Monitoring of the lubrication system of an aircraft engine through a Prognostic and Health Monitoring approach

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Figure 1, CFM56 by CFM International[i]

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	Master of Science Thesis,	
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Prognostic and Health Monitoring (also called *PHM*), applied to mechanical components, is a new way to monitor their health and to anticipate the failures. This paper will determine whether the monitoring of the health of the lubrication system using a *PHM* approach and currently made by *SNECMA* on its engines can be improved and how it can be done. An abnormal oil consumption of a lubrication system indicates a poor health of the engine and that is the main reason why this consumption should be supervised as precisely as possible.

Nowadays, *SNECMA* is already monitoring the oil consumption of its engines by studying the data extracted before the take-off and after the landing, but the algorithm used can still be improved. Several options have been considered to improve the monitoring of the lubrication system, but it appears that studying the third main phase of the flight, between take-off and landing, could bring additional data useful to increase the precision on these calculations.

During this study, raw data will be analyzed and normalized in standard conditions in order to compare them and to modify the calculation of the oil consumption.

The results of this study will either lead to an improvement of the accuracy of the calculated oil consumption, and thus a better anticipation of the failures, or to the fact that the data extracted between take-off and landing do not allow an improvement of the current algorithm.

Keywords: *lubrication system, normalization, failure, Prognostic and Health Monitoring*

I would like to thank Audrey Dupont, my tutor at *SNECMA*, who made this internship realizable. She brought me guidance, help and assistance through this internship and allowed me through her availability to reach the goals defined at the beginning of this internship.

I also would like to thank Jean-Robert Pougeon as well as the rest of the team for their constant advices and for welcoming me warmly in the team as if I was part of it.

In particular, I would like to address special thanks to François Demaison since he allowed me to work on its previous work, and allowed me not to start from scratch.

I would like to thank all the teachers that I met through my studies at Arts et Métiers ParisTech and KTH and allowed me to complete this double degree and gave me knowledge to work as an engineer in a field that I like. Amongst them, I would like to thank Nenad Glodic and Thiery Stéphane, my tutors respectively at KTH and Arts et Métiers ParisTech for following me during this internship and giving me advices and help.

Finally, I would like to thank again Nenad Glodic, who extended my knowledge in turbomachinery applied to aircraft, and also Ulf Ringertz for his very "living" class of Flight Mechanics at KTH, who both reinforced my will to work in the field of aeronautics.

Due to some confidentiality issues, some sensitive data might not appear in this report and numerical values might be normalized. However, I made sure that it is possible to understand the principles used and the ins and outs of this study.

Pierre Grassart

Paris, November 2015.

3.1 Notations

Symbol	Description
F	Net thrust (N)
$\dot{m}_{air}$	Rate of flow of the air entering the engine (kg/s)
V_{out}	Velocity of the fluid at the outlet of the engine (m/s)
V_{in}	Velocity of the fluid at the inlet of the engine (m/s)
N	Rotation speed

3.2 Abbreviations

Abbreviations	Meaning
SNECMA	Société Nationale d'Etude et de Construction de Moteurs d'Aviation (National Company for the Design and Construction of Aviation Engines, in English)
PHM	Prognostic and Health Monitoring
IFSD	In Flight Shut Down
FMECA	Failure Mode, Effects and Criticality Analysis
ACOC	Air Cooled Oil Cooler
OPT	Oil Pressure and Temperature
OFDP	Oil Filter Differential Pressure
ODMS	Oil Debris Monitor
OLS	Oil Level System
AGB	Accessory GearBox
IDG	Integrated Drive Generator
IGB	Inlet GearBox
TGB	Transfer GearBox
PMA	Permanent Magnet Alternator
FE	Forward Enclosure
RE	Rear Enclosure
EOL	Engine Oil Level
EOP	Engine Oil Pressure
EOT	Engine Oil Temperature
WEFA	Wireless Extension For Aircraft condition monitoring system

4. TABLE OF CONTENTS

5.1   Personal context

This master thesis was written in the context of my double degree between Arts et Métiers ParisTech (Lille, France), and Kungliga Tekniskan Högskolan (Stockholm, Sweden), also called KTH or Royal Institute of Technology, in English.

After two years of studying mechanical engineering at Arts et Métiers ParisTech, which is a French engineering school, I had the chance to take a double degree in Stockholm, at the Royal Institute of Technology, in the Aeronautical and Vehicle engineering department. There, I had the opportunity to select the courses that I wanted to follow. I started to take classes dealing with basics in aerospace, since I only had a few notions in this field, but I quickly drifted to classes dealing with aeronautics. I had some previous knowledge from Arts et Métiers ParisTech in the field of turbines and compressors, through the thermodynamics classes, and I had the opportunity at KTH to apply these principles to airplane's engines. I realized that aircraft's engines were a really interesting field, because almost all the areas which compose physics in general are mixed: thermodynamics, electronic, chemistry, solid-state physics, fluid mechanics, materials science…

It is where I understood that I really wanted it to be the field I would like to work in.

To complete my master at KTH, I had to write a master thesis, which I did while realizing an internship at *SNECMA* (subsidiary of *SAFRAN*) on the site of Villaroche (France). I was, during this internship, part of the *Prognostic and Health Monitoring* team, which belongs to the *Systems Division*.

5.2   Company context

5.2.1   SAFRAN

SAFRAN is a high-technology group, currently leading in several fields such as aerospace, aeronautics, defense and security on an international level. *SAFRAN* gathered at the end of 2014 69000 employees in almost 60 countries and realized a turnover of €15.4 billion on the same year[1] (see Figure 2).
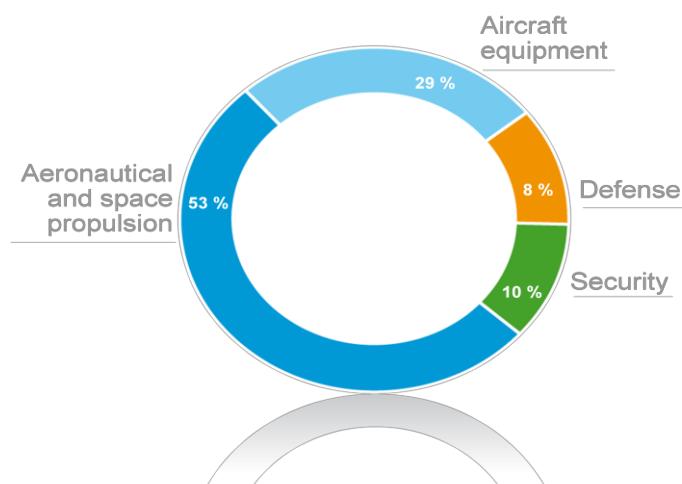
Figure 2, Distribution of SAFRAN's turnover in 2014[ii]

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[1] Retrieved on October 22nd, 2015 from SAFRAN's intranet and https://en.wikipedia.org/wiki/Safran

5.2.1.1   Aeronautical and space propulsion

This branch of the company gathers several subsidiaries (see Figure 3) leading on an international level in their field such as:

- *SNECMA* which is amongst the leader in commercial aircraft engines, through its joint venture *CFM INTERNATIONAL* with *GENERAL ELECTRIC AVIATION*. It is also ranked fourth in the area of military engines;
- *TURBOMECA* which is the world leader in helicopter engines;
- *HERAKLES* which is leading the market of propellant production for space application.

5.2.1.2   Aircraft equipment

SAFRAN also supplies aircraft manufacturers with systems and engine components. Amongst the subsidiaries, we can find:

- *MESSIER-BUGGATI-DOWTY*, producer of brakes and landing gears;
- *AIRCELLE*, producer of engine nacelles;
- *HISPANO-SUIZA*, developing power transmission systems;
- *LABINAL* is involved in wiring systems.

5.2.1.3   Defense and security

Finally, *SAFRAN* offers an extended range of services related to security and defense matters. The most important subsidiaries in this field are:

- *MORPHO*, dealing with identity management, homeland protection or even public safety;
- *SAGEM DÉFENSE SÉCURITÉ*, developing electronic systems for aeronautics and defense.
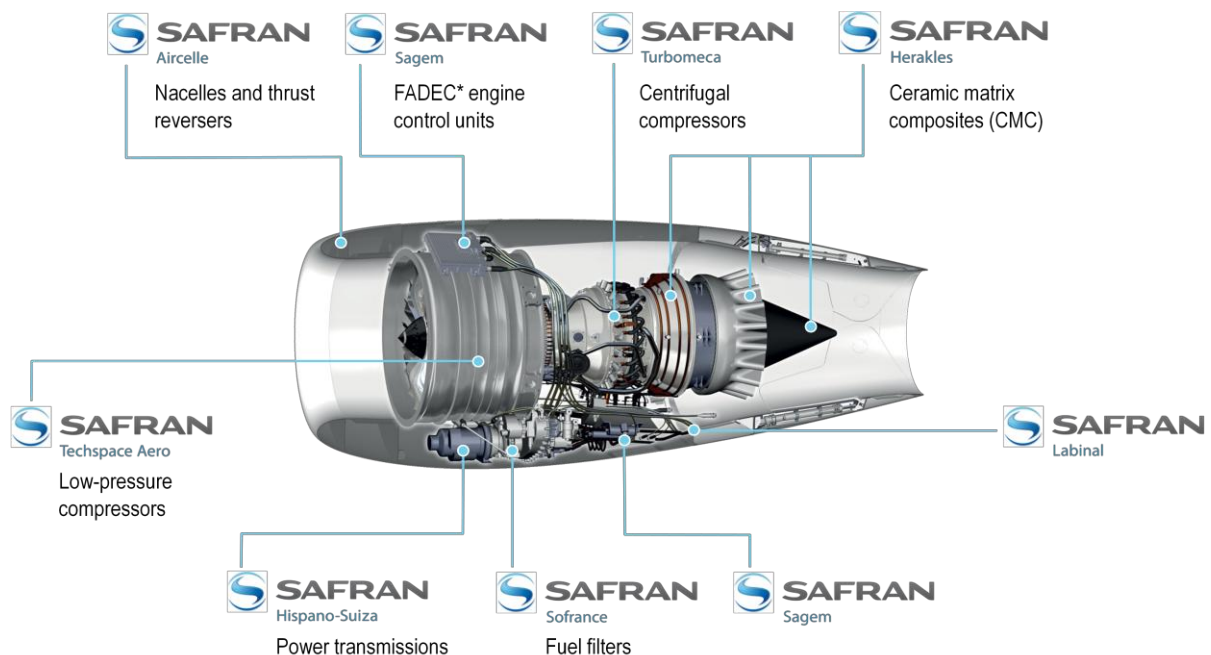
Figure 3, Example of the segmentation of the main subsidiaries on an aircraft's engine[iii]

5.2.2   *SNECMA*

Aircraft and rocket engine manufacturer, *SNECMA* takes in charge the designing, development, production and marketing of engines for civil aircraft, military aircraft but also for space application. *SNECMA* gathered at the end of 2014 15015 employees on 35 sites across the world and realized a turnover of €6.5 billion on the same year[2]. Here is a quick review of the main activities of *SNECMA*.

5.2.2.1   Commercial engines

SNECMA has developed the *CFM56* through its joint-venture *CFM INTERNATIONAL*. This engine is the best-selling engine in the history of aviation with about 11000 single-aisle commercial jetliners equipped worldwide[3]. Still under its joint-venture, *SNECMA* is currently developing the successor of its previous best-seller: the *LEAP* which will offer exceptional performance while retaining the legendary reliability of its ancestor[4] (see Figure 4). Finally, *SNECMA* also develops engines for regional jets such as *SAM146*, for widebody jets such as *GE90* and for business jets such as *SILVERCREST*.

Figure 4, From left to right: CFM56[iv], LEAP[v] and SILVERCREST[vi]

5.2.2.2   Military engines

SNECMA also develops military aircraft engines to cover a wide range of combat, transport and training missions. Amongst them, we can cite the *M88* and the *M53* which power respectively the *RAFALE* and the *MIRAGE* from *DASSAULT*, two of the world's best fighters, while the *TP400* powers the *A400M* from *AIRBUS* which is a military airlifter[5] (see Figure 5).
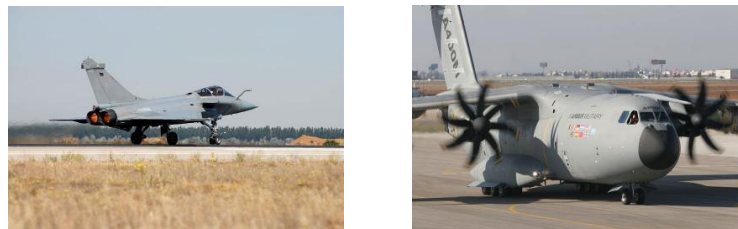
Figure 5, Left: RAFALE MARINE equipped with M88[vii]; Right: A400M equipped with TP400[viii]

5.2.2.3   Space engines

SNECMA is the prime contractor for the propulsion system on the main stages of *ARIANE 5*. *SNECMA* will also develop the *VINCI* cryogenic engine and a new version of *VULCAIN 2* for

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[2] Retrieved on October 22nd, 2015 from http://www.snecma.com/our-company#1
[3] Retrieved on October 22nd, 2015 from http://www.snecma.com/commercial-engines/single-aisle-commercial-jets/cfm56-success-story
[4] Retrieved on October 22nd, 2015 from http://www.snecma.com/commercial-engines/single-aisle-commercial-jets/technological-leap-forward
[5] Retrieved on October 22nd, 2015 from http://www.snecma.com/snecma-rises-todays-multifaceted-defense-challenge

the next-generation *ARIANE 6*. *SNECMA* is also developing a range of plasma thrusters in order to increase the payload and reduce launch costs on geostationary satellites[6] (see Figure 6).
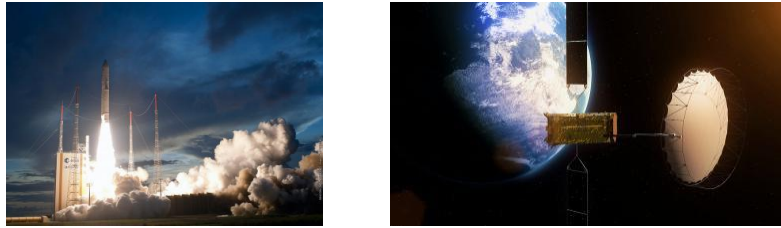
Figure 6, Left: ARIANE 5[ix]; Right: Plasma propelled satellite[x]

5.2.2.4   Services

SNECMA offers its expertise to the clients to meet their requirements. The services cover the entire engine life cycle, from design to service entry to dismantling at end-of-life. Maintenance can be on-wing or in shop and personalized support as well as consulting services is offered[7].

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[6] Retrieved on October 22nd, 2015 from http://www.snecma.com/space-propulsion-systems-all-seasons
[7] Retrieved on October 22nd, 2015 from http://www.snecma.com/services-our-expertise-geared-your-requirements

6. INTRODUCTION

6.1 Background

Airplane travel, whether it is for work, vacation, freight or even military application, is one of the most convenient mean of transportation. As a consequence, air traffic is growing, and airplanes need to be more efficient, not only in terms of costs of production, but also when it comes to fuel consumption or even sustainable development.

From an economic point of view, overhaul and servicing are a big part of the expenses that the companies have to face, after the purchase of the airplane itself. Not only engineers and technicians have to be paid, replacement parts have to be bought, but the airplanes can remain grounded for quite a long period while being repaired, which leads to loss of money because flight tickets cannot be sold. Some flights can also be delayed or cancelled, leading at the end to a loss of time, and thus money for the company.

From a safety point of view, failures should be avoided on many levels. Sometimes, they can have a small impact on the flight, since they can happen on auxiliary equipments (for example, equipments whose aim is it to make the flight more comfortable for the passengers such as TV, lights…). It can also lead to the shutdown of an engine (also called *In Flight Shut Down*, or *IFSD)*. However, these failures can also be more substantial, like the break of one the blades of the rotating elements of the engine, which could penetrate through the cabin, or even lead to a crash and the loss of priceless lives[8].

Knowing all the issues going on around air traffic, one can easily understand the interest of the *Prognostic and Health Monitoring*, also called *PHM,* on an airplane. Indeed, the *PHM* allows, through a surveillance of various components, to anticipate future failures and to avoid them. This preventive maintenance can be summed up by the following motto: *"Better safe than sorry"*.

This new way of considering the life of an element is quite different from what was done before. However, they are not conflicting. Among the main types of maintenance which exist, one can mention the *Hard-time maintenance* or the *Condition-based maintenance*. The first one deals with maintenance after a certain amount of time, or cycle (or whatever significant parameter), while the second one deals with maintenance when there is a need, i.e. when one or several indicators warned that there were a failure.

If one focuses on the engine, which is one of the most important components of the airplane, it can be seen that developing services such as *PHM* has a real importance for the companies in charge of building and maintaining these engines.

A new type of maintenance contract is now used. Engines manufacturers do not wait for a failure to occur no more than they only service the engine after a certain amount of time. They monitor the engine's parameters during its life and operate servicing when needed to anticipate the potential failures. This is beneficial from an economic point of view for engines' manufacturers since the overhaul would be their responsibility; it is indeed less expensive to correct the defaults before malfunctions occur than to wait for bigger and more expensive component to break. The downtime can also be reduced.

Finally, companies who can sell those services to aircraft manufacturers can also provide their customers with more reliable engines, and thus benefit from a better reputation which can help to sign new contracts and thrive on the market.

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[8] Retrieved on November 10th, 2015 from http://www.tibco.com/blog/2013/09/01/major-plane-crashes-are-always-technology-failures-not-human-error/

6.2 Goals and delimitations

In this paper, the author will give details, explanations and results on his study about the lubrication system that can be found in the engine of the airplane. Indeed, this component is a major part of the engine and is the subject that concerns the author while realizing its internship in *SNECMA*.

Previous studies have been made and the Health Monitoring of the lubrication system is currently made through the supervision of the oil consumption of this lubrication system.

The first aim of this study is to analyze what could be made to improve the surveillance of this lubrication system. After that, the improvement with the biggest interest will be selected and the author will explain how the surveillance could be enhanced.

During the first part of his work, the author will explain why he chose to focus on the calculation of the oil consumption. He will establish a list with what is currently done around the lubrication system and what should be done or not in the future.

During the second part of his work, the author will work on real data. He will focus on the data extracted between take-off and landing, but he will also use the data extracted before take-off and after landing. However, he will not bring any modification to the work which has already been done for the two last phases. He will then be dependent of what has been done in the past and will have to deal with these outputs, whether they are faultless or not.

6.3 Method

As said previously, *PHM* is a service which is sold to the customer to allow to save money in different ways (see above), but it doesn't aim to fulfill any laws or specifications regarding safety. Knowing this, one has to keep in mind that the surveillance given through the *PHM* really needs to focus on the failures that occur at a high frequency and/or that would have a big impact, whether it is material of financial.

The first step to improve the monitoring and the detection of failures is to establish an exhaustive list of all the failures that could occur on the lubrication system. This work has already been done when the engines were being designed, using the experience feedback from previous engines, and this list of failures was thus not exhaustive. The aim of the first part of the study is then to decide whether it is interesting to create a way to anticipate and prevent new failures or if it would be beneficial to improve the actual monitoring.

To do so, not only the failure modes have to be listed, but also the effects and the criticality of these failures should be studied. This way of processing is called the *Failure Mode, Effects and Criticality Analysis*, or *FMECA*[9]. It has been developed by the U.S. military in the 1940's and is now commonly used in the vehicle industry, whether it is related to automotive industry, civil aviation or even space programs, but also in any kind of industry when improvements are needed.

The second step is then to select among these failures which one would be interesting to anticipate from safety and economical points of view. Because of the result of this analysis, the author will focus on the monitoring of the oil consumption. Since *SNECMA* already monitors the lubrication system by studying its oil consumption, the basic principle of the current algorithm will be explained to the reader. After this, the author will present the final part of its work and the results will be discussed.

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[9] Retrieved on October 22nd, 2015 from
http://www2.warwick.ac.uk/fac/sci/wmg/ftmsc/modules/modulelist/peuss/slides/section_12a_fmeca_notes.pdf?bcsi_scan_cb895f69027bc0de=tF8AeVK8NllfFnobBaTVhs1N5QgVAAAA4aWEkQ==:1

In order to make everything easily understandable by the reader, the author judged useful to explain in the next paragraph some basic working principles of the engine of an airplane, as well as the functioning of the lubrication system of this engine.

7. FRAME OF REFERENCE: THE ENGINE AND ITS MAIN COMPONENTS

7.1 Working principle of the engine of an airplane[10]

A prerequisite to understand the ins and outs of this study is to know how a turbofan works. It is compulsory to master the functioning of a motor used to propel an airplane to fully perceive the need to have an efficient system of lubrication.

To calculate the net thrust produced by an engine to propel an aircraft, two quantities have to be taken into account:

- The difference of momentum between the gas that goes into the engine and the gas ejected from it;
- The force coming from the difference of pressure between the exit of the duct and in front of the engine (where the air is not disturbed).

For an airplane, the second term can be neglected when compared to the first one. Moreover, the rate of flow of fuel entering the engine is small compared to the rate of flow of the air through the engine. It can then be assumed that the net thrust is almost equal to:

$$F \approx \dot{m}_{air} * (V_{out} - V_{in}) \tag{1}$$

From (1), one can see that there are two main ways to increase the net thrust: either the rate of flow of the air through the engine can be increased; either the speed at which the gases are ejected from the engine can be increased.

This leads to the two main categories of engines that can be found currently:

- The turbofans ,which posses a rather big diameter at the entrance, to suck as much air as possible, and thus making a lot of noise, and which are commonly used for civil aircrafts. These work best for high sub-sonic speeds;
- The turbojets, which posses a small diameter at the entrance and which are commonly used in military applications. These are more efficient at high speed (super-sonic speeds).

The working principle of these two kinds of engine is almost the same. The air enters at the intake, because it is sucked by the fan (or the low-pressure compressor if there is no fan). The air goes through several stages of compressor and turbine, depending on the engine. Usually, for a two-spool engine, the air goes through a low-pressure compressor, then a high-pressure compressor, then it gets heated while being mixed with the fuel in the combustion chamber and then is expanded through the high-pressure turbine at first and the low-pressure turbine finally.

One has to note that the low-pressure turbine and compressor and the fan are on the same shaft while the high-pressure turbine and compressor are on the same shaft (see Figure 7).

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[10] Saravanamuttoo, Herbert Ian Howard, Gordon Frederick Crichton Rogers, and Henry Cohen. *Gas turbine theory*. Pearson Education, 2001.
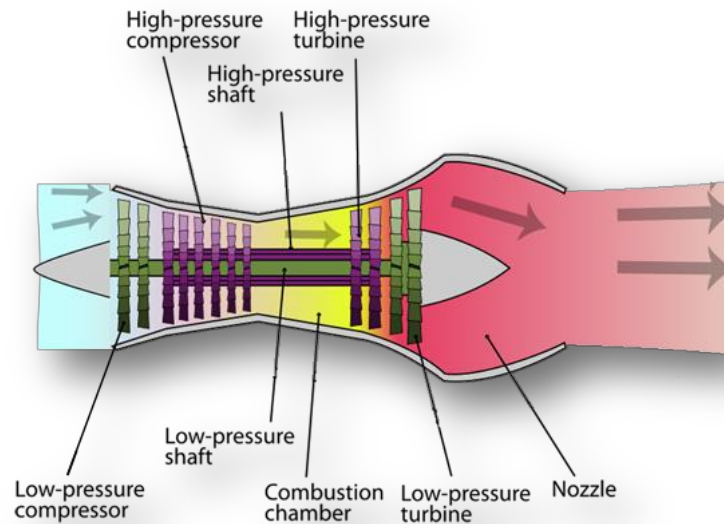
Figure 7, Two-spool engine, without fan[xi]

The difference between the two types of engine comes from the fact that in a turbofan engine, not all the air goes through the combustion chamber. An important part of it is accelerated by the fan (which is driven by the low-pressure turbine) and is bypassed around the core. This cold air usually provides up to 80% of the total thrust. That is why an important parameter, the bypass ratio, helps to characterize these engines: less than 1 percent of the air is bypassed around the core for military turbojet but it can go up to a ratio of 10:1 (10 units of flow goes in bypass for every unit of flow that goes to the core) for a turbofan (see Figure 8).
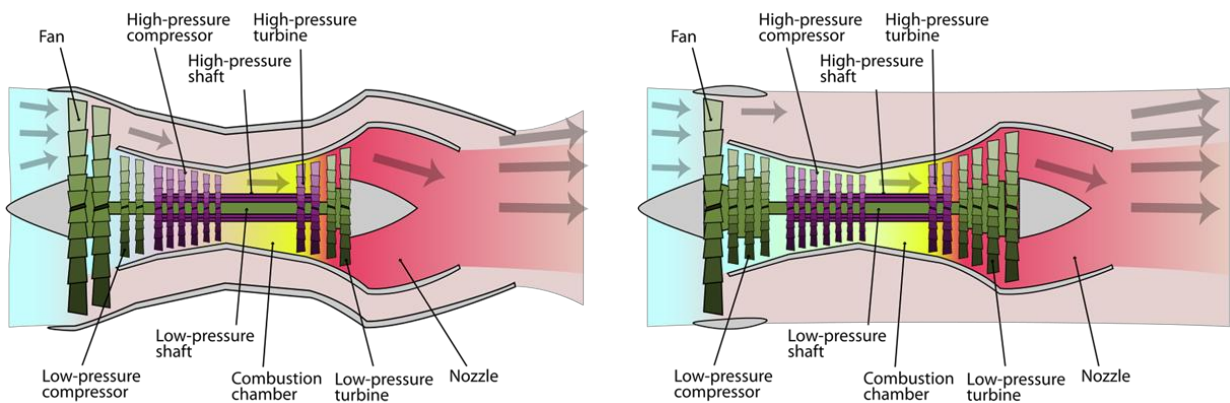
Figure 8, Two-spool engine with: Left: low bypass ratio[xii]; Right: high bypass ratio[xiii]

This paragraph allows the reader to understand how the core of the engine works. However, the core of the engine has to work in co-operation with other components, such as the *accessory gearbox*, whose functioning will be described in the next paragraph.

7.2   The accessory gearbox

The *accessory gearbox* (or *AGB*), although not a part of the engine's core, belongs to the engine. Indeed, it is thanks to this component that the accessories are powered, but also the different pumps. The *AGB* often includes an *Integrated Drive Generator* (*IDG*) which will give the initial motion to the high-pressure shaft at the start-up of the engine. Amongst the accessories (see Figure 9), we can find:

- A *Permanent Magnet Alternator* (*PMA*);
- A starter;

- Some hydraulic and fuel pumps.
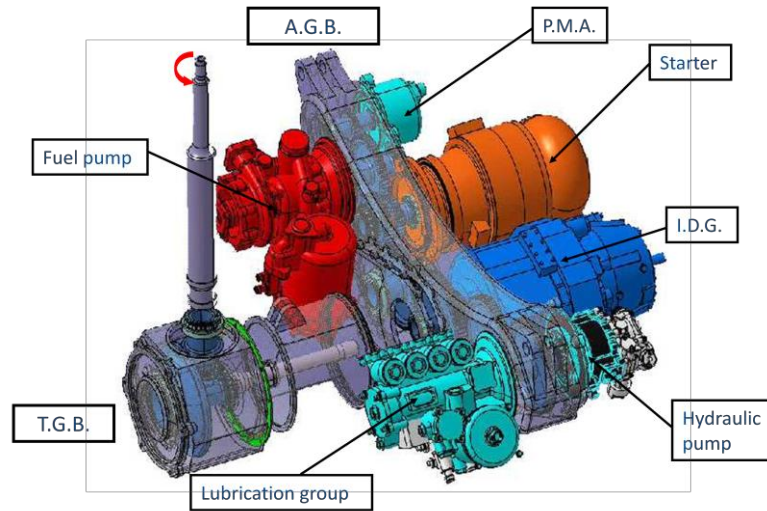
Figure 9, Example of an accessory gearbox and its components for civil aviation application[xiv]

The accessory gearbox is connected to the high-pressure shaft through a series of gearbox (see Figure 10):

- The *Inlet GearBox* (*IGB*) take the power on the high-pressure shaft;
- This power is then transmitted through another shaft (the radial shaft) to the *Transfer GearBox* (*TGB*);
- Finally, from the *TGB*, which is an angular gearbox, the transfer shaft transmits the power to the *AGB*.
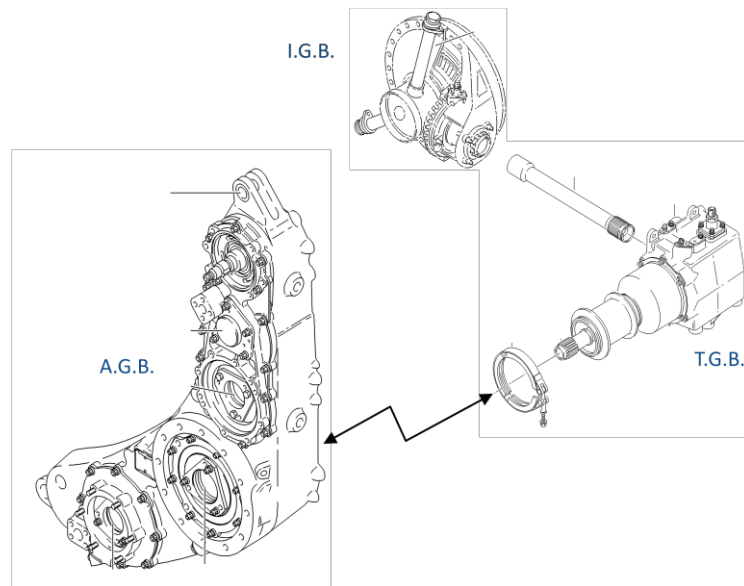
Figure 10, Connection between the high-pressure shaft and the AGB[xv]

7.3 Lubrication System

7.3.1 Main Purposes

The engine (core and auxiliary parts) is a mechanical piece that gathers a lot of rotating components, which all need lubrication. A whole system is then set around the engine to reach

well-defined aims (see Figure 11). The oil inside of this system has many functions. The main ones can be listed[11]:

- Collect and evacuate the heat produced around the components (such as gears, bearings, joints…);
- Redistribute this heat to heat the fuel coming from the tanks;
- Reduce the friction by creating an oil film under the rotating components (contained in the forward enclosure (*FE*), in the rear enclosure (*RE*), the *AGB* or even the *TGB*);
- Gather and evacuate the debris created by eventual dysfunction;
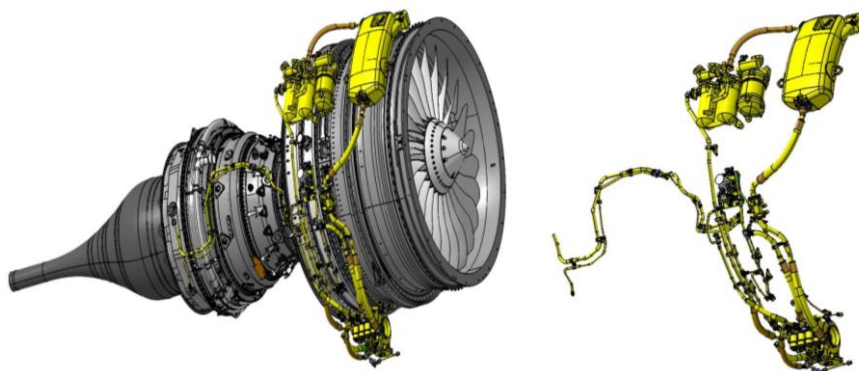
Figure 11, Lubrication system : Left: on the engine (in yellow)[xvi], Right: Alone[xvii]

It is estimated that that if it were only for the reduction of friction and evacuation of the debris, only 10% of the oil quantity would be needed. The main task of the oil is then to evacuate the heat[12].

7.3.2 Circuit of lubrication

The circuit of lubrication will now be studied in details. It has been said that the engine contains 4 main subsystems:

- The *forward enclosure* (*FE*);
- The *rear enclosure* (*RE*);
- The *AGB*;
- The *TGB*.

These 4 components have to be linked by oil ducts so that the oil can go from one to another. They must also be linked to the group of lubrication and other elements such as the tank, the pumps and the heat exchangers.

Other elements such as filters, strainers, anti-siphon valves or even a deoiler will be needed for the proper functioning of the circuit.

A simplified version of the circuit gathering the main elements can be seen on Figure 12. One has to note that this version of the circuit is called "cold tank": the heat exchangers are located upstream of the tank and they cool the oil at the exit of the engine, before its reentry in the tank. The measured oil temperature is then the same as the one in the tank.

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[11] *SNECMA document : engine training: lubrication system*
[12] Retrieved on November 24th from http://www.exxonmobil.com/aviation/Files/learningandresources_tech-topics_jet-engine-oil-system-part1.pdf

Figure 12, Simplified version of the oil circuit[xviii]

7.3.3 Main sensors on the circuit

Finally, sensors are added in order to monitor the various parameters as well as the health of the circuit. The sensors that can be found on the current engines are the followings (see Figure 13):
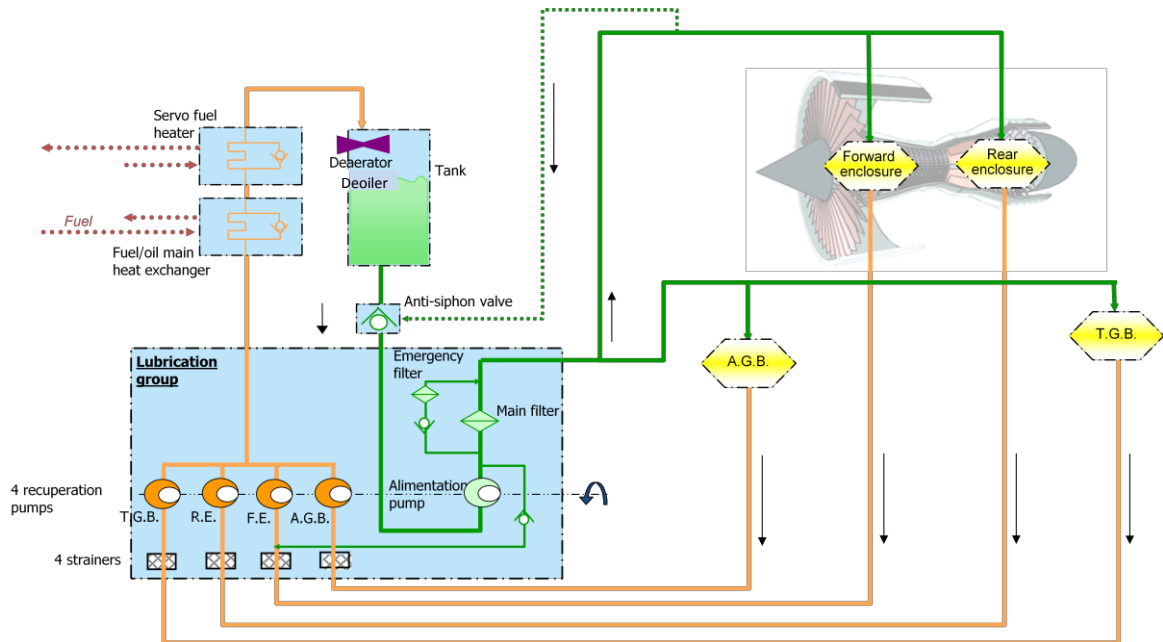
- *OPT* sensor: Oil Pressure and Temperature sensor. This sensor is located as close as possible from the point we want to get information, to avoid pressure losses. The more critical components in the circuit are the ball bearings; that is why this sensor is usually located next to the forward enclosure. On some engines, it can be located at the entrance of the AGB, because the pressure is the same than the one in the enclosure, except for the pressure losses which can easily be readjusted.

  This choice is also motivated by the fact that it is not interesting to know the pressure on the recuperation circuit: the bigger diameter of the ducts and the presence of filter both imply that less trouble might happen there. As a consequence, there is no economical advantage to monitor the pressure there.

  Two alarms are set on the pressure: high-pressure and low-pressure. The low-pressure alarm warns the pilot in case of lack of oil pressure on the supply circuit on the most sensitive components. This alarm is activated when the oil pressure reaches a fixed threshold, which is often very low and does not allow to detect failure for example at full throttle. This fixed threshold is now more and more replaced by an adaptive threshold (adaptive with throttle and temperature) which allows a more efficient surveillance of the pressure.

  Only one alarm is set on the temperature: high-temperature. This alarm is needed because at a too high temperature, the risks of degradations for the components (mechanical pieces, joints…) and for the oil are high. However, this alarm is rarely if ever activated since the heat exchangers are oversized: they are designed with security factors which allow them to cool better than needed.

- *OFDP* sensor: Oil Filter Differential Pressure sensor. This sensor allows the measurement of the pressure loss across the filter.

- *ODMS* sensor: Oil Debris Monitor System sensor. This sensor counts and sizes wear metal particles that would come from the circuit components. It is made with a magnetic coil assembly and uses the disturbances of the magnetic fields caused by the surrounding particles to detect and count their presence.

- *OLS* sensor: Oil Level System sensor. Located in the oil tank, the accuracy of this sensor depends on several parameters such as its resolution, but also the geometry of the tank and the conditions of functioning of the engine. Most of them work with a magnetic float which will activate the fixed receptors on the tank while being in front of them. This technique implies that the volume is not precisely known: only the volume at the moment of the activation is true because the float is in front of the sensor, but it will not be true again until the next time the float reaches a new receptor.
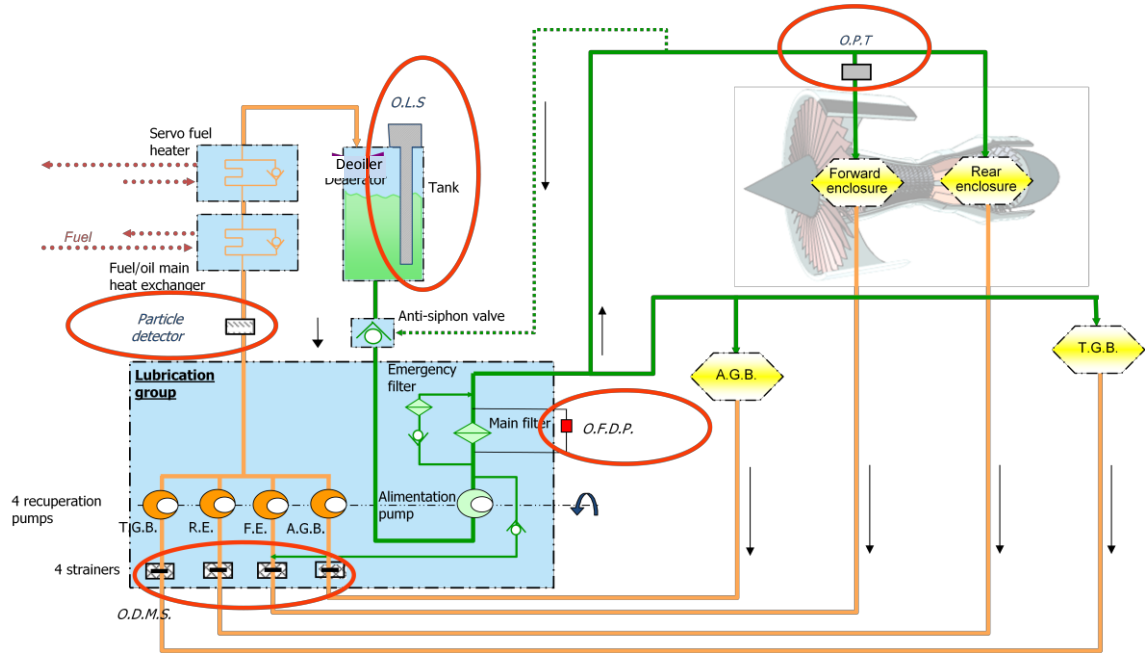
Figure 13: Simplified version of the oil circuit with sensors[xix]

It is to note for the rest of the study that the sensors will be considered non-defaulting; in fact, as every component, they could suffer from various failures which would result in a dysfunction of the whole engine. However, the aim of this study is to monitor the lubricant system itself, assuming that the sensors are not a source of failure. A surveillance of the health of the sensors could be made, but it is out of the limitations of this study.

8. FMECA METHOD AND POTENTIAL FAILURES OF THE LUBRICANT SYSTEM

Even though all the failures should be addressed, some of them might not really endanger the security of the passengers or change the instantaneous functioning of the airplane. However, these "non-critical" failures often lead to a decrease in efficiency and a functioning of the related components that could be modified over the time. This is the main reason why the author will present here a list of the potential failures on such a lubrication system. Once the main failures will be listed, it will be interesting to wonder whether they can be detected through existing sensors or not, but no further investigation will be made to know which sensors should be added. Indeed, since this study focus on already existing engines, it would be useless to do it since it is very hard or even impossible to change architecture choices that have already been done.

To achieve this study, some criteria should be set. Here, the following system will be chosen to rank the failures:

- Gravity of the failure:
  - 0 : no impact modifying the behavior of the system
  - 1 : impact on the system with long-term consequences
  - 2 : impact on the system with short-term consequences
  - 3 : impact on the system endangering its immediate health
- Rate of occurrence:
  - 0 : never
  - 1 : few cases in the aviation history
  - 2 : from time to time
  - 3 : almost every flights
- Can be monitored with existing sensors:
  - 0 : no
  - 1 : yes

8.1 Potential failures

8.1.1 Rate of flow variations

The lubricant system gathers various pumps and hydraulic elements. As a consequence, it was designed to be run at a nominal value of the rate of flow. In reality, the rate of flow never (or seldom) reaches its nominal value while the system is working. It can fluctuate around this value, without damaging the system. The efficiency will not be as good as what it would be when the engine works at its design point, but the system will still work, as security factors are taken in account while designing.

The oil, however, can be physically impacted. Indeed, when the rate of flow sees a substantial decrease of its value, it will imply that the oil will stay longer in contact with the hot elements which should be cooled by the oil. The temperature of the oil will then increase abnormally, and its power of removing the heat from the various elements will then be reduced, since the oil will be saturated in energy.

This problem, which would be quite critical, has a rate of occurrence rather low. Indeed, the pumps are extremely reliable, and the rate of flow does not suffer from too big variations around the design point. Moreover, even though the oil temperature increases, the heat exchangers (oil-air and fuel-oil) are oversized and will reduce the oil temperature.

- Gravity of the failure:
  - 2 : impact on the system with short-term consequences

- o The heat exchangers would indeed compensate this failure
- Rate of occurrence:
  - o 0 : never
  - o The pumps are extremely reliable
- Can be monitored with existing sensors:
  - o 1 : yes

8.1.2 Coking

The coking phenomenon is one amongst those which are the most feared by the engine manufacturers. The coke is a residue that appears through a chemical transformation when the oil faces extreme engine temperatures. Hardness and temperature of oxidation are severely correlated. The coke formation starts when the temperature of the elements the oil is in contact with overpasses 300°C[13][14].

This mostly happens when the engine is being stopped. In fact, when it is running at normal speed, and even though its elements (like for example the low-pressure turbine) can reach up to 500 or 600°C, the oil does not stay enough time in contact with the hot elements. Nonetheless, when the engine is being stopped, its speed, as well as the oil speed in the lubricant system, are dramatically reduced. The oil temperature increases and a thin film of coke (similar to a varnish) is created on the walls. As time goes by, this phenomenon will be repeated again and again, increasing the size of the film which will end to separate from the wall and create impurities in the system. These impurities, spreading in the whole lubrication system, will affect the lubrication power of the oil, but can also aggregate and obstruct the hoses and injectors of the system. A rise of pressure will then appear, leading to a fast deterioration of the system.

If the injectors were to be totally obstructed, no oil would lubricate the different elements anymore and the engine would suffer from an *IFSD* in the next 15 seconds. That is why this is an important failure mode. However, according to the experts, this problem happened only 2 or 3 times in the 20 last years on the *SNECMA*'s engines. As a matter of fact, the filters can recuperate these particles most of the time before they block the injectors.

- Gravity of the failure:
  - o 3 : impact on the system endangering its immediate health
  - o An *IFSD* would appear in the next 15 seconds
- Rate of occurrence:
  - o 1 : few cases in the aviation history
- Can be monitored with existing sensors:
  - o 1 : yes
  - o It could be monitored through *ODMS* or *OPT* sensors

8.1.3 Deterioration of rotating components

Because of the friction and due to normal functioning conditions, the rotating components, such as the turbine and the rolling bearings will lose some of their material. These components are designed to suffer from those events, which can be considered as normal in their life cycle, but the impurities created will be transported by the oil and can engender troubles if they are not intercepted by the filters. For example, the *ACOC* exchanger's cooling fins can be hit by these

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[13] Retrieved on November 24th from http://www.exxonmobil.com/aviation/Files/learningandresources_tech-topics_oil-coking-part1.pdf

[14] Retrieved on November 24th from http://www.exxonmobil.com/aviation/Files/learningandresources_tech-topics_oil-coking-part2.pdf

particles and see their efficiency decreased. However, *SNECMA* has shown through studies that up to 40 cooling fins could be lost without having any impact on the efficiency of the heat exchanger. Moreover, when an impurity encounters a fin, the fin is not totally destroyed and useless. Therefore, these impurities are not really disturbing for the system.

These components also have to rotate at a higher speed to be as efficient once they lose part of their mass. The temperature will then be affected and could lead to problems already cited above.

- Gravity of the failure:
    - 0 : no impact modifying the behavior of the system
- Rate of occurrence:
    - 2 : from time to time
- Can be monitored with existing sensors:
    - 1 : yes

8.1.4 Oil filter clogging

As said previously, the sources which can add particles in the circuit are numerous (usury of mechanical parts, chemical transformation, add of particles such as dust while pressurizing the enclosure but also while filling the oil tank, or even while servicing the circuit). This will lead to a more or less fast clogging of the different oil filters. Once a threshold of pressure loss across the filter is reached, the oil is bypassed: it goes around the filter which does not act anymore and the oil is not filtered. The consequences can be important: the non-filtered oil will still possess the unwanted particles and the risk of clogging of other components will increase.

The pressure losses should then be correlated with the contamination level and the temperature of the oil, which are the main parameters that have influence on the clogging, in order to be able to anticipate this phenomenon. However, only few accidents due to clogging happen between two consecutive overhauls of the circuit, and *SNECMA* already developed auto-washable emergency filters in the vicinity of the most sensitive components. Finally, the behavior of the filter is already monitored by *SNECMA*.

- Gravity of the failure:
    - 1 : impact on the system with long-term consequences
- Rate of occurrence:
    - 2 : from time to time
- Can be monitored with existing sensors:
    - 1 : yes

8.1.5 Tube rupture in the heat exchangers

As explained previously, the heat exchangers play a huge role in the evacuation of the heat stored in the oil. Yet, it could happen that some chips remain after the machining. These chips could even engender perforations in the tubes of the exchangers. If there is a rupture in any of the tubes of an oil/fuel heat exchanger, and since the fuel pressure is more important than the oil pressure, the fuel will penetrate in the oil circuit. Oil will be replaced by a mixture of oil and fuel and the *AGB* will first be filled with this mixture. Depending of the size of the perforations, this event could, in a short period of time (less than the average duration of a flight), lead to an *IFSD*. This failure is then very hard to detect upstream by the sensors. However, in the majority of the cases, when it happens, the perforations are quite small and the technician in charge of filling the tank detects, through the smell, the presence of fuel in the oil circuit.

- Gravity of the failure:
    - 1 : impact on the system with long-term consequences for small perforations

o 3 : impact on the system endangering its immediate health for large perforations
- Rate of occurrence:
    o 0 : never for large perforations
    o 2 : from time to time for small perforations
- Can be monitored with existing sensors:
    o 0 : no

8.1.6 Failure of the bypass system of the ACOC heat exchanger

The *ACOC* heat exchanger owns a bypass system which will bypass the exchanger if the oil temperature is less than 70°C (no need to cool it) or if the pressure losses through the exchanger are more than 4bar. If this bypass system, which is composed of thermostatic valves, happens to be broken, the oil will prefer to go through this bypass instead of going through the exchanger, since the resistance is least in the bypass. As a consequence, the oil temperature at the entrance of the engine will increase, and it will engender an abnormal behavior. These kinds of failures could be monitored through the existing sensors of temperature. Even though a method could be set to detect a potential failure of the bypass system, it would be hard to say which valve is defective. Only a technician could determine it while intervening.

- Gravity of the failure:
    o 1 : impact on the system with long-term consequences
- Rate of occurrence:
    o 2 : from time to time
- Can be monitored with existing sensors:
    o 1 : yes

8.1.7 Excessive oil consumption

One could wonder how a closed circuit could consume oil. This comes from the fact it is not a totally closed circuit[15]. Indeed:

- The deoiler rejects some air which still possesses a small quantity of oil. If this component suffers from degradation, this oil quantity rejected could grow;
- The labyrinths (joints between the different enclosures) can get old and lose their oil-proof power;
- The ducts can be defective after badly-done servicing.

An external leakage of the oil circuit would have terrible consequences. An *IFSD* would occur quickly, on a low-pressure alarm, resulting in the loss of one of the engines. However, for a minor external oil leakage, it might be harder to detect. The oil level in the tank (where it is measured) changes a lot due to some factors: changes of direction of the airplane, change of speed of the turbine which makes more oil goes from the tank to the other components of the circuit (this phenomenon is called "gulping" and will be explained later), regular consumption through the circuit, changes of temperature which modify the viscosity of the oil[16]...

That is the reason why a slow drift in the consumption is hard to detect. For example, a leakage "drop-by-drop" is not directly detectable by the sensors since their resolution is too low.

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[15] Retrieved on November 24th from http://www.exxonmobil.com/aviation/Files/learningandresources_tech-topics_jet-engine-oil-system-part2.pdf
[16] Retrieved on November 24th from http://www.exxonmobil.com/aviation/Files/learningandresources_tech-topics_viscosity.pdf

However, if a model can be established for these factors of influence such as "gulping" or change of direction for example, it would be possible to detect abnormal oil consumptions through the life of the engine.

- Gravity of the failure:
    - o 2 : impact on the system with short-term consequences for small leakage
    - o 3 : impact on the system endangering its immediate health for large leakage
- Rate of occurrence:
    - o 2 : from time to time for small and large leakage
- Can be monitored with existing sensors:
    - o 1 : yes

8.1.8 Degradation of the oil quality

It takes only 15 seconds for the oil to come back to its position after having run through the whole circuit. Moreover, it has been seen that through its life in the circuit, the oil is facing severe conditions of temperature and pressure. The quality of the oil can then be modified very quickly. One way to avoid the oxidation of the oil while facing these conditions is to add antioxidant additives. When the oil is new, the content of these additives is 100% in the oil. When the engine is running, the oil faces oxidation and these additives are consumed. After some servicing, the used oil, whose content in additives is less than 100% is mixed with new oil whose content in additives is 100%, leading to a mixture of oil whose content in additives is an average weighted by the oil level. This content, decreasing with the fillings, need to not go under a threshold, or it would lead to an oil of bad quality which would deteriorate the whole oil circuit and thus the engine.

This used not to be a problem, because the high oil consumption of the engine implied that the oil had no time to get old or dirty. With the new engines, where engineers try to get the lowest consumption possible, this becomes a problem: the oil remains longer in the circuit since the consumption has been lowered. This way of monitoring of the oil quality by studying the physicochemical characteristics seems however complicated since no sensors allowing to measure the content of additives is present in the circuit yet[17][18].

- Gravity of the failure:
    - o 1 : impact on the system with long-term consequences
- Rate of occurrence:
    - o 2 : from time to time
- Can be monitored with existing sensors:
    - o 0 : no

8.2 Conclusion of the FMECA method

The best way to understand the outputs of a *FMECA* method is to sum up all the results in a table. To do so, failures, their gravity and occurrence are listed. The grade that is given to each parameter is based on the information that the author could gather while discussing these failures with experts working at *SNECMA*. These criteria are relatively arbitrary since they are chosen by the author. One could argue and choose another method to characterize the failure.

The indicator that has been chosen to rank the different failure is:

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[17] Retrieved on November 24th from http://www.exxonmobil.com/aviation/Files/learningandresources_tech-topics_jet-engine-oil-consumption.pdf
[18] Retrieved on November 24th from http://www.exxonmobil.com/aviation/Files/learningandresources_tech-topics_used-oil-evaluation.pdf

$$\text{Indicator} = \text{Gravity of the failure} * \text{Rate of occurence} \qquad (2)$$

Indeed, it seems natural that the failure which happens the most and which has the biggest impact has to be dealt with first. In case of two failures with the similar ranking, the one with an existing sensor will be treated in priority. It is indeed easier to deal with a failure if it can be monitored with an already existing sensor.

Nature of the failure	Gravity of the failure	Rate of occurrence	Existing sensors	Gravity x Rate	Ranking
Rate of flow variations due to pump malfunction	2	0	1	0	9
Sealing of the injectors due to coking	3	1	1	3	3
Deterioration of rotating components	0	2	1	2	4
Oil filter clogging	1	2	1	2	4
Tube rupture in the heat exchangers (small perforation)	1	2	0	2	7
Tube rupture in the heat exchangers (large perforation)	3	0	0	0	10
Failure of the bypass system of the ACOC heat exchanger	1	2	1	2	4
Excessive oil consumption due to small leakage	2	2	1	4	2
Excessive oil consumption due to large leakage	3	2	1	6	1
Degradation of the oil quality	1	2	0	2	7

Table 1, Summary of the FMECA method

It results from this study that the failures which are ranked in the two first positions are related to excessive oil consumption (see Table 1). It can be seen that **an excessive oil consumption due to a leakage would be both critical and occur often**. Moreover, through the mean of the *OPT* sensor, surveillance could be achieved and this is a big advantage: no modification is needed on the existing engines. This is the reason why **this study will focus on the oil consumption of the lubrication system**.

9. CURRENT ALGORITHM DEVELOPED BY *SNECMA*

9.1 Aim of the surveillance of the oil consumption

The result of the previous *FMECA* study highlighted that it would be interesting to focus on the oil consumption. The monitoring of the oil consumption answers then to a need of the client (whether he is an airliner or an aircraft manufacturer). The expected outputs are[19]:

- Detection and quantization of the fillings. This would add reliability to what is actually done: the fillings are currently logged in a servicing book, but some mistakes are made such as omission, wrong number of oil can added …;
- Consumption calculations and detections of abnormal consumptions: drifts in consumption (low or high) are consequences of degradation of the lubrication system;
- Localization of the failing component;
- Estimation of the remaining time before that the degradation implies a servicing.

Nowadays, at *SNECMA*, the monitoring of the oil consumption is already made along the different flights but is limited to the data extracted before the take-off and after the landing. The aim of this study is to improve to accuracy of this surveillance, by studying the data extracted between the take-off and the landing.

Among these phases, sub-phases can be found where the main parameters (such as core-speed and altitude) remain almost constant. The oil consumption is however hard to monitor between take-off and landing because a lot of parameters suffer from heavy changes. The main parameters that can be observed when it comes to oil system monitoring are:

- The *Engine Oil Level* : *EOL*;
- The *Engine Oil Pressure* : *EOP*;
- The *Engine Oil Temperature* : *EOT*;
- The rotation speed : *N*;
- The altitude.

Thanks to these parameters (mostly *N* and altitude), it is possible to give precise criteria to define the phase of flight.

9.2 Definition of the flight phases

One can easily get a rough idea of which flight phase the aircraft is in and some qualitative criteria can be set. If one visually sees the plane climbing from the ground, one can say that it is the phase of climb. Likewise, if one sees an airplane over his head, flying at relatively stable altitude and speed, one can think that the plane is currently in the phase of cruise. The aim of this section is to establish a list of the different phases of flight, and then to give criteria for an algorithm to know exactly how to select the phase.

The different phases can be found in the list below:

- Start
- Taxi-out: once all the luggage and passengers are in the plane, and all the authorizations are received, the plane will drive to the runway where it should take-

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[19] *SNECMA* : Pratique de conception – algorithme PHM de suivi de la consommation d'huile

off. During this phase, the altitude is constant (the plane is one the ground) and the engine turn at quite a slow pace.

- Take-off: once the airplane is on the runway, it will increase its speed and will finally leave the ground. It can be considered that this phase ends once the airplane leaves the ground, or when the landing gears fold away (if possible). The engine speed increases during this phase, and the altitude remains almost constant.
- Climb: after the plane has left the ground, it has to climb until it reaches its cruise altitude. Its orientation can also change during this phase, regarding the flight path. The engine is active during this phase and running at the rather high speed.
- Cruise: during this phase, which is for most of the flights the longest one, the airplane fly at a rather constant altitude. The engine is running at high speed, and the flight direction does not change that much (unless the flight path is not defined as a straight line to avoid some meteorological events, other flight paths, or even some forbidden areas...).
- Descent: After the cruise phase, the airplane has to reduce its altitude in order to prepare a future landing at the arrival airport. As for the climb phase, the orientation can also change.
- Landing: once the altitude and the speed are reduced, the airplane has to go back to the ground. It can be considered, once again, that this phase starts as soon as the airplane touches the ground or when the landing gears expand.
- Taxi-in: this phase consists in the travel from the runway to the place where all the passengers will exit the airplane. The speed of the airplane and the speed of the engine are reduced, and the altitude is constant.

These phases can be segmented to respect the flight path. For example, the airplane can climb to a certain altitude, start a cruise phase, and then start to climb again in order to reach a new altitude. It goes the same way for the descent. One can find an illustration of these phases on Figure 14.
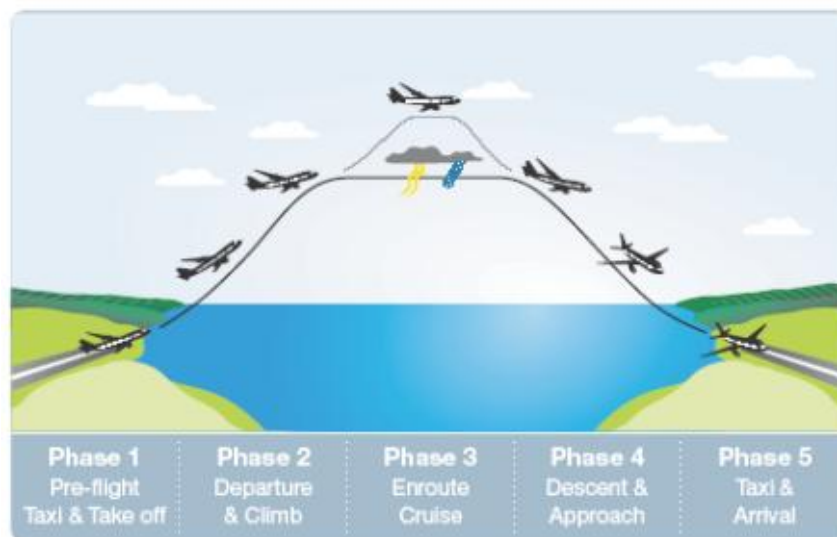
Figure 14, Illustration of the different flight phases[xx]

Some other phases, that are components of a flight, can exist like the boarding of the passengers, the boarding of the luggage, the phases where the airplane is put into a hangar for maintenance or to protect it while it does not fly. However, they are not really important for this study. They will thus not be detailed.

Likewise, some phases will only happen in exceptional scenario, for example, in case of an emergency procedure, but they will not be detailed here.

However, the criteria given before are more or less a rule of thumb. The aeronautics industry needs precise and quantitative criteria with ranges or threshold to correctly define the phases. An example of the conditions is given on Figure 15.

PREFLIGHT 1	ENGINE START 2	TAXIOUT 3	TAKE OFF 4	CLIMB 5	CRUISE 6	DESCENT 7	APPROACH 8	LANDING ROLL 9	TAXI IN 10
GROUND	GROUND	GROUND	GROUND	AIR	AIR	AIR	AIR	GROUND	GROUND
ENGINE START VALVES CLOSED	ENGINE START VALVE 1 OR 2 OPEN	ENGINE START VALVES CLOSED	BOTH TLA >	BOTH TLA >	ALT > FT	IVV < FT/MN	LANDING GEARS DOWN & LOCKED	GS > KTS	GS < KTS
BOTH N2 < %		AT LEAST ONE N2 > %	BOTH N2 > %	IVV > FT/MN					AT LEAST ONE N2 > %
			SLATS EXT OR FULL EXT	TAKE OFF TIMER FLAG =					
			BOTH REVERSERS NOT UNLOCKED						
PREVIOUS FLIGHT MODES		3 OR 9	4 OR 9	2,5 OR 7	2,5 OR 6	5,6 OR 7	4 OR 8	4 OR 8	4 or 9

Figure 15, An example of criteria used to distinguish the flight phases[xxi]

It is to note that all the values have been removed from Figure 15 for confidentiality reasons but this document is shown to the reader to illustrate the fact that criteria based on parameters such as core-speed or altitude are used to make the selection of the phase.

9.3 Data gathering

9.3.1 Onboard and ground systems

In order to analyze the data and to evaluate the oil consumption, the aircraft needs to transmit them to the processing unit on the ground. Indeed, technology limitations do not allow processing all data onboard. The Health Monitoring system is then divided into two subsystems:

- An onboard system which gathers the data all along the flight to build one or several reports and transmit them to the ground;
- A ground system which receives the reports and, from them, builds health indicators to monitor the system, diagnose and warn about potential failures.

The onboard system suffers from a lot of constraints that are not found on the ground system:

- The calculation power is limited, as well as the memory;
- A scalable algorithm cannot be set : it is impossible to store the data along the engine's life and use them from one flight to another to build an adaptive algorithm;
- It is hard and pricey to update this kind of system.

9.3.2 Transmission

The transmission between these two systems can be made through two solutions:

- After each flight, a technician can go on site and gather the data which would have been collected along the flight;
- The data can be transmitted automatically using a wireless transmission.

These methods of transmission possess however disadvantages. For a wireless satellite transmission, the cost of data emission is related to the number of characters sent. This implies that some operations of pre-processing must be done onboard to select which data shall be sent to the ground. This is very constraining because the major limitations regarding the resources (calculation power, memory…) take place onboard. When it comes to the solution where a technician would go on site to gather the data, there still remains the resources limitation that has been seen on-board, but the problem of the amount of data transmitted is no more a problem. However, this solution requires the presence of a technician after each flight to collect the data. The number of technicians required to operate would then be substantial and this solution is thus not adapted to big fleet of engines.

A technology called *WEFA*, similar to Wi-Fi but for aeronautics and developed by *SAGEM* should in the future allow to transmit data in a wireless way, at high speed and low cost. This implies new perspectives: there will be fewer constraints on the quantity of data that can be transmitted.

Whichever solutions require a pre-processing of the data which should be done on-board or on the ground depending on the chosen solution.

9.3.3 Onboard pre-processing and extraction

In the case of the study of the oil consumption, some pre-processing has to be done. Indeed, the main indicator that will be studied is the oil level in the tank. However, as it has been said previously, the sensors on the engines being studied only allow a discrete measurement of the level. These sensors are working with a network of resistors and relays with an even spatial distribution. The magnetic float at the surface of the fluid activates and deactivates the relays, modifying the resistance of the whole network. The measured voltage is then proportional to the height of fluid in the tank. The height of fluid is then converted into a volume with respect to the shape of the tank. One has to keep in mind that the resolution of the sensors for the studied engines can bring some limitations.

A selection of the data to extract has then to be made. It has indeed no meaning to extract points which does not correspond to a change of oil level, since the level would not be accurate (see Figure 16).
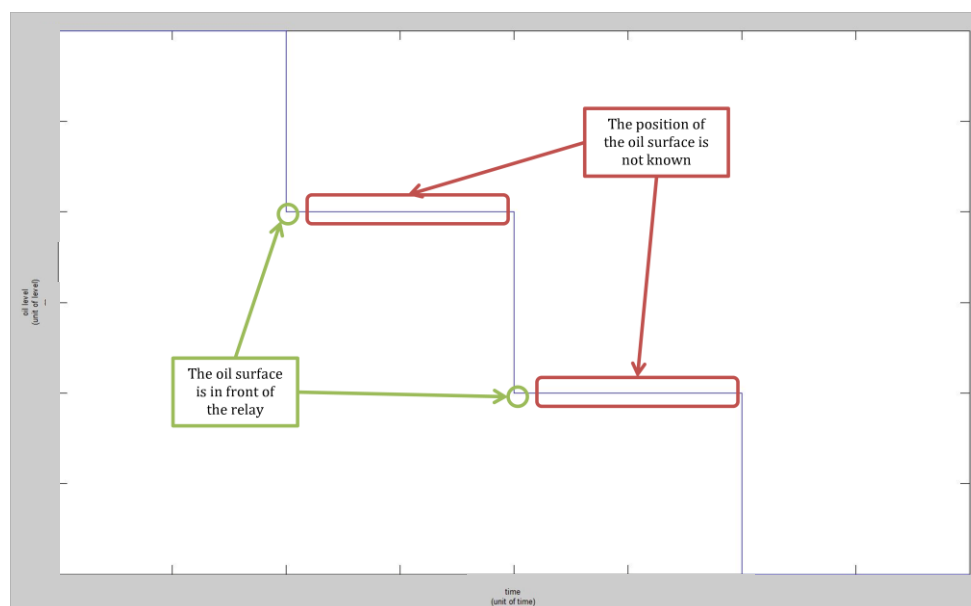

Figure 16, Difficulties encountered with a discrete sensor

However, it is not because the oil surface and thus, the magnetic float, are in front of a relay that it has a meaning to extract data.

In fact, it would mean that, at this time, the oil level is the one given by the sensor. But in the case, for example, where the inclination of the plane would abruptly change or during a turn, the oil level would bob and the extracted data would temporarily not have a meaning.

Some parameters can be defined as external parameters and will have an influence on the oil level:

- Sudden change of altitude;
- Sudden change of ground speed;
- Sudden change of cape;
- Sudden change of ambient conditions (temperature, pressure...).

Other parameters, classified as internal parameters, will have an influence on the oil level. This influence will be translated by a change of the "gulping", which is the quantity of oil which is in the circuit (outside of the tank), and thus cannot be measured. The influent parameters on this "gulping" are:

- The oil temperature: the viscosity of the oil decreases with a gain of temperature. It thereby changes the pump performance and leads to an increase of "gulping". The oil in the tank is also dilated with the heat, and it occupies then more space, leading again to an increase of the oil level.
- The rotation speed: the oil pump is indeed linked to the *A.G.B.*, itself connected to the high-pressure shaft. The faster this shaft will turn, the more oil will be injected by the oil pump, and as a consequence the less oil will be found in the tank.
- The ambient pressure: the mass flow rate coming into the gear pump varies with the ambient pressure, and thus the altitude. It has an effect on the efficiency of the gear pump and need then to be taken in account.

That is why it is important to set a fetching logic to gather the data: data collected right after a sudden change of cape or after an impulsion of rotation speed would be meaningless since the oil level would not be steady.

9.3.3.1   Note for the reader

In the following paragraphs, it will be discussed how the data are currently extracted during the flight. For confidentiality reasons, the author will divide the flight into three phases:

- Phase 1: before take-off;
- Phase 2 : between take-off and landing;
- Phase 3: after landing.

### 9.3.3.2   Data extraction before the take-off

During this phase, the altitude remains constant. As a consequence, there is no substantial variation of the ambient pressure. The rotation speed also remains almost constant: its value is around 60% of the maximum speed reachable.
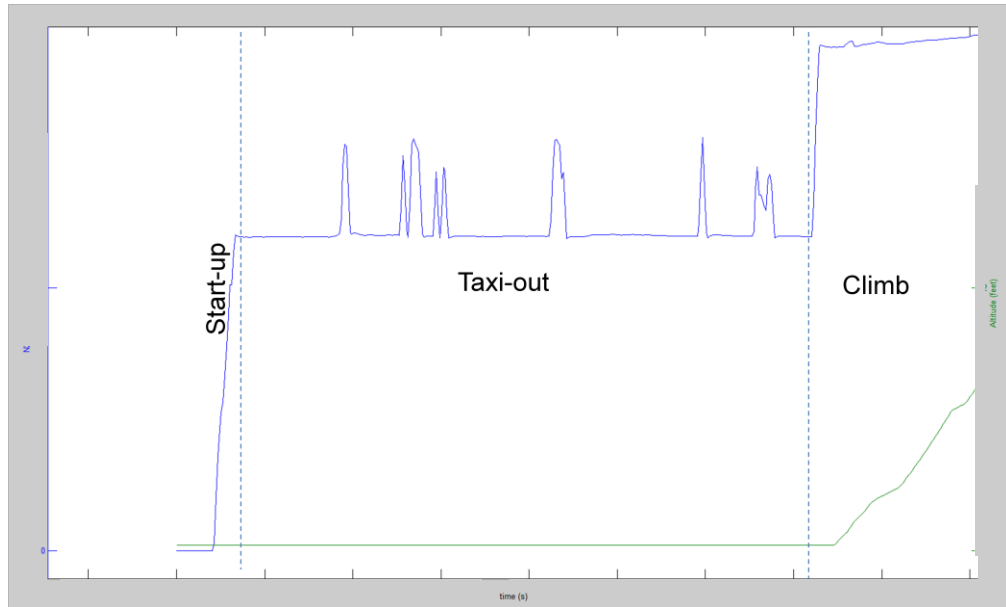
Figure 17, Profile of altitude (green) and N *(blue) before the take-off*

As seen on Figure 17, the engine is mostly idle during this phase, with some impulsions used to drive the airplane on the lane. No data should then be extracted when N indicates that the engine is not idle.

The oil temperature increases during this phase (see Figure 18). The oil is supposed to be cold at the start-up (unless the plane had just flown, which is often the case for low-cost companies). After a certain amount of time, the oil stops getting hotter: equilibrium is reached between the energy stored by the engine and the energy dissipated in the heat exchangers. In real conditions, and since the duration of this phase is short, this equilibrium starts to appear but is seldom reached.
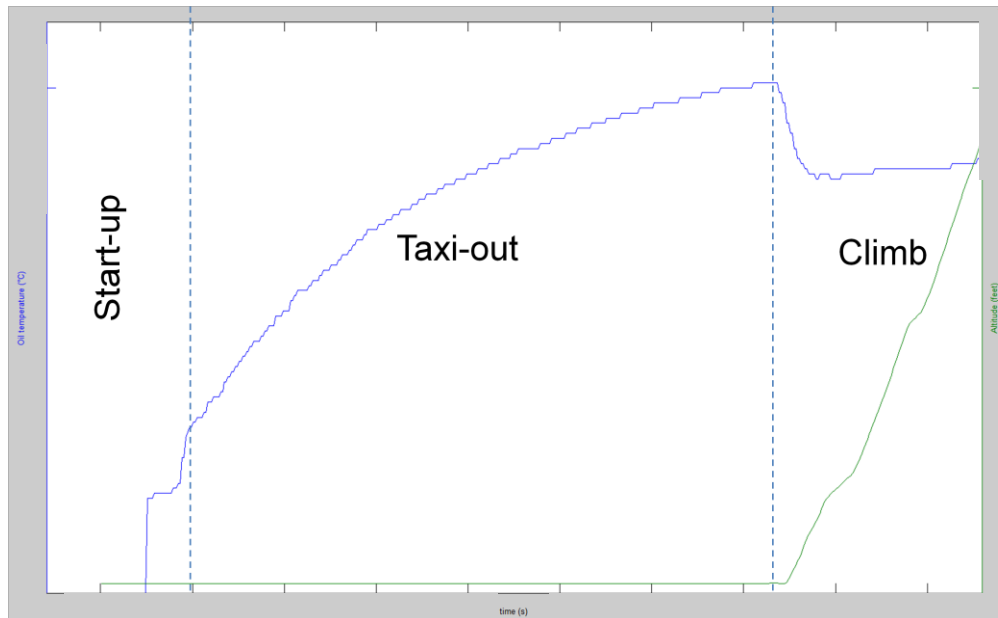
Figure 18, Profile of altitude (green) and oil temperature (blue) before the take-off

As for the oil level, two phenomena can be seen (see Figure 19):

- First, the oil level decreases. After the last stop, the recuperation pumps worked and they send most of the oil located in the circuit to the tank. That is why the oil level is high and decreases;

- Second, the oil level progressively augments: it is the combined effects of the rise of the oil temperature (thermal dilatation in the tank and reduction of the oil viscosity).

The peaks in the variation of the oil level can be explained by external parameters: change of orientation on the lane, change of ground speed...
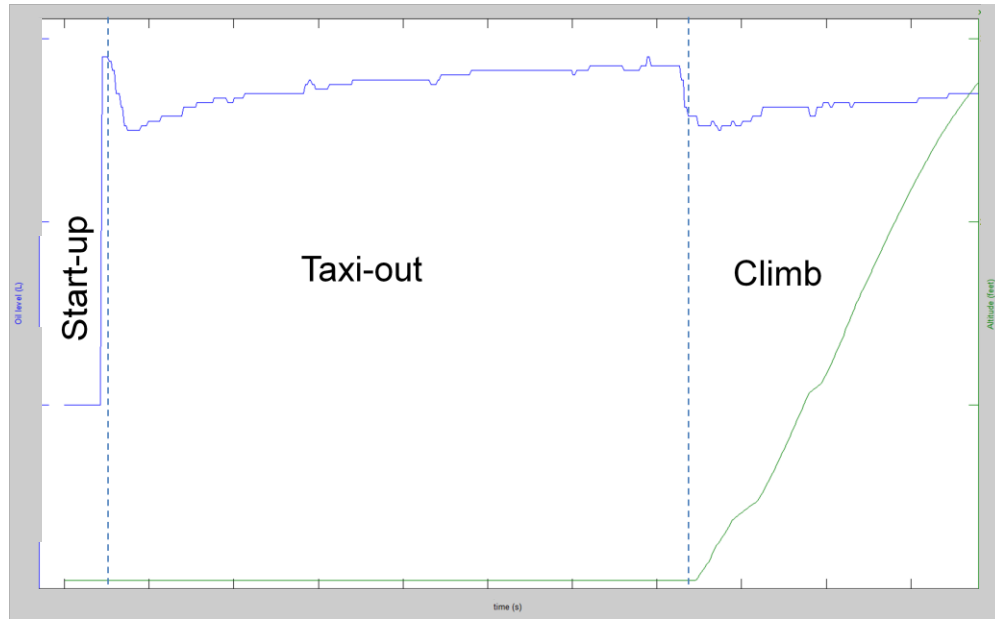

Figure 19, Profile of altitude (green) and oil level (blue) before the take-off

Finally, to extract data, one has to be sure that the engine runs in a stabilized mode and is no more in a transient state (such as the start-up). A time-delay can be set to ensure that no extraction is made during a certain period.

As it can be seen on Figure 20, the transient mode is also characterized by peaks of oil pressure. No extraction should be made around these peaks.
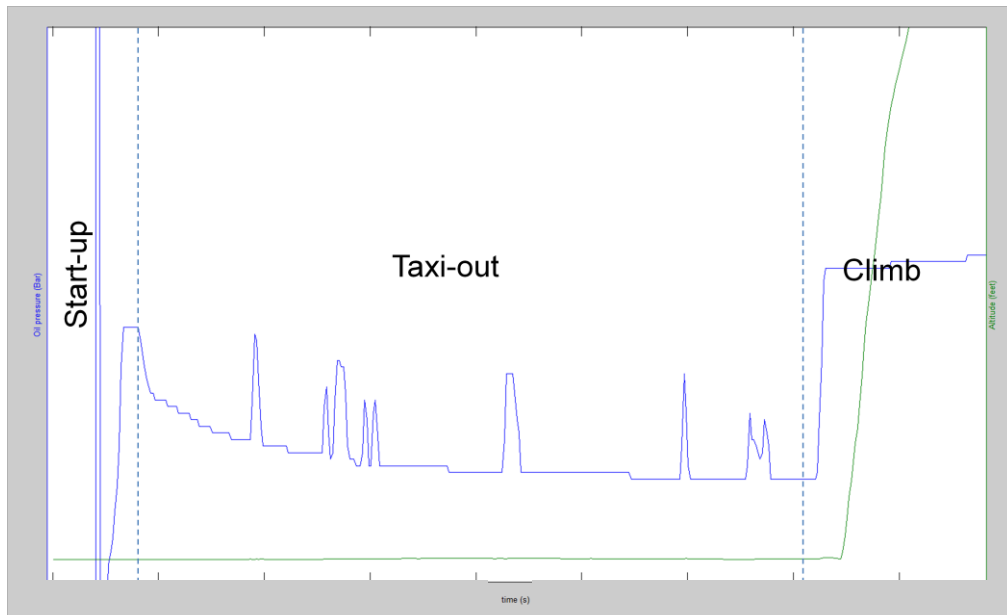

Figure 20, Profile of altitude (green) and oil pressure (blue) before the take-off

An exhaustive list of criteria has been defined by *SNECMA*. These criteria are set on the variations of the influent parameters of the oil level (described before) and ensure to get several "screenshots" of the conditions in which the oil is.

9.3.3.3　Data extraction after the landing

During this phase, the engine speed is almost the same as the one before the take-off. The oil level does not change a lot under the effect of the variations of oil temperature since the oil is already hot. The pressure remains stable and the oil level does not evolve, unless there are changes of external parameters (just after the landing, turn on the lane…). This phase is often very short since the engine is turned off after it reaches its parking position. The evolution of the parameters can be seen on the right of Figure 21.
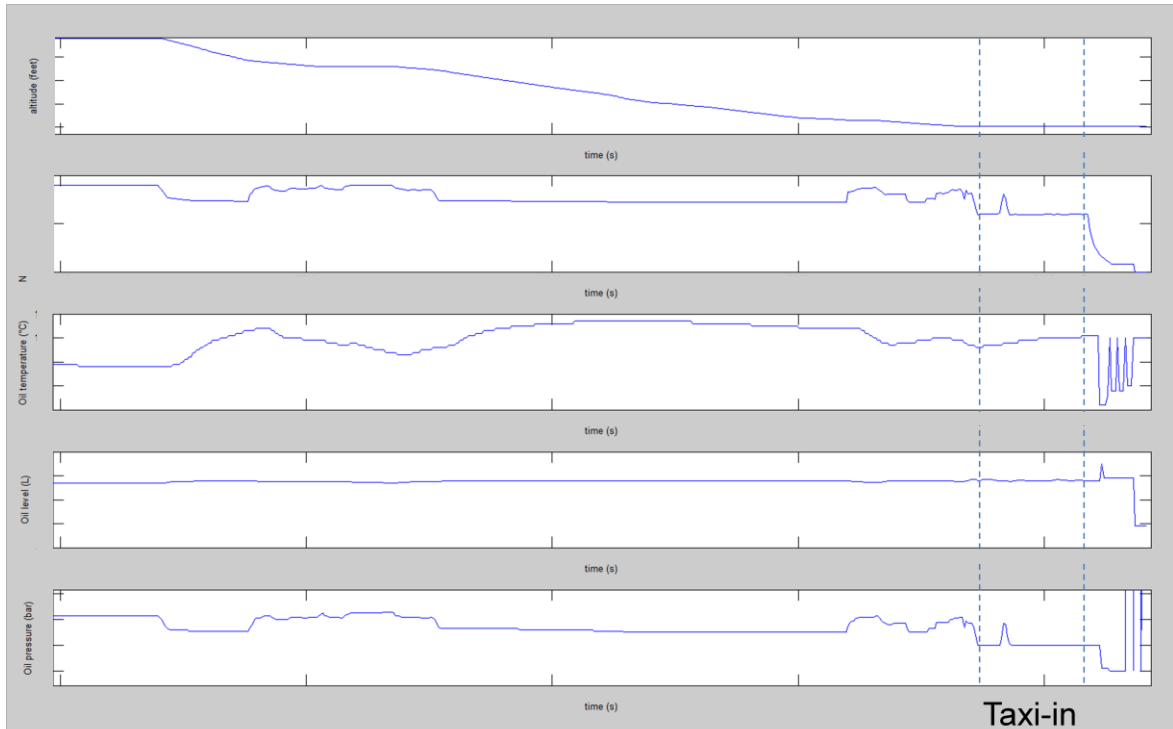
Figure 21, Profile of the different parameters after the landing

Once again, an exhaustive list of criteria has been defined by *SNECMA*. These criteria are set on the variations of the influent parameters of the oil level (described before) and ensure to get several "screenshots" of the conditions in which the oil is.

9.3.3.4　Data extraction between take-off and landing

During this phase, the engine is rotating at a high speed. The altitude should remain constant during such a phase, but varies from one flight to another, since the flight path is defined by various parameters (location of departure and arrival, atmospheric conditions, traffic, area to avoid for political reasons…). The "real" oil level should decrease regularly under the effect of the consumption. However, as soon as N or the oil temperature change, the oil level varies as well.

To study the variation of the consumption, not only the oil level is extracted but the oil pressure, the oil temperature, N and the altitude are also extracted. The time between each extraction is also collected: it will allow to locate the extracted data during the phase and to evaluate the influence of the consumption. The oil level changes indeed under the influence of the time, whereas it was not the case before take-off and after landing.

Since the work done by the author focuses on the improvement of the measurement of the oil level during this phase, it is possible in the context of this study that these criteria change. In fact, the author can access to raw data (time, oil pressure, oil temperature, oil level, N, altitude, cape,

ground speed) which can be used to make sure that the extraction logic during this phase is correct.

9.3.3.5 Report transmitted to the ground

The report which is transmitted to the ground gathers the data for the three phases as said in the previous paragraphs. On this report, some additional information, such as the departure and arrival airports, can also be found. These data are, of course, available for both engines of the airplane.

9.4 Treatment of the data extracted before take-off and after landing

As it has been seen previously, the parameters that influence the oil level are numerous. This is the reason why the measurement of the oil level in the tank at a given time does not allow getting a value for the oil consumption. Indeed, the oil level varies artificially under the effect of the context parameters and thus, it is a necessary condition to have identical parameters to compare the oil levels. Likewise, right after the start-up of the engine, and only if a certain amount of time elapsed since the last flight (to make sure that the engine is cold), one could make a measurement of the oil level in the tank. A measurement can be made for each flight and these measurements could then be compared since all the parameters would be the same (no influence of the oil temperature, no influence of N). However, this is not an option because not all the oil is gathered in the tank and a part of it still remains in the other components of the circuit. Moreover, there might be some problems with the calculators right after the start-up of the engine.

Therefore, there is a need to normalize the oil level in order to get rid of (or more precisely to take into account) the influence of context parameters.

Two kinds of process are hereby considered:

- Before the take-off and after the landing, which are quite short (relatively to the flight duration), there is almost no consumption of oil if the engine is healthy. This first type of normalization consists in getting rid of the influence of the parameters that fluctuate a lot, and to extract one point, which can be considered as a "refined measurement". For several flights, these points, considered as "refined measurements", can be compared, since the normalization process normalizes these points "as if they were in the same conditions of external parameters". This normalization is already developed by *SNECMA* and allows to monitor the oil consumption.
- Between the take-off and after the landing, where the oil consumption cannot be neglected, the normalization would consist in taking in account the variation of the oil level due to the external parameters. The normalized points could then be put in the same conditions than the points normalized before take-off and after landing, and could then be compared. Another option is to put them all in the same conditions (not compulsorily the same than before take-off and after landing) and to compare these points among them.

First, *SNECMA* focused on the phases where the context was almost the same: before take-off and after landing.

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9.4.1 Normalization of the data extracted before take-off

9.4.1.1 Principle

The first idea which comes to one's mind in order to get rid of the variation of the context parameters would be to extract one single point in conditions of *N* and oil temperature common to all the flights. These oil levels extracted could then be compared from one flight to another. However, this is too restrictive: it is not sure that these fixed conditions would be encountered for each flight. The problem does not come from the *N*(it has been said previously that the engine was idle during this phase and thus that the *N* remained almost constant) but from the temperature which varies a lot.

The model that will be set will then be a univariate model where the oil level will be linked with its temperature. This model is not known and will be built empirically. As a matter of fact, through the coefficient of thermal expansion, the thermal dilatation can easily be turned into a linear model. However, the changes of "gulping", due to changes of viscosity, are harder to turn into a model.

The model which is adopted is a quite simple variation of the oil level with respect to the oil temperature, as seen in (3):

$$EOL = f(EOT) + b \qquad (3)$$

The (simplified) process used to get a normalized point for the phase before the take-off is the following:

- The model is adjusted to data from the current flight;
- Under certain conditions, this model is updated and its precision is improved;
- The model is finally used to obtain a normalized value of oil level in standard conditions.

These standard conditions will be defined as conditions that are often met in the three concerned phases. This way, the difference between the real conditions and the standard conditions will be least, and thus the error made while normalizing will be least as well.

9.4.1.2 Accuracy of the normalized oil level

If the extracted data were perfectly fitting a model such as the one described in (3), it could be estimated that the accuracy on the normalized oil level would be maximum. However, it is not always the case. The model never fits perfectly the raw data and thus, the accuracy of the normalized oil level can be defined by the square root of the mean squared error of this fitting: the lower the mean squared error, the higher the accuracy on the normalized oil level.

9.4.2 Normalization of the data extracted after the landing

9.4.2.1 Principle

For the data extracted after the landing, the process is reduced. In fact, the short duration of this phase leads to the steadiness of the parameters. There is almost no oil consumption during this phase: as a consequence, the "real" oil level does not change. The oil temperature and *N* are supposed to be stabilised as well: the oil level will not change under their influence.

To get a normalized oil level, the oil level and the oil temperature will be averaged and the results of this operation will be a unique point (*EOT*, *EOL*). The model of the normalization operated before the take-off is then used to once again obtain a normalized point in the standard conditions.

9.4.2.2   Accuracy of the normalized oil level

The accuracy of this normalized oil level is not clearly defined. The quality of these points could be very bad and they should not, as far as possible, be used to evaluate the variations of oil level in the circuit.

9.4.3   Detection of missing flights

As it has already been said, the transmission of the data between the onboard system and the ground system can suffer from defaults, which can seldom lead to a lack of information extracted. However, to make any consumption calculations, information from the current flight but also the previous flight will be required. That is why the missing flights are detected by the current algorithm (by checking the airport history of the airplane, checking the numbers of cycle operated by the components of the engines...) and will be taken into account as far as possible by the author in its study.

9.4.4   Detection of the fillings

The detection of the fillings is quite easy and can be made by comparing the oil level at the end of a flight to the oil level at the beginning of the following flight. The comparison between the fillings detected by the algorithm and the log of fillings is the major method to make sure that the algorithm is powerful.

One way to validate that the author managed to improve the accuracy of the calculation of the oil consumption (and thus the detection and the quantization of the fillings) will be to compare this log (which can however be imprecise and not complete) to the result of this study.

9.4.5 Calculation of the consumption based on information extracted before the take-off and after the landing

In the two last paragraphs, it has been seen that it is possible to get a "refined measurement" of what would be the oil level in standard conditions. After the first treatment of the data, the outputs are for each flight:
- A normalized oil level for the phase before the take-off, and its accuracy;
- A normalized oil level for the phase after the landing, and its accuracy (lower than the previous one).

These levels are information of points that would be in the same standard conditions: same oil temperature and same rotation speed. They can then be compared with each other.

It has been decided to use, as far as possible, the information coming from the phase before the take-off; the comparison of two consecutive values of the normalized oil level during these phases and also the duration of the flight between these two points allows the evaluation of the local oil consumption during the flight.

After the fillings are detected (ruptures of the slope of the consumption lines), the consumption can be calculated on each segment (a segment corresponds to a sequence of following flights without any filling: the oil levels are supposed to be aligned in the time) (see Figure 22).
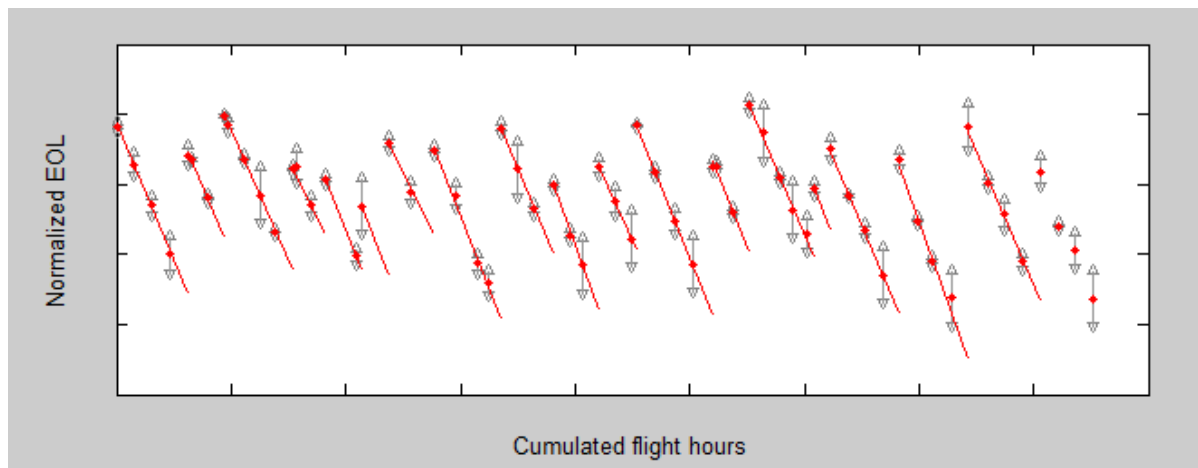
Figure 22, Consumption calculated on each segment (consecutive flights without filling)[xxii]

10. IMPROVEMENT OF THE CALCULATION OF THE OIL CONSUMPTION BY PROCESSING THE INTERMEDIATE DATA

Unlike what happens before the take-off and after the landing, the data collected between the take-off and the landing should not be at the same oil level even if the other external parameters remained the same. Indeed, during this phase, there is a consumption of oil which is not negligible. The oil level will then decrease with respect to the time, and that is precisely the speed of this decrease that is interesting since it characterizes the oil consumption. In contrast to the previous part, the results will come from the study of the author and no more from what already exist in the current algorithm.

10.1 Principle of normalization

To interpret any information extracted between the take-off and the landing, one has to be aware of the following observations:

- It is not legitimate to operate a comparison of the raw oil levels among different flights. Indeed, the oil levels in the tank before each flight are different. This has a direct impact on the oil levels between take-off and landing. It has then no meaning to compare directly two oil levels from different flights;
- Even during the same flight, several raw oil levels cannot be compared. Indeed, two sets of data extracted at different time between take-off and landing will have different oil levels due to the oil consumption which cannot be neglected during this phase.

The principle that will be used here is to normalize these levels, in order to get fictive information of each level as if they were extracted in the same context parameters. This way, the only influence on these oil levels will be due to the oil consumption.

As it can be seen on Figure 23, the oil level extracted between take-off and landing should be aligned with the two values normalized before the take-off and after the landing if this point was in standard conditions.
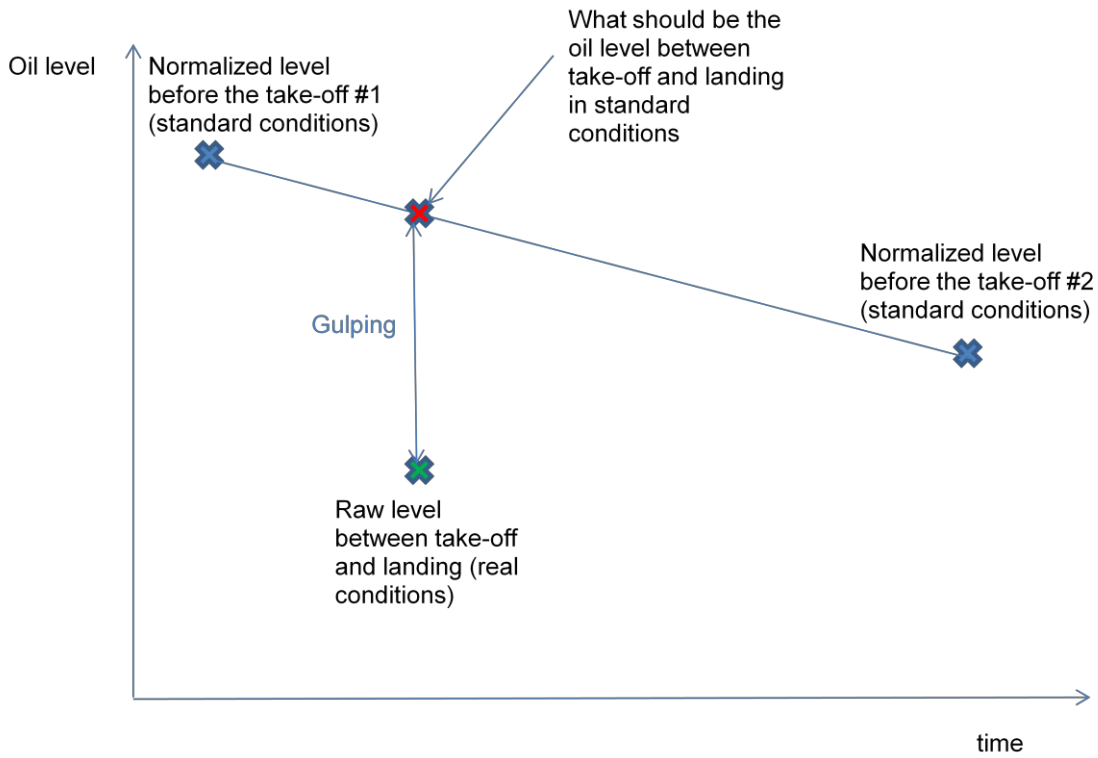
Figure 23, Diagram illustrating the need to normalize

However, it is not the case. The conditions met between take-off and landing are different from the standard conditions. That is where the notion of "gulping" appears. This difference of level (gulping) can be explained (at least, in the theory) by the difference between the true conditions and the standard conditions. In the Figure 24, "i" and "j" are two context parameters, which could be for example *EOT* and *N*.
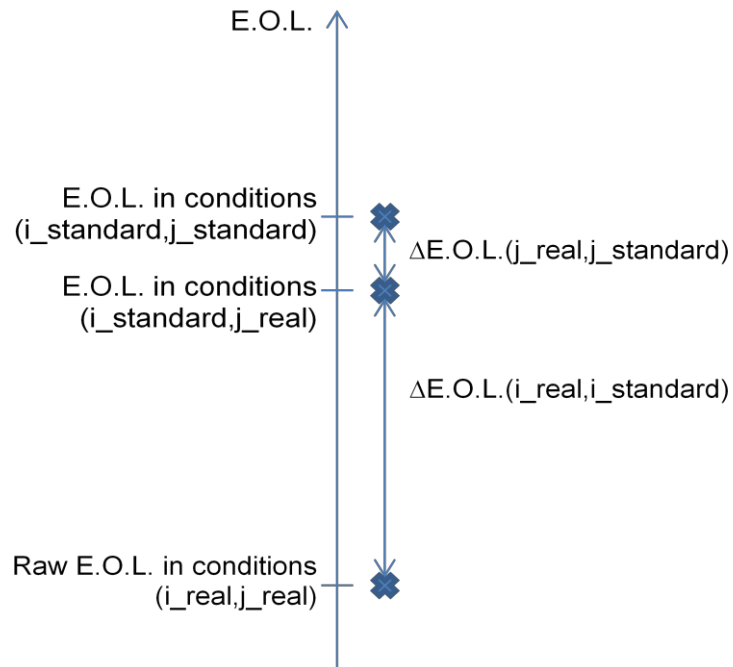

Figure 24, Normalization between take-off and landing (case of 2 context parameters "i" and "j")

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This principle can be turned into an equation (4):

$$EOL_{standard\ conditions} = EOL_{true\ conditions} + gulping$$

<div align="center">where</div> (4)

$$gulping = \sum_{i=context\ parameters} \Delta_{EOL}(real\ value\ of\ i, standard\ value\ of\ i)$$

In order to normalize the level, the functions Δ_{EOL} giving the gulping with respect to each context parameter have to be learnt. Once this will be done, all the points (between take-off and landing , but also before the take-off and after the landing) will be normalized in the same conditions and it will be possible to compare them and thus to improve the calculation of the oil consumption.

10.2 Choice of the influent context parameters

As it has been said previously, the main parameters that evolve significantly between take-off and landing and that might have an effect on the oil level are:

- The oil temperature;
- The rotation speed;
- The altitude.

That is the reason why this study will focus on them. It is true that any change of parameters of the airplane during the flight will have an effect on the oil level. However, this effect might not be significant. If a model is found during this study, it could be interesting, afterwards, to evaluate the influence of other parameters if they can lead to an improvement.

One also has to keep in mind that the number of parameters extracted during the flight is limited and that it is not easy to get an access to other parameters.

Finally, the higher the number of parameters used to model the gulping, the more complex the model. This mean that more flights will be needed to learn the model, while the algorithm has to be efficient as soon as possible. For this reason, the number of parameters should be reduced to its minimum.

10.3 Modelling of the gulping

10.3.1 First approach: linear regression with respect to the selected parameters

The first approach to model the gulping is to directly evaluate the gulping for all the points extracted between take-off and landing and to operate linear regressions with respect to the different parameters[20]:

- Three variables
  - Gulping=f(EOT, N, altitude);

No figure can be presented for this regression, since it depends on three variables. However, the quality of this regression is bad. No linear model which allows the modelling of the gulping with respect to these three parameters pops into mind immediately.

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[20] Regressions operated with respect to EOT will also be done with different simple functions of EOT.
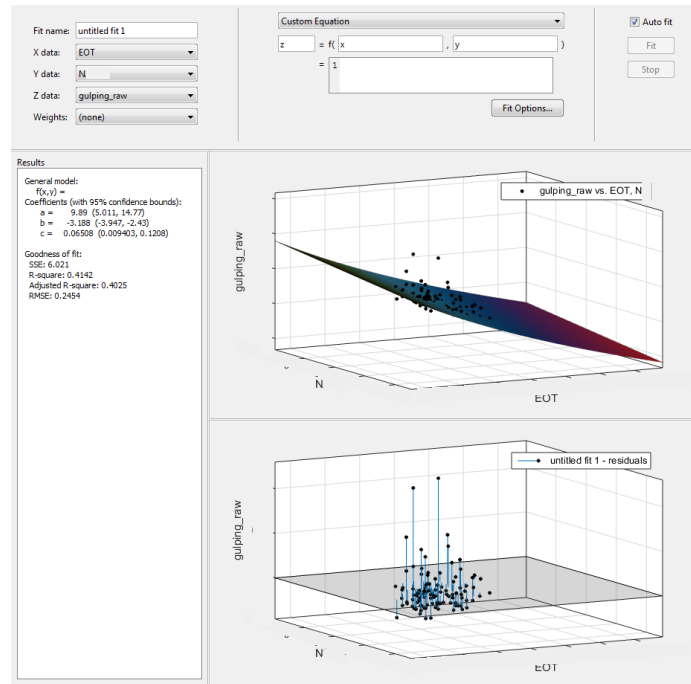
- Two variables
  - o Gulping=f(*EOT*, *N*);

Figure 25, Evolution of the gulping with respect to EOT and N

Except for some outliers, it seems to be a strong correlation between the gulping and *EOT*. However, no model giving the gulping with respect to *EOT* and *N* can be directly found. The effects of *EOT* and N_2 have to be studied separately before to draw any conclusion.
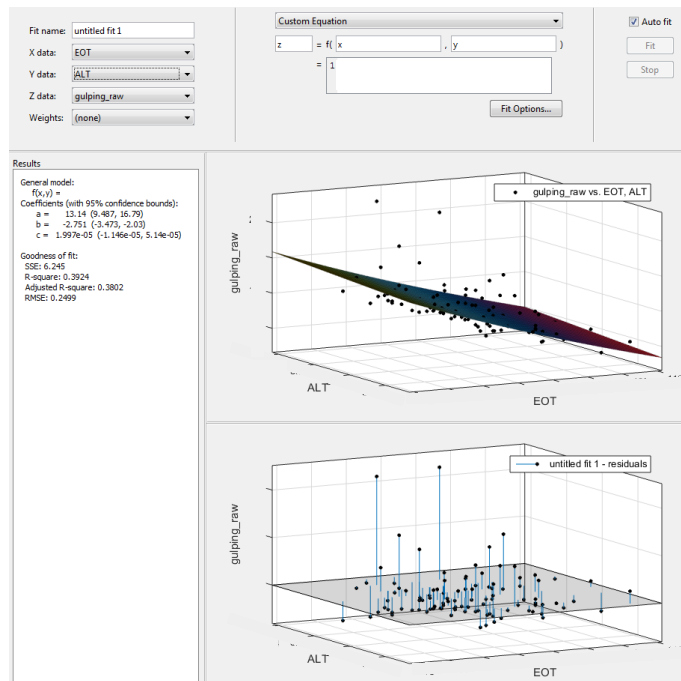
  - o Gulping=f(*EOT*, altitude);

Figure 26, Evolution of the gulping with respect to EOT and the altitude

On this plot, it can be concluded that the gulping cannot be explained only by *EOT* and the altitude. The strong link between gulping and *EOT* still appears, but the distribution with respect to the altitude seems random.

○ Gulping=f(N, altitude);
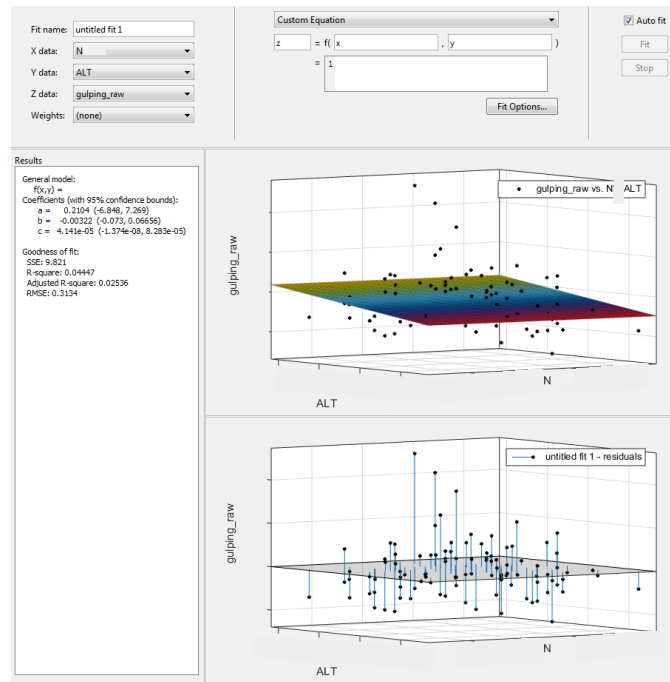
Figure 27, Evolution of the gulping with respect to N *and the altitude*

Once again, no conclusion can be drawn here. The distribution of the altitude seems random. One can wonder if the influence of the altitude on the gulping is marginal.

- One variable
  ○ Gulping=f(*EOT*);
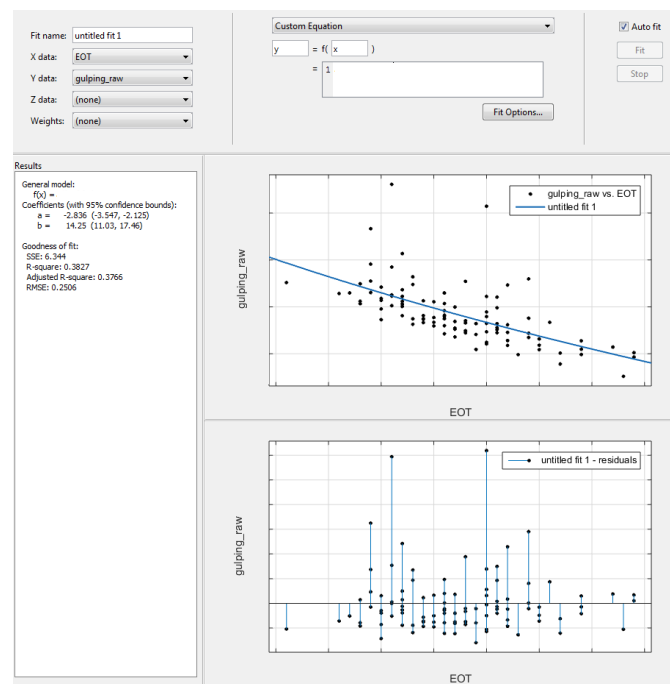
Figure 28, Evolution of the gulping with respect to EOT

As it was expected from the previous figures, the influence of *EOT* on the gulping is significant. However, some points still present large residuals. Some refinement has to be done, but it clearly seems that *EOT* is an influent parameter that should be kept.

o Gulping=f(N);
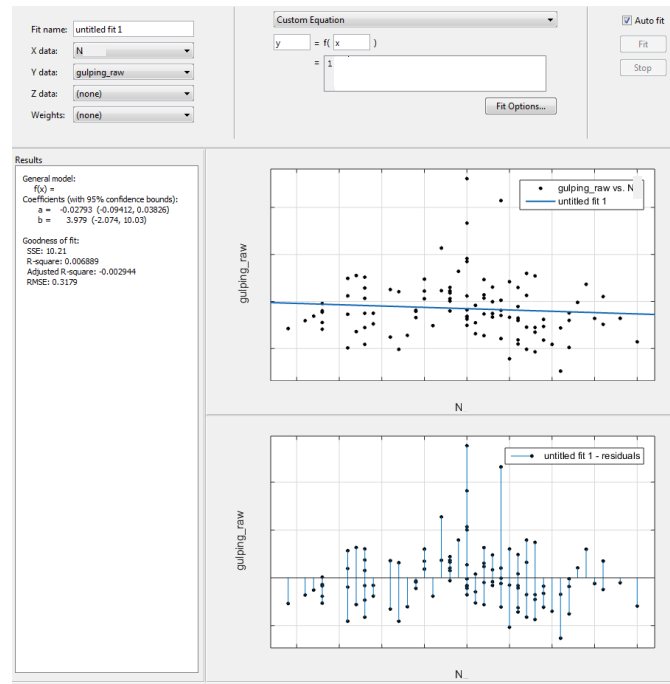
Figure 29, Evolution of the gulping with respect to N

Apart from some outliers, a trend can be recognized here for the influence of N on the gulping. Once again, some refinement on the selection of the point has to be made because it is not possible to explain anything from here.

o Gulping=f(altitude);
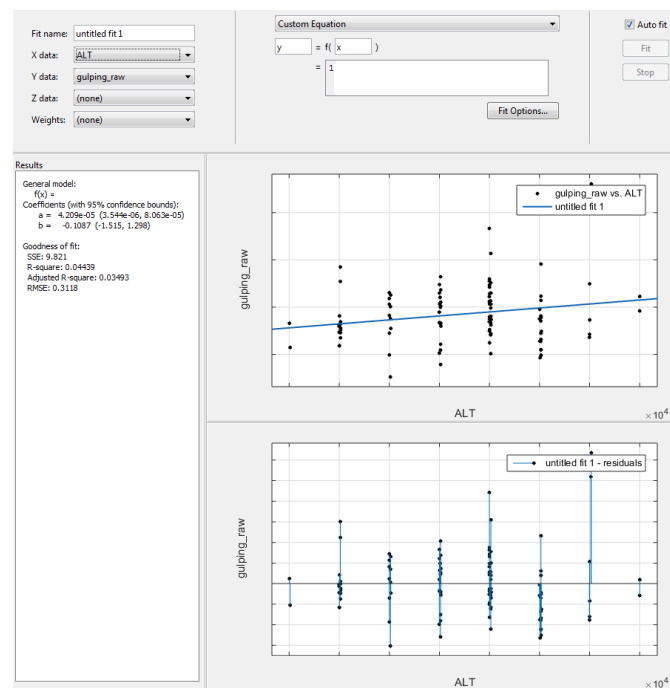
Figure 30, Evolution of the gulping with respect to the altitude

On the previous figure, one can notice that gulping and altitude are not directly linked. The altitude being discrete (the flight levels are multiple of 1000 feet), it does not seem necessary to establish a continuous model for the gulping with respect to the altitude.

What should be observed from the previous figures (from Figure 25 to Figure 30) is:

- The fact that it does not seem to exist a direct trend for the gulping with respect to the altitude. Moreover, the influence of the atmospheric pressure has also been studied because it would have a more physical meaning. Since this data is not available in the report, it is computed using the barometric formula[21] which is for the concerned altitude of this study (5):

$$Pressure_{atmospheric}\ (altitude) = 1013.25 * (1 - \frac{0.00625 * altitude}{288.15})^{5.255}) \tag{5}$$

where the altitude is in meters and the result is hectopascals.

Yet, since the variations of altitude are small (the altitude is a multiple of 1 000 feet in the range [30 000 feet – 40 000 feet]), no significant change is detected in the gulping with respect to either the altitude or the atmospheric pressure;

- As it has been seen before the take-off, the oil temperature seems to influence the oil level. The higher the oil temperature, the lower the gulping;
- N also seems to have an influence on the gulping, but no formula can be established yet.

10.3.2 Conclusion of the first approach

However, this approach (study of the gulping with respect to the different parameters) does not lead to results that allow an acceptable evaluation of the gulping with respect to the three selected parameters. Several sources can be identified for this failure:

- Other parameters have an influence on the gulping. However, as things stand now, these three parameters are the only ones that are extracted by the calculator.
- The fetching logic between take-off and landing can be perfected. Indeed, if between take-off and landing the airplane changes abruptly, for example, its cape, the oil level would suffer directly from this change. Also, if for example N fluctuates a lot right before an extraction, one can wonder which value of N should be extracted. As it has been said in the paragraph dealing with the data extraction between take-off and landing, the author can access to raw data that might allow him to refine the fetching logic.
  If no model for the gulping can be established, even with a refined fetching logic, this will mean that another source of error given in this list plays a prominent role that prevents to establish the model. The effect of refining the fetching logic should have as a consequence to obtain fewer points extracted between take-off and landing, but these points would be of "better quality" since they would be in steady conditions;
- The modification of the fetching logic should allow the get rid of the imprecision on the exogenous variables of the regression. Another source of error could come from the fact that there is an imprecision on the endogenous variable: the gulping, which is defined as the difference of level between the extracted oil level, and the "consumption line" (see Figure 23). The slightest mistake made on this "consumption line" will have a direct repercussion on the gulping which will prevent to establish of a model.
  As it has been said previously, the oil levels normalized before take-off are defined with an accuracy, which leads to an imprecision on the "consumption line". It is then necessary to get rid of this imprecision by selecting the consumption lines that will be used to establish the model.
- The last hypothesis is that the gulping cannot be explained at all by any parameters, and it would be a random phenomenon. It is possible that the parameters needed to explain the gulping and also the relations between these parameters and the gulping are too complex, and this phenomenon appears as random since it cannot been explained by any regression.

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[21] Retrieved on November 3rd , 2015 from https://en.wikipedia.org/wiki/Barometric_formula

10.3.3 Modification of the fetching logic

As it has been explained previously, reports are created from the calculator and sent to the ground. These reports include data extracted between take-off and landing. The existing fetching logic might not be adequate and might be a potential explanation of why it seems difficult, as things stand now, to establish a model for the gulping.

To minimize the influence of such an error, the author will try to refine the fetching logic, in order to extract data coming only from a steadier environment. Once this will be done, several paths can be followed:

- If this modification allows the establishment of a model for the gulping with respects to three parameters listed above, i.e. if the regressions that have been tried before fit now perfectly the raw data, this would mean that the previous failure to establish a model only comes from here. The fetching logic should then be modified on the calculators onboard to select only points in a steady environment;
- If this modification does not allow to establish a model for the gulping with respects to three parameters listed below:
  - Either the modified fetching logic is kept and another source of error is investigated. The fact that points comes from a steady environment can only improve the calculations;
  - Either the modified fetching logic is too restrictive and too few points are extracted, which results in the impossibility to exploit these data. In this case, the original fetching logic can be kept or the criteria for the new fetching logic can be tempered (this will have for consequences to increase the number of points extracted but also to potentially decrease the quality of the points extracted).
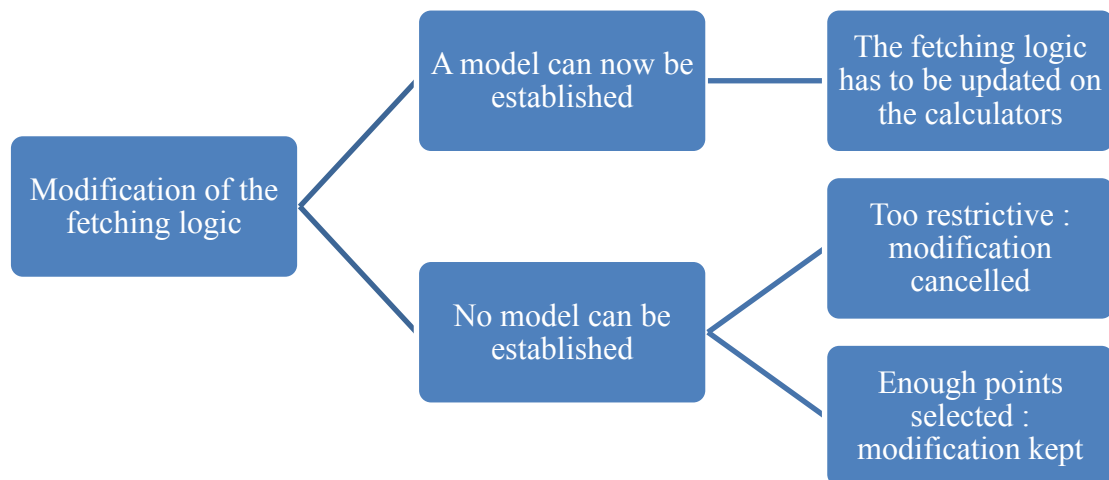
Figure 31, Modification of the fetching logic

10.3.3.1 Semi-automatic extraction tool

In order to extract points between take-off and landing which only come from a steady environment, the author created a tool (see Figure 32 and Figure 33) on *MatLab* which browses the raw data of each flight, makes a pre-selection of the points potentially extractible (see list below) and asks the user to determine whether or not to extract the point regarding the environment of the point.

Several conditions have to be met for a point to be selected. Criteria such as the one in the following list are set:

- Conditions on the change of the oil level (can be seen on the plots 9 and 11);

- Conditions on the altitude and its variations: the airplane has to be between take-off and landing (high and quite constant altitude) and the altitude should not vary too much before and after the extraction of the point. In fact, even if the change of altitude appears just after the extraction of the point, the inclination of the airplane will be modified to prepare the change of altitude and this could cause a bobbing of the oil level (can be seen on the plots 1,2 and 13);
- Conditions on N and its variations: the value of this parameter between take-off and landing should be high. If it is not the case, it could reflect an abnormal behaviour. The same way, if it has been for example at a steady value of 93% during the last minute, but just dropped to 89% for the point extracted, the gulping should decrease (it has been seen that the higher the N, the more oil is sent outside of the tank). However, if the N just went from 93 to 89%, the entirety of the oil has not gone back to the tank yet. The oil level measurement suffers then from an error and the point should not be extracted (can be seen on plots 7,8 and 12);
- Conditions on the cape and the ground speed are also set to make sure that these values remain constant and that no bobbing is due to the sudden changes of these parameters (can be seen on plots 3,4,5,6);
- Finally, the oil temperature can be seen on the plot 10 so that the user can check that there is no abnormal behaviour (very high or very low temperature) but no condition is set on this parameter.
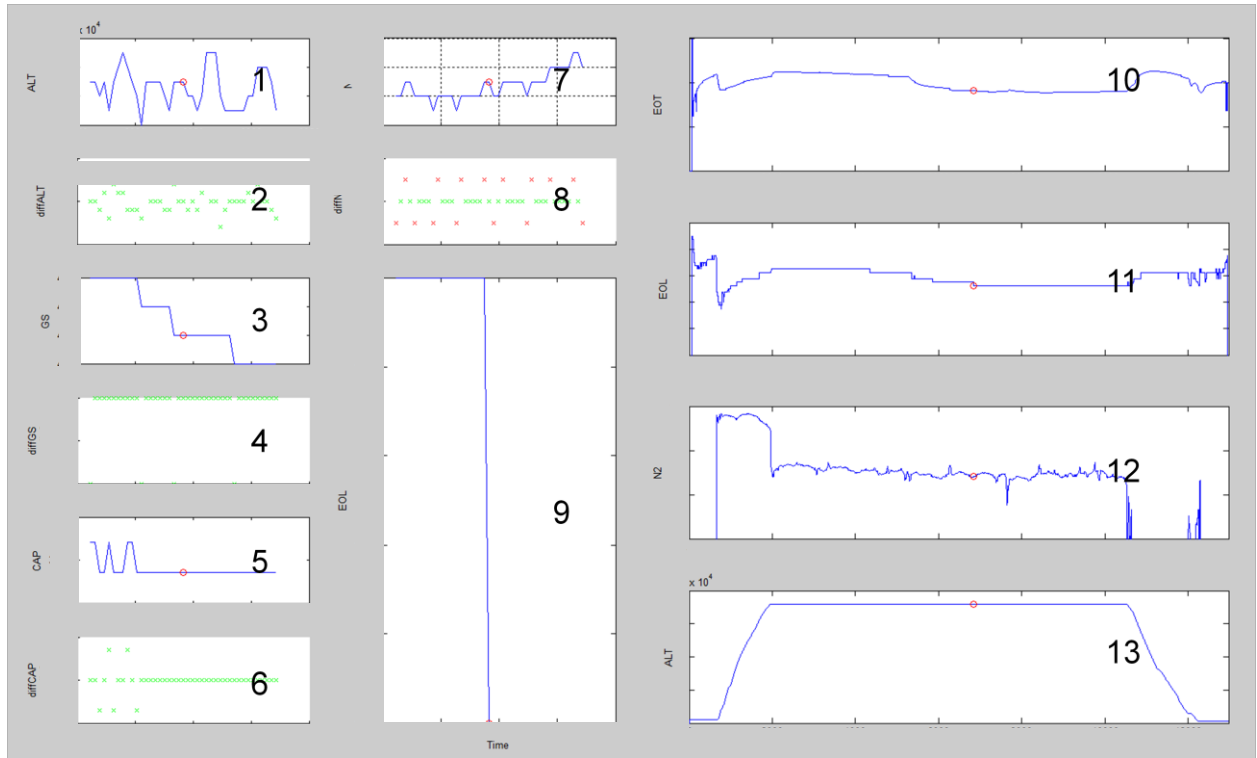
Figure 32, Semi-automatic extraction tool

Once a point is selected by the criteria listed above, a prompt appears (see Figure 33) asking the user if he wants to keep the point or not, or even modify N.
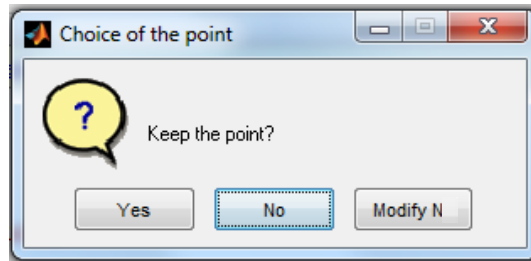
Figure 33, The tool is waiting for an action from the user

The last option allows to keep the point but to change the extracted value of N. This is useful in the case where N is relatively steady in the vicinity of the extracted point and shows a small change which could be due to the inaccuracy of the sensor. For example, on Figure 34, it can be seen that it would be more correct to affect the extracted point with a N of 92.3 instead of 92.2%.
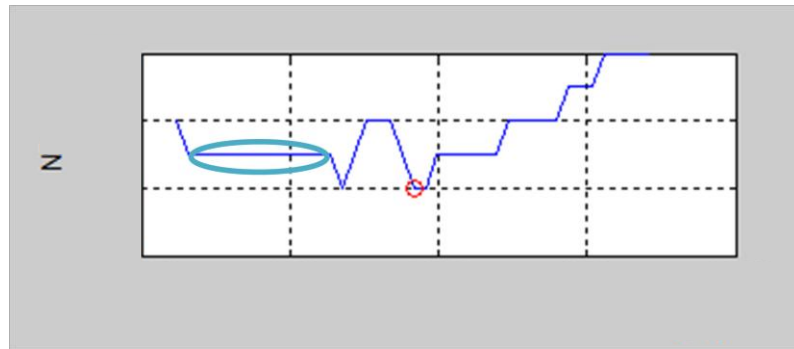
Figure 34, Modification of the N of the extracted point

However, this last option might not be used often. Indeed, a variation of N of several tenths of percent will not have a noticeable effect on the gulping.

10.3.3.2 Results of the modification of the fetching logic

After creating this tool, the author ran it on the raw data in its possession. It allowed him to observe and get a better understanding of the dependence between the different parameters. For example, it seems that it can be considered that it takes 20 seconds for the oil level to become steady after an abrupt variation of N, while more time seems to be needed after a change of altitude (60 seconds).

This modified fetching logic does not, however, allow to explain the gulping with respect to the above mentioned parameters. As it has been explained previously, this modified logic will be kept for the study, to make sure that the impossibility to explain the gulping does not come from a bad selection of the points. The difference is that these points come now from a steadier environment, which can only improve the future results.

10.3.4 Other attempts to evaluate the gulping

As it has been seen previously, it is not possible to model directly the gulping with respect to the three selected parameters, even with a refined fetching logic. Some other attempts are here presented in order explain as closely as possible the gulping.

10.3.4.1 Creation of different models for each altitude and N

In this part, the hypothesis that the variables are not uncorrelated will be made. If one wants to establish a model for the gulping, a solution is to set as many parameters as possible as a constant. This technique allows to fix the influence of the fixed parameters. Indeed, the parameters being set as constants, their influence on the gulping will be fixed as well.

- Creation of a model for each set of altitude and N

- Normalization of the points in standard conditions using the corresponding model
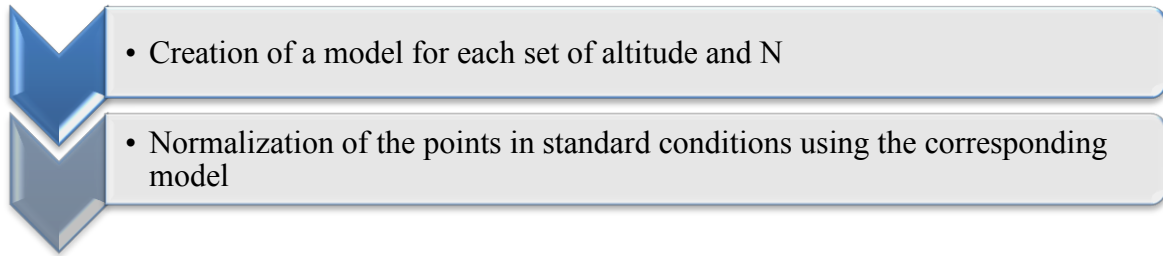
Figure 35, Process of normalization using different models

This method presents a limitation: if only points with the same altitude and same N are observed, the only influent parameter that remains variable is the oil temperature. However, the conditions are too severe and not enough points (among the database that the author can access) would be available to establish a model. This method allows however to observe trends: it can be seen that for a fixed altitude and N, the gulping decreases with the oil temperature, but no other conclusion can be drawn. This approach is thus not successful.

10.3.4.2 Utilization of the model built before the take-off

Before the take-off, only the oil temperature varies. A model has been established and gives the variation of the gulping with respect to the temperature, for a fixed N whose value is around 60% and a fixed altitude almost null. An idea would be to consider that the variation of the gulping due to temperature does not change significantly during the phase between take-off and landing. However, it is appropriate to wonder whether the parameters of this model can change when the conditions vary a lot: N around 90% and much higher altitude.

In this approach, the model described in (3) is used. The value of the raw oil level would be equivalent to: $f(EOT) + b$, where b depends of the current flight. The oil level at the reference temperature would be equivalent to: $f(EOT_{reference}) + b$ (see Figure 36).
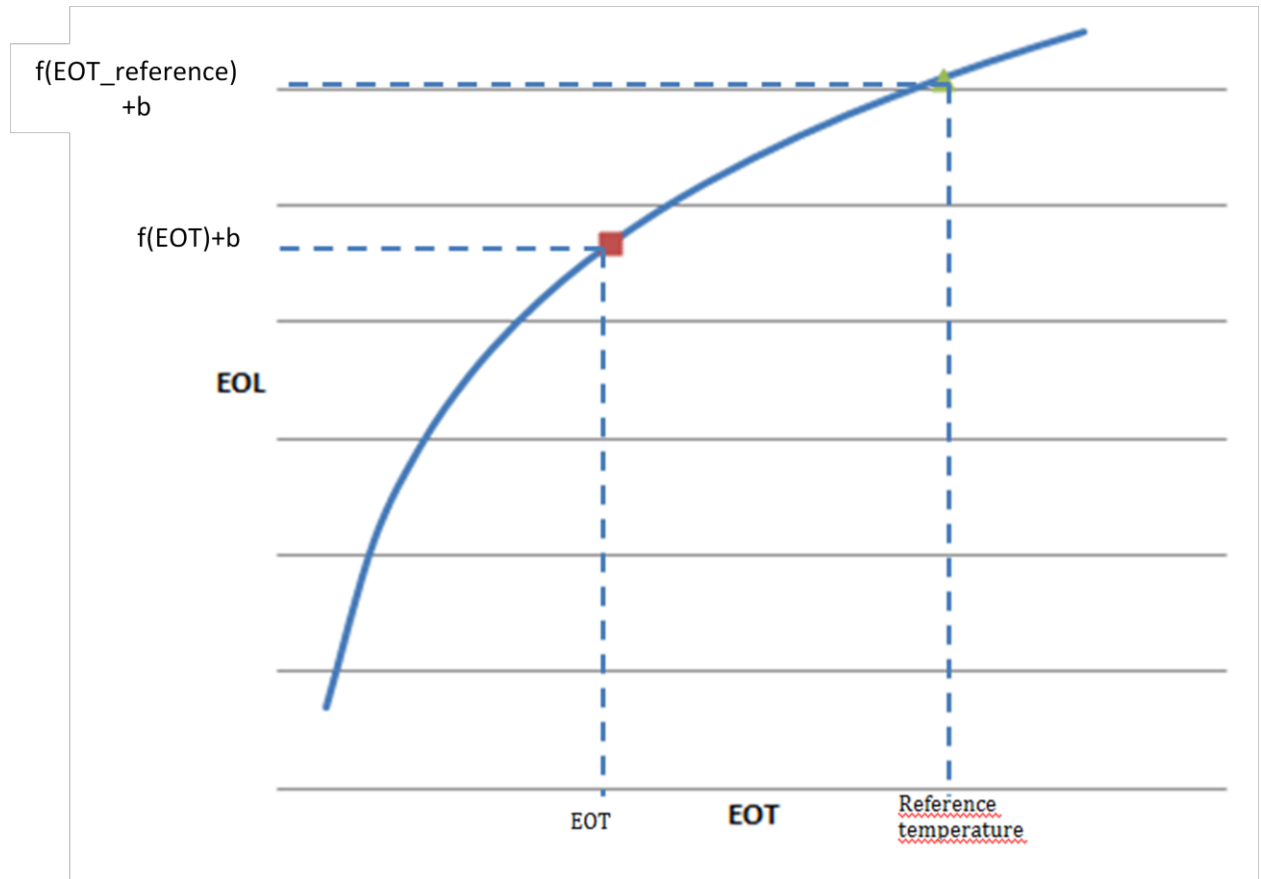
Figure 36, Variation of the oil level with respect to the oil temperature between take-off and landing

The variation of the gulping between a point in real conditions (EOT) and a point in reference conditions ($EOT_{reference}$) can be calculated and has to be added to the raw value of level in order to get a value of the level normalized with respect to the temperature.

Once this operation is made on all the points extracted between take-off and landing, the points normalized in standard conditions of temperature should all be "as if they were extracted at a temperature whose value is the reference oil temperature". The remaining gulping (between these points and the consumption line) should only be explained by the remaining influent parameters, i.e. N and altitude.

- Normalization of the points in standard conditions of temperature using the model created before take-off

- Creation of a model giving the gulping with respect to N

- Normalization of the points in standard conditions using the previous model
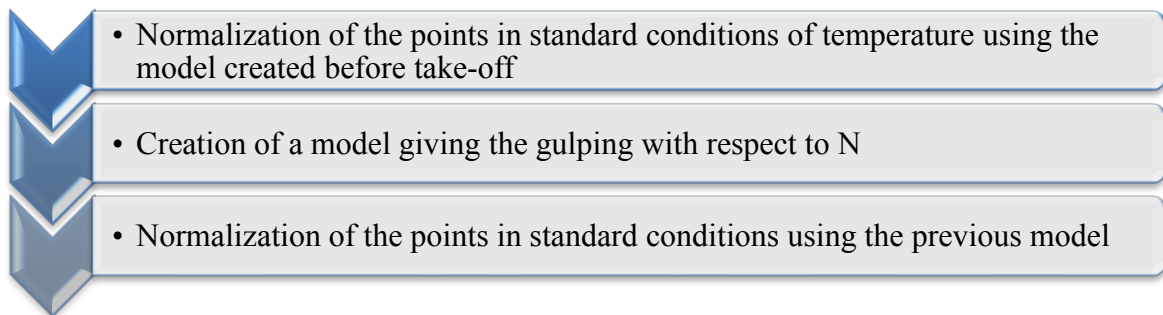
Figure 37, Process of normalization using the model created before take-off

As it can be seen on Figure 38, after excluding some outliers, a trend can be observed for the remaining gulping against N. This is not a straight line, but due to the imprecision on the measurement of the oil level, it can be considered that the residuals are acceptable. Moreover, since the range of variation of N is small (only a few percents), it can be considered that it is very good to observe a trend.
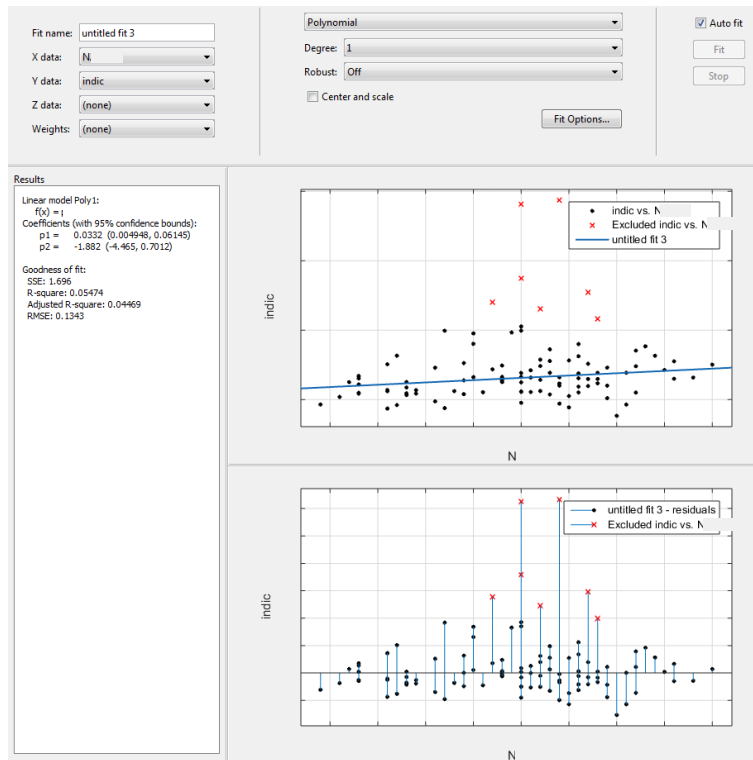
Figure 38, Evolution of the remaining gulping for the points normalized in standard temperature with respect to *N*

On the next figures (from Figure 39 to Figure 42), it can be seen that this method allows to normalize the points extracted between take-off and landing in order into take in account the difference of oil temperature and *N* between the raw points extracted between take-off and landing and the consumption line. Since both the normalized data from between take-off and landing and data from before take-off (and thus the consumption line) are supposed to be normalized in the same standard conditions, they can be compared and plotted on the same figures.

The different symbols on the next figures are:

Symbol	Corresponds to
Error bar	Normalized information in standard conditions from before take-off
Red line	Consumption line
Blue dot	Data from between take-off and landing (raw)
Green star	Data from between take-off and landing normalized in standard conditions of temperature
Red star	Data from between take-off and landing normalized in standard conditions of temperature and *N*

Table 2, Symbols of the figures for the normalization using the model created before the take-off
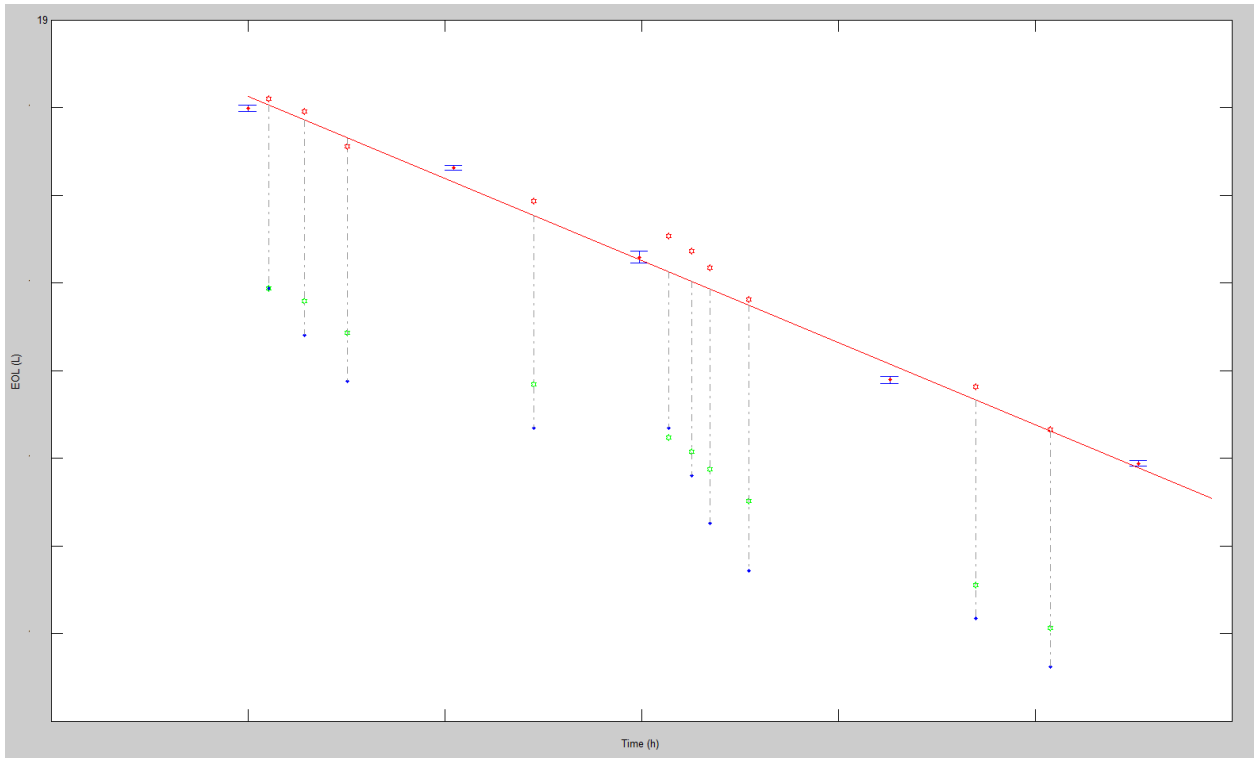
Figure 39, Example #1 of data from between take-off and landing normalized in standard conditions using the model created before take-off
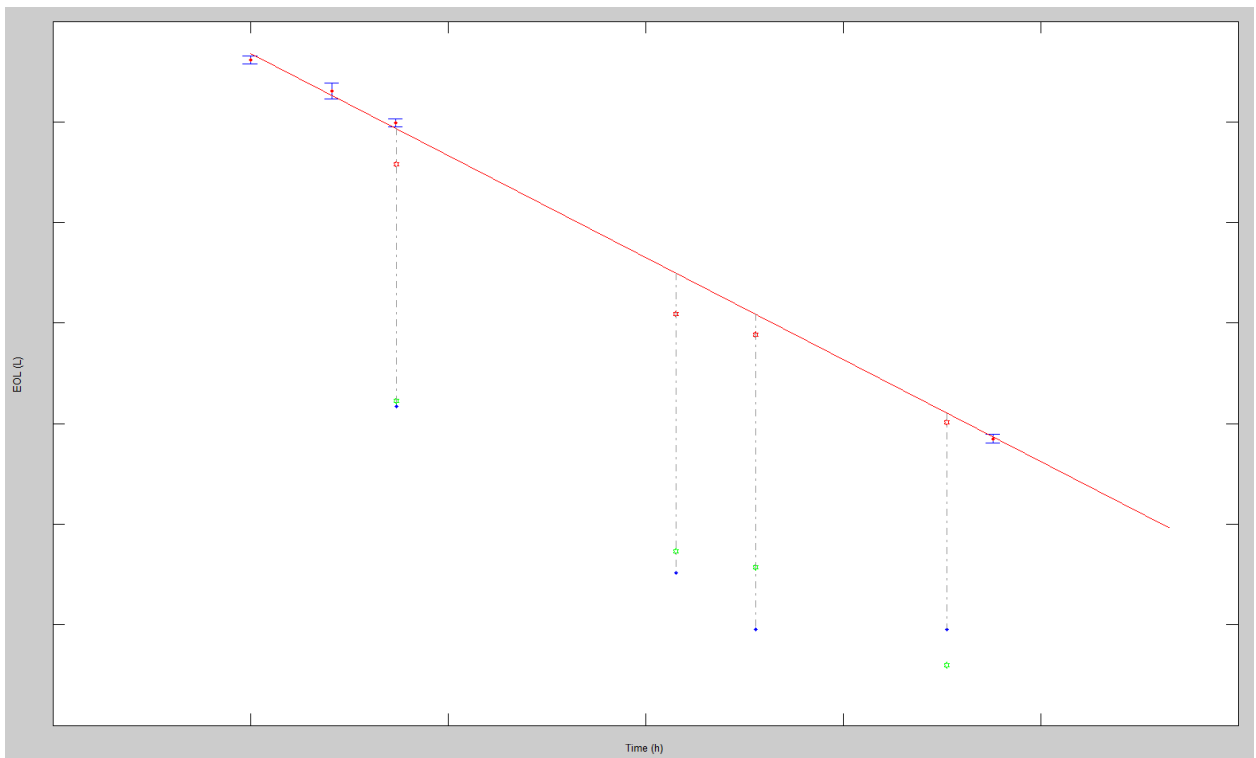
Figure 40, Example #2 of data from between take-off and landing normalized in standard conditions using the model created before take-off
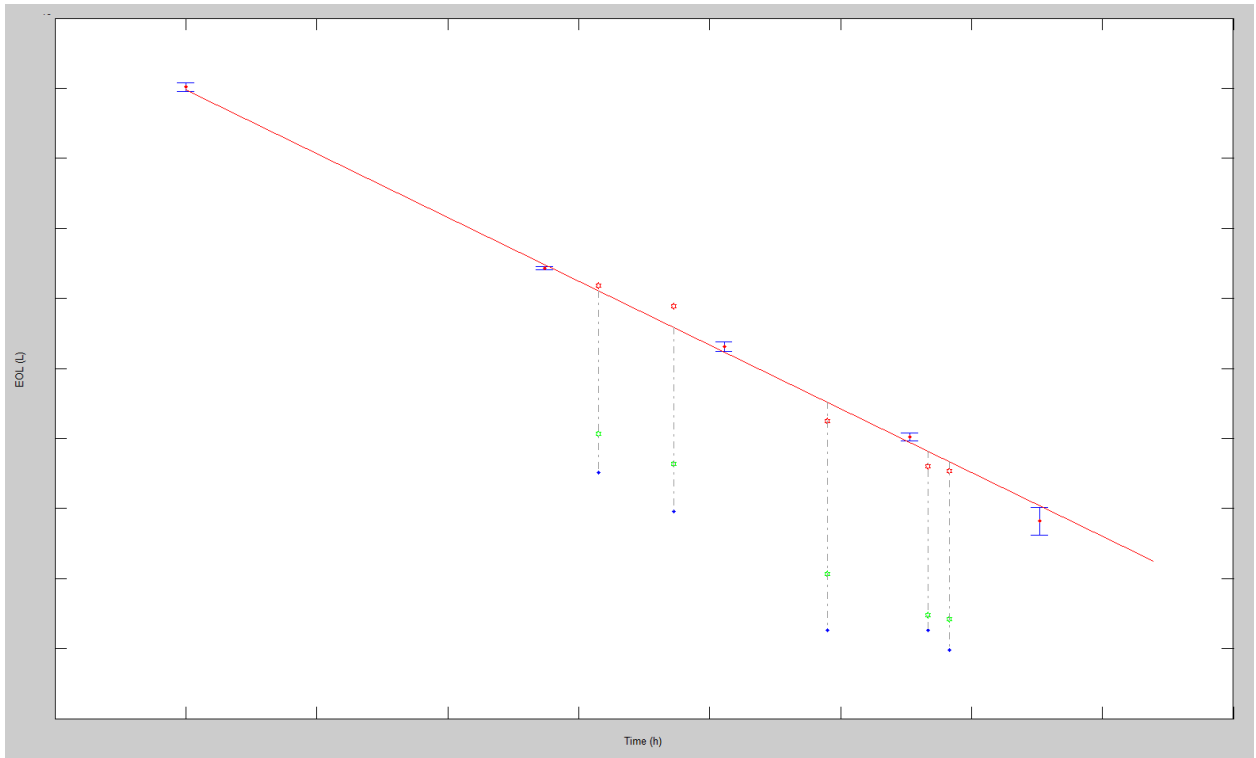
Figure 41, Example #3 of data from between take-off and landing normalized in standard conditions using the model created before take-off
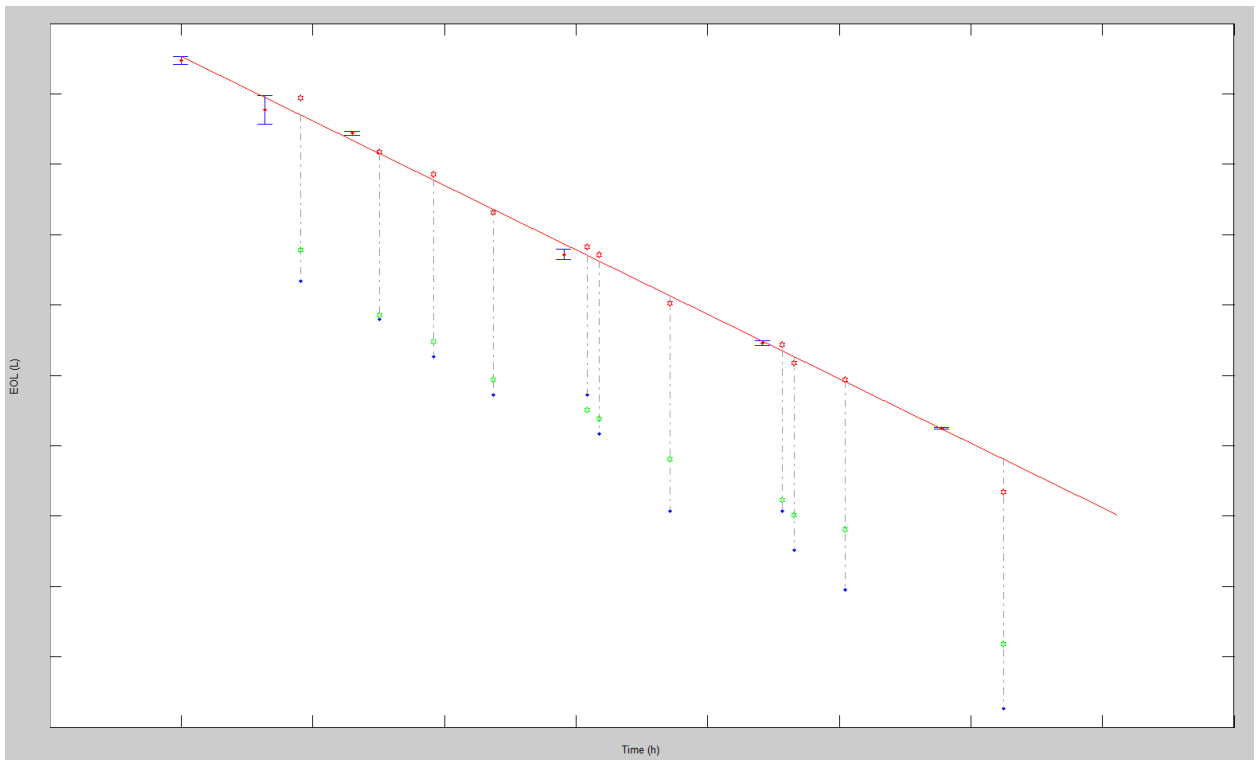
Figure 42, Example #4 of data from between take-off and landing normalized in standard conditions using the model created before take-off

On each figure (from Figure 39 to Figure 42), consecutive flights are shown. The normalized points coming from before the take-off (blue error bars) are plotted at the same time as the normalized points coming from between take-off and landing (red stars).

The remaining residuals (difference between the red stars and the consumption line) seem acceptable. The results cannot be perfect: the imprecision on the measurement of the oil level

will always have an influence on the gulping. One also has to note that the influence of the altitude has not been corrected. Indeed, adding this information to the regression did not improve the quality of the normalization. It seems then that the variations of gulping through the altitude are marginal, at least for this narrow range of altitude.

The results are quite good: the red stars are very close to the consumption line (errors less than 0.2L). However, one can wonder if these results can be improved (reduction of the error).

10.3.4.3 Correction of the gulping due to *N* then to *EOT*

As it has been said in the previous paragraph, one has to keep in mind that the model created before the take-off might not be valid for this range of N. The change of parameters of the model should not be too important and this model should offer a quite good method of normalization. One has however to wonder whether it can be improved or not.

Another method is here considered: for the data coming from between the take-off and landing whose oil temperature is around the standard temperature, the gulping should only be explained by N[22]. The points whose temperature is in the range [standard oil temperature $\pm$ tolerance] will be considered to model the gulping due to the variations of N. The tolerance should be high enough in order to get as many points as possible but not too high so that these variations of temperature do not influence the gulping.

Once this will be done, a model explaining the gulping with respect to N will be created and the remaining gulping should, with the hypothesis made, only be explained by the variations of oil temperature.

- Creation of a model giving the gulping with respect to N using the raw data whose temperatures are in the vicinity of the standard conditions
- Creation of a model giving the gulping with respect to the oil temperature, using the points normalized in standard conditions of N
- Normalization of the points in standard conditions using the previous model.
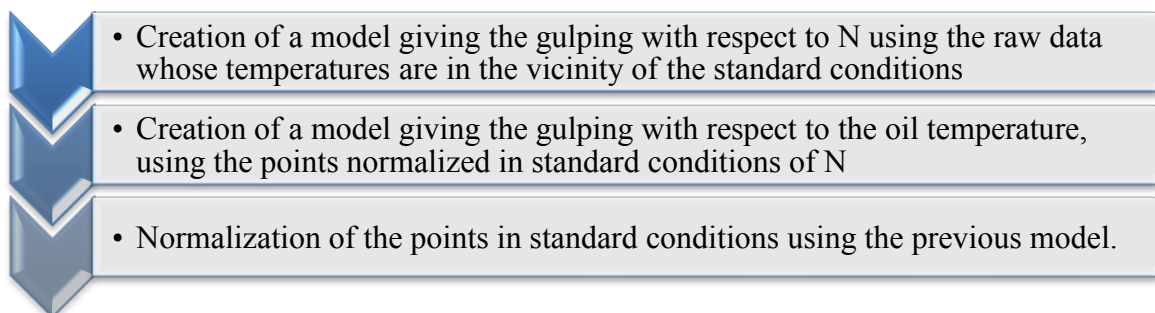
Figure 43, Process of normalization (correction of N then EOT)

The reader has to be aware that the same remark as for the previous method can be emitted: the model giving the gulping with respect to N will be valid for the standard temperature, but might be different for other temperatures.

a) Gulping due to N

As it can be seen on Figure 44, for the points whose temperature is in the vicinity of the standard temperature, there is a linear relationship between the gulping and N (after the exclusion of some outliers).

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[22] From the previous paragraph, it has been seen that the influence of the altitude is marginal and is here thus not considered.
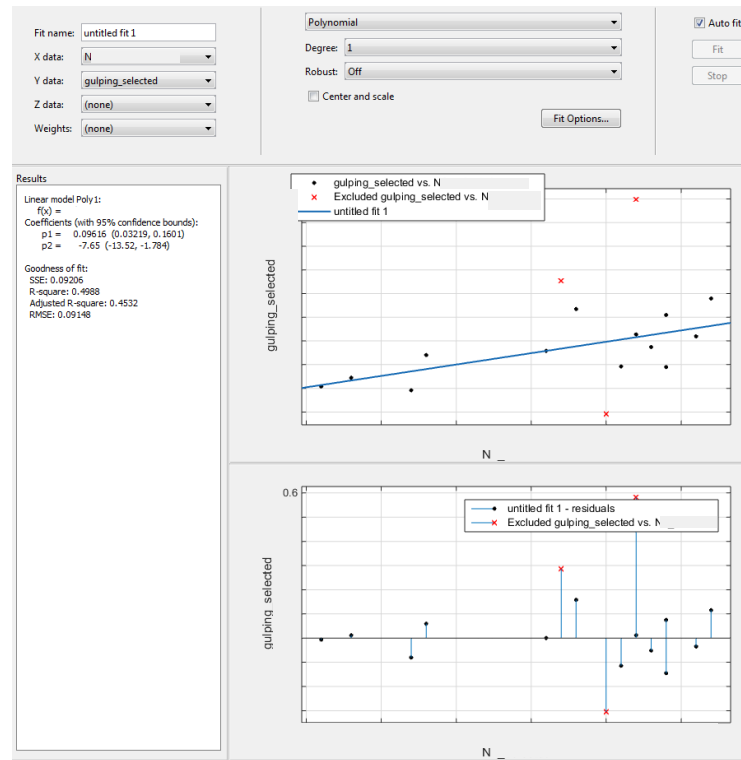
Figure 44, Gulping with respect to N for points whose temperature is in the vicinity of the standard temperature

b) Remaining gulping due to *EOT*

Once this model is established, the raw data can be normalized in standard conditions of *N*. The remaining gulping is then plotted against the oil temperature.
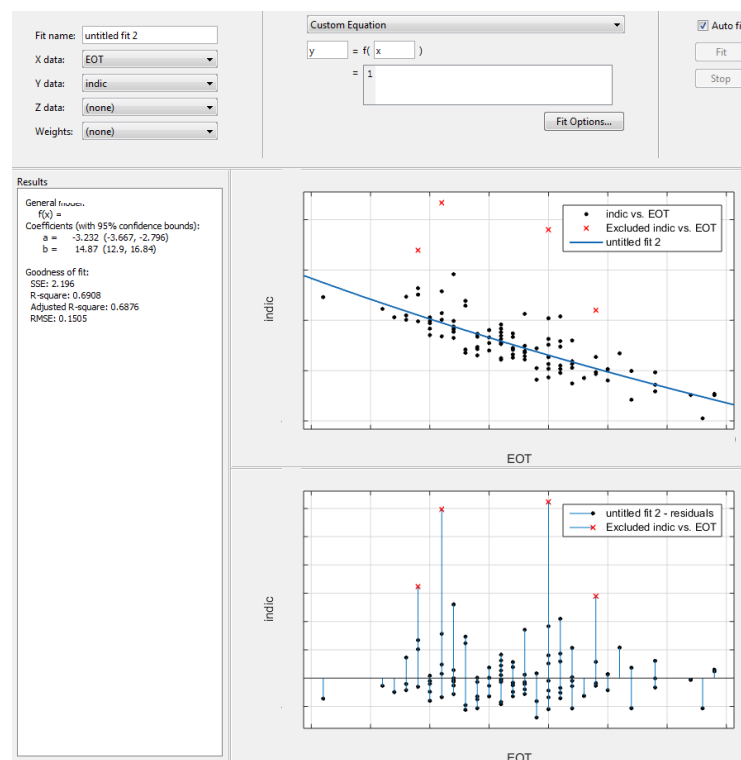
*Figure 45, Evolution of the remaining gulping for the points normalized in standard N with respect to EOT*

c) Results of this approach

On the next figures (from Figure 46 to Figure 49), it can be seen that this method allows to normalize the points coming from between take-off and landing in order to take into account the difference of oil temperature and N between the raw points and the consumption line. Since both the normalized data coming from between the take-off and landing and the data coming from before the take-off (and thus the consumption line) are normalized in the same standard conditions, they can be compared and plotted on the same figures. The segments that are displayed here are the same as for the previous process of normalization (in order to allow a comparison).

The different symbols on the next figures are:

Symbol	Corresponds to
Error bar	Normalized information coming from before the take-off in standard conditions
Red line	Consumption line
Blue dot	Data from between take-off and landing (raw)
Circled blue dot	Data from between take-off and landing whose temperature is in the vicinity of the standard temperature
Green star	Data from between take-off and landing normalized in standard conditions of N
Red star	Data from between take-off and landing normalized in standard conditions of temperature and N

Table 3, Symbols of the figures (correction of N *then EOT)*
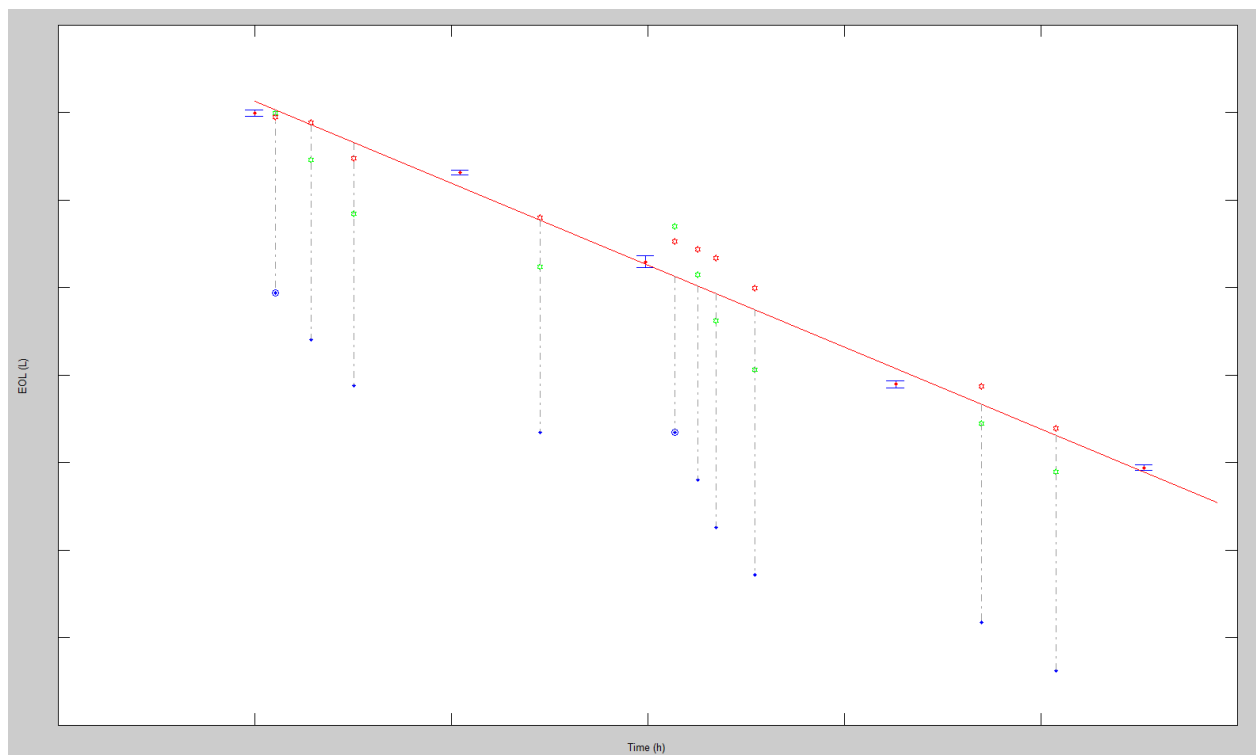
Figure 46, Example #1 of data from between take-off and landing normalized in standard conditions (correction of N *then EOT)*

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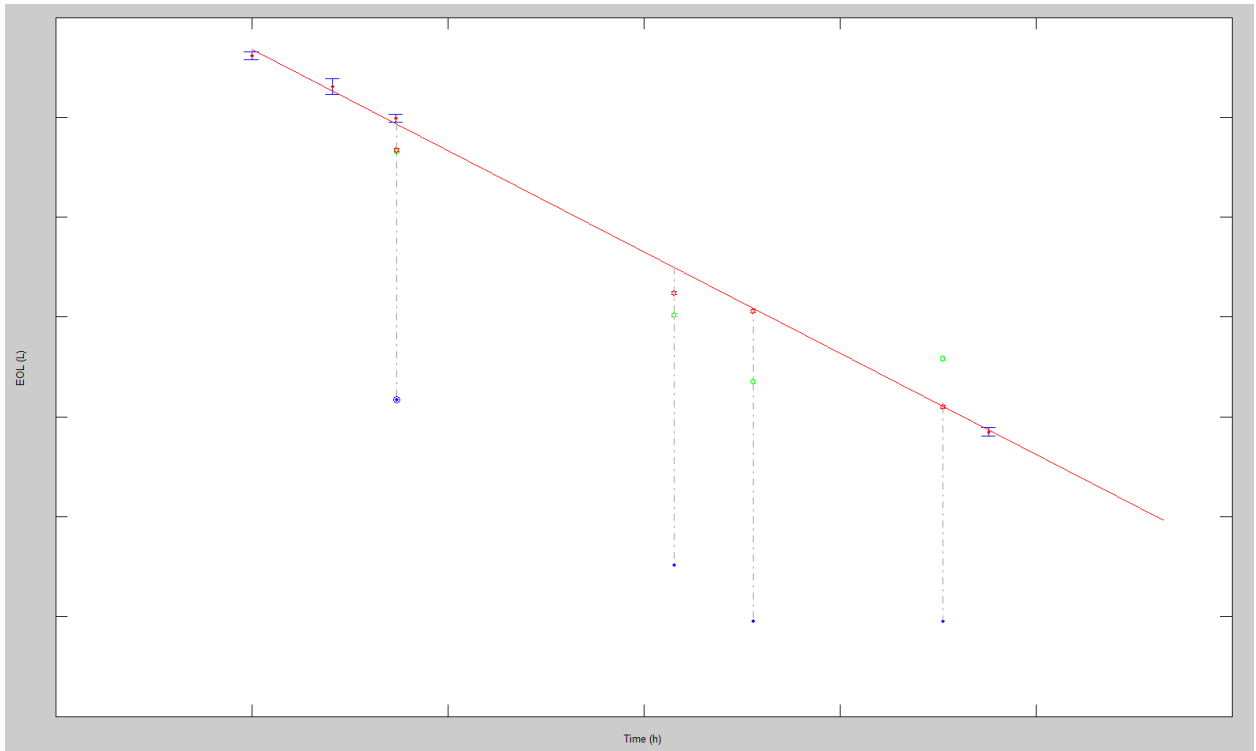
Figure 47, Example #2 of data from between take-off and landing normalized in standard conditions (correction of N then EOT)
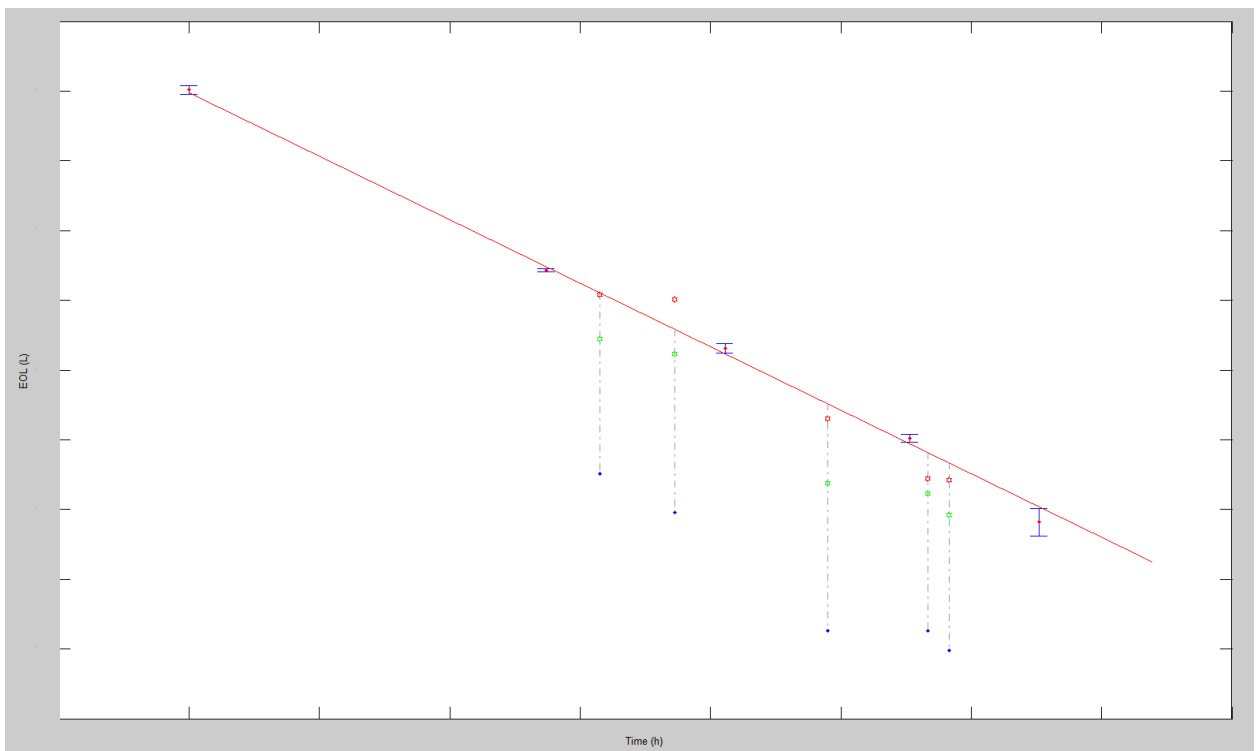
Figure 48, Example #3 of data from between take-off and landing normalized in standard conditions (correction of N then EOT)
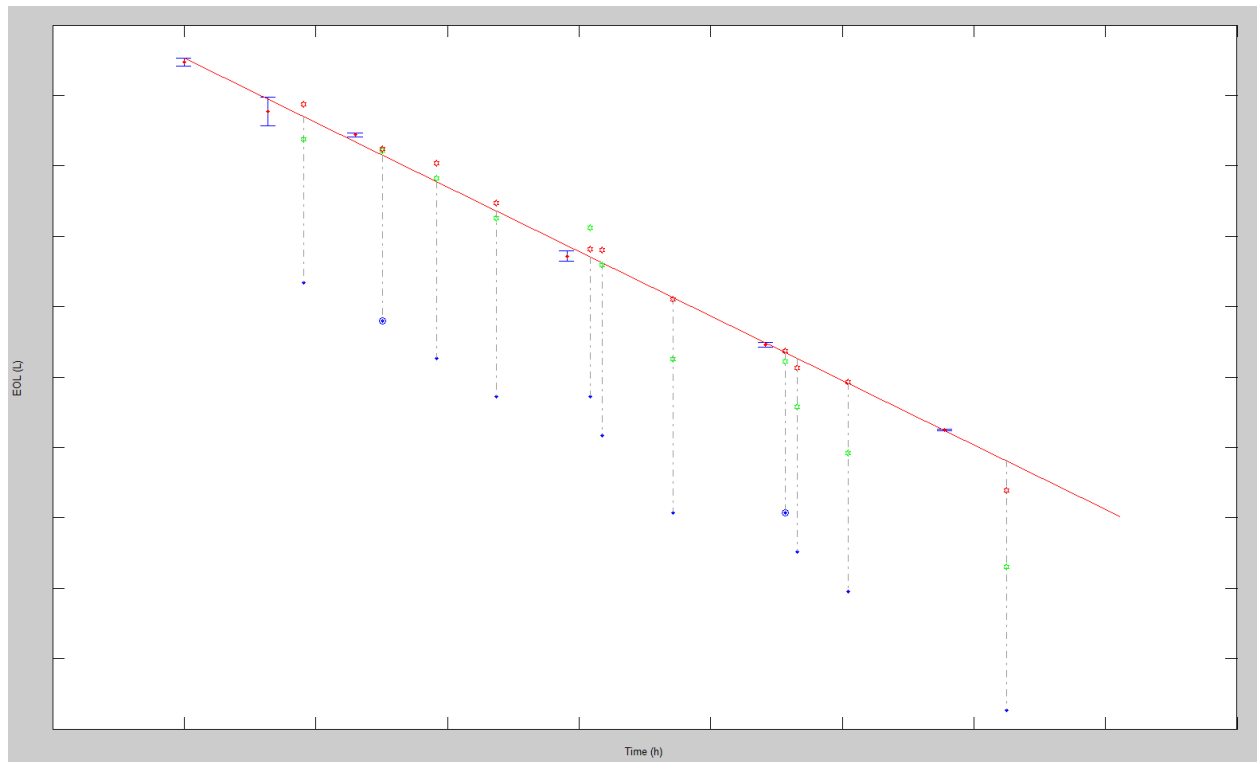
Figure 49, Example #4 of data from between take-off and landing normalized in standard conditions (correction of N then EOT)

One can note that for the circled blue dots (points whose temperature is in the vicinity of the standard temperature), the red stars and green stars almost match: that makes sense because the difference between these two kinds of stars is the correction of the gulping due to the variations of oil temperature between standard and real conditions.

The remaining residuals (difference between the red stars and the consumption line) are smaller than with the previous process of normalization .The results are then considered better. Besides, the assumption made for the validity of the model seems less restrictive than for the 1st process of normalization.

Once again, it can be concluded that the results are good, given the imprecision on the measurement of the oil level which will always have an influence on the gulping. Even with a refined selection of the raw data coming from between take-off and landing, some disturbances will still be present (the airplane during this phase will never be as steady as when it is on the ground). It can then be concluded that these results are satisfying in order to continue the study and these normalized points will be used to attempt to refine the calculation of the oil consumption.

10.4 Treatment of the normalized data

For the rest of this study, normalized points will be considered for all the phases. As a consequence, for the rest of this part, "oil level" refers to "normalized oil level".

As it has been seen in the previous paragraph, it can now be considered that it is possible to obtain a value of the oil level for each point extracted between take-off and landing, as if they were extracted in standard conditions. The points extracted before take-off should be aligned with respect to the time and the consumption line should cross these points. However, these points, extracted before take-off, are not aligned (because there is noise on the measurements, which affects the levels), and the consumption line is the line that fits the best these points with a least-squares regression. That is why it is interesting to add the points extracted between take-off

and landing. They should allow to refine the calculation of the consumption lines by giving less weight to the inaccuracy observed on the points extracted before take-off.

The approach that will then be followed is to recalculate the oil consumption not only by taking into account the points extracted before take-off, but also those extracted between take-off and landing.

This should add accuracy in many ways:

- If a flight is preceded and followed by a filling, the only way to know the oil consumption is to calculate the slope of the line between the level from before the take-off and the level from after the landing. However, the accuracy on the second level is not precisely known, and this can lead to miscalculation. There is thus an interest in adding the intermediate points if they are available.
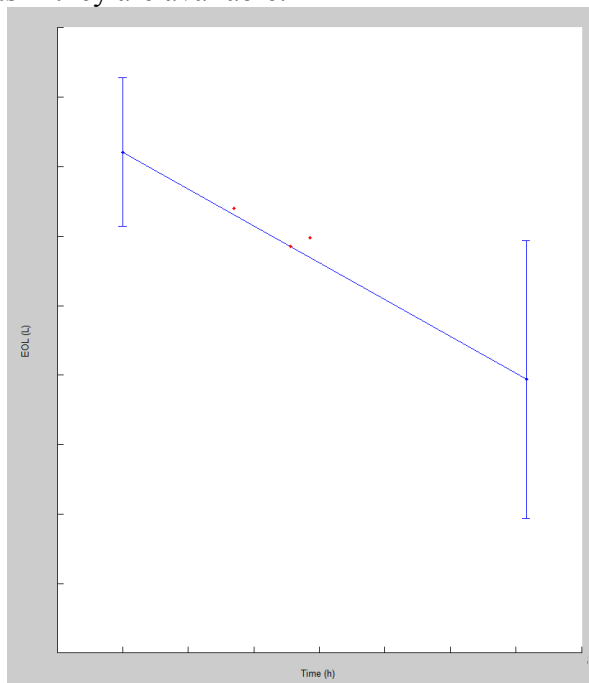
Figure 50, Flight between two fillings

On Figure 50, one can see the levels from before the take-off and after the landing, with their accuracy, the consumption line drawn between them, and also the levels extracted between take-off and landing in red. These last three points will be very useful to improve the calculation of the consumption line;

- Likewise, if two consecutives flights are between two fillings, the level coming from after landing of the second flight will be added to the regression to avoid operating a regression on only two levels (two points will indeed always be aligned). Once again the precision of the level extracted after the landing is not clearly defined.

  Adding the intermediate points can allow to improve the quality of the previous regression. Moreover, if they are numerous enough, they can allow to get rid of the level extracted after the landing for the regression and to replace it by the intermediate points;
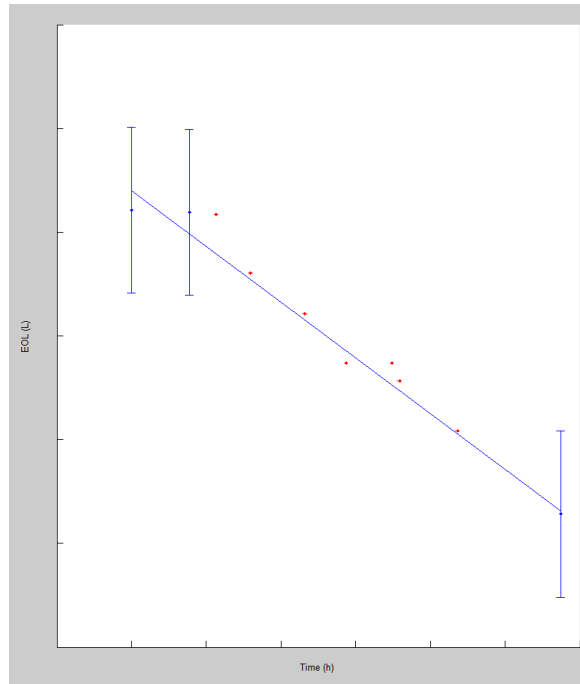
Figure 51, Two consecutives flights between two fillings

- Apart from this, two cases can be considered:
    - o Enough flights between two fillings and poor alignment of the levels from before the take-off;
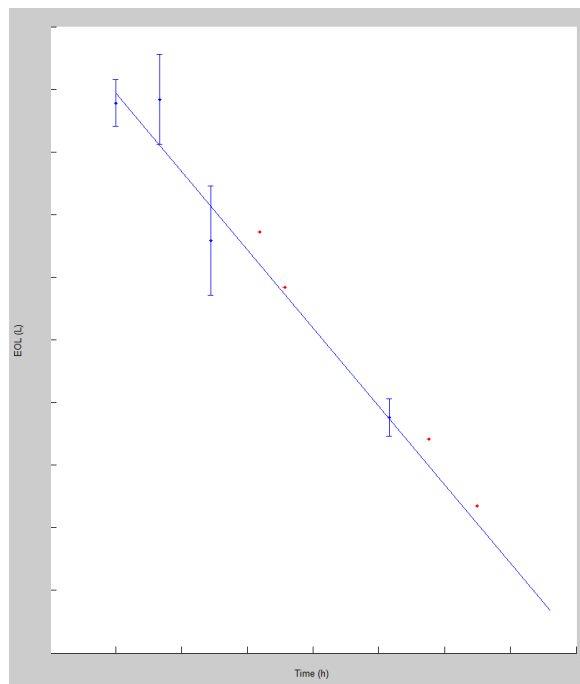
Figure 52, Example of poor alignment of the levels from before the take-off

In this case, it will be possible to indicate that some levels extracted before the take-off are inaccurate (the second one for example). It will be possible to remove it from the regression, which was not possible without the intermediate points, since the regression would have been made on too few points;

- o Enough flights between two fillings and good alignment of the levels from before the take-off.
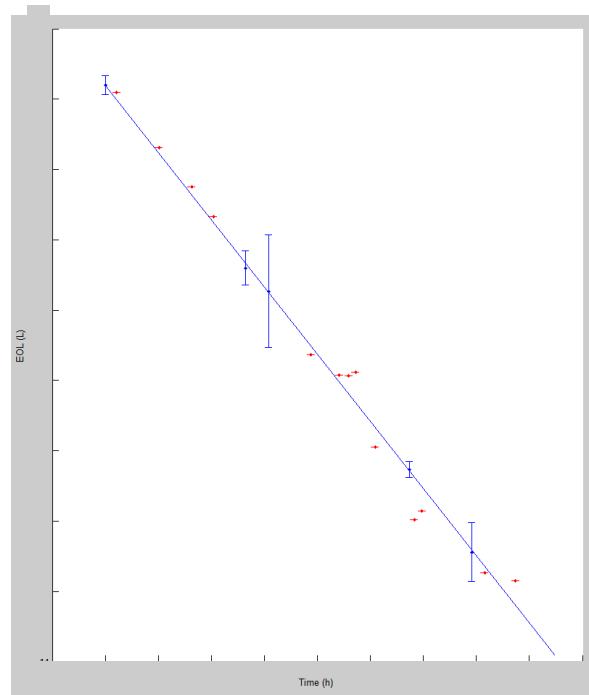
Figure 53, Example of good alignment of the levels from before the take-off

In this case, the levels from before the take-off and the intermediate levels are well aligned. The regression will then be better.

Taking in account the intermediate points can also improve the quality of the calculations for the last two cases. When it comes to recalculating the consumption lines, two questions have to be answered:

- How can the accuracy of the intermediate levels be defined?
- In which way the new consumption line is better that the previous one?

10.4.1 Accuracy of the intermediate oil levels

If one wants to compare at the same time the points coming from the different phases, weights should be given to these points. The accuracy of each level should indeed be taken into account. A point which is likely to be false should be given less credit than a point which is known to be sure. For the points coming from before the take-off and after the landing, this is already settled. However, one can wonder how precise the intermediate oil levels are.

For example, if a point is located just after the climb or just before the descent (which will seldom happen since the fetching logic has been modified), this point should be less trusted than a point in the middle of the phase. Indeed, the phenomena of bobbing can have been underestimated and this would cause some errors.

Another way to weight the points would be, as it is done for the first phase, to relate this accuracy to the error made with the model.

A logic should be created to weight the intermediate points, in order to recalculate the consumption lines under their influence. In the next paragraph, it will be discussed how the new consumption lines can be analyzed.

10.4.2 Recalculated consumption lines

The question that should now be discussed is how to process the new consumption lines?

On Figure 54, the red line is the consumption line that takes into account the points from before the take-off with their accuracy but also the intermediate points with a fixed accuracy of 0.1L. It can be seen that the new line and the previous one differ slightly. The problem is that it cannot be said that one line is better than another. In fact, the expected oil consumption is known (it is a specification of the engine), but the real consumption (which we want to determine) is not. It has then no meaning to say that the red line is the real consumption line because it would take into account the intermediate points.
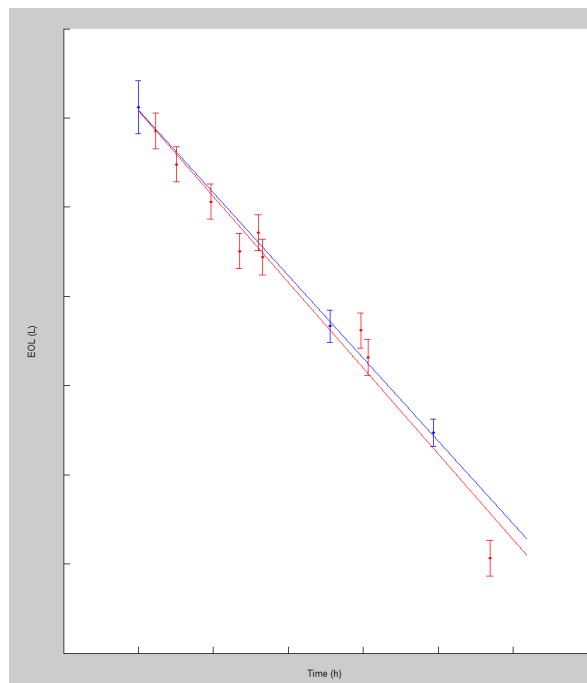
Figure 54, Recalculated consumption line

However, what can be done is to say that the first consumption line (in blue) is not absurd since the intermediate points are in the vicinity of this blue line. The small difference between these two lines ensures that the first consumption line is quite realistic. The presence of the intermediate points in the vicinity of the blue line can then, at best, allow to reduce the imprecision on the consumption that was given by the current algorithm.

Another approach that could be studied is the quantization of the fillings. Indeed, since the consumption line will be modified, the quantization of the filling (difference between two consecutive consumption line at the time of the filling) (see Figure 22) will also be modified. These fillings should be integers since cans of oil, whose capacity is 1L, should, in theory, be added. However, with the previous algorithm, it is not always the case.

Even when the intermediate points were added, with different weights, the quantization of the fillings changed slightly, but not all of them became integer. The problem comes from the fact that when the technicians fill the oil tank, they often do not respect the rules about the number of can which should be integer. Since *SNECMA* does not access to these real not integer values, it is not possible to compare the output of the algorithm with the reality.

The value of the oil consumption and the quantization of the fillings can hardly be improved by adding the intermediate points. However, the detection of the fillings can be improved, and this represent the main output of this study

10.4.3 Improved detection of the fillings

On Figure 55, one can be seen in blue what was done by the current algorithm (without the intermediate points). It seems that the algorithm did not detect any filling. As things stood (without the intermediate points), it was logical because the points from before the take-off were

almost perfectly aligned. The reason why no filling was detected probably comes from the level from after the landing of the 3rd flight (not plotted here) which is probably too high: the difference between