Fault Analysis Methodology and Maintenance Improvement

Application to Aircraft Fleets on NetJets

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The starting point of all achievement is desire.

— Napoleon Hill

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Resumo

Tanto na aviação comercial como executiva, um controlo rigoroso dos **custos** é vital para uma operação economicamente viável e lucrativa. Além disso, existe atualmente uma exigência por elevados níveis de segurança, os quais se podem traduzir em elevados custos operacionais. Assim, é necessário um equilíbrio entre os custos e segurança, o qual pode ser alcançado através de um Plano de Manutenção de Aeronaves (PMA) eficiente.

A evolução da tecnologia revelou-se importante na monitorização de parâmetros relevantes das aeronaves, contribuindo para uma maior eficiência de manutenção. Como exemplo, determinadas falhas podem ser irrelevantes e indetectáveis em termos de operação. No entanto, quando combinadas com outras falhas (ou repetidas ao longo do tempo), podem indicar falhas importantes iminentes e a necessidade de manutenção adicional. Um software usado para armazenar e analisar dados de falha é o Computerized Aircraft Maintenance Program (CAMP).

Com esta tese, uma metodologia de análise de falhas nas frotas de aeronaves da NetJets, nomeadamente nas de Cessna Latitude e de Bombardier Challenger 350, foi implementada. Através desta, foram detectados os diversos modos de falha nos sistemas analisados, bem como os riscos das falhas para a operação.

Posteriormente, e uma vez que a metodologia foi aplicada num contexto real de aviação, os itens de risco crítico foram investigados. Tal resultou na determinação de possíveis causas de falha, bem como de soluções plausíveis para prevenir a recorrência das falhas. Era expectável que, como consequência da implementação da metodologia, fosse possível uma melhoria da eficiência dos PMA, com tarefas específicas, reduzindo os custos a longo prazo.

Com este estudo, é possível concluir que o impacto de falhas no fabrico é relevante para a operação, uma vez que os componentes podem já estar defeituosos e a prevenção de falhas pode não ser possível. Além disso, e baseando na ideia de Pareto, é observado que as falhas que mais contribuem para disrupções na operação estão relacionadas com os Sistemas de *Engine Fuel and Control*. Ademais, e através da Análise FMECA, a criticidade para a operação das frotas é comparável: os valores de RPN mais elevados nos componentes da frota de Challenger 350 tornam-na na mais crítica das duas em análise.

Como resultado das análises, duas *Engineering Orders* foram produzidas por forma a melhorar os planos de manutenção. Foram também desenvolvidos (ou projectados) pelos fabricantes quatro novos componentes, por forma a reduzir o número de eventos não programados relacionados com componentes defeituosos ou desajustados à operação.

Palavras-Chave: Aeronaves, Falhas, Manutenção, Metodologia, Risco

Abstract

Both in civil and private aviation, a strict control of costs is key for economically viable and lucrative operations. Also, there is a demand for increasingly higher levels of safety that can translate into more operational costs. As a consequence, a balance between both costs and safety is necessary and can be achieved via efficient Aircraft Maintenance Plans (AMP).

The evolution of technology has aided in the close monitoring of relevant operational aircraft parameters, contributing to the efficiency of its maintenance. As an example, some faults can be irrelevant for the operation and be undetected, but when combined with other faults (or if repeated over time) they can indicate possible impending failures and the need for additional maintenance. One software that is used to store and analyse this data is the Computerized Aircraft Maintenance Program (CAMP).

In this thesis, a methodology was implemented to analyse failures on NetJets' fleets of aircraft, namely the Cessna Latitude and the Bombardier Challenger 350. It focused on understanding the failure modes on the analysed systems and on the risks for the operation.

Furthermore, and as implemented in a real aviation scenario, the risk critical items were further investigated, determining possible causes of failure, as well as plausible solutions to prevent their recurrence. It was expected that the implementation of the methodology would result in more efficient plans, with custom tasks, reducing costs in the long term.

It is concluded that the impact of manufacturing failures is relevant, as items can be faulty from factory and not able to be prevented via maintenance. Also, based on the Pareto's idea, it is noticed that the failures that most contribute to disruptions in operation are related with the Engine Fuel and Control Systems. Furthermore, using the FMECA Analysis, the criticality of the fleets is compared: the higher RPN values of the Challenger 350's components make it the most critical of both fleets.

Ultimately, two Engineering Orders were produced to improve the preventive maintenance plans, alongside four new component developments by the manufacturers to reduce the number of unscheduled events related with faulty items.

Keywords: Aircraft, Failures, Maintenance, Methodology, Risk

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Nomenclature

ΔN_f	Total Number of Failures
Δt*	Total Service Time
λ	Failure Rate
$\overline{FH}$	Average Aircraft Flying Hours per Year
$N_{A/C}$	Number of Aircraft per Fleet
Y	Total Years in Service
A/C	Aircraft
A/I	Anti-Ice
AAIP	Approved Aircraft Inspection Program
AGB	Accessory Gearbox
AMM	Aircraft Maintenance Manual
AMP	Aircraft Maintenance Plans
APU	Auxiliary Power Unit
ATA	Air Transport Association
AVG	Average
BOV	Bleed-Off Valve
CAMP	Computerized Aircraft Maintenance Programs
CM	Condition Monitoring
EDHP	Engine-Driven Hydraulic Pump
EDU	Engine Diagnostic Unit
EEC	Electronic Engine Control
EHM	Engine Health Monitoring

EICAS	Engine Indicating and Crew Alerting System
EMM	Engine Maintenance Manual
EngFH	Engine Flight Hours
EO	Engineering Order
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Engine Control
FC	Flight Cycles
FEC	Failure Effect Categories
FFIB	Fuel Filter Impending Bypass
FH	Flight Hours
FMECA	Failure Mode, Effects and Criticality Analysis
FOD	Foreign Object Debris
GVI	General Visual Inspection
HT	Hard Time
I.M.	Infant Mortality
IATA	International Air Transport Association
LRU	Line Replaceable Unit
MSG	Maintenance Steering Group
MSI	Maintenance Significant Items
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MXi	Maintenix
NJA	NetJets Aviation
NJE	NetJets Europe
OC	On Condition
P/N	Part Number
PMA	Plano de Manutenção de Aeronaves
PM	Preventive Maintenance

RCA	Root Cause Analysis
RCM	Reliability Centered Maintenance
RPN	Risk Priority Number
S/N	Serial Number
SB	Service Bulletin
SIL	Service Inspection Letter
STD	Standard Deviation
T/R	Thrust Reverser
TLD	Time Limited Dispatch
TOF	Time of Fault
WO	Work Order

Chapter 1

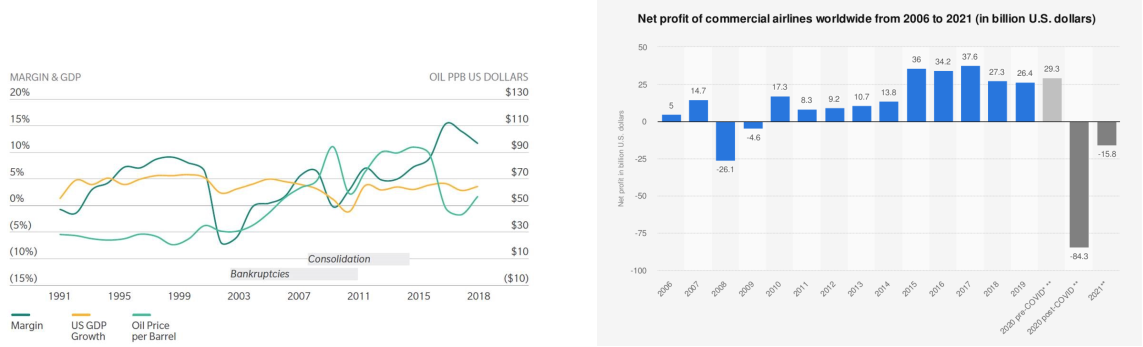
Introduction

1.1 Overview and Motivation

The evolution of the world's economy has a strong impact on the profitability of airlines, which focus on air transport. Thus, *air transport is a major contributor to global economic prosperity*, playing a vital role in several sectors, such as: (a) world trade – increasing *access to international markets* and contributing to exportation; (b) connectivity – contributing to higher productivity and efficiency, as well as *encouraging investment and innovation*; (c) tourism – as more than 50% of tourists travel by air [1]; and (d) humanitarian and health operations – with supplies being easily transported between countries.

Several economical scenarios influence the air transport sector, for instance: if there is an economic recession, there are less travelers willing to spend money flying, whereas if there is an economic boom there is a growth in the sector.

In the past few years, there have been examples of economic recessions (seen in Figure 1.1), such as: in 2001, the terrorist attacks on the Twin Towers led to a generalization of the fear of air travelling; in late 2008, the worldwide economic recession; in 2020, the COVID-19 pandemic causing a standstill to most commercial aircraft.



(a) From 1991 to 2018; includes 2001 and 2008/09 economic recessions [2].

(b) From 2006 to 2021; includes COVID-19 pandemic recession and possible scenario [3].

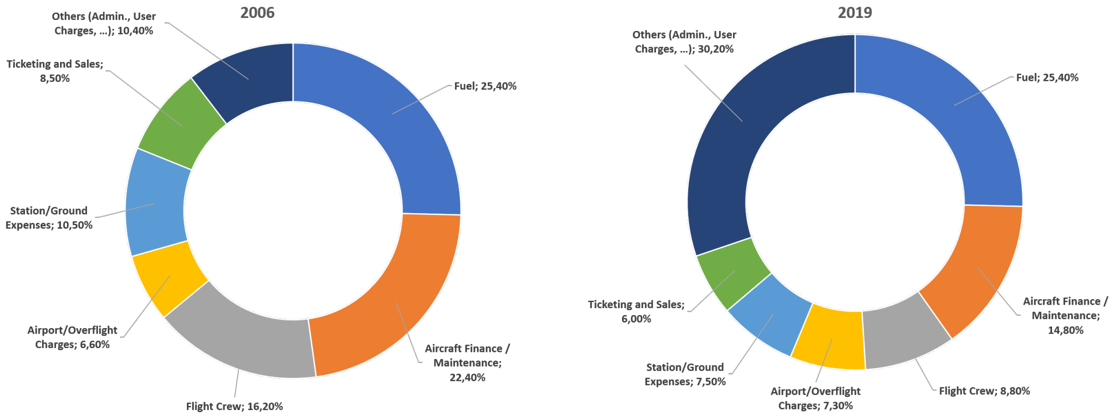
Figure 1.1: Evolution over the years of the profit margin of airlines.

On one hand, as seen in Figure 1.1, during an economic recession, profits suffer a hard negative impact, resulting in an increase of the number of bankrupt airlines [4].

On the other hand, during economical growth, the increase in number of passengers is clear: from 2001 to 2018, the number of passengers flown more than doubled, from 1.65 to 4.23 billion [5].

However, the growth of the air transport sector is perceived as more than just the number of passengers, as it also contributes to the evolution of globalisation. Consequently, the maintenance sector must focus on the increase of the number of hours flown, which can lead to a higher number of aviation incidents or accidents. As such, an increase in aviation safety levels must follow, with novel aircraft, in conjunction with tighter schedules of preventive maintenance or even with the evolution of predictive maintenance [6].

A downside to an increase of maintenance are the costs, being of the most importance to reach a balance between the risk of incidents and the costs associated with their prevention. For that, it is first necessary to understand the breakdown of costs within an airline and also its evolution. Figure 1.2 represents such distribution in 2006 and 2019.



(a) In 2006, data according to Doganis [7].

(b) In 2019, data according to IATA [8].

Figure 1.2: Breakdown of expenses by airlines, in percentage.

Costs associated with Maintenance have the second highest values in both 2006 and 2019. These include price of spares, time between inspections, failure rate of components, labour associated with performing tasks, among others [9].

But, over the years, instead of an expected increase, there has been a decrease of the impact of the Maintenance sector in the total costs of an airline, from 22.4% to 14.8%. It results from the efforts to reach the described balance, with a more efficient management of the maintenance plans, reducing downtime of aircraft and therefore the associated costs [10]. Complementing, analysis of the operational failures can lead to highly customized plans, reducing the occurrence of costly unscheduled events.

Based on this principle of reducing the impact of Maintenance costs in an airline, the motivation of implementing a methodology that allows for the analysis of operational failures on NetJets Transportes Aéreos arises, leading to more efficient and customized maintenance strategies and possibly reducing long term costs.

1.2 Objectives

The main purpose of this project is to develop and implement a methodology of failure analysis and decision making, intended to be very systematic and of generic approach to systems. This work will focus on understanding the failure modes and the risks to operation, basing further decisions regarding maintenance on these risks.

Furthermore, and as it will be applied in a real aviation scenario, individual analysis on risk-based selected items shall be performed. They will consist on understanding causes and possible patterns of failure, as well as interpreting the corrective actions performed upon failure.

It is expected that the investigation has an impact on the maintenance sector of the Company, by reducing costs in the long term. These savings can be obtained by implementing new preventive maintenance tasks or by leading manufacturers into the creation of new components to replace faulty ones. When new maintenance tasks are met as possible solutions, cost assessments need to be performed to evaluate if they are of value to the Company.

1.3 Thesis Outline

To achieve the proposed goals and objectives, this work is divided into three main chapters: the Theoretical Background, the Case Study and the Conclusions.

On Chapter 2 – Theoretical Background, the basis for the developed and implemented methodology is described. Also, context and overview on how the maintenance plans are built and implemented in aviation are approached, mainly by detailing maintenance types and their evolution with time, as well as on how the maintenance documents are organized. Finally, the methods of decision making and risk analysis are detailed, in addition to the assumptions adopted and the limitations encountered in developing the work.

On Chapter 3 – Case Study, all the work performed at NetJets is described in detail. It includes categorization and study of the available failure data, as well as processes of decision making and risk analysis for choosing the critical components in terms of failure. For each critical component, a deep analysis is performed, determining root causes and possible solutions to prevent recurrence of failure events. In some cases, where new maintenance tasks were proposed, cost assessments were also performed.

On Chapter 4 – Conclusions, the achievements obtained and the challenges occurred in this project are stated, as well as possible future related work.

Chapter 2

Theoretical Background

Maintenance represents around 14% of airlines' operational costs [8], as stated in Section 1.1. Maintenance can be defined as *a set of organized activities that are carried out in order to keep an item in its best operational condition with minimum cost acquired* [11].

The main goals of maintenance consist of: improving performance, failure diagnostic, preventing future flaws and failures, ensuring safety, maximizing operational efficiency, reducing downtime due to failure and reducing maintenance costs [12].

2.1 Types of Maintenance

Perfect systems are unattainable. They have imperfections that increase with time and usage, degrading the systems' performance during service life, leading to possible breakdowns [13]. The impact of such imperfections is measured by the Reliability, defined as the *probability that a component or system will perform a required function for a given period of time when used under stated operating conditions* [14].

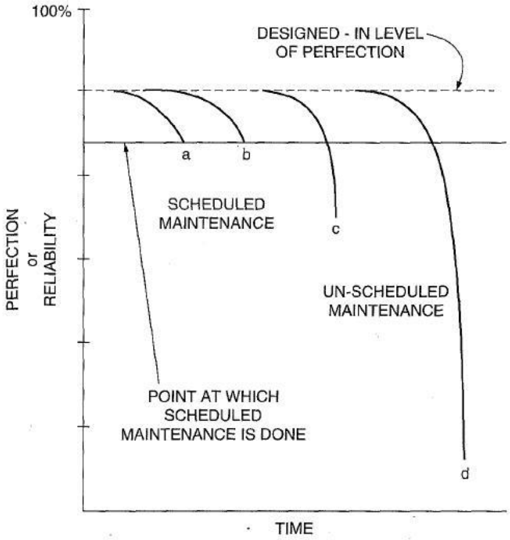


Figure 2.1: Scheduled and Unscheduled Maintenance Reliability vs. Service Time [13].

The relation between the level of reliability (vertical axis) and the service time of an item (horizontal axis) is shown in the graphic of Figure 2.1. Each curved line represents an hypothetical item subjected to degradation with time. All depicted items, from *a* to *d*, have a designed level of perfection in the beginning of their service lives, represented by the dashed line.

On one hand, items *a* and *b* suffer an expected degradation, before reaching a threshold of reliability at which time maintenance shall be performed – a scheduled maintenance event. The system is then restored to its designed level of perfection.

On the other hand, due to various factors, items *c* and *d* suffer a rapid unexpected degradation, dropping below the threshold ahead of the expected time. In these cases, the items shall be *restored in a not predetermined fixed time interval* [15] – an unscheduled maintenance event –, re-establishing the designed level of perfection.

Other than scheduled and unscheduled, maintenance can also be described in terms of the policy it is based on. As such, three different main categories for policies exist, as follows [16] [17]:

- ◇ Corrective Maintenance: mainly related with unscheduled events, it consists in the repair or replacement of components that have already failed, re-establishing the system to its normal functions;
- ◇ Preventive Maintenance: it consists in any planned maintenance action, usually performed periodically in very specific time intervals; designed to improve the service life of a system and to prevent unscheduled events by reducing the probability of failure; examples are basic actions of lubrication, cleaning or visual inspections; it is also stated as Systematic Preventive Maintenance;
- ◇ Predictive Maintenance: regards actions performed following the assessment of the status of components, via frequently monitored parameters (such as vibration or temperature); actions are performed when the parameters reach pre-determined values associated to non-ideal working states; it is also stated as Condition-Based Preventive Maintenance.

Despite both being proactive, the main difference between preventive and predictive policies is that the first is based on periodicity for tasks regardless of the component's state, whereas the latter relies on information from technology to assess if a certain component requires an action [18]. Figure 2.2 briefly summarizes the differences between the three policies.

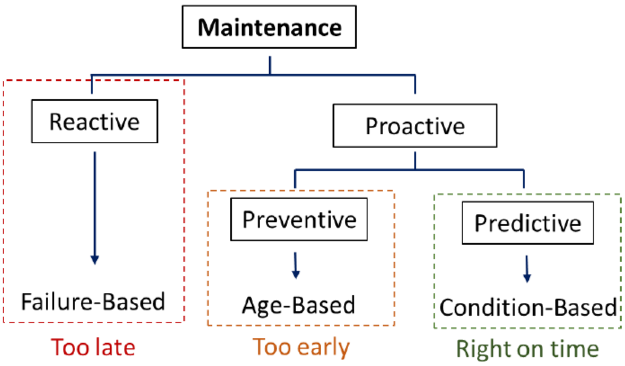


Figure 2.2: Differences on Types of Maintenance [19].

