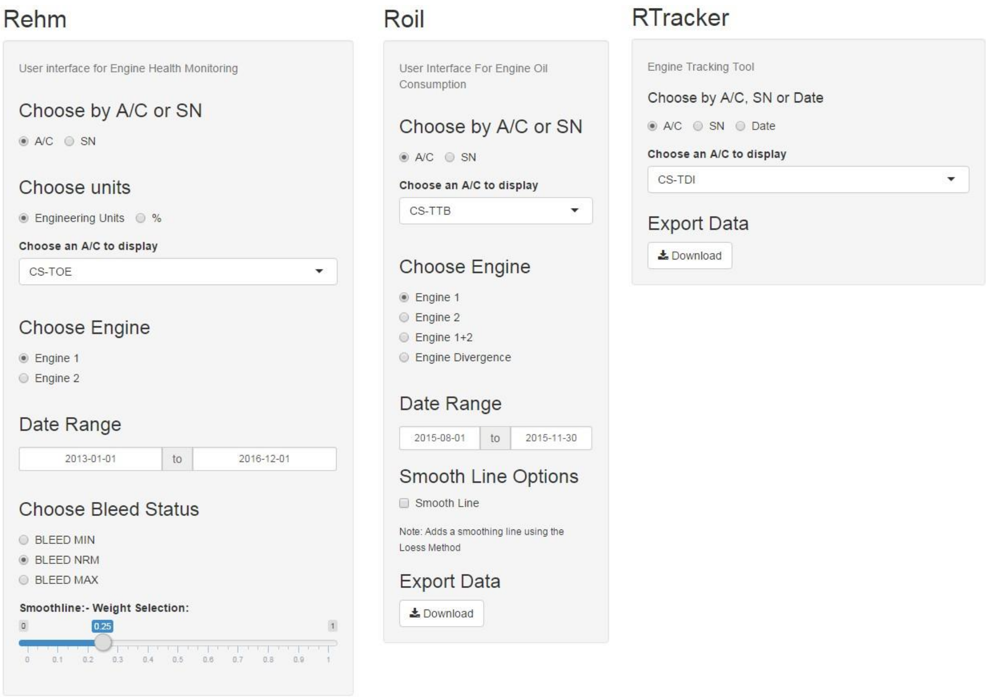


Figure 5.15: User interface for all the Rehm Roil and Rtracker

The Roil tool has some unique features which are not part of the current patch of the Rehm tool. including a download button in the main menu to download the data currently selected in Roil. This includes the aircraft engine position or serial number, the date range selected and points removed from the plots by double clicking. This button will download the current data with these filters as csv so it is possible to work with the oil data on an external software or to visualize it in a table form.
The "Toggle points" button function is to remove or add multiple points at once, just click and drag an area with the mouse directly in the plot to select the area of points to remove or add and click this button.

In this regard, when the mouse cursor is standing over a point in a total oil consumption or oil consumption per hour plot (mouse hover feature), it is shown in an area next to these plots the date, raw hour consumption value and smoothed value of the same point. It is also possible for Roil users to add/remove points directly in the total oil consumption and the oil consumption per hour plots. This is a feature that can be extremely useful regarding outliers, to do so, it is only necessary to double click the point to add/remove. After doing so, the y axis is adjusted automatically every time a point is added or removed. Note that every point removed will turn to light gray with an empty fill. To restore all the deleted points at once click the "reset" bottom in the top left corner of the plot.

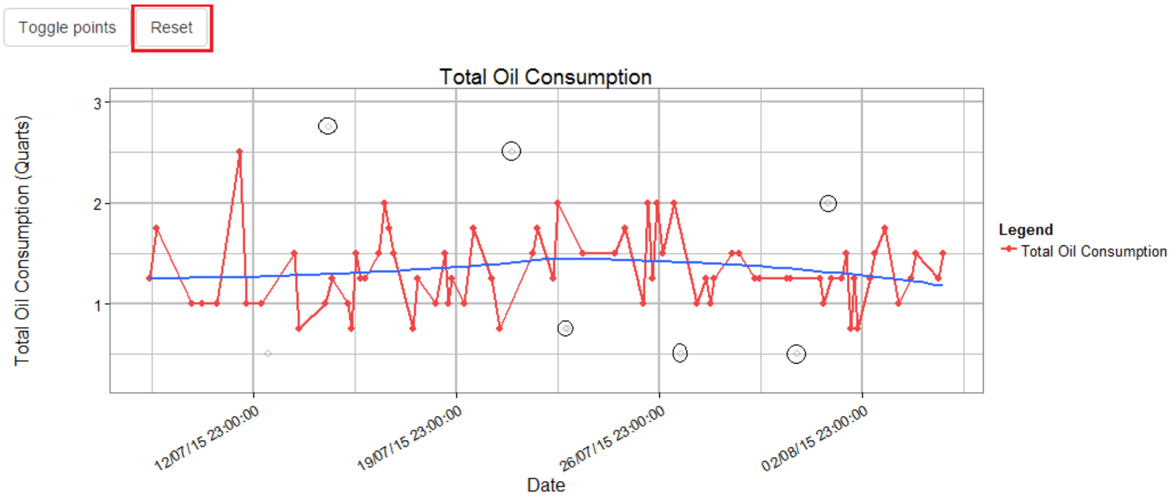


Figure 5.16: Outlier removal example

5.6 Conclusion

All the tools developed are dependent on the information of the database created, so it is mandatory that the database is always up to date. Background routines and scripts developed are in charge of data acquisition and treatment. They guarantee the best compromise between the amount processed of data and computational effort In the development of every tool, features were included in order to provide assistance in interpreting the data.

Chapter 6

Results

This chapter will address some results and conclusions that can be drawn using the developed programs. Some test cases were selected to be discussed and to validate the concepts behind the development of all the tools. In summary, this chapter will attempt to demonstrate the utility and the potential of the work developed during the current thesis.

6.1 Case Studies

Case studies for every tool will be presented in this section. Firstly to validate the tool, and secondly to demonstrate the utility of the program developed and support the considerations made across the document.

6.1.1 Rehm

Case 1

The first case is the same case used to validate the previous algorithm used in [4], which corresponds to a High Pressure Turbine Clearance Control (HPTCC) valve failure on a Pratt & Whitney engine.

Based on figure 6.1 which has the results obtained using both algorithms, we can clearly conclude that the graphical representation of the delta parameters is identical. There was no permanent damage caused to the engine, since after the maintenance procedure the engine was able to recover the efficiency demonstrated prior to the incident. This example proved that the improvements and modifications made on Rehm Tool previously developed, such as the new script for the stability point calculation didn't affect the final result.

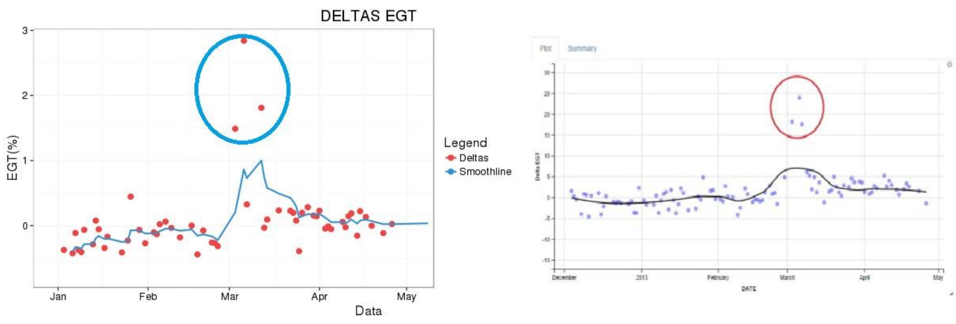


Figure 6.1: Delta EGT Parameter for the first Case study

Case 2

The validation of the algorithm was the first step. Afterwards, a dataset of an engine's output was selected, as seen in figure 6.2 in order to prove some of the considerations made along the document and illustrate the utility of the developed tool. The figure contains all the data available for this engine, it comprehends three and a half years of operation, between 2013 and mid 2016. There are four regions delimited in the figure in which we can easily identify different characteristics: There are four regions

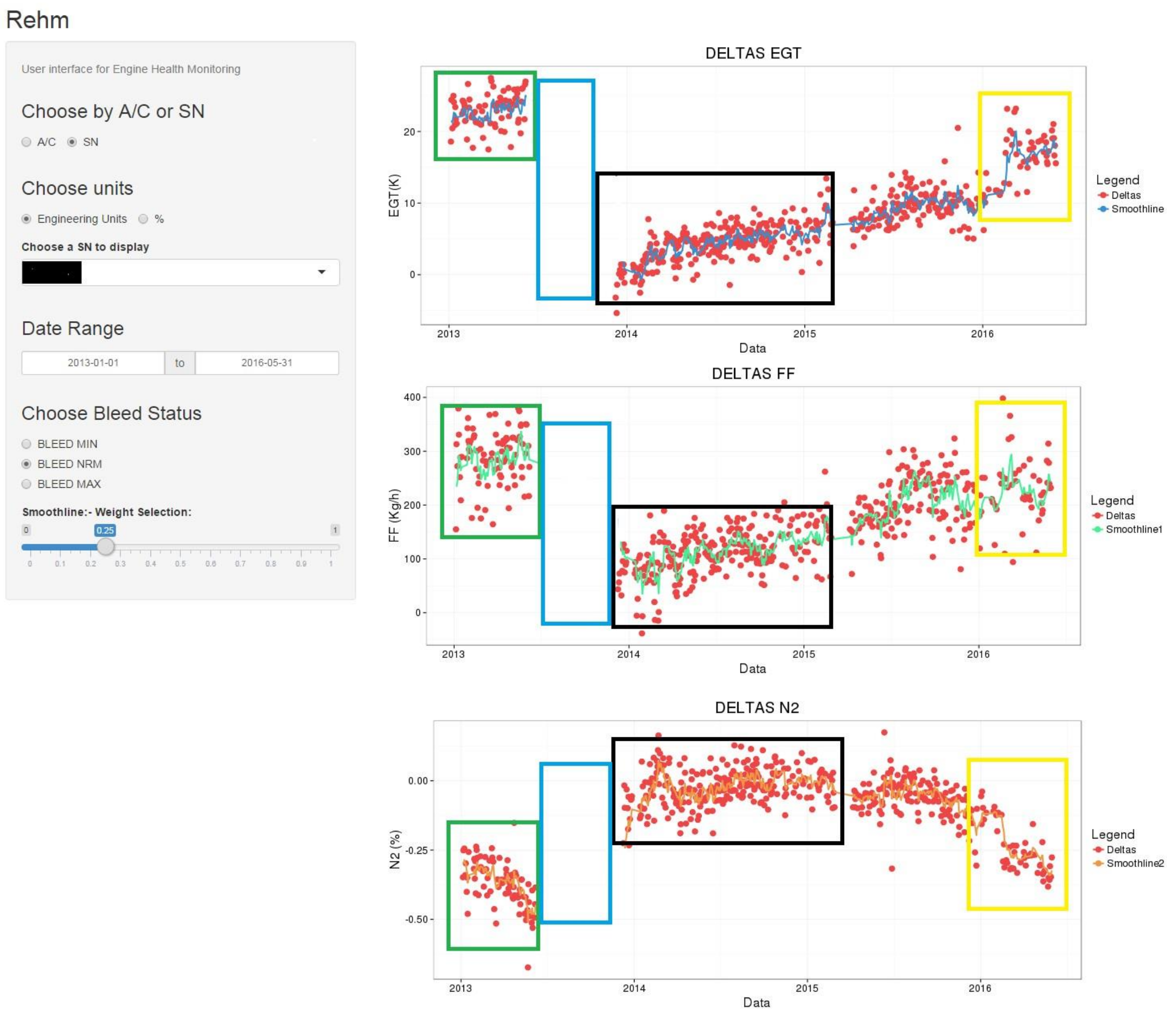


Figure 6.2: Rehm Tool Output fo the second Case Study

delimited in the figure in which we can easily identify different characteristics:

- The green zone is an example of low efficient engine operation patterns, which are defined by high values of the delta parameters for the EGT and FF variables and a decreasing trend on the N2. Since the deltas of both EGT and FF remain high, but fairly stable, throughout the whole period, it can be concluded that an incident-free time frame for this engine is present. We can conclude that the low efficiency showed in this period is the result of deterioration along time and not from an engine part sudden failure.

- The blue region which doesn't have any data available. This is an indication that this engine was not in operation or that in the considered period the algorithm wasn't able to calculate any stability. points. After consulting Rtracker, it was verified that this engine was removed from the aircraft due to loss of performance. This fact reinforced what was stated regarding the green region.

- The black zone comprehends more than one year of operation. The engine was installed on a new aircraft at the end of 2014. The gap between the values between this region and the green one are evident. In the first period of this region the values of the delta parameters are much closer to the reference, which indicates a newly installed engine. Across this period it is clearly observable the expected degradation of engine performance by accumulation of the cycles and use, since there is no sudden shift in any delta parameter. The decreasing engine performance over time is represented by an increasing trend in the EGT parameter and fuel flow parameter, while the N2 parameter has the opposite trend.

- The yellow zone highlights a sudden shift of all parameters. Despite being able to identify the change in the parameters, which lead to a decrease of performance through Rehm, it is not possible to identify the engine part causing the shifts. What we are able to conclude is that the problem wasn't solved by the end of the study or the problem was solved but the damage was permanent and therefore it was not possible to recover performance. After receiving the feedback from TAP ME for this case it was confirmed that since early 2016 this engine has presented some problems with the nacelle cool valve and several maintenance actions were performed trying to find the source of the problem. Another comment that can be made is that despite the cause of the shift not being identified and solved by the end of the study, is that it didn't lead to considerably higher levels of fuel consumption (the trend of the delta fuel consumption is fairly stable). However, during this period, engine parts were enduring an undesirable higher temperature which can speed up the engine degradation. That being said, it can be stated that this shift didn't have an immediate impact on the operation's cost of the aircraft but the acceleration of the degradation process could result in a much higher expense in the future.

Analyzing now all the four regions simultaneously, several comments can be made. The delta EGT parameter is the one that assesses the engine health more accurately. When an engine is subject to a maintenance action it will not always reflect a performance enhancement.

A fact that may go unnoticed, is that this type of analysis made for this case cannot be reproduced with the current software used at TAP ME since is presented the health monitoring data for one specific engine and the current software is not able to provide data from three and a half years of operation. It was mentioned previously that the search option was one of the major advantages of the tool developed because this features allows to assess the performance for a specific engine in a different aircraft and wing position.
The conclusions made previously prove that the objectives of developing the Rehm tool were accomplished. Also is important to state how Rtracker can be usefull.

6.1.2 Roil

Case study

An example of the output of the Roil Tool will be presented. The unique features of this Tool, namely the statical studies, were already listed before in section and will not be discussed.
This case comprises four months of operation of an aircraft. The black dash line in figure 6.4 identifies

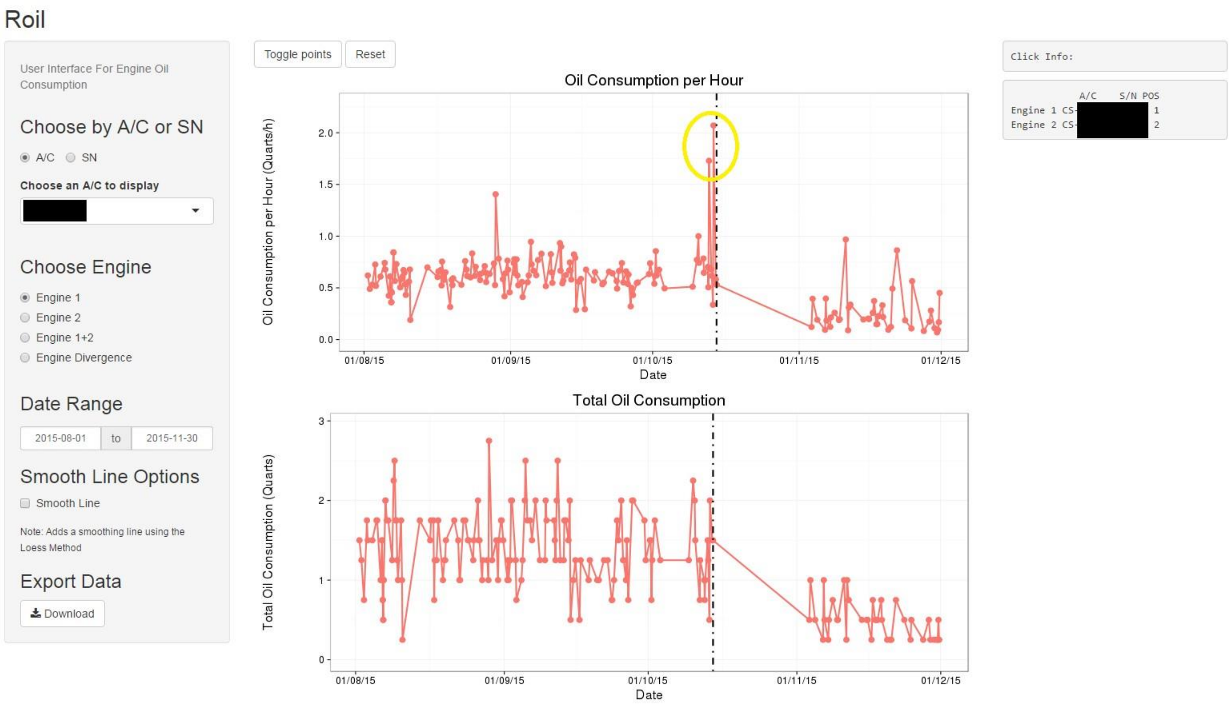


Figure 6.3: Roil Tool for the case study

a change in the engine installed on the aircraft wing. Days before the change in the engine, some outliers are identified in the oil consumption per hour and, according to the graphic, it almost triplicates. It can also be noted that the new engine installed has low values of fuel consumption which is to be expected and can be confirmed by Rtracker.

It is not possible to cross information between the Rehm Tool and Roil Tool. Since for the oil consumption analysis, the Roil Tool wasn't able to estimate trustworthy oil points for Pratt & Whitney P4168 engine.

Furthermore, the data for performing the Rehm studies was still not processed for engine manufacturer other than Pratt & Whitney.

6.1.3 Rtracker

The utility of the Rtracker tool was already mentioned in section 6.1.1 But it is important to mention that the table entry ”Reasons for Shop” contains descriptions regarding engine removals that were discussed in chapter 3. The figure 6.5 illustrates one of those outputs.

Engine Removal Table

Show 25 entries Search:

Removal Date	Engine SN	Engine Pos	TSN	CSN	N1 Trim	EGTM	Reason to Shop
20[redacted]	[redacted]	1	28908	4353	[redacted]		HPT T2 VANES DAMAGE
20[redacted]	[redacted]	2	28889	4523	[redacted]		T2 VANES CRACKS
20[redacted]	[redacted]	1	35129	5728	[redacted]		Fan Disk Damage
20[redacted]	[redacted]	2	51319	6470	[redacted]		Engine failure(HPT 2 vanes and hpc damage)
20[redacted]	[redacted]	2	48430	6639	[redacted]		damage on HPT1 VANE
20[redacted]	[redacted]	1	42040	6060	[redacted]		performance degradation
20[redacted]	[redacted]	1	47608	7859	[redacted]		HPT blades Damaged
20[redacted]	[redacted]	2	29393	6817	[redacted]	39	S/N OUT rented
20[redacted]	[redacted]	1	58344	7889	[redacted]	9	Starter drive gearshaft damaged
Removal Date	Engine SN	Engine Pos	TSN	CSN	N1 Trim	EGTM	Reason to Shop

Showing 1 to 9 of 9 entries Previous 1 Next

Figure 6.4: Example of Rtracker Tool Output

6.2 Conclusion

Based on the results presented in this chapter, it can be concluded that the main objectives of the dissertation were accomplished. The Rehm tool was able to demonstrate the gradual deterioration of the engine performance due to cycle accumulation and identify parameter shifts caused by faults in engine components. As for the Roil tool, the feedback of TAP ME was positive and the results obtained through our method show the consistency that is required in this kind of analysis. Rtracker Tool also received good reviews from its target users.

Chapter 7

Conclusions

In an industry as competitive as aviation, the optimization of resources and operation gains even more relevance due to factors like airlines experiencing low profit margins and being highly influenced by external factors such as fuel price fluctuations. Flight data departments can and should play an important role as they provide critical information for the operation of many other departments such as maintenance, safety or performance. The work developed in the current dissertation is such an example where at TAP, the leading Portuguese airline, started a new relationship between the TAP FD Department and TAP ME by making good use of the data available in order to improve not only engine maintenance monitoring but also by developing a set of tools, with some simple but new features. These features contribute to the overall efficiency of the company and, consequently, an operation cost reduction.

7.1 Achievements

Engine performance is without any doubt one of the main concerns of airlines. Since a good performance is associated with lower fuel consumptions, lower exhaust gas temperature and less pollution, it leads to cost savings directly and indirectly. Hence, it is important that airlines are able to assess the condition of any engine of their fleet without any major effort and follow its gradual degradation in order to increase maintenance planning efficiency. For that reason some methods were developed, as the one used in the current thesis regarding engine performance parameters trend monitoring.

More accurate information about the condition of the engine can be withdrawn by monitoring oil quantity and consumption of the engine. The Roil Tool results show the consistency required for this kind of analysis the exception being the Pratt & Whitney 4168 engine. The Roil maintenance procedure is already implemented in AGS at the TAP FD department and is performed daily.

Chapter 6 also demonstrates some of the concepts developed in this document like the degradation of the engine performance with cycles accumulation, and that the EGT is the parameter that best represents engine condition.

One of the main advantages of the program developed is the very friendly user interface and its search option, the development of the database allows the possibility of searching by engine serial number which was one of the greatly appreciated features by TAP ME since none the available software has this option available. Another advantageous result of the program interaction with the database is the amount of data and the velocity in which the information is provided to the user. The login module created also facilitates the integration of different departments at TAP that could require access to this data.

7.2 Future Work

All the tools developed have already demonstrated their utility and have proved to be an upgrade in some aspects over the currently used software according to those who perform the same kind of analyses. But there are always ways to improve.

For the engine condition monitoring tool, by using data available via the database already created the integration of machine learning concepts to the software could result in the creation of its own fingerprints for the parameter delta's shifts which would allow the tool to successfully identify the faulty engine part. Also, performing trend analyses for other engine parameters, like engine vibration, can contribute to a better assessment of the engine condition.

For the oil consumption analysis, it was still not possible to successfully estimate oil points for the PW engine. So further studies must be performed to set different conditions that can be met by this engine model without compromising the accuracy of the data.

The implementation of a notification via email can be a great help in detecting sudden changes in parameters. Since it allowed the user to have knowledge of the event without having to be logged into the tool. Thus the problem could be detected sooner.

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Appendix A

Exported Parameters

Parameter	Description	Description
T	Recorder Clock Counter	8Hz
TIME_R	Recording Timer	1Hz
DATE	Date	1Hz
FM_FWC	Flight Phase (Flight Warning Computer)	1Hz
FLIGHT_PHASE	Flight Phase	1Hz
FNAI1	Engine anti-ice valve pos 1	1Hz
FNAI2	Engine anti-ice valve pos 2	1Hz
WAO1	Wing Anti-ice outer pos - left filtered	1Hz
WAI1	Wing Anti-ice inner pos - left filtered	1Hz
WAO2	Wing Anti-ice outer pos - right filtered	1Hz
WAI2	Wing Anti-ice inner pos - right filtered	1Hz
EG_PRV_POS	Engine PRV position	1Hz
O_EGPRV_POS	Opposite engine PRV position	1Hz
EG_HPV_POS	Engine HPV position	1Hz
O_EGHPV_POS	Opposite engine HPV position	1Hz
ALT_STDC	Standard Altitude corrected	1Hz
MACHR1	Mach Number	1Hz
XBV_POS2	Cross feed valve position	1Hz
APUBV_O	APU bleed valve position	1Hz
IALT	Inertial Altitude	1Hz
GSC	Corrected ground speed	1Hz
ROLL	Roll Angle	2Hz
TAT	Total Air Temperature	1Hz
N21C	Corrected N2 engine 1	1Hz
N22C	Corrected N2 engine 2	1Hz

EGT1C	Corrected EGT engine 1	1Hz
EGT2C	Corrected EGT engine 2	1Hz
GVRTI	Vertical acceleration	8Hz
N11C	Corrected N1 engine 1	1Hz
N12C	Corrected N1 engine 2	1Hz
PT21	Local pressure engine 1	1Hz
PT22	Local pressure engine 2	1Hz
FF1C	Corrected FF engine 1	1Hz
FF2C	Corrected FF engine 2	1Hz
EPR1	EPR engine 1	1Hz
EPR2	EPR engine 2	1Hz
HPT1	Selected HPTC engine 1	1Hz
HPT2	Selected HPTC engine 2	1Hz
LPT1	Selected LPTC engine 1	1Hz
LPT2	Selected LPTC engine 2	1Hz
ABLD_PB_POS	Air bleed push-button position	1Hz
O_ABLD_PB_POS	Opposite air bleed push-button position	1Hz
BLD_MAX_PACK	Engine bleed mode	1Hz
BLD_NOM_PACK	Engine bleed mode	1Hz
BLD_MIN_PACK	Engine bleed mode	1Hz
AC_TAIL_23	Aircraft tail registration	0.25Hz
AC_TAIL456	Aircraft tail registration	0.25Hz
AC_TAIL7	Aircraft tail registration	0.25Hz
DUR_CRS	Duration of cruise (s)	1Hz
AIR_DURN	Airborn Duration (s)	1Hz
FLTNUM	Flight Number	1Hz
ORIGIN	Origem	1Hz
DESTINATION	Destino	1Hz

Table A.1: Parameters extracted from AGS

Appendix B

Baselines Coefficients

EGT baselines

baseline_id	ac_id	engine_id	eng_model_id	parameter	b	m	R	date
1	[redacted]	[redacted]	14	egt[redacted]	-1.3038991218608	8.7769824109933	0.980018065806077	[redacted]6-10
2	[redacted]	[redacted]	14	egt[redacted]	-40.4067842463106	9.21227704776402	0.967234543231134	[redacted]6-10
7	[redacted]	[redacted]	14	egt[redacted]	46.336452892422	8.22682638643227	0.927575674016535	[redacted]3-10
8	[redacted]	[redacted]	14	egt[redacted]	95.1185870509992	7.66335881966069	0.939297485661722	[redacted]3-10
13	[redacted]	[redacted]	14	egt[redacted]	-52.2796270144882	9.41445726543085	0.890822040877798	[redacted]6-12
14	[redacted]	[redacted]	14	egt[redacted]	-65.6220142285664	9.56743628313968	0.785139478356804	[redacted]6-12
19	[redacted]	[redacted]	14	egt[redacted]	44.6058678931201	8.1718844421998	0.979398506089247	[redacted]2-22
20	[redacted]	[redacted]	14	egt[redacted]	62.1583200556686	7.95406122488172	0.935026104194654	[redacted]2-22
25	[redacted]	[redacted]	14	egt[redacted]	32.0095615096069	8.35360371552732	0.990510200687944	[redacted]2-09

Figure B.1: EGT Baselines coefficients

N1 baselines

baseline_id	ac_id	engine_id	eng_model_id	parameter	b	m	R	date
3	[redacted]	[redacted]	14	FF[redacted]	-25246.7431852849	387.530150644256	0.984144092854694	[redacted]0
4	[redacted]	[redacted]	14	FF[redacted]	-24863.250024009	382.892404654917	0.980620895519854	[redacted]0
9	[redacted]	[redacted]	14	FF[redacted]	-25458.5088017017	390.939135748259	0.990817170236422	[redacted]0
10	[redacted]	[redacted]	14	FF[redacted]	-23798.7617741092	372.060383574268	0.990811238842392	[redacted]0
15	[redacted]	[redacted]	14	FF[redacted]	-24435.824349008	379.884530516424	0.991003773207449	[redacted]2
16	[redacted]	[redacted]	14	FF[redacted]	-23804.17689752	372.603403734838	0.974287913832711	[redacted]2
21	[redacted]	[redacted]	14	FF[redacted]	-23555.9979900138	367.869356891649	0.99644969001092	[redacted]2
22	[redacted]	[redacted]	14	FF[redacted]	-22101.2248220932	351.347676988047	0.989138355530915	[redacted]2

Figure B.2: EGT Baselines coefficients

N2 baselines

baseline_id	ac_id	engine_id	eng_model_id	parameter	b	m	R	date
5	[redacted]	[redacted]	14	N2[redacted]	49.1783531834547	0.484817454115528	0.981270914602692	[redacted]
6	[redacted]	[redacted]	14	N2[redacted]	49.1620491241495	0.485383078471138	0.979236871771895	[redacted]
11	[redacted]	[redacted]	14	N2[redacted]	49.2743734562023	0.483909692379892	0.992512705272923	[redacted]
12	[redacted]	[redacted]	14	N2[redacted]	51.7437508396394	0.456782317355058	0.986672760303596	[redacted]
17	[redacted]	[redacted]	14	N2[redacted]	47.9596497449847	0.500139821929663	0.93065815482705	[redacted]
18	[redacted]	[redacted]	14	N2[redacted]	49.180193306357	0.486296731052076	0.85280155979459	[redacted]
23	[redacted]	[redacted]	14	N2[redacted]	44.6558842292527	0.536765281591145	0.996292278037737	[redacted]
24	[redacted]	[redacted]	14	N2[redacted]	47.338109123718	0.506733343525734	0.986892334783942	[redacted]

Figure B.3: EGT Baselines coefficients