Selecting the correct policy for maintenance tasks is heavily linked with the effectiveness of the preventive maintenance and, consequently, the operational costs. The requisites for corrective and preventive maintenance must be well defined as they affect the cost of the life cycle of an item and the availability of a system. A good definition will lead to a good balance between cost and preventive maintenance actions.

Such balance is represented by Figure 2.3. Although preventive maintenance costs are usually smaller that corrective, when there is a *high frequency* of preventive maintenance activities, these will *increase the total maintenance costs* [20].

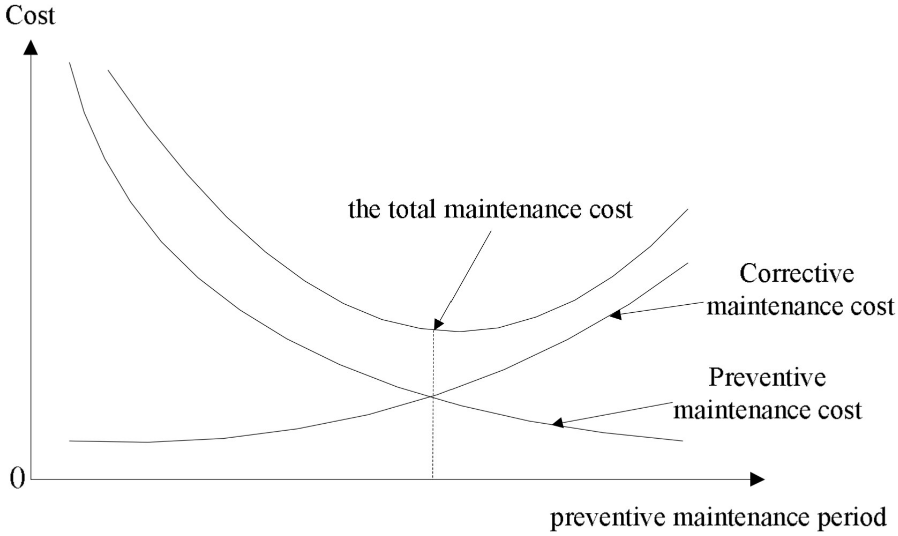


Figure 2.3: Balance between Preventive and Corrective Actions [20].

2.2 Maintenance Steering Group – MSG

Early on in aviation, the impact of systems' degradation on the safety of operations was not fully understood. As such, maintenance was solely based on two aspects: corrective actions upon failure; and replacement or overhaul at specific time intervals based on Flight Hours (FH), Flight Cycles (FC) or calendar.

With the evolution towards modern jets and the expansion of civil aviation, air transport increased and therefore higher levels of safety were required, making more robust and systematic maintenance processes necessary [6]. These would also contribute to a better operational efficiency, by reducing the downtime due to maintenance.

The introduction of the new aircraft Boeing 747 exposed such necessities [21]. Therefore, in 1966 and 1967, Boeing arranged several meetings with industry representatives: International Air Transport Association and Air Transport Association (IATA and ATA, from airlines), Airports Operators Council International (from airport operations) and Aerospace Industries Association (from aircraft manufacturers). The group became known as the Industry Working Group [22].

2.2.1 MSG-1 and MSG-2

From the meetings resulted the first handbook MSG-1 (named *Maintenance Evaluation and Program Development*), released in 1968. It included logic procedures of decision making in order to develop scheduled maintenance on the Boeing 747-100 [21]. *This was the first attempt at applying reliability centered maintenance concepts when developing an aircraft maintenance program* [23]. Three main maintenance principles were then introduced: Hard Time (HT), On-Condition (OC) and Condition Monitoring (CM).

In 1970, an updated version of the document was released, eliminating specific procedures of the 747, making it more generic. The *Airline/ Manufacturer Maintenance Program Planning Document*, or MSG-2, was used to develop the maintenance plans of the DC-10 and L-1011 (Lockheed TriStar) [23].

The MSG-2 philosophy is parts-driven and bottom-up, focusing on specific items instead of the whole system. It is also process-oriented, in which the HT/OC/CM principles are used to describe inspection tasks [21] [24]. These can be described as such:

◇ Hard Time Limit (HT): *maximum interval* to perform a maintenance task, mainly applied to overhaul and also *to total life of parts or units* [25];

◇ On-Condition (OC): periodic and *repetitive inspections or tests* in order to evaluate the *condition of units or systems or portions of structure* [25] [26]; considered as preventive maintenance;

◇ Condition Monitoring (CM): when HT limits are not necessary neither OC is the primary maintenance process; it is *accomplished by appropriate means available to an operator for finding and resolving problem areas*, with *no specific monitoring system implied for any given unit* [25].

Condition Monitoring is not considered to be a preventive maintenance process, as *it allows failures to occur*, although not allowing *a direct adverse effect on operating safety*. Under CM, *no services or checks are programmed to determine integrity or serviceability, however the mechanical performance is monitored and analyzed* via some *operating characteristic of the equipment* [27].

2.2.2 MSG-3

In 1979, and upon the development of new aircraft (namely the Boeing's 757 and 767), an ATA task force identified several flaws on the MSG-2 philosophy, mainly:

◇ No distinction between safety or economic reasons for maintenance [23] [27];

◇ Demanding individual tracking of several components [27];

◇ Unable to cope with more complex aircraft systems [27];

◇ No addressing of regulations on damage tolerance and fatigue evaluation of structures [27].

As such, in 1980, the *Operator/Manufacturer Scheduled Maintenance Development*, or MSG-3, including a full review of the MSG-2 procedures based on the results of a decade of usage.

The MSG-3 philosophy is top-down and task-oriented, analyzing system failure modes from a system level, instead of focusing on single components [21]. As a consequence, there is *no need for a routine maintenance activity* if a *functional failure of a particular system* has no negative impact *on operational safety* or no negative *economic repercussions* [27].

Under MSG-3, the logic of decision making also leads to a more rational process of task definition, with a concern to approach the consequences of a failure [23]. As such, the idea of Maintenance Significant Items (MSI) arises, defined as items that [28]:

- Might affect safety (airborne or on-ground);
- Are undetectable during operation;
- Have significant operational impact;
- Have significant economical impact.

A functional failure is, therefore, categorized by its consequence, being included in one of two basic categories: Safety or Economic. Later on, and based on the failure visibility for the crew, failures were also subcategorized as evident or hidden. As such, and according to the MSG-3 document [29], five categories are defined for the risk of failure assessment, described as follows:

- Cat. 5 – Evident Safety: Failures that are evident for the crew and that have a direct adverse effect on operating safety;
- Cat. 6 – Evident Operational: Failures that are evident for the crew and that have a direct adverse effect on operating capability, not compromising safety;
- Cat. 7 – Evident Economic: Failures that are evident for the crew and that only have a direct economical adverse effect, not compromising operating capability and safety;
- Cat. 8 – Hidden Safety: Failures that, when alone or combined with other failures, have a direct impact on operating safety, but that are not detectable during normal aircraft operation;
- Cat. 9 – Hidden Non-Safety: Failures that are not detectable during normal aircraft operation and, when alone or combined with other failures, don't have a direct impact on operating safety.

A flowchart overview on the Failure Effect Categories (FEC) is found on Figure 2.4. The FEC analysis systematized the assessment of failures and allowed for a more rigorous task selection process. Consequently, maintenance procedures became more efficient with the exclusion of non-significant items from the analytical process [30].

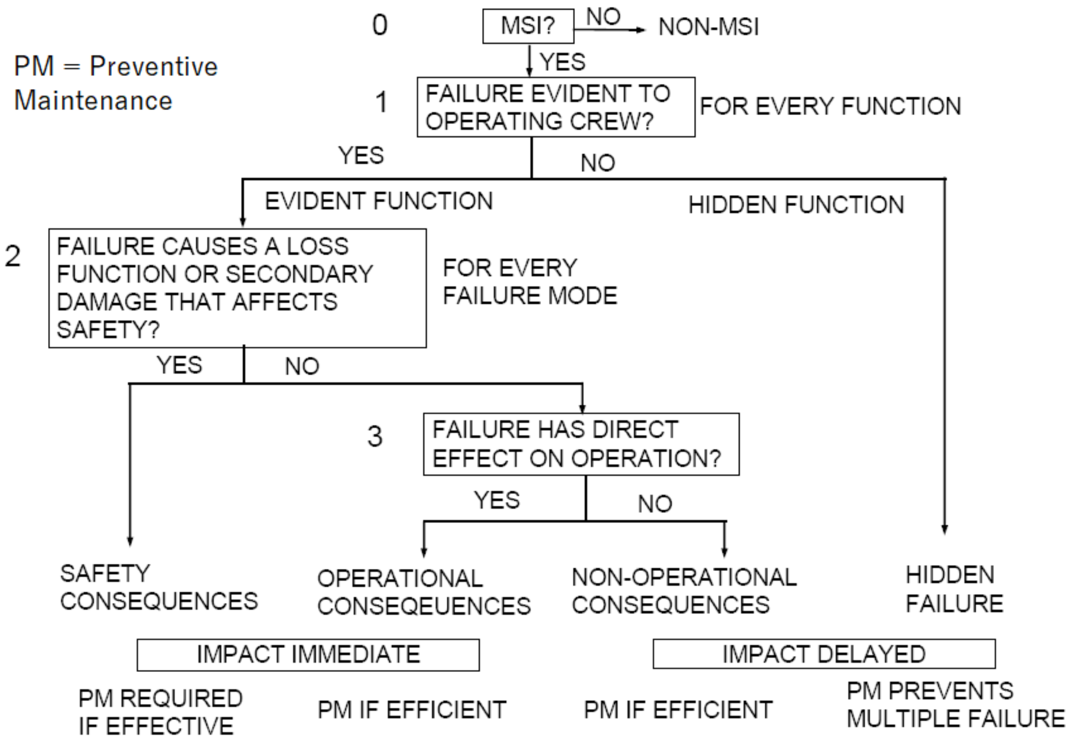


Figure 2.4: MSI and Failure Effect Categories Flowchart [31].

2.2.2.1 Development of the Scheduled Maintenance

Before an aircraft is brought into service, its scheduled maintenance strategy has to be defined, containing the required tasks necessary to maintain the airworthiness of an aircraft [30].

These tasks are the basis for the emission of the Approved Aircraft Inspection Program (AAIP), which helps guide the maintenance policy of each aircraft. Further adjustments can be performed for each individual operator in order to include unique operational and/or environmental factors [27]. According to the US Department of Transportation [32], the main goals of the AAIP are:

- *To ensure realization of the design level of safety and reliability of the equipment;*
- *To restore safety and reliability to their design levels when deterioration has occurred;*
- *To obtain the information necessary for design improvements of those items whose design reliability proves inadequate;*
- *To accomplish these goals at a minimum total cost, including maintenance costs and the costs of residual failures.*

With these four goals, scheduled maintenance solely does not correct eventual aircraft inherent faults regarding the levels of safety and reliability, only being able to prevent their deterioration. If these are shown to be unsatisfactory, project modifications are required for their correction [33] [34].

According to MSG-3, there are five main groups of maintenance tasks, as follows [15] [35]:

- With the intent of *maintaining the inherent design capabilities*, Lubrication – the act of *replenishing oil, grease, or other substances*, reducing friction or conducting away heat – and Servicing – *attending basic needs of systems or components*;
- With the intent of determining if an *item is fulfilling its intended purpose*, Operational Check and Visual Check are both failure-finding tasks and do not require quantitative tolerances;
- Functional Check – a quantitative check in order to determine *if each function of an item performs within specified limits* – and Inspection – examination of an item by comparing it *against a specific standard*; there are three levels of inspections:
  - General Visual Inspection (GVI): visual inspection by human eye (such as detecting apparent leaks or damage to the structure);
  - Detailed Inspection: intensive visual inspection of a specific detail, assembly or installation using adequate lighting and, if necessary, inspection aids as mirrors or hand lenses;
  - Special Detailed Inspection: intensive examination of a specific location with special techniques such as non-destructive inspections;
- Restoration – performing all the necessary work so that an item is brought up to its specific standard; it may vary from cleaning a unit, replacing a single part or even a complete overhaul;
- Discard – the *removal from service of any item at specified life limit*.

Although these tasks are mainly used in scheduled maintenance, they can also be used in additional non-scheduled events, in order to *restore the aircraft to an acceptable condition* [35]. These are currently being replaced by the Aircraft Health Monitoring, predictive maintenance relying on sensors and data transmission to optimize maintenance, increasing reliability and decreasing maintenance costs and needs for preventive maintenance [36] [37].

Additional tasks and requirements can be part of the AAIP, such as Service Bulletins (SB) and Airworthiness Directives, being incorporated by the operators. The most common requirements of an AAIP are shown in Figure 2.5. The Vendor Manuals englobe the Aircraft Maintenance Manual (AMM), Illustrated Parts Catalogue and Engine Maintenance Manual (EMM), used on the Case Study on Chapter 3.

To be efficient, a maintenance program will only schedule the *tasks necessary to meet the stated objectives*. The inclusion of other additional tasks *will increase maintenance costs without a corresponding increase in reliability protection* [36].

NetJets also uses the concept of Engineering Orders (EO). These are in place when technical unforeseen problems that occurred during operation are to be tackled, via an additional requirement of inspection. Changes to the AAIP imply slow bureaucratic work, requiring the approval of an aeronautical airworthiness authority (such as ANAC in Portugal). As EOs only require operator approval, these are a faster method to add maintenance tasks and procedures to the maintenance plan, in conjunction with the AAIP. EOs can be applied to individual aircraft, a specific fleet or the entire NetJets' fleet.

In order to produce an EO, the following items need to be defined:

- Recurrence: *when* shall the tasks be performed?
- Scope: *what* tasks are to be performed and *how*?
- Resources: how much do the tasks *cost* and how much *time* is required to perform them?

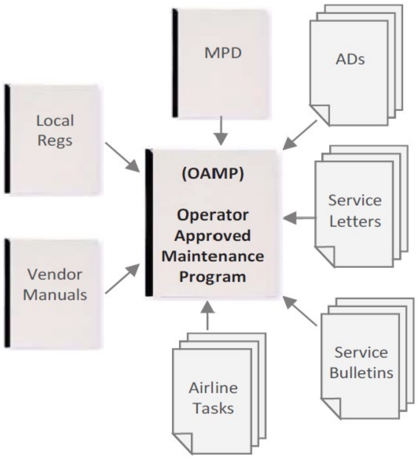


Figure 2.5: Inputs to an AAIP [27].

2.2.3 RCM *vs.* MSG-3 in Aviation

Reliability Centered Maintenance (RCM) is a strategy created to develop *optimum maintenance plans*, by defining *tasks to be performed in achieving, restoring, or maintaining the operational capability of a system or equipment* [38] and also to eliminate tasks that have been proven inefficient with time.

The MSG-3 philosophy is based on the RCM's, but is applied specifically in aviation and aeronautics [23]. As such, the MSG-3 analysis is superior to the more broad-used RCM programs on commercial and military aircraft [39], as:

- MSG-3 has been *evolving for the past 35 years* and was created exclusively for aircraft [39];
- MSG-3 incorporates a *simple and concise inspection convention with standard and enhanced zonal inspections* [39];
- MSG-3 integrates hierarchical maintenance concepts, leading to a better optimization of aircraft downtime by *facilitating a shift of structural inspections to later intervals* [39].

Also, MSG-3 *moves systems' inspections to lower level inspection intervals, significantly improving aircraft reliability and availability* [39].

Although the latest MSG-3 methodology *implicitly incorporated the principles of RCM to justify task development*, it did not implement the RCM criteria *to audit and substantiate the initial tasks being defined* [23] [40].

2.3 Computerized Aircraft Maintenance Programs – CAMP

CAMP is a management system for the maintenance plans of aircraft. It includes Maintenance Management, Inventory Management, Flight Scheduling and Engine Health Monitoring [41].

CAMP Maintenance Tracking includes a very large database of aircraft maintenance requirements, such as the latest revisions of Maintenance Manuals, Maintenance Planning Documents, Illustrated Parts Manual, Regulatory Airworthiness Directives and Service Information. Such database allows CAMP to assure the highest level of safety and compliance for an aircraft.

To maintain the operational standards of an aircraft's engines, as a vital part of an aircraft, CAMP includes an Engine Health Monitoring (EHM) sector. For this, CAMP makes use of all data collected by the on-board computers, from which crew-hidden faults or trends can be identified before failures occur. As such, preventive actions can be performed when deemed necessary to avoid corrective actions.

Figure 2.6 is an example CAMP's EHM sector, including information regarding the fleet and aircraft registration, engine serial number, as well as the date, duration and the EMM code of the event.

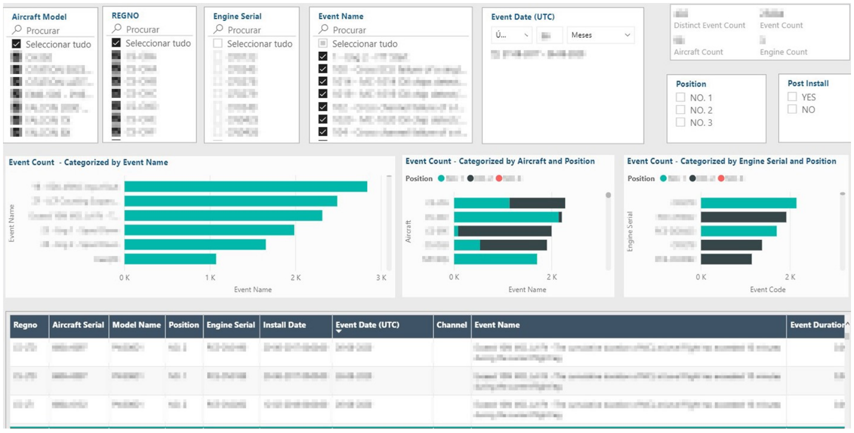


Figure 2.6: Example of the Engine Health Monitoring sector on CAMP [41].

2.3.1 Fault vs Failure

Fault and Failure are both concepts that will be used throughout the Case Study. Therefore, it is important to understand the differences.

A fault is an anomaly (a difference to the normal condition) that has been detected by an aircraft's sensor. It generally appears to the crew as a code on the on-board computer (and that can be later downloaded by maintenance technicians).

A failure is the outcome of one or multiple faults that were not attended in time (variable, depending on the fault), producing consequences that affect the normal operation of the aircraft. Failures usually ground the aircraft, either immediately or upon landing, depending on the severity.

2.4 ATA 100 Numbering Criteria

Aviation companies and manufacturers base the numbering system of technical publication on the ATA 100 (Air Transport Association Specification Number 100) [42].

ATA 100 includes the norms to present technical data of aircraft, engine and manufacturer components, uniformizing information between manufacturers and all maintenance personnel.

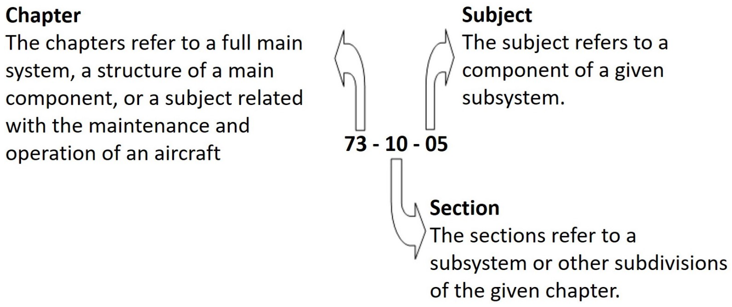


Figure 2.7: ATA 100 Reference Number.

The ATA 100 reference number consists on three elements of two digits each, as shown on Figure 2.7: the Chapter, the Section and the Subject. The ATA 100 system also divides the main system or function of the aircraft into a group of chapters, as per Table 2.1.

Section	Chapters
Introduction	0
General Aircraft Group	5 – 12
Systems Group	20 – 49
Structures Group	51 – 57
Engines	70 – 80

Table 2.1: Groups of Chapters on ATA 100 [43].

The first three digits are ATA's responsibility whereas the following digits are defined by the manufacturer. As an example, the task represented on Figure 2.7 can be split into the following:

Task	Description
73	Engine – Fuel and Control
73 – 10	Fuel Distribution
73 – 10 – 05	Fuel Shutoff and Drain System

Table 2.2: Example of an AMM Task.

2.5 Mean Time Between Failure

The Mean Time To Failure (MTTF) is the average of times of failure of a certain component (or components in a certain sample) [44]. As in aviation several components can be overhauled and reinserted into operation, a Mean Time Between Failure (MTBF) is more appropriated. The calculus of MTTF and MTBF is equal.

Considering the useful life models and assuming that the components behave as such (translating into a constant failure rate λ), the MTBF can be calculated by inverting the failure rate [44]:

$$MTBF = \lambda^{-1} \tag{2.1}$$

As the components are replaceable (*with replacement* scenario), the failure rate of a certain component is calculated by dividing the total number of failures (ΔN_f) by the total service time ($\Delta t^{\star}$) in which those failures occurred [44]. In this work, the total service time of a component is a result of the number of years in service (Y), the average aircraft flying hours per year ($\overline{FH}$) and the number of aircraft in the fleet ($N_{A/C}$), as follows:

$$\Delta t^{\star} = Y \times \overline{FH} \times N_{A/C} \tag{2.2}$$

As such, and considering the specific conditions of constant failure rate and *with replacement* scenario, the MTBF can be obtained by dividing the total operational experience time by the number of failures occurred [44] [45]:

$$MTBF = \Delta t^{\star} \times \Delta N_f^{-1} \tag{2.3}$$

2.6 Decision Making

Every failure has a reason for occurring and a Root Cause Analysis (RCA) is a powerful tool to *analyze failures and problems down to their root cause* [46]. As a consequence, instead of only managing the consequences of a failure, with an RCA, measures can be proposed to reduce its probability of occurring again.

The investigation is built upon several steps, as such [46]:

- ◇ *Step 1* – Problem Definition and Data Gathering: collect as much information possible regarding a failure such as: conditions of the occurrence (before, during and after) and environmental factors. Some questions shall also be answered, for example: *What happened and what are the symptoms?* ; *When and during what phase did it happen?* ; *Where and within what equipment failed?* ; *What happened during the incident and what was its outcome?*;

- ◇ *Step 2* – Cause and Effect Analysis: after answering the questions on Step 1, the causal factors (major contributors to the problem) must be discovered;

- ◇ *Step 3* – Root Cause Identification: several causal factors, with several root causes each, can be possible; its identification may lead to possible solutions in order to reduce the number of events;

- ◇ *Step 4* – Corrective Actions Effectiveness Assessment: generating recommendations or solutions for preventing similar incidents from happening again, with preventive or corrective actions possibly being established; also, risk and cost assessments may be performed.

2.6.1 Pareto Diagram

To focus the scope of an analysis, the important data must be selected with the help of a quality control tool such as the Pareto Principle. It states that 80% of problems occur due to only 20% of the causes [47]. The principle can be translated into a chart.

A Pareto Chart is a bar graph, with the height of the bars reflecting the frequency of problems or causes. These bars are ordered from left to right in a *descending order of height*, implying that the causes on the left contribute more to incidents than those on the right. As such, efforts can be focused on the important factors, possibly leading to maximum returns [46].

It can be used in two work stages: early in the study, in order to identify the problems that should be analysed first; further along, to *narrow down which causes of the problem to address first* [46]. Figure 2.8 serves as an example of a Pareto Chart.

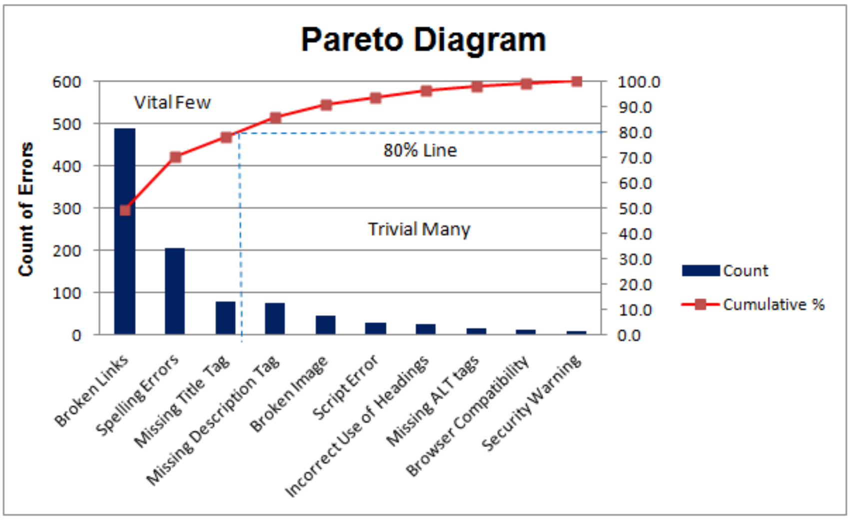


Figure 2.8: Example of a Pareto Chart [48].

The 80/20 rule is presented with the help of the dashed line: the first three causes are responsible for nearly 80% of the the incidents, whilst the other causes are only responsible for the remaining 20%. Even though these numbers might not always be exact, the idea remains: a large percentage of incidents occurs due to a small percentage of causes.

2.6.2 Risk Analysis

In addition to the Pareto's Diagram, that relies only on the count of events and contribution to a total, a Risk Analysis shall be performed. This relies on understanding the hazards to the operation upon failure of selected components.

As stated on Section 2.2.3, the MSG-3 process is the subpart of RCM specific for aviation [39]. Therefore, a legitimate approach to perform the Risk Analysis is to understand how it is performed under

RCM.

The Failure Mode, Effects and Criticality Analysis (FMECA) is used to prioritize the risk of failures. It consists on a *logical method that ranks the risks*, helping with focusing on the items that *can cause the greatest problems and, therefore, greatest costs* [49]. Upon selection of the failure modes, these can be rated according to three different features [50], as follow:

- Detection (D): the probability of detecting a failure previous to realizing its effect;
- Severity (S): the possible consequence of the failure to the operation;
- Occurrence (O): the frequency or probability of occurring a failure (mostly related with MTBF).

With a combination of these three factors, a Risk Priority Number (RPN) can be calculated and several items can be compared via their respective RPNs, as the numbers are dimensionless: the higher the RPN, the higher the consequences to the operation [51]. The Detection, Severity and Occurrence are each assigned with a number from 1 to 10 [49] [50]. The RPN is obtained by multiplying the three numbers, as follows:

$$RPN = D \times S \times O \tag{2.4}$$

An event Detection is defined as the ability of tracing the undesired event or failure. This detectability is heavily linked with the controls and mechanisms to identify a failure or cause of failure [51]. The higher the number, the more difficult it is to detect a failure. For example, a temperature sensor can easily identify a sudden temperature variation, being a high detectability event, corresponding to a low Detection number. Table 2.3 details the ranking of Detection [52].

The Severity ranking will not be based on the MSG-3 Failure Effect Categories (described in Section 2.2.2). Instead, the ranking will be based on the Standardized Aircraft Event Hazard Levels for the Propulsion System and Auxiliary Power Unit (APU), established by the Federal Aviation Administration (FAA). It consists of 5 levels of hazard, based on the consequences that a possible failure can have on the operation, either to the aircraft or to the passengers and crew [53] [54]. They are as follow:

- Level 1 – Minor Consequences;
- Level 2 – Significant Consequences;
- Level 3 – Serious Consequences: *any event involving the operation of an aircraft other than an accident where the event, or the event coupled with any other reasonably probable second event, has the direct potential to result in an accident* [54];
- Level 4 – Severe Consequences;
- Level 5 – Catastrophic Consequences: resulting in *multiple fatalities, usually with the loss of the airplane* [53].

Each level has possible consequences of an event described (check references [53] and [54]). For each event that occurs in the analysed fleets, in order to select the hazard level, it is important to know the consequences of a failure.

In order to apply these concepts into the Risk Analysis, the hazard levels have to correspond to Severity numbers. As such, Table 2.4 has the correspondence between both categorizations. The first method consisted in each hazard level corresponding to two Severity levels. But Level 1 events are extremely common in aviation, therefore is is understandable that more discretization is required. As Level 5 events are extremely rare, less discretization is necessary. As such, Level 1 hazard levels correspond to the first three Severity levels, whereas the Level 5 hazard level correspond to the ultimate Severity level.

Definition	Detection
Almost Certain	1
Very High	2
High	3
Moderate-High	4
Moderate	5
Low	6
Very Low	7
Fairly Remote	8
Remote	9
Very Remote	10

Table 2.3: Failure Detection Ranking [52].

FAA Hazard Level	Severity
Level 1	1
	2
	3
Level 2	4
	5
Level 3	6
	7
Level 4	8
	9
Level 5	10

Table 2.4: Failure Severity Ranking.

The Occurrence factor is heavily linked with the MTBF of the components of the selected fleets, as it is a measure of the frequency of the failures. A high value of MTBF will correspond to a low level of Occurrence, and vice-versa. As such, in order to have a uniform criteria for the Occurrence, it is necessary to analyse the failure data of both fleets and reach a consensus. Table 3.2 details the Occurrence's levels.

2.7 Methodology

As stated before, the purpose of this project is to improve the maintenance plans of selected aircraft fleets. For that, a general methodology had to be created.

Considering the theoretical background, the methodology consists of several steps, so that there is a systematic approach to any possible study, as follows:

- *Step 1* – Fleets and Main System Selection: the aircraft fleets and major sections of each fleet shall be selected to be analysed (for example, fleet of Cessna Latitude and engine section);

◇ *Step 2* – Data Collection and Categorization: all data related with failures of the selected section shall be compiled, as well as organized according to parameters that will support the study later on (Corrective Action as an example of a parameter);

◇ *Step 3* – Decision Making and Pareto Analysis: to focus the investigation on important subsystems, the exclusion of those that don't contribute to a certain amount of the total failures is essential; also, this will reduce the workload and time consumed on further steps;

◇ *Step 4* – Data Analysis: understand all items that caused failures on each subsystem, how many failures occurred as well as the respective corrective actions taken;

◇ *Step 5* – Risk Analysis and Critical Items Selection: each item that failed is assessed on the values of Detection, Severity and Occurrence, with consequential calculus of the Risk Priority Number; the critical items (with highest values of RPN) shall be selected for further analysis; the number of items selected depends on the available time-frame of the project;

◇ *Step 6* – Critical Item Analysis and Potential Solution Finding: in each selected critical item, all events shall be analysed, as well as detecting related tasks on the maintenance plans; furthermore, possible solutions shall be drawn (either via maintenance tasks or the manufacturer); cost analysis on new (or improved) maintenance tasks shall also be performed.

2.8 Assumptions and Limitations

NetJets is divided into the European (NJE) and the American (NJA) branches, with the scope of the project being on NJE. But as NJE has a substantially smaller aircraft fleet than NJA, analysis of NJE's failure data might not always show potential failure patterns or failures that have yet to occur.

As such, and as the fleets of both branches have the same configuration, an assumption was made to consider that NJA and NJE have a similar operation. As a consequence, possible differences on environmental factors or airport locations were disregarded, that can have potential impact on the types of failure.

With this assumption, all failures can be analysed, resulting in a larger data pool, possibly leading to more failure patterns and maintenance outcomes.

The cost values for the corrective actions and also for the time an aircraft was grounded were not provided. With this limitation, the only cost assessments performed are related with the proposed EOs and preventive maintenance tasks. As such, a comparison between costs of the proposed preventive maintenance and corrective actions was not performed.

Chapter 3

Case Study

3.1 NetJets Transportes Aéreos, S.A.

NetJets Inc., formerly Executive Jet Aviation, was founded in 1964 as the first private business jet charter and aircraft management company in the world. Figure 3.1 shows a timeline of the history of the Company.

Its subsidiary was launched in Europe in 1996 and, backed by Warren Buffett's Berkshire Hathaway, the Fractional Ownership Program provides unmatched freedom and flexibility – all the advantages of owning a private jet, without having to maintain one.

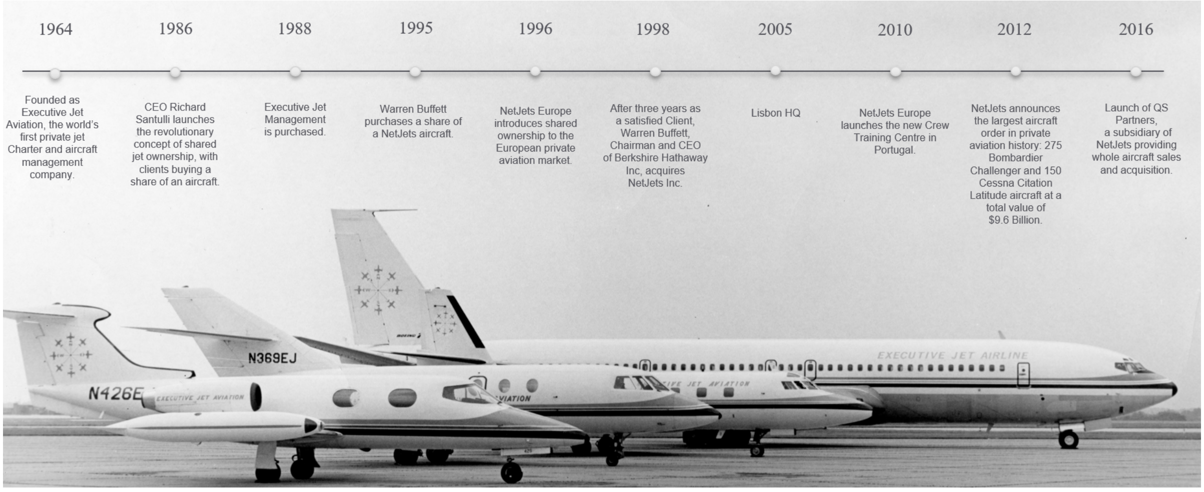


Figure 3.1: Timeline of the History of NetJets [55]

NetJets sells fractions of specific aircraft, chosen from several available types at the time of purchase. Owners then have guaranteed access (50–400 hours annually, depending on share size) to that aircraft with as little as four hours' notice. If the owner's aircraft is unavailable for some reason, another aircraft of the same type, or a larger aircraft, will be provided [55].

As of now, NetJets is divided into two main branches: NetJets Aviation (NJA), based in Columbus, Ohio, and that operates all aircraft in the NetJets US fleet; NetJets Europe (NJE), based in Lisbon, Portugal, and that operates all the European registered fleet.

NetJets has the largest private jet fleet both globally and in Europe, with more than 650 aircraft worldwide and around 100 in Europe.

3.2 Fleet and Main System Selection

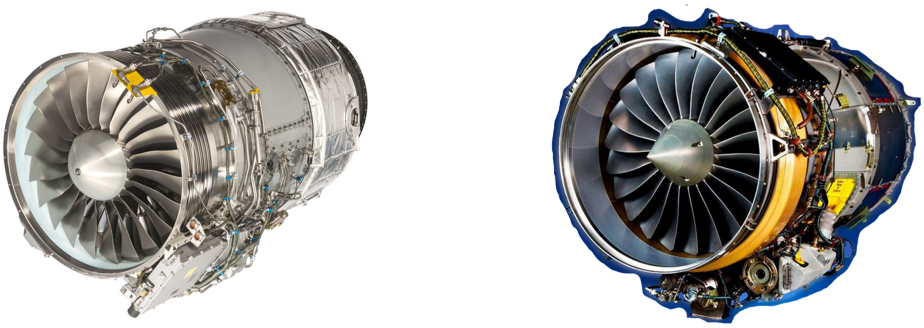
The first step regarding the Case Study is to select the Fleets and Main System to be studied. One of the Company's requirements was to make use of CAMP to improve the maintenance plans. As such, the selected fleets have to be fully maintenance tracked on CAMP.

Another consequence of the usage of CAMP is on the selection of the Main System. As CAMP is a very complete Engine Condition Trend Monitoring, it makes sense that the general system selected for analysis is the Powerplant, specifically the engines.

Based on the previous conditions, two engines are good candidates for analysis: the *Pratt and Whitney's PW306D1* (on Figure 3.2c) and also on the *Honeywell's HTF7350* (on Figure 3.2d). These power the Cessna Citation Latitude (on Figure 3.2a) and Bombardier Challenger 350 (or CH350; on Figure 3.2b), respectively, making these the selected fleets.

(a) Cessna Citation Latitude [56].

(b) Bombardier Challenger 350 [56].



(c) PW306D1 Engine [57].

(d) HTF7350 Engine [58].

Figure 3.2: Analysed fleets and corresponding engines.

Regarding the Risk Analysis that will be performed in each of the fleets, it is important to understand that all components of the Engines are Maintenance Significant Items as at least one of the parameters explained in Section 2.2.2 is fulfilled. As all share this property, and there are no non-MSI components, no selection of Categories to be analysed will be performed based on it.

3.3 Data Selection and Systematization

Data related to engine failures is not stored in just a single file, as it involves information from maintenance tracking, crew reporting, among others. Therefore, for systematization, all the data had to be collected into a single file.

To start, and with the help of a tool named OMI, data from the maintenance tracking system *Maintenix* (MXi) was downloaded in the form of an Excel Spreadsheet. This includes all details related with maintenance of the fleets, as seen on Figure 3.3, with the most relevant for this project being:

- the Work Order (WO) and corresponding WO type (check Table 3.1 for the most relevant types for this case study);
- the Aircraft Registration and Type/Model;
- the Airframe and Engines Flight Hours;
- the Discrepancy, being the reason why the WO was issued in the first place;
- the Corrective Action performed in order to resolve the issue;
- the Date of occurrence (both of the discrepancy and corrective action);
- the Part Description, Part Number (P/N), Serial Number (S/N) and Action Performed of the affected parts (for example, if any were swapped or removed/installed due to the corrective action).

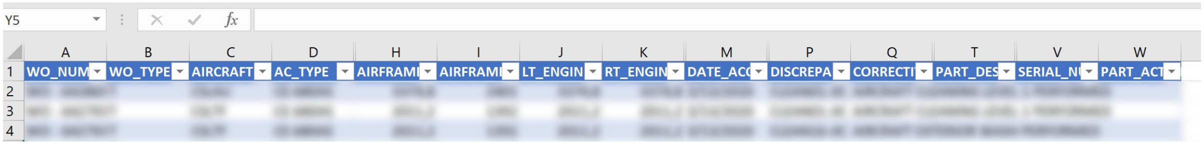


Figure 3.3: Example of data extracted from MXi.

Acronym	Type of WO	Brief Description
I	Inspection	Due to the AAIP or a small event that occurred.
JIC	Job Information Card	With instructions on what and where to do.
U	Unscheduled	Due to a non-scheduled event.

Table 3.1: Relevant Work Order Types.

The differences between a Part Number and a Serial Number are as such: the first uniquely identifies a specific design of a part or assembly (which may or may not account for variations or optional features), whereas the second uniquely identifies a single specific unit (the number in the sequential series of production).

Some faults, due to its simplicity or because they don't produce a failure event, don't require proper inspection. Therefore, these are not registered on MXi, although reported by flight crew. The reports can lead to more thorough investigations if there are several minor faults that constitute a pattern. As such, these were added to the data collection.

The data collected so far is connected with NJE alone. Analysing data from both branches (NJA and NJE) would not be viable in the time frame of this case study, as NJA has six times more aircraft than NJE. If more information is required to consolidate a failure pattern, NJA's data regarding similar failures can be collected via the OMI.

To be stated that all data collected dates from the beginning of operation of every aircraft (each registration) until the 2^{nd} of March of 2020, the internship's starting date in which this case study was developed.

The following step is to organize the collected data. Some of the columns described in Figure 3.3 are selected to be a part of a new spreadsheet, such as: the Date, Aircraft Registration, Discrepancy (now named Reported Failure), Corrective Action and Engine FHs. The WO Type is also selected but with slight differences: instead of the acronyms stated in Table 3.1, *Scheduled* and *Unscheduled Events* are used.

So that a process of Decision Making can be performed, either according to Pareto or with a Risk Analysis (check Section 2.6), the failure events require a categorization. For that, two columns were added:

- ◇ Failure Category: based on the ATA 100 chapters and on the description of the failure;
- ◇ Corrective Action Category: based on the description of the affected item and performed action.

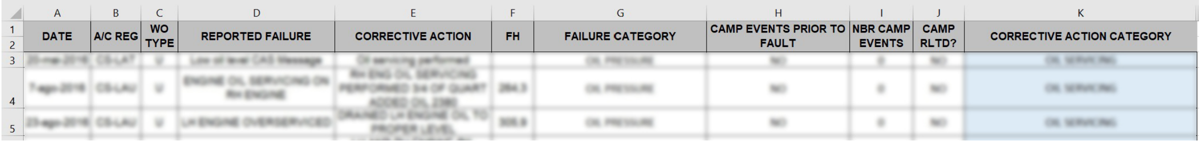
Information collected on CAMP shall also be displayed on the sheet, as it can help correlate faults with failure events. As such, three related columns were included:

- ◇ CAMP Fault Codes Prior to Failure and Number of CAMP Fault Codes: state all faults that occurred in a time frame prior to the failure – the EMM fault code, corresponding meaning and the number of times that each code occurred;
- ◇ CAMP Related?: if the events are (or not) related to the Failure and the Corrective Action categories.

The CAMP Fault Codes that were used in the Case Study are shown on Appendix A: Table A.1 for the Latitude and Table A.2 for the Challenger 350.

One month was concluded to be the most appropriate time frame for an analysis on the fault codes, based on field and practical experience of the maintenance team.

Figure 3.4 shows how all the described categories are displaced on the new spreadsheet.



A	B	C	D	E	F	G	H	I	J	K
DATE	A/C REG	WO TYPE	REPORTED FAILURE	CORRECTIVE ACTION	FH	FAILURE CATEGORY	CAMP EVENTS PRIOR TO FAULT	NBR CAMP EVENTS	CAMP RLTD?	CORRECTIVE ACTION CATEGORY

Figure 3.4: Example of the new spreadsheet.

3.3.1 Risk Analysis Occurrence Parameters

With a quick analysis of both fleets' data, the MTBFs were calculated for all items. Based on these, and also on the operational times of both fleets, a uniform criteria was decided, as detailed on Table 3.2.

Interval [EngFH]	Occurrence
MTBF $\geq$ 36 000	1
32 000 $\leq$ MTBF $<$ 36 000	2
28 000 $\leq$ MTBF $<$ 32 000	3
24 000 $\leq$ MTBF $<$ 28 000	4
20 000 $\leq$ MTBF $<$ 24 000	5
16 000 $\leq$ MTBF $<$ 20 000	6
12 000 $\leq$ MTBF $<$ 16 000	7
8 000 $\leq$ MTBF $<$ 12 000	8
4 000 $\leq$ MTBF $<$ 8 000	9
MTBF $<$ 4 000	10

Table 3.2: Failure Occurrence Ranking.

These values will be used on both the Latitude and Challenger 350 fleets. As the criteria is uniform, the RPN values of both fleets can be compared later on.

3.4 Latitude Fleet

As stated on the previous section, the Failure Categories are created to be as broad as possible and are mainly based on the ATA 100 Chapters (check Section 2.4). For an initial further knowledge on the system, some subcategories were also included, being these based on the Latitude's EMM.

As such, detecting the units (or items) that are most prone to failure (and therefore increasing maintenance costs) will be possible. The categories are as follow:

- Bleed Air System: includes malfunctions on the *Engine Bleed Valves* and also on the *Anti-Ice System*;
- Engine Fuel and Control System: includes *Fuel System*, *Fuel Filter* and *ECTM No Transmit* malfunctions, as well as *Engine Dispatch Limited Messages* (Section 3.4.1 with further information);

- Engine Indicating System: includes *Incorrect Engine Temperature* indications;
- Exhaust System: includes malfunctions on the *Thrust Reversers*;
- Fire Protection System: includes *Fire Detector Warnings*;
- Ignition System: includes *Engine No Start*, *APU No Start*, as well as other *Engine Ignition* malfunctions;
- Oil System: includes *Oil Pressure* (for example, leaks or overservicing) as well as *Oil Filter* malfunctions;
- Structural Damage: includes external impacts of *FOD or Birdstrike*, *Internal and External Structure Damage* (for example, broken duct or damaged pylon), *Engine Vibration* and *Corrosion*.

3.4.1 Fault and Aircraft Dispatch

Not all faults lead to the same outcome when it comes to dispatching an aircraft, due to the severity and risk of said outcome. Therefore, the PW306D/D1 engine FADEC system is equipped with Time Limited Dispatch (TLD) capability to permit Short Term Dispatch and operation in the presence of certain detected faults. The dispatch TLD message is enunciated by the aircraft's EICAS avionics.

According to the Latitude's EMM [59], the operational status consists of:

- No TLD message: dispatch and operation permitted with no limitation;
- Short Term Dispatch: dispatch and operation permitted up to 125 flight hours before faults are rectified;
- No Dispatch: dispatch for flight is not permitted until faults are rectified.

3.4.2 Maintenance Time Intervals

On the Latitude, scheduled maintenance is mostly performed with a recurrence of 800 or 1200 flight hours, as shown on Figure 3.5. They coincide every 2400 flight hours. For naming purposes, they were called inspections α and β.

Figure 3.5: Latitude's Maintenance Recurrence Hours.

3.4.3 Data Processing

After all data has been collected and analyzed, the next step is to process it. With the help of the Pivot Table tool on Microsoft Excel, categories were counted and results are displayed.

To start, it is important to understand how the failures are distributed per engine systems. As such, Table 3.3 details the Failure Category, corresponding Failure Subcategories, the Total Events per Subcategory and the Total Events per Category.

Failure		Sub-Total	Total
Category	Subcategory		
Engine Fuel and Control System	Engine Dispatch Limited Message	21	39
	Fuel Filter	9	
	ECTM No Transmit	6	
	Fuel System	3	
Oil System	Oil Pressure	21	24
	Oil Filter	3	
Structural Damage	FOD or Birdstrike	10	15
	Corrosion	2	
	Internal or External Damage	2	
	Engine Vibration	1	
Ignition System	Engine No Start	12	13
	APU No Start	1	
Exhaust System	Thrust Reversers	11	11
Bleed Air System	Anti-Ice System	4	8
	Engine Bleed Valves	4	
Engine Indicating System	Incorrect Engine Temperature	5	5
Fire Protection System	Fire Detector Warnings	2	2

Table 3.3: Latitude's Failure Category and Number of Events.

There is a total of 117 events concerning all categories, with these not contributing evenly for the total. For example, the Engine Fuel and Control System Failures correspond to over 30% of the total amount of events, whereas the Fire Protection System Failures contribute with less than 2%.

Before proceeding, and after a quick review of this preliminary data with the Company's maintenance managers, some Categories or Subcategories were excluded from further analysis. These, as well as the reasons for exclusion, are as follow:

- ◇ ECTM No Transmit Subcategory: mainly due to mobile carrier unpreventable issues;
- ◇ Structural Damage Category: mostly due to damage occurring after sporadic Birdstrikes or FOD Impacts, having no effect on preventive maintenance practices.

With the exclusion of the two categories, there is now a total of 96 events available for analysis.

Pareto's idea, as explained in detail in Section 2.6.1, stated that 80% of the failures are due to only 20% of the causes [47]. These are reference values and might not be followed strictly, but the idea remains: a high number of failures is caused by a small number of causes.

With this idea in mind, a consensus was reached in order to select which Categories were to be detailed afterwards: those that didn't contribute to at least 10% of the 96 events were to be excluded. As such, the Bleed Air System, Engine Indicating System and Fire Protection System Failure Categories were left out of the scope of the study.

The next step is to understand the components or items that lead to the failures, as well as to analyse their importance to the operation. Therefore, the following Tables 3.4 to 3.7 detail the Components that caused each Failure Subcategory, the Number of Failure Events, the Risk Analysis elements, such as the Detection (D), Severity (S), Occurrence (O) and calculated Risk Priority Number (RPN), as well as a possible Mitigation or Corrective Actions based on the actions performed upon failure.

The tables are organized based on the number of events in each Subcategory, from the highest to the lowest. For time and space saving purposes, the tables will not display single occurrences as they are sporadic events and don't contribute to a failure pattern. Also, the MTBF values for the items that follow can be found on Appendix A, Table A.3.

Starting with Table 3.4, the Engine Fuel and Control System Failures are approached in more depth. To be noticed that the Fuel System Subcategory is not present as all 3 events were single and isolated.

Failure Category: Engine Fuel and Control System							
Subcategory	Component	Events	D	S	O	RPN	Action
Engine Dispatch Limited Message	EEC Electrical Connectors	9	5	3	9	135	Cleaning
	No Failure Found	7	–	–	–	–	N/A
	EEC	3	5	3	6	90	Reset
Fuel Filter	FFIB Switch	7	5	3	9	135	Replacement
	Fuel Filter	2	4	3	4	48	Replacement

Table 3.4: RPN Analysis on the Latitude's Engine Fuel and Control System Failure Category.

Regarding the Engine Dispatch Limited Messages, and excluding the times where no failure was found, it can be seen that almost 50% of the failures are due to the *EEC Electrical Connectors*. There is no related task defined on the AAIP as scheduled maintenance, preliminarily making it a good candidate for further analysis.

Regarding the Fuel Filter System, almost 80% of the failures are due to the *Fuel Filter Impending Bypass (FFIB) Switch*. Also, the *Fuel Filter* is responsible for 2 failures. As occurred above, there is no FFIB Switch related task defined as scheduled maintenance, making it also a good candidate for in-depth analysis.

The next Category corresponds to the Oil System Failures, with the corresponding RPN Analysis detailed on Table 3.5.

Failure Category: Oil System							
Subcategory	Component	Events	D	S	O	RPN	Action
Oil Pressure	Oil Level	12	2	2	9	36	Servicing
	No Failure Found	4	–	–	–	–	N/A
	Oil System Seals	3	4	3	6	72	Replacement
Oil Filter	Oil Bypass Switch	2	5	2	4	40	Replacement

Table 3.5: RPN Analysis on the Latitude's Oil System Failure Category.

From a total of 21 events related with Oil Pressure, 12 are related with the *Oil Level* (low or high) and 3 with the *Oil System Seals*; in 4 events, no failures were found. Regarding the first, and as analysing engine oil consumption trends on CAMP would be unfeasible during this study's time frame, this is a possible future work but not up for current pursuit. Empirically, the number of events related with the seals appears to be reduced for further analysis.

Regarding the Oil Filter subcategory, out of the total of 3 events, 2 are related with the *Oil Bypass Switch*, a small number to constitute any apparent pattern of failure.

The next Category corresponds to Ignition System Failures, with the corresponding RPN Analysis detailed on Table 3.6.

Failure Category: Ignition System							
Subcategory	Component	Events	D	S	O	RPN	Action
Engine No Start	GCU	2	4	3	4	48	Replacement
	Spark Ignitor	2	5	2	4	40	Replacement
	Starter Generator	2	5	2	4	40	Replacement
	Start Switch	2	5	2	4	40	Swap

Table 3.6: RPN Analysis on the Latitude's Ignition System Failure Category.

Regarding the Engine No Start subcategory, all four components (namely, the *GCU*, the *Spark Ignitor*, the *Starter Generator* and the *Start Switches*) failed 2 times each. It is also important to notice that 80% of the events occurred while the aircraft was grounded, not compromising the safety of the operation. Empirically, and comparing to other components, the individual number of events appears to be reduced for further analysis.

The following Category corresponds to Exhaust System Failures, with the corresponding RPN Analysis detailed on Table 3.7.

Failure Category: Exhaust System							
Subcategory	Component	Events	D	S	O	RPN	Action
Thrust Reversers	Control Valve	5	5	5	8	200	Replacement
	Control Valve Connectors	2	5	5	4	100	Cleaning
	Thrust Reverser Doors	2	1	2	4	8	Lockout

Table 3.7: RPN Analysis on the Latitude's Exhaust System Failure Category.

Regarding the Thrust Reversers subcategory, 5 failure events are a direct consequence of a *Control Valve* malfunction. Also, the *Control Valve Connectors* and the *Thrust Reverser Doors* failed 2 times each.

To be noted that the Lockout is a procedure of temporarily disabling the Thrust Reversers until a solution is discovered for the malfunction. As such, the hazard related with the T/R Doors is reduced, as opposed to an elevated hazard of an in-flight deployment of the T/R due to a valve malfunction.

To select components for further investigation, a compilation of all calculated RPNs, organized from the highest to the lowest, can be found on Table 3.8.

Component	RPN
Thrust Reverser Control Valve	200
EEC Electrical Connectors	135
FFIB Switch	135
Thrust Reverser Control Valve Connectors	100
EEC	90
Oil System Seals	72
Fuel Filter	48
GCU	48
Oil Bypass Switch	40
Spark Ignitor	40
Starter Generator	40
Start Switch	40
Oil Level	36
Thrust Reverser Doors	8

Table 3.8: Latitude's Ranking of RPNs.

As it can be seen, the Thrust Reverser Control Valves have the highest RPN (of 200), implying that its failure brings the most impact to the operation. It is followed by the EEC Electrical Connectors and FFIB Switch, both with a RPN of 135. The Thrust Reverser Doors, with a RPN of 8, bring the smallest impact to the operation.

As the time frame for this case study is limited, only three items were selected for further investigation, summarized up next:

- the Thrust Reverser Control Valves, due to *Exhaust System Failures* that resulted in *Thrust Reverser* malfunctions;
- the EEC Electrical Connectors, due to *Engine Fuel and Control System Failures* that produced *Engine Dispatch Limited Messages*;
- the Fuel Filter Impending Bypass Switches, due to *Engine Fuel and Control System Failures* that resulted in *Fuel Filter* malfunctions.

3.4.3.1 Thrust Reverser Control Valves

Thrust Reversers (T/R) are responsible for a *temporary diversion of an aircraft engine's thrust so that it acts against the forward travel of the aircraft, providing deceleration* [60]. They are mainly used upon touchdown to increase safety, by reducing brake wear as well as landing distances. When faulty (causing, for instance, in-flight deployments), safety can be severely compromised, as occurred with the Aircraft PT-MRK in 1996: an in-flight deployment of the aircraft's right thrust reverser lead to the crash of the plane, causing 99 fatalities [61].

Among the several types of thrust reversers, the Cessna Latitude has a bucket type, similar to the one displayed (deployed) on Figure 3.6.

Figure 3.6: Deployed Bucket Type Thrust Reverser.

This type of reverser acts as a barrier to the flow of engine thrust, by creating an angled wall aft of the exhaust section. When engaged, an electrical input reaches the T/R Control Valve in the engine, which analyses if all deployment conditions are met. If so, the doors of the reverser are deployed via hydraulic actuators. The contrary occurs when the T/R is disengaged, with the doors being stowed.

On NJE's fleet, some T/R failures were registered and their description is displayed on Table 3.9. It has information regarding the Aircraft (A/C), CAMP Fault Codes Prior to Failure, Time of Fault (TOF), the Faulted Component and the Corrective Action performed to solve the failure.

A/C	Fault Codes	TOF [EngFH]	Component	Action
A	N/A	103.5	Arm Light Switch	Replacement
A	TW	119.6	Control Valve	Replacement
B	TW	684	Reverser Doors	Lockout
C	N/A	1990	Control Valve Connector	Cleaning
B	TW; TE	707.3	Control Valve	Replacement
D	TC	2010.5	Control Valve Connector	Cleaning
E	TW; TE	1879.1	Control Valve	Replacement
F	N/A	342.2	Reverser Doors	Lockout
F	TE	405	Control Valve	Replacement
A	TY; TE	1570.7	Control Valve	Replacement

Table 3.9: Times of Fault, CAMP Fault Codes and Corrective Actions upon T/R Malfunction.

It is important to state that all related CAMP Fault Codes occurred almost simultaneously with the failures. As such, if the pattern remains, they are not helpful in predicting future failures or in scheduling inspections for when the aircraft is grounded.

Analysing Table 3.9, failure of the T/R Control Valves (example in Figure 3.7), with 5 events, is the main contributor to a malfunction on the reversers. The Control Valves' Electrical Connectors were also subjected to cleaning twice. The T/R Doors were disabled (Lockout) twice as a temporary corrective action, allowing conditional operation until permanent correction is performed. As such, the investigation will proceed with the analysis of data regarding the T/R Control Valves.

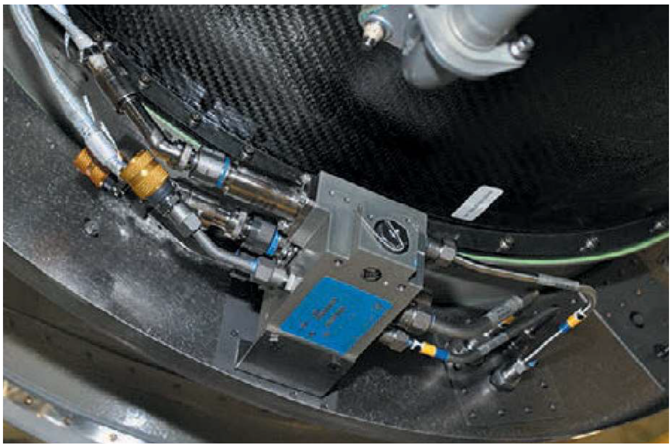


Figure 3.7: Example of a T/R Control Valve [62].

A failure of the T/R Control Valves always resulted in a replacement. As such, the investigation must focus on discovering the cause of these replacements, as well as on how they can be reduced or eliminated.

As the number of NJE events is relatively small for an investigation, NJA's data shall also be added. Both branches' data regarding the T/R Control Valves is detailed on Table 3.10, with: valve's Serial Number, the number of Removals (Rem.) and Installations (Ins.) per S/N, as well as the Current Usage Condition (if the valves are *in use* or *not in use* at the time of data collection).

S/N	Rem.	Ins.	Condition
336	1	2	in use
778	1	1	in use
798	1	0	not in use
806	2	2	in use
811	1	1	in use
824	1	1	in use
827	1	0	not in use
829	1	1	in use
837	1	1	not in use
838	2	2	in use
842	1	0	not in use
846	1	0	not in use
851	1	0	not in use
861	1	0	not in use
876	1	0	not in use
878	2	2	in use
881	2	1	not in use
888	1	1	not in use
893	1	0	not in use
895	2	1	not in use
899	1	1	in use
906	2	2	in use
908	1	0	not in use
910	1	0	not in use
917	1	0	not in use
925	1	0	not in use
986	1	1	in use
1007	1	2	in use
1023	1	0	not in use
1041	1	1	not in use
1158	1	0	not in use
—	—	—	—

Table 3.10: Serial Number and Details of Usage of the T/R Control Valves.

At first, it is important to understand that, when a valve is removed, it can be overhauled. As such, it can be reinstalled in an aircraft in a *good as new* condition. As examples:

- the valve with *S/N 837* was installed once and removed afterwards, and was not overhauled as it was not in use again after the removal;

- the valve with *S/N 829* was removed once but reinstalled afterwards, as it was in use after the removal, implying an overhaul has occurred.

Secondly, an event corresponds to both a removal and an installation. In consequence, and per relevance for the study, Table 3.10 only details valves that have already failed at least once. As such, 37 Control Valve removals and 23 installations are documented. As sometimes data is incomplete, it is not possible to assess all removals or installations, hence also the difference between the number of both. From a total of 40 events, there are 31 different valve serial numbers.

Out of the 31 different valves, 18 (meaning 58%) have a S/N of the form *8xy*. Out of these 18, 11 valves (or 61% of the *8xy* series) were ultimately removed, no longer being in service. The remaining 7 valves (or 39%) are still in use, although being overhauled at least once. The data suggests an issue affecting specific serial numbers, with manufacturing errors or faulty batches being probable causes.

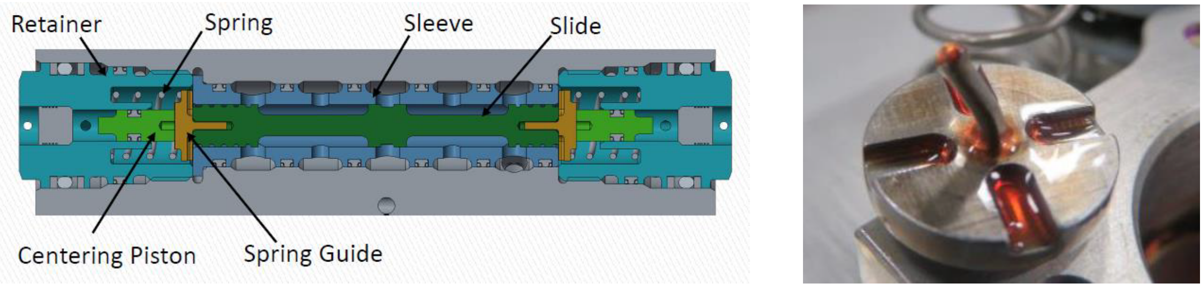
Regarding the type of events that led to replacements, from the total of 40 events, 23 (or 58%) were related with inspections. The remaining 17 (or 42%) were unscheduled events where the plane had to be grounded, which is a high number for a system whose failures can have dangerous outcomes.

In addition, 12 out of the 17 events (or 71%) concerned valves that did not complete 800FH (average of 623FH of operation, less than an inspection α). As such, even if the possible failures could be prevented with maintenance, tasks would not be efficient as they would not be coincident with any existent scheduled maintenance.

No other information regarding the repairs or causes of failure was known, as the only task that concerned the Company was the replacement of the valves. Therefore, the manufacturer was contacted and debriefed on all the information collected so far. As more airlines had already reported similar events, there was already an investigation being performed by the manufacturer, to which were added the serial numbers of the valves replaced on NetJets' fleet.

During the course of this case study, the manufacturer determined the cause of the failures. Two malfunctions on the valves were discovered:

- a bent spring guide internal to the control valve (*vd.* Figure 3.8), not allowing the spring to fully contract and therefore not leading to the deployment of the T/R;
- an incomplete drill depth on the supply pressure channel, leading to an incorrect attachment with the subsequent connected lines and generating fault messages.



(a) T/R Control Valve Drive Train

(b) Bent Spring Guide

Figure 3.8: Damage to the Spring Guide and corresponding location on the Control Valve.

Replacement was required for the affected valves, corresponding to 79 different serial numbers. As such, a Service Bulletin was issued for that effect, occurring during the next maintenance opportunities.

3.4.3.2 EEC Electrical Connectors

In the early days of aviation, engine control systems were mechanical and were physically connected to the engine. As aviation became more complex and high safety levels were required, computers were introduced to help the crew in flight.

The Electronic Engine Control (EEC) is a digital computer, made of two independent and similar channels of operation (Channels A and B), considered the heart of the Full Authority Digital Engine Control (FADEC). It was created to control aspects of the engine performance, having *full-range authority over the engine power or thrust* [63]. The EEC is considered a Line Replaceable Unit (LRU), a component designed to be removed and replaced on the aircraft by the technician with time constraints (excluding subsequent testing) [59].

Each of the EEC's channels receives multiple flight condition inputs (such as pressure, temperature, throttle lever position and air density). Based on such inputs, the EEC then computes the required outputs (as the required fuel flow or fan speed) for better performance. Figure 3.9 represents the PW306D1 Engine's Block Diagram, with each arrow representing an electrical connection (*input* or *output* depending on the arrow's direction).

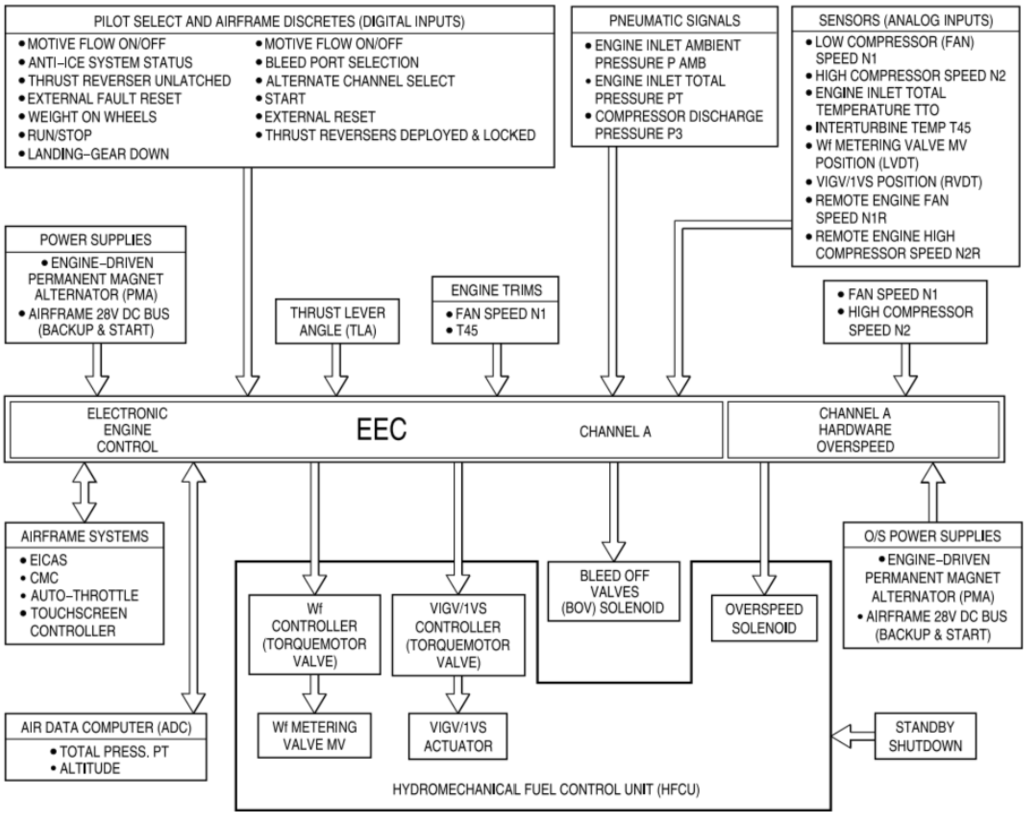


Figure 3.9: PW306D1 Engine EEC Block Diagram [59].

EEC failures are generally low hazard. Nonetheless, some can bring serious consequences: in 2015, an Airbus A400M crashed in Spain due to an incorrectly installed EEC software, causing loss of thrust on several engines [64]. As such, it is important to understand and resolve the failures occurring in NJE's Latitude fleet.

It is also important to understand the EEC's location and possible consequences for the system. As seen on Figure 3.10 (inside the yellow box), the EEC is mounted inside the engine nacelle (housing that holds and protects the engine). In here, the EEC and corresponding connectors are subjected to massive vibrations, as well as to environmental agents (dust and moisture) that can escape into the EEC's protected area. Due to its design and elevated number, the connectors can be negatively affected by such factors, with possible frequent failure events.

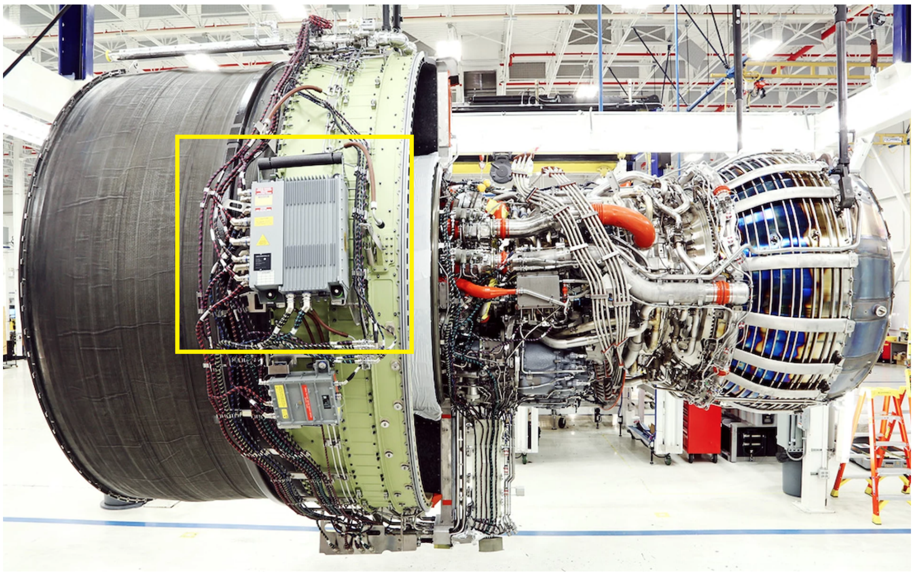


Figure 3.10: Example of an EEC mounted on an engine [65].

Data regarding the EEC connector's failure events are detailed in Table 3.11a. It has information regarding the Aircraft (A/C), CAMP Fault Codes Prior to Failure and Time of Fault (TOF). The TOF's Average (AVG) and Standard Deviation (STD) can be found on Table 3.11b. The corrective action in these failure events was always the Cleaning of the EEC Electrical Connectors.

A/C	Fault Codes	TOF [EngFH]
A	CC	224.6
A	CC	346.1
B	KB	1251.4
C	KB	837.3
B	KB	2166.4
C	KB	1300
D	KB	1539.9
E	KB; YC	933.5
C	N/A	1774.7

(a) Times of Fault and CAMP Fault Codes.

Parameter	Value [EngFH]
Average	1152.6
Standard Deviation	601.4

(b) Parameters of TOF at Failure.

Table 3.11: Failure Events and TOF Parameters on EEC Electrical Connectors.

In first place, from Table 3.11b, it is noticed that the value of Standard Deviation is very high comparing to the Average value. This means that the times at which a failure occurs are not very similar. It can be explained by the occurrence of the two premature events of Aircraft A, in the early days of operation. The Average and Standard Deviation values without these two events are displayed on Table 3.12. These will be important in planning the recurrence of possible maintenance tasks.

Parameter	Value [EngFH]
Average	1400.5
Standard Deviation	433.2

Table 3.12: Parameters of TOF at Failure, excluding premature events.

In second place, it is important to understand how the corrective action was selected. According to the EMM [59], the process of selection of corrective actions upon failures is a decision tree. For each TLD event and corresponding fault code, there is a tree with tasks to be performed, starting from the most simple task and with increasing complexity.

The first task in the EMM is a cleaning and lubrication of the affected electrical connectors. This was the only task performed on the events of Table 3.11a, as the failure was resolved afterwards.

But it is also important to understand the time span of effectiveness of this task. By observing CAMP's data posterior to the failure events, the corrective action of Cleaning the EEC Electrical Connectors is deemed highly effective as no fault codes are shown immediately after the corrective action. Nonetheless, after variable periods of time, these start occurring again, leading to more unscheduled events. Due to NJE's fleet being small, some failure patterns cannot be established.

Upon contact, NJA expressed similar concerns to NJE's regarding the number of TLD events occurring due to the electrical connectors. Between January of 2019 and February of 2020, NJA had a total of 144 TLD Events, resulting in 61 events (or 42%) of Cleaning of EEC Electrical Connectors. As with NJE, the corrective actions were highly effective in the short term, but in the long term the fault codes would appear again.

This data indicates that a recurrent preventive maintenance task can be effective while the manufacturer does not find a permanent solution for the failures. As such, an EO will be drafted.

In first place, the recurrence of the tasks is to be defined. It is important to schedule the tasks to be performed coincidentally with other maintenance procedures, mainly the recurrences defined in Section 3.4.2. Most events occurred in the interval $\text{AVG} - \text{STD} < \text{TOF} < \text{AVG} + \text{STD}$. Based on Table 3.12, and disregarding the premature events, the interval limit values can be found on Table 3.13.

Interval Limit	Value [EngFH]
AVG – STD	967.3
AVG + STD	1833.7

Table 3.13: Time Interval Limits.

If the task was performed at every inspection β (or 1200 EngFH), unscheduled events would most likely occur beforehand, not being suitable as the 1200 EngFH value is inside the previously referred time interval. As such, the recurrence was chosen to be every inspection α (or 800 EngFH).

In second place, it is important to define the scope of the EO. In this case, the task is already defined as a Cleaning of the EEC Electrical Connectors. But as there are several, it is important to define which should be included in the task.

Each fault code is associated with specific LRUs, with corresponding specific electrical connectors. In the NJE's fleet, as seen in Table 3.13, there are three different fault codes occurring: CC, KB and YC. According to the EMM [59], the fault codes are related with the LRUs as follows:

- ◇ *Does cleaning and reinstalling the EEC or P1/T1 sensor connectors correct the problem?* reads on the KB fault code decision tree; the corresponding LRUs are the EEC and P1/T1;
- ◇ *Does cleaning and reinstalling the EEC or BOV Solenoid connectors correct the problem?* reads on the CC fault code decision tree; the corresponding LRUs are the EEC and BOV Solenoid;
- ◇ *Does cleaning and reinstalling the EEC or EDU connectors correct the problem?* reads on the YC fault code decision tree; the corresponding LRUs are the EEC and EDU.

Data regarding the LRUs and electrical connectors is detailed in Table 3.14. It has information regarding the LRU, the corresponding Electrical Connectors and the Distribution of Events per LRU (related with the events on Table 3.13).

LRU	Connectors	Distribution
EEC	P1; P2; P4; P5	56%
P1/T1	P22; P23	25%
EDU	P36; J36	12.5%
BOV SOLENOID	P13; P14	6.5%

Table 3.14: LRUs, Connectors and Distribution of Events.

It can be seen that the EEC and P1/T1 LRUs are the most impacted by corrective actions, whereas the EDU and BOV Solenoid suffer the least impact. In order to select which connectors would be included in the tasks, Pareto's idea was used.

As the EEC and P1/T1 LRUs produce the most impact in failure events, with 81% of the cases, the corresponding electrical connectors will be included in the EO's tasks.

In third place, the resources to perform these tasks need to be defined. These are related with the time consumed in performing the tasks, as well as the costs associated.

After contacting a Service Center, and providing details of the tasks, the man-hours required for their completion was obtained. If the aircraft is already undergoing maintenance, with engine access already available, the EO would take a total of 5 hours per aircraft: 2 hours per engine to clean the EEC and P1/T1 electrical connectors; and 1 hour of functional checks afterwards.

Regarding the costs, the man-hour value is not even across Europe. As such, and taking into account the distribution of inspections per service center in Europe (and corresponding man-hour values), an average man-hour value of 93€ is reached. This implies that the EO will have a cost of 465€ per aircraft, yearly translating into a total of 7440€.

In summary, the extent of the analysis resulted in an EO, where a maintenance task of cleaning and inspecting the EEC and P1/T1 LRUs' electrical connectors was defined, at every inspection α, as a preventive measure to reduce groundings related to TLD Messages. Also, all data was reported to the manufacturer so that a permanent solution can be developed.

3.4.3.3 Fuel Filter Impending Bypass Switches

Current turbine engines have a very high efficiency mainly due to the close tolerance of the fuel control units. As such, only the necessary amount of fuel is delivered at each time, being *imperative that the fuel delivered to them is clean and contaminant free* [66].

To achieve such fuel quality, fuel filters with a small mesh size are used, absorbing any debris or water incorrectly present [66]. Figure 3.11 represents the Latitude's Fuel System (investigated section inside green lines).

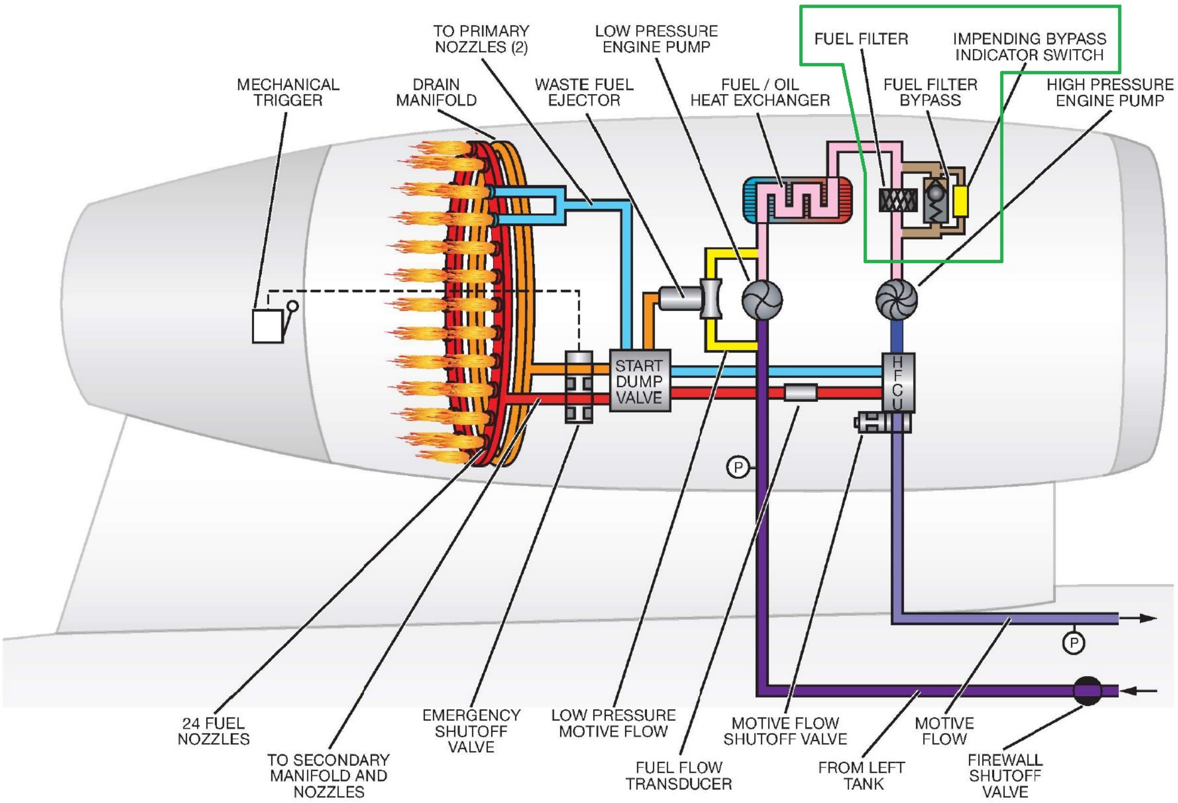


Figure 3.11: Latitude's Fuel System Schematics [62].

The filter is prone to blockages due to the mesh size. To prevent a total cutoff of fuel supply to the engine, with subsequent shutdown, a relief valve is installed. It acts as a bypass, preventing a build-up of pressure as a result of a possible filter blockage. The opening of the valve physically activates a switch (the FFIB Switch, seen in Figure 3.12), signaling the crew to a possible filter failure.

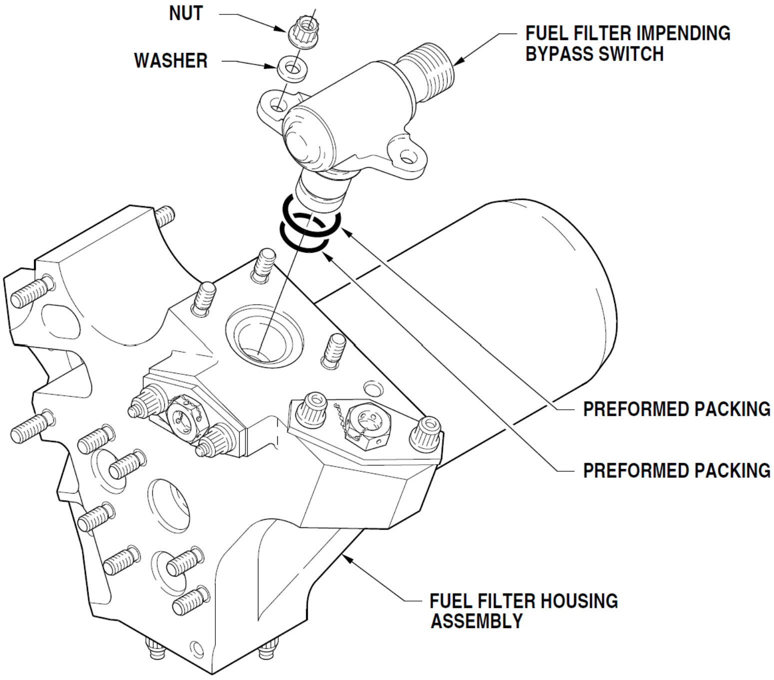


Figure 3.12: Latitude's FFIB Switch Schematics [59].

When the valve is open, the fuel is not filtered and enters directly into the engine. If contaminated fuel reaches the engine, it may cause blockages on the fuel injectors and, as such, the aircraft shall undergo inspection within a short period of time.

According to Table 3.4, there are 9 Fuel Filter System failures registered during NJE's operation. These resulted in 7 FFIB Switch Replacements and 2 Fuel Filter Replacements. To understand how the switch replacement corrective actions were determined, the respective failure decision tree was analysed, as follows [59]:

i *Are there any fault codes present?* As there are no fault codes (those on Table A.1), the next step is due;

ii *Are there any other CAS Messages present?* As the FFIB Message was the only one present, the next step is due;

iii *What is the result of a Fuel Filter Inspection?* The filter is sent for analysis to determine weight and make up (biological or inert) of debris. As there is no contamination, the next step is due;

iv *Does the fault follow when the FFIB Switch is swapped from one engine to the other?* As the fault followed the swap of the switch, it was clear that a faulty switch was the cause of the FFIB CAS Message. As such, the corrective action of replacing the FFIB Switch is due.

To have a bigger picture of the occurrences, more data was collected from NJA's branch. According to this data, there is a total of 169 removals of the FFIB Switch. As the total of events is extremely high, only the factual analysis of the data will be detailed. As such:

- ◇ there were 26 removals in 2017, 32 removals in 2018, 41 removals in 2019 and 61 removals in 2020;
- ◇ the 169 FFIB Switches removed all have the same P/N 30B3500-03;
- ◇ only 1 FFIB Switch (corresponding to 1 S/N) was overhauled and reinstalled after a first removal, with all others being discarded;
- ◇ there is no direct correlation between a group of S/N (for instance, a batch) and failure, with a great diversity of the S/N.

In first place, the growing number of removals per year indicates that the significance of these unscheduled events has been growing with time. In second place, the fact that all switches have the same P/N, but variable S/N, might indicate a baseline manufacturing issue with all switches rather than simply a faulty batch.

No other information regarding the repairs or causes of failure was known, as the only task that concerned the Company was the replacement of the valves. As such, the manufacturer was contacted and debriefed on all the information collected so far. As occurred in Section 3.4.3.1, more failures were also reported, already under investigation.

During the course of this case study, the preliminary conclusions were reached. The first cause of the failures was found to be a contamination of the switch's contacts, leading to two changes:

- ◇ a *physical change*, with the replacement of the connecting gasket (or seal) for a better one;
- ◇ a *procedural change*, by changing the hand balm of the workers that worked on the switches.

To test the changes, 20 new switches were placed on aircraft. Within a short period of time under operation, the switches failed again. Therefore, two analysis were conducted to find the yet unknown causes of failure:

- ◇ a Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS), providing *elemental, chemical state and molecular information* from the surface of the switch [67];
- ◇ an Auger Electron Spectroscopy (AES), a *surface-sensitive analytical technique that utilizes a high-energy electron beam* and is able to detect surface particles and defects on the switches [68].

A non-specified contamination was discovered, leading the manufacturers to develop a fully new switch.

The faulty switch was a normally closed switch, implying that the switch's circuit was always closed (requiring permanent physical contact of the switch with the circuit). A pressure build-up would trigger a response, opening the circuit and, consequently, the bypass valve.

The new switch was developed using the idea that the permanent physical contact was the source of the faults, which implied that less contact was necessary for it to work properly. Therefore, it was built to be a normally open switch, with an inverter. The circuit would be normally open, with the inverter sending closed-circuit signals to the on-board computer, keeping the bypass valve closed. If a pressure build-up was to occur, the switch would close the circuit, leading the inverter to send open-circuit signals and the bypass valve to open.

An SB was then issued, requiring the replacement of all old P/N switches for the new P/N. Since then, the faulty older switches have been undergoing replacement on all aircraft, and in those where the new ones are in place, there has been no failures reported.

3.5 Challenger 350 Fleet

Similarly to what happened with the Latitude's fleet, the step following collecting all information (regarding the Challenger 350) is organizing it. It was performed by creating a spreadsheet, having the same columns described in Section 3.3 and Figure 3.4.

This being a different fleet from the Latitude's, it is expected that not all the Failure Categories are equal. Nevertheless, these were also mainly based on the ATA 100 Chapters, with the subcategories being mostly based on the CH350's EMM.

These categories will be important in detecting systems that are increasing maintenance costs due to recurrent failures. They are as follow:

- Bleed Air System: includes *Bleed Fault Messages* as well *Anti-Ice System* malfunctions;
- Engine Fuel and Control System: includes *FADEC Memory* malfunctions as well as *Short Term Dispatch Messages* (Section 3.5.1 with further information) and *FADEC Fail Messages*;
- Engine Indicating System: includes *Engine Fluctuations* (either with unsteady parameters or with slow rise in numbers);
- Hydraulic Power System: includes *Hydraulic System* malfunctions;
- Ignition System: includes *Engine No Start* malfunctions, as well as *Power Faults*;
- Oil System: includes *Oil Chip Messages,* as well as *Oil Pressure* malfunctions;
- Structural Damage: includes external impacts of *FOD or Birdstrike*, as well as *Internal and External Structure Damage* and *Corrosion* problems.

3.5.1 Fault and Aircraft Dispatch

The CH350, similar to the Latitude, also has a Time-Limited Dispatch system, where each fault has its own procedure and time limitation for resolution.

There are three types of operational status, according to the CH350's EMM, as such [69]:

- ⋄ No Dispatch Faults: dispatch not allowed with this condition present;
- ⋄ Short Time Faults: dispatch is permitted with short time faults present; the maximum exposure time of the system to these faults must be limited to 125 FH;
- ⋄ Long Time Faults: dispatch is permitted with long time faults present; the maximum average exposure time of the system to these faults must be limited to 350 FH.

3.5.2 Maintenance Time Intervals

While on the Latitude, there are only two recurrence intervals for engine related scheduled maintenance, on the Challenger 350 there are eight different time intervals. Maintenance tasks are performed on the engines at every 400, 800, 1200, 1600, 2000, 4800, 9600 and 25000 Engine Flight Hours.

The first three 400 EngFH recurrence tasks are performed at 400, 800 and 1200 EngFH, whereas the first three 1200 EngFH recurrence tasks are performed at 1200, 2400 and 3600 EngFH, as an example.

Figure 3.13 intends to provide visual image of the last paragraphs. For naming purposes, they were called inspections α through θ.

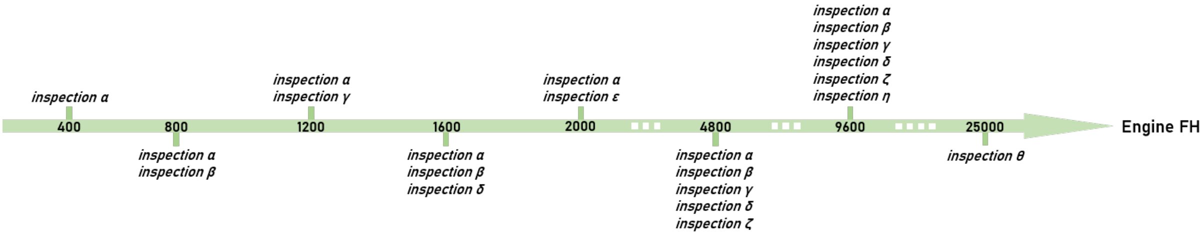


Figure 3.13: CH350's Maintenance Recurrence Hours.

3.5.3 Data Processing

After all data has been collected and analyzed, the next step is to process it. A similar table to the Latitude's was created, so that understanding the distribution of the failures per engine systems is possible.

Failure		Sub-Total	Total
Category	Subcategory		
Engine Fuel and Control System	Short Term Dispatch Message	28	38
	FADEC Fail Message	6	
	FADEC Memory	4	
Oil System	Oil Pressure	24	32
	Oil Chip Message	8	
Structural Damage	FOD or Birdstrike	4	9
	Internal or External Damage	3	
	Corrosion	2	
Bleed Air System	Anti-Ice System	5	9
	Bleed Fault Message	4	
Hydraulic Power System	Hydraulic System	8	8
Ignition System	Engine No Start	4	5
	Power Fault	1	
Engine Indicating System	Engine Fluctuations	2	2

Table 3.15: CH350's Failure Category and Number of Events.

As such, Table 3.15 details the Failure Category, corresponding Failure Subcategories, the Total Events per Subcategory and the Total Events per Category.

There is a total of 103 events concerning all categories, with these not contributing evenly for the total. For example, the Engine Fuel and Control System Failures correspond to over 35% of the total amount of events, whereas the Engine Indicating System Failures contribute with less than 2%.

Before proceeding, a quick review of the preliminary data was also performed with the Company's maintenance managers. As a consequence, some Categories or Subcategories were excluded from further analysis. These, as well as the reasons for exclusion, are as follow:

- FADEC Memory: mainly due to reaching maximum storage capacity, not compromising safety and solvable in minutes upon landing with a data download;
- Oil Chip Message: the aircraft's manufacturer is aware of problems due to engine distress and metal chips in the oil, with the Oil Chip Indicator System being already a preventive measure for massive destructive engine failure;
- Structural Damage Category: mostly due to damage occurring after sporadic Birdstrikes or FOD Impacts, having no effect on preventive maintenance practices; also, the Corrosion problems were already solved.

With the exclusion of the two categories, there is now a total of 82 events available for analysis.

As occurred with the Latitude's Fleet, it is important to understand that a high number of failures occurs due to a small number of cases, following the Pareto's idea [47]. With this idea in mind and in order to focus the investigation on important Failure Categories, a consensus was reached: those that didn't contribute to at least 10% of the total of 82 events were to be excluded. As such, the Ignition System as well as the Engine Indicating System were left out of the scope of the study.

The next step is to understand the components or items that lead to the failures, as well as to analyse their importance to the operation. Therefore, the following Tables 3.16 to 3.19 detail the Components that caused each Failure Subcategory, the Number of Failure Events, the Risk Analysis elements, such as the Detection (D), Severity (S), Occurrence (O) and calculated Risk Priority Number (RPN), as well as a possible Mitigation or Corrective Actions based on the actions performed upon failure.

The tables are organized based on the number of events in each Subcategory, from the highest to the lowest. For time and space saving purposes, the tables will not display single occurrences as they are sporadic events and don't contribute to a failure pattern. Also, the MTBF values for the items that follow can be found on Appendix A, Table A.4.

Starting with Table 3.16, the Engine Fuel and Control System Failures are approached in more depth.

Failure Category: Engine Fuel and Control System							
Subcategory	Component	Events	D	S	O	RPN	Action
Short Time Dispatch Message	Anti-Ice Valve	13	6	5	10	300	Replacement
	No Failure Found	7	–	–	–	–	N/A
	EEC	2	5	3	6	90	Swap
FADEC Fail Message	ECU	2	5	3	6	90	Replacement
	OSSD Sensor	2	3	3	6	54	Replacement

Table 3.16: RPN Analysis on the CH350's Engine Fuel and Control System Failure Category.

Regarding the Short Time Dispatch Messages, and excluding the times where no failure was found, it can be seen that almost 50% of the failures are due to the *Anti-Ice Valves.* There is no related task defined on the AAIP as scheduled maintenance, preliminarily making it a good candidate for further analysis. Also, 2 events related with the *EEC* were registered, but they don't constitute an obvious failure pattern.

Regarding the FADEC Fail Messages, there were 2 events related with the *ECU*, as well as 2 events related with the *OSSD Sensor*. Empirically, it does not seem apparent that any preventive measures are necessary due to the small number of events.

The next Failure Category on Table 3.15 is related with the Oil System. Nonetheless, due to the high number of Anti-Ice (A/I) Valve failure events on Table 3.16, the following Table 3.17 details the RPN analysis for the Bleed Air System.

Failure Category: Bleed Air System							
Subcategory	Component	Events	D	S	O	RPN	Action
Anti-Ice System	Anti-Ice Valve	5	6	5	10	300	Replacement
Bleed Fault Message	Bleed Air Leak Detector Connector	2	6	2	6	72	Replacement

Table 3.17: RPN Analysis on the CH350's Bleed Air System Failure Category.

Regarding the Anti-Ice System, it can be seen that all 5 events are related with *Anti-Ice Valve* failures. Combined with the 13 events that led to a Short Time Dispatch Message, there is a total of 18 failure events. This is a very elevated number, empirically implying that there is a problem in need of further analysis.

Regarding the Bleed Fault Message subcategory, out of the total of 4 events, 2 are related with the *Bleed Air Leak Detector Connector*. It is a small number of events, not constituting a pattern and no apparent preventive measures are necessary.

The next Category corresponds to Oil System Failures, with the corresponding RPN Analysis detailed on Table 3.18.

Failure Category: Oil System							
Subcategory	Component	Events	D	S	O	RPN	Action
Oil Pressure	Oil Pump	11	5	5	10	250	Replacement
	Oil System Seals	4	4	3	8	96	Replacement
	No Failure Found	3	–	–	–	–	N/A
	Oil Level	3	2	2	8	32	Servicing

Table 3.18: RPN Analysis on the CH350's Oil System Failure Category.

Regarding the 24 events on the Oil Pressure subcategory, 11 are related with an *Oil Pump* failure. Although there are related tasks on the AAIP, it is a very high number of failures, empirically constituting a good event to be further analysed. There were also 4 events related with the *Oil System Seals*, as well as 3 events related with the *Oil Level*.

The next Category corresponds to the Hydraulic Power System Failures, with the corresponding RPN Analysis detailed on Table 3.19.

Failure Category: Hydraulic Power System							
Subcategory	Component	Events	D	S	O	RPN	Action
Hydraulic System	Eng. Driven Hydraulic Pump	5	4	6	9	216	Replacement
	Hydraulic Pump Filter	2	5	5	6	150	Replacement

Table 3.19: RPN Analysis the CH350's Hydraulic Power System Failure Category.

Regarding the 8 events on the Hydraulic System subcategory, 5 were related with the *Engine Driven Hydraulic Pump*. Although not a very elevated number, a hydraulic system failure can pose severe risks to an aircraft's airborne manageability, empirically implying that further investigation is required. Also, there are 2 failure events related with the *Hydraulic Pump Filter*, both occurring simultaneously with the hydraulic pump failures.

After all failure modes have been described and the risk analysis performed, it is time to select the components for further investigation. A compilation of all calculated RPNs, organized from the highest to the lowest, can be found on Table 3.20.

Component	RPN
Anti-Ice Valve	300
Oil Pump	250
Engine Driven Hydraulic Pump	216
Hydraulic Pump Filter	150
Oil System Seals	96
EEC	90
ECU	90
Bleed Air Leak Detector Connector	72
OSSD Sensor	54
Oil Level	32

Table 3.20: CH350's Ranking of RPNs.

As it can be seen, the Anti-Ice Valves have the highest RPN (of 300), implying that its failure brings the most impact to the operation. It is followed by the Oil Pumps and Hydraulic Pumps, with RPNs of 250 and 216, respectively. The Oil Level, with an RPN of 32, brings the smallest impact to the operation.

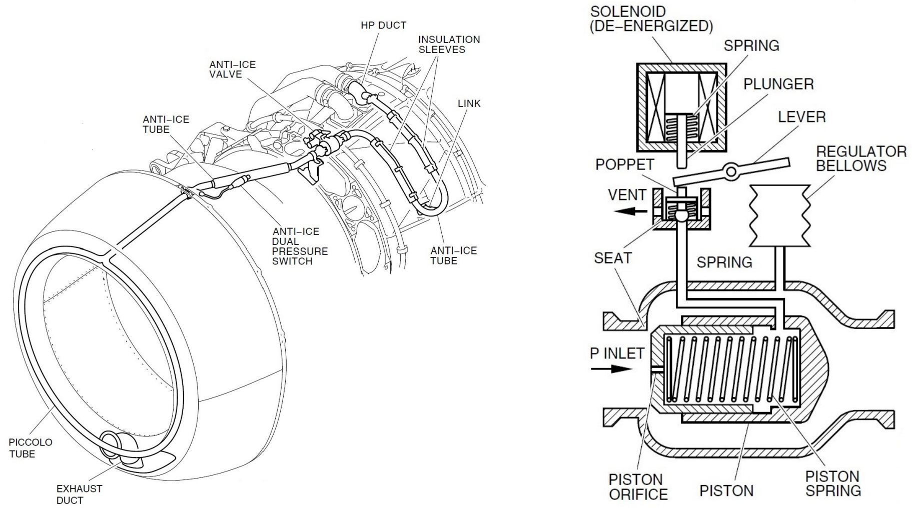
As the time frame for this case study is limited, only three items were selected for further investigation, summarized up next:

- the Anti-Ice Valves, due to *Engine Fuel and Control System Failures* and *Bleed Air System Failures* that resulted in *Anti-Ice Valve Replacements*;
- the Oil Pumps, due to *Oil System Failures* that translated into *Oil Pump Replacements*;
- the Hydraulic Pumps, due to *Hydraulic Power System Failures* that resulted in *Hydraulic Pump Replacements*.

3.5.3.1 Anti-Ice Valve

Ice on the wing and engine of an aircraft can be a severe problem. On the wing, it destroys the smooth flow of air, generating loss of lift and increase in drag, potentially leading to a crash. On the engine, ice crystals that bounce off the inlet and into the engine's core can build up, quench combustion and cause the engine to shutdown. The anti-icing systems are designed to prevent the formation of ice on surfaces of the aircraft whenever icing conditions are detected.

Several anti-ice systems rely on heat to evaporate liquid water that hits the surfaces. In turbine-powered aircraft, heated bleed air from the engine is directed to the cowlings or wings via ducts, over the course of which are valves to regulate the flow. The Challenger 350's Anti-Ice System and Engine Anti-Ice Valve are depicted in Figures 3.14a and 3.14b, respectively.



(a) Anti-Ice System Schematics

(b) Anti-Ice Valve Cut Schematics

Figure 3.14: Challenger 350's Anti-Ice System and Valve Schematics [69].

Each engine has its own anti-ice valve, electrically operated and pneumatically controlled. The valves have a push-type solenoid for the shut-off function. When the solenoid is energized, the solenoid plunger pushes on the regulator lever that pushes on the control section poppet. That causes the poppet to seal against the seat. This closes the control section airflow and causes the valve to close. The valve is normally in this condition.

When the solenoid is de-energized, its spring causes the solenoid plunger to move away from the regulator lever. Pneumatic pressure in the valve piston causes the control section poppet to move up or down from the seat, opening the control section airflow and causing the valve to open.

When the valve receives a command input to close at higher inlet pressure, the regulator bellows moves the lever, placing the control section poppet near the seat. When the solenoid energizes, this causes the plunger to move the regulator lever and control section poppet to the closed position.

As such, two types of failure can occur, with different outcomes, as follows [69]:

- ◇ Fail ON: a Short Time Failure, where the A/I system remains activated, keeping the supply of heat even if turned off by the crew;
- ◇ Fail (or Fail OFF): a No Dispatch Failure, where the A/I system cannot be activated, not providing heat even if turned on by the crew.

The severity of the outcomes is different: the first type might lead to a slightly higher fuel consumption, whereas the second type can lead to a dangerous ice accumulation.

Data regarding the Anti-Ice Valve's failure events are detailed in Table 3.21a. It has information regarding the Aircraft (A/C), the Type of Failure and Time of Fault (TOF). The TOF's Average (AVG) and Standard Deviation (STD) can be found on Table 3.21b.

A/C	Type	TOF [EngFH]	A/C	Type	TOF [EngFH]
A	ON	1174.4	B	ON	604.4
C	ON	1940.4	D	ON	1669.9
E	ON	2132.3	C	ON	2413.7
C	ON	2496.5	F	OFF	1030.1
B	OFF	1782.2	B	ON	2001.3
B	ON	2112.4	F	ON	1893.4
E	ON	3241.8	D	OFF	3151
A	ON	3730.2	G	ON	1701.4
H	ON	725.9	I	ON	2308.5

(a) Times of Fault and Failure Type.

Parameter	Value [EngFH]
Average	2006.1
Standard Deviation	811.6

(b) Parameters of TOF at Failure.

Table 3.21: Failure Events and TOF Parameters on Anti-Ice Valve.

It can be seen that roughly 83% of the failures are of the Fail ON type. Analysing the CAMP Fault Codes, only two occur in relation with the failure events: the MCID 1207 and MCID 1213. The failure decision trees of both codes are similar, with the first step being the replacement of the A/I valve. As this corrective action resolves the failure event, it implies that there is a defect on the valves.

In general, the assessment performed of the valves is as follows:

- the 18 A/I Valves removed all have the same P/N WBA3020G103-005;
- there are no A/I Valves reinstalled, all being discarded after removal, implying that all valves have different S/N;
- there is no direct correlation between a group of S/N (for instance, a batch) and failure, with a great diversity of the S/N.

No other information regarding the repairs or causes of failure was known, as the only task that concerned the Company was the replacement of the valves. As such, the manufacturer was contacted and debriefed on all the information collected so far, prompting the launch of an investigation.

This investigation demonstrated problems with inner parts of the valve, namely with the bellows. As explained earlier, it expands and contracts when in contact with hot or cold air, respectively.

With the thermal expansion and contraction, the bellows material becomes brittle and damaged. This has an effect on the control section airflow, causing the valves to malfunction.

The manufacturer decided to create a new valve, with a new P/N, being under development as of the time of this project. As such, and whenever the new P/N is available, the valves will be replaced according to the manufacturers' guidelines.

3.5.3.2 Oil Pump

In an aircraft, the oil system is vital for maintaining a continuous flow of oil to the jet engine. The oil is used for lubricating and cooling every gear, spline, bearing and carbon seal present.

Most oil systems are constituted by an oil supply tank, an engine-driven pressure oil pump, a scavenge pump, an oil cooler with an oil cooler control valve, an oil tank vent, an oil filter, as well as the necessary pressure and temperature indicators and tubing.

The engine-driven pressure oil pump is responsible for delivering the oil to the engine components, being driven by the Accessory Gearbox (AGB). Although the AGB is not a part of the engine's core, it is responsible for driving several engine accessories, such as the oil pumps, hydraulic pumps and generators. It is driven by the engine via the N2 shaft, that connects the high pressure turbine to the high pressure compressor. The EMM's oil pump schematics can be found in Figure 3.15 [69].

An AGB related maintenance task is found on the AAIP: at every 800 EngFH, a GVI must be performed to the AGB's Assembly, looking for exterior leaks or damage to the structure. Further analysis of this task reveals that only the AGB and corresponding links and connectors are checked. As such, the GVI does not affect the Oil Pumps directly and therefore they are not inspected at this time.

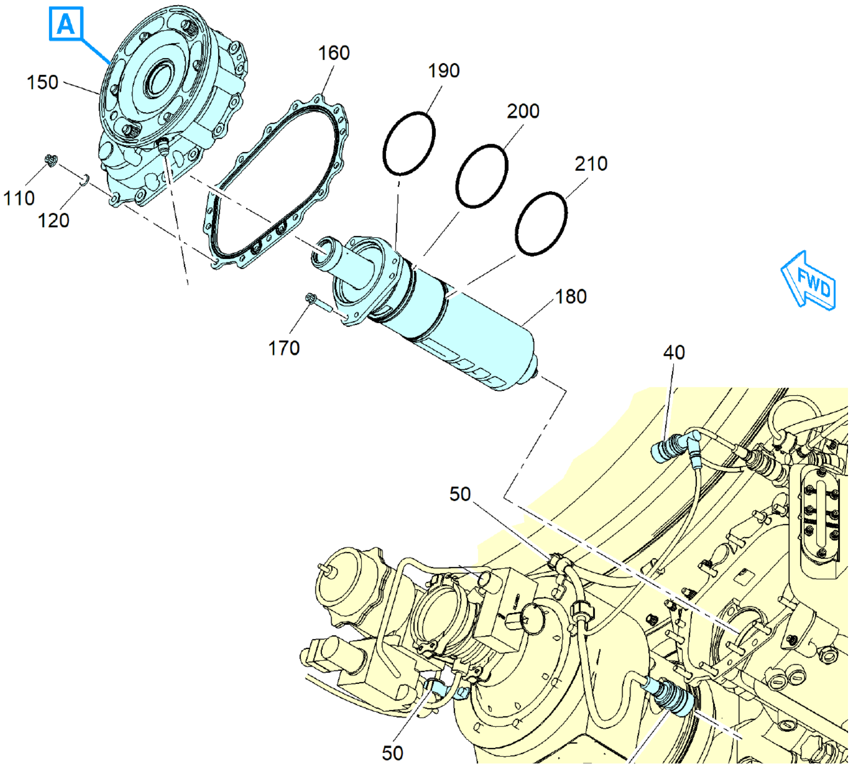


Figure 3.15: Schematics of the CH350's Oil Pump Location on the AGB [69].

The CH350's oil pumps have a gerotor design, with a *pair of toothed rotors*, as seen on Figure 3.16. While the *outer rotor has a circular profile*, the inner has a *related coupled trochoid profile*. In theory, contacts between both rotors should be *simultaneous at all teeth*, but there are unavoidable gaps and clearances in a real profile. These cause *volumetric losses* and therefore a *variation of pressure in gerotor pump chambers* [70].

Figure 3.16: CH350's Oil Pump Component Breakdown.

Data regarding the Oil Pump's failure events are detailed in Table 3.22a. It has information regarding the Aircraft (A/C), the pump's Part Number (P/N) and Time of Fault (TOF). The TOF's Average (AVG) and Standard Deviation (STD) can be found on Table 3.22b.

A/C	P/N	TOF [EngFH]
A	-3	2200.2
B	-3	407.6
C	-3	943.5
B	-3	559.1
D	-5	1621.6
E	-5	2742.7
D	-5	2081.6
F	-5	2964.7
G	-5	3423.3
A	-5	3027.3
C	-5	2076.9

(a) Times of Fault and Part Number.

Parameter	Value [EngFH]
Average	2004.4
Standard Deviation	976.4

(b) Parameters of TOF at Failure.

Table 3.22: Failure Events and TOF Parameters on Oil Pump.

In first place, it can be seen that there are two different part numbers (for name purposes, they will be called *P/N-3* and *P/N-5*). The P/N-3 occurred first, being replaced by the P/N-5 that continued to fail. This demonstrated that an attempt was performed by the manufacturer to stop the failure events.

In second place, from Table 3.22b, it is noticed that the value of Standard Deviation is very high comparing to the Average value. This means that the times at which a failure occurs are not very similar. It can be explained by the occurrence of premature failure events regarding the P/N-3 pumps.

On CAMP, the most recurrent fault codes registered that precede the oil pump failures are the MCID 2005 and MCID 2015, related with a low oil pressure. But due to the simultaneous occurrence of the fault codes and failure events, it was clear that the codes could not be used to prevent the failures.

The *P/N-5* had minor design changes compared to the *P/N-3*, namely an increased spring tension of the internal components. This kept the subparts closer together, thus reducing the gaps and clearances and, consequently, pressure variations.

The manufacturer was not convinced that the changes would be sufficient to resolve all failures experienced with the P/N-3 oil pump. As such, a Service Instruction Letter (SIL) was issued to perform a pump inspection at every 300 EngFH. NetJets further reduced the interval to 150 EngFH in order to have more data and also to increase the possibility of detecting faults before failure events.

In conjunction with the SILs, ECTM analysis was performed every 15 days. But as stated previously, and now proven, these were found to be unnecessary as the failures were sudden and catastrophic, with no warning signs.

As a proactive measure, the manufacturer continued to seek possible manufacturing defects on both pumps *P/N-3* and *P/N-5*. As such, an Energy-Dispersive X-Ray Spectroscopy was performed, consisting on an *analytical technique used for the elemental analysis or chemical characterization of a sample* [71].

There were FODs discovered present on the pumps, rich in Silicon, Oxygen and Aluminum. These were consistent with two known factors:

- ◇ the sand from which the mold of the pump was built with;

- ◇ the glass and sand particles from the jet blast used for cleaning purposes.

As the SILs were executed, the *P/N-5* pump kept failing several times, implying that the minor design changes were not sufficient. Taking this information into account, allied to the Spectroscopy findings, a replacement pump was under development.

The new pump, *P/N-6*, was released during the course of this case study. It further reduced the internal movement of the pump by reducing the gaps and clearances, and added a new section of pressure relief, similar to one already being in use in the industry (the Airbus A350's APU pump).

This new design fully eliminated the radial forces of the discharge pressure by routing the flow of fluid through eccentric rings and wear plates instead of through the body and came of the pump. In addition, new manufacturing techniques were used so that contamination of the pumps doesn't occur.

Full fleet replacement of the pumps for the new *P/N-6* is undergoing. So far, a few are already in service, and the corresponding SILs were executed once, with no failures being registered until September 2020.

One unscheduled event related with a *P/N-6* pump has been detected in October 2020, possibly indicating that not all problems were solved with this new pump.

3.5.3.3 Engine Driven Hydraulic Pump

In smaller aircraft, some control surfaces are controlled via physical cables. But in bigger and heavier aircraft, physical human force is no longer viable. As such, the control surfaces, as well as the landing gear and flaps, are powered by the Hydraulic Systems.

Hydraulic systems use fluid and pressure to operate the surfaces. Also, to achieve the necessary redundancy, the systems are composed of several subsystems, such as: a power generating device (usually, an engine-driven pump), an accumulator, heat exchanger, filtering system, among others [72]. An example of a Hydraulic Pump is seen on Figure 3.17.

Figure 3.17: Example of a Hydraulic Pump [72].

In order to develop a more robust investigation, data from NJA and NJE will be analysed. As the total of events is relatively elevated, only the factual analysis of the data will be detailed. As such:

- there is a total of 62 events, resulting in 58 replacements (removal and installation) of the EDHP;
- the 58 removed EDHP all have the same P/N 51160-06;
- only 1 EDHP (corresponding to 1 S/N) was overhauled and reinstalled after a first removal, with all others being discarded.

To evaluate the risk and the importance of developing this investigation, it is important to understand in which flight phase the events occurred and what failures lead to the events. As such, the data related with the EDHP replacements is detailed on Table 3.23, with: Flight Phase, Failure Description, as well as the Total of Events occurred per failure.

Flight Phase	Failure Description	Sub-Total	Total
AIRBORNE	CAS Fail Message	16	17
	Hydraulic Temperature High	1	
GROUND	Leak	34	41
	CAS Fail Message	3	
	Damaged B-Nut	1	
	Return Fitting Frozen	1	
	Dry Operation Damage	1	
	Hydraulic Temperature High	1	

Table 3.23: Flight Phase, Failure Categories and Events related with replacement of the EDHP.

It can be seen that 17 events occurred during flight and 41 were detected whilst the aircraft was still grounded. Most of the airborne events (94%) result from a CAS Fail Message, whereas Leaks (83%) lead the reasons for failure on the ground.

It is important to understand the causes for the 16 airborne CAS Fail Messages. As such, the related data is detailed in Table 3.24, with the Found Failure and the Total of Events per failure. To be noticed that multiple events combined can lead to a CAS Message, making the total failures found to be more elevated then the number of CAS Messages.

Reason	Failure Found	Total
CAS Fail Message	Leak	11
	Contaminated Case Drain Filter	8
	Ruptured Shaft	4
	Excessive Pressure	1

Table 3.24: Causes for CAS Fail Messages while Airborne related with the EDHP.

The main reason for the airborne CAS Fail Messages are Leaks, with 11 events. Also, in 8 of these events, there was a Contaminated Case Drain Filter. Combining all ground and airborne leak events, a total of 45 leakages is reached. Figure 3.18 shows a real leak of the CH350's EDHP.

Figure 3.18: CH350's EDHP Leak.

Similar to what occurred with the Oil Pumps on Section 3.5.3.2, the EDHP is related with the AGB. Due to the high speed rotations on the shafts, these might lead to ruptures and also leaks, requiring recurrent inspections.

The AAIP has a GVI for the AGB, but as the EDHP is not a part of the AGB (only driven), the GVI does not affect the EDHP directly and therefore it is not inspected. The AGB and EDHP (number 10) can be seen on Figure 3.19.

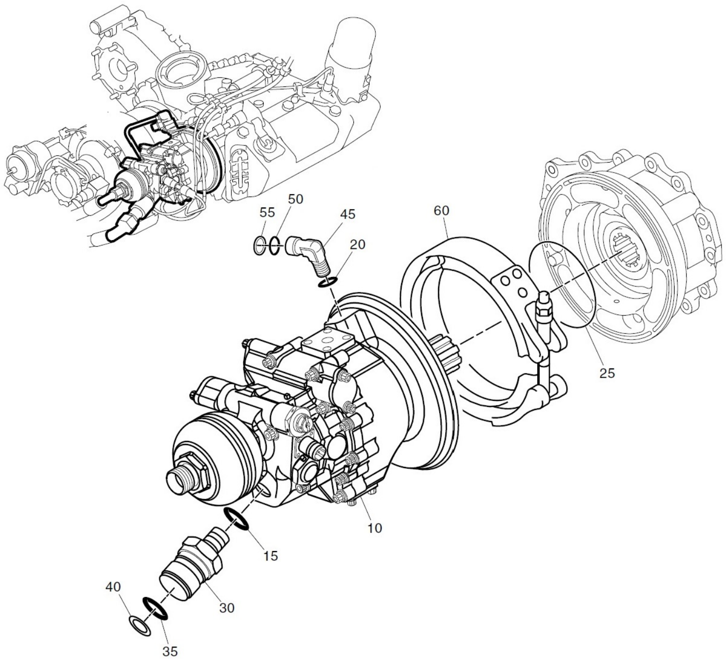


Figure 3.19: Accessory Gearbox and EDHP (as number 10) [69].

Out of the 58 replacement events, it is important to understand when the EDHP failed. As such, the Times of Failure (TOF) can be found on Appendix A, Table A.5. With these, the Average (AVG) and Standard Deviation (STD) were calculated and are presented on Table 3.25a.

To focus the investigation on the most representative failures, and understand when most of the events were occurring, a parametrization consisting on three time intervals was created using the AVG and STD values, as follows:

- ◇ TOF $<$ AVG – STD: Interval Φ, where events occurred at an early stage of usage, most likely due to manufacturing errors causing infant mortality (I.M.);
- ◇ AVG – STD $<$ TOF $<$ AVG + STD: Interval Ψ, with most of the events and therefore the most representative interval;
- ◇ TOF $>$ AVG + STD: Interval Ω, where items surpassed the considered normal times of failure due to unknown causes.

The TOF Interval Limits and the Number of Events per interval are detailed on Table 3.25b.

Parameter	Value [EngFH]
Average	2305
Standard Deviation	1353

(a) Parameters of TOF at Failure.

Interval	TOF [EngFH]	Events
Φ	TOF $<$ 952	11
Ψ	952 $<$ TOF $<$ 3658	38
Ω	TOF $>$ 3658	9

(b) Failure Time Intervals.

Table 3.25: Average, Standard Deviation and Failure Time Intervals on EDHP.

As most events occur in Interval Ψ, with a TOF between 952 and 3658 EngFH, then a possible maintenance task should also be scheduled inside this interval. As it is a very broad interval, a more fractioned approach shall be taken.

For efficiency purposes, it is best to schedule a task for an already used maintenance inspection interval. As such, distributing the events and corresponding TOF per intervals of known inspections was deemed the best idea. The results are displayed on Table 3.26, divided into three columns: the Time Interval, the Number of Events per interval, as well as the corresponding Percentage (out of a total of 58 events).

Time Interval [EngFH]	Events	Percentage
TOF $<$ 400	6	10%
400 $<$ TOF $<$ 800	5	9%
800 $<$ TOF $<$ 1200	2	3%
1200 $<$ TOF $<$ 1600	6	10%
1600 $<$ TOF $<$ 2000	7	12%
2000 $<$ TOF $<$ 2400	5	9%
2400 $<$ TOF $<$ 2800	5	9%
2800 $<$ TOF $<$ 3200	5	9%
3200 $<$ TOF $<$ 3600	7	12%
3600 $<$ TOF $<$ 4000	4	7%
4000 $<$ TOF $<$ 4400	1	2%
4400 $<$ TOF $<$ 4800	3	5%
4800 $<$ TOF $<$ 9600	2	3%

Table 3.26: Distribution of EDHP Failure Events per Inspection Time Intervals.

This table was constructed using the smallest maintenance interval possible, corresponding to the inspection α of 400 EngFH. For space purposes, and as the number of events was small, the last interval does not respect this process.

It is also important to understand that performing a maintenance task every 400 EngFH would not be economically viable. As such, events related with infant mortality (with TOF $<$ 800 EngFH) are not relevant for the investigation.

To correctly assess a timing for a maintenance task to be scheduled, and considering that the pattern of failure remains constant, Table 3.27 was constructed. It represents the number of events that could be missed (and therefore cause an unscheduled event) if a maintenance task was performed at a given time.

To be stated that the percentages of *All Missed Events* is obtained by taking into consideration all 58 events, whilst the percentages of the *Missed Events without I.M* is obtained considering only 47 events. As it is a cumulative table, the sum of the percentages will not correspond to the total of cases.

Task Recurrence	All Missed Events		Missed w/o I.M.	
1200 EngFH	13	22%	2	4%
1600 EngFH	19	33%	8	17%
2000 EngFH	26	45%	15	32%
2400 EngFH	31	53%	20	43%
Total of Events	58	100%	47	81%

Table 3.27: Cumulative Missed Events on the EDHP.

On one hand, it is seen that 19% of all events are related with infant mortality. Although it is an elevated number, as the EDHP is a very complex system, contacting the manufacturer is not the primary option.

On the other hand, when analysing the data, some conclusions are drawn, as follows:

- If a maintenance task was performed at every 1200 EngFH, there would be a very small percentage of possible events missed. This would be very effective, but also economically expensive, as the number of yearly tasks would increase in 25%.
- If a maintenance task was performed at every 2000 EngFH, the number of possible missed events would be too high. This would lead to questionings regarding the reasons for preventive maintenance to be performed in the first place.

As such, a trade-off between the number of inspections and number of possible missed unscheduled events is necessary. Therefore, the recurrence of the maintenance task is set at 1600 EngFH, with roughly 17% of events possibly missed.

To select the maintenance task, information regarding the EDHP's assembly is necessary. The EDHP is closed, therefore interior access is off-limits as it would require several hours to remove the pump, inspect and reinstall it. There are also no access points to insert a borescope to check the shaft and possible state of the seals. As such, only a General Visual Inspection can be performed.

At this moment, an EO was ready to be redacted as all necessary information is available. As such, the EO contains the following:

- Recurrence: to be performed at every 1600 EngFH, aligned with another maintenance opportunity;
- Scope: General Visual Inspection to detect any damage to the structure, leaks or other items that might be considered relevant for the safety of the item, according to the EMM;
- If Failure Found: a Detailed Inspection shall be carried out to determine if the item is safe for operation; if unsafe, a replacement of the EDHP is mandatory.

According to the AAIP, the 1600 EngFH scheduled tasks do not require opening of the engines' cowlings. As such, it will imply a longer time to perform the proposed tasks. After contacting a Service

Center, and providing details of the tasks, the man-hours required for their completion were obtained, as follows:

- ◇ Access Gain: 30 minutes per engine;
- ◇ General Visual Inspection: 45 minutes per engine;
- ◇ Total Man-Hours: 2.5 hours per aircraft.

Regarding the costs, and taking into consideration the man-hour value used on Section 3.4.3.2 of 93€ , the EO will have a cost of 233€ . This totals an approximate of 2796€ every two years, if the average flying time is considered.

In summary, the extent of the analysis resulted in an EO, where a maintenance task of a GVI of the EDHP was defined, at every inspection δ, as a preventive measure to reduce (or eliminate) groundings related to faulty Hydraulic Pumps. Also, all data was reported to the manufacturer so that a future new EDHP can be developed.

Chapter 4

Conclusions

The main goal of this thesis was to develop a methodology to analyse and categorize aircraft failures, leading to more custom and efficient maintenance plans. This thesis demonstrates the benefit of applying theoretical decision making processes to analyse the occurrence of failures, instead of a simple empirical analysis.

With Pareto, the causes that did not contribute to a large percentage of incidents were excluded [47], focusing the analysis on the most important subjects.

With the Risk Analysis, the process of selecting the critical items or systems was factual and based on pre-defined criteria, such as the detectability, severity and occurrence [50]. As such, only the components that most affect the operation were analysed in depth.

Also, it is concluded that a preventive maintenance task is not always the solution to avoid failures. Sometimes, manufacturing problems lead to failures that cannot be prevented and new components shall be developed by the manufacturers.

4.1 Achievements

The selection of the fleets and aircraft system to be investigated was mainly defined by the usage of the EHM software CAMP. The Latitude and Challenger 350 fleets had the most data available on such software.

Next, the categories created to systematize events allowed a good understanding of all the failures, corresponding systems and consequences to the operation. An average of 110 failures per fleet was compiled. These were mainly a result of malfunctions with the Engine Fuel and Control System as well as the Oil System.

The usage of the Pareto's theory was useful in reducing the number of events possibly under investigation. The systems that didn't contribute to a minimum percentage of failure events were excluded, such as the ECTM No Transmit on the Latitude and FADEC Memory on the Challenger 350. There was an average reduction of 12% in events to be assessed.

Also, the Risk Analysis, based on the RPN, allowed a good understanding of the importance of each component or item to the NetJets operation. As such, the most critical components of both fleets, per order of RPN, are as follows:

- Anti-Ice Valve (CH350 – RPN 300);
- Oil Pump (CH350 – RPN 250);
- Engine Driven Hydraulic Pump (CH350 – RPN 216);
- Thrust Reverser Control Valve (Latitude – RPN 200);
- EEC Electrical Connectors (Latitude – RPN 135);
- Fuel Filter Impending Bypass Switch (Latitude – RPN 135).

Comparing both fleets, it is concluded that the Challenger 350 has failures with a higher risk for the operation than the Latitude, as the Top-3 Critical Items belong to the Challenger 350.

Furthermore, as the Occurrence's ranking was based on the MTBF values of both fleets' components, it is not permanently settled. Future analysis can alter the ranking and consequently the RPN values, possibly leading to different critical items.

Several solutions for the failures were achieved. It can be concluded that not all solutions for failures are maintenance tasks, as some components may suffer from manufacturing errors or can be poorly manufactured for the location they are installed in.

Regarding the critical items, the following was achieved:

- the Anti-Ice Valve bellows became damaged due to thermal expansions and contractions; no preventive maintenance was possible; a new valve is under development by the manufacturer;
- foreign debris were discovered on the failing Oil Pumps, due to manufacturing errors; new pumps were developed with different manufacturing techniques; also, a pressure relief section was added; pumps are undergoing installation, with one failure registered already; follow up necessary with manufacturer;
- a general visual inspection on the Engine Driven Hydraulic Pump is possible to prevent unscheduled failure events; if precursor of failure is found, replacement is mandatory; manufacturer contacted to possibly develop a new pump to discover and prevent causes of failure;
- a faulty batch of Thrust Reverser Control Valves was discovered due to a bent spring guide and an incomplete drill depth; affected valves are undergoing replacement; no further actions required;
- due to their location, the EEC Electrical Connectors are prone to contamination; a recurrent cleaning maintenance task is possible to prevent unscheduled events; manufacturer contacted to possibly develop new connectors less prone to contamination;
- contamination was found on the Fuel Filter Impending Bypass Switches; also, permanent contact of the switch was found to be a cause for the failures; a new switch was developed to minimize contacts, being installed with no subsequent failures registered.

4.2 Future Work

Facing all the work performed, some topics can be proposed for future work:

- performing a sensitivity analysis to the collected data, to assess their coherence as well as if there is a need for more failure related information (as an example, the Mean Time to Repair or the failure rate);
- performing a functional analysis so that the functions of every system are understood, leading to a better definition of possible problems and more clear paths to plausible solutions;
- performing a continuous risk analysis in order to reach a threshold of RPN, so that every time an item reaches that value, maintenance is triggered;
- performing a full RCM analysis (in which the FMECA analysis is included) to understand which failures may occur as a consequence of the operation (and not just based on previous occurrences), focusing on the most critical areas;
- application of the methodology to all NetJets fleets, using the corresponding maintenance tracking software;
- performing a trend analysis on the engine tracking software to understand if predictive maintenance tasks can be scheduled in conjunction with the other AMP tasks.

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Appendix A

Tables for Case Study

A.1 Latitude's EMM Fault Codes

Fault Code	Meaning
CC	Handling BOV Solenoid Circuit Fault
KB	TTO Input Fault
TC	T/R Unlatched in Flight
TE	T/R Switch Discretes Fault
TW	T/R Unlatched But Not Deployed on the Ground
TY	T/R Inadvertent Stow
YC	EDU UART Receiver 1 Fault

Table A.1: Typical Latitude Fault Codes on CAMP, as per the EMM [59].

A.2 CH350's EMM Fault Codes

Fault Code	Meaning
MCID 1207	MDC Message: A/I Control Valve 5
MCID 1213	MDC Message: Anti-Ice On Without Command
MCID 2005	MDC Message: Low Oil Pressure Exceedance
MCID 2015	MDC Message: Low Oil Pressure Notice

Table A.2: Typical CH350 Fault Codes on CAMP, as per the EMM [69].

A.3 Mean Time Between Failures per Fleet

A.3.1 MTBF on the Latitude

Item	MTBF [EngFH]
EEC	17066.7
EEC Electrical Connectors	6400.0
FFIB Switch	7313.3
Fuel Filter	25600.0
GCU	25600.0
Oil Bypass Switch	25600.0
Oil Quantity	4266.7
Oil System Seals	17066.7
Spark Ignitor	25600.0
Start Switch	25600.0
Starter Generator	25600.0
Thrust Reverser Control Valve	10240.0
Thrust Reverser Control Valve Connectors	25600.0
Thrust Reverser Doors	25600.0

Table A.3: MTBF of Latitude's Items.

A.3.2 MTBF on the CH350

Item	MTBF [EngFH]
Anti-Ice Valve	1955.6
Bleed Air Leak Detector Connector	17600.0
ECU	17600.0
EEC	17600.0
Hydraulic Pump	7040.0
Hydraulic Pump Filter	17600.0
Oil Pump	3200.0
Oil Quantity	11733.3
Oil System Seals	8800.0
OSSD Sensor	17600.0

Table A.4: MTBF of CH350's Items.

A.4 CH350’s EDHP Times of Failure

TOF [EngFH]	Interval
3790.9	Ω
3770	Ω
3477.5	Ψ
3374.1	Ψ
588,5	Φ
2760,5	Ψ
4488,4	Ω
2157,8	Ψ
3626,5	Ψ
1910,8	Ψ
2292,4	Ψ
4816,7	Ω
1786,2	Ψ
1605,8	Ψ
2403,7	Ψ
1893,4	Ψ
1893,4	Ψ
1537,3	Ψ
2575,5	Ψ
781,4	Φ
2901,2	Ψ
584,4	Φ
1558,1	Ψ
3055	Ψ
2994,1	Ψ
1499,2	Ψ
1843,5	Ψ
1586,8	Ψ
133,7	Φ
3718,8	Ω
1847,3	Ψ
2994,1	Ψ
2299,8	Ψ
1463,6	Ψ
93,8	Φ
953,3	Ψ
1276,2	Ψ
796,4	Φ
964,3	Ψ
655,8	Φ
5344,2	Ω
3463,6	Ψ
4750,7	Ω
4558,9	Ω
0	Φ
4342,8	Ω
0	Φ
2114,6	Ψ
3582,2	Ψ
3211	Ψ
222,5	Φ
3399	Ψ
2914,9	Ψ
2708,2	Ψ
2105,4	Ψ
3260,4	Ψ
2676,9	Ψ
286,5	Φ

Table A.5: EDHP Times of Failure (EngFH) and Relation with Table 3.25b’s Time Intervals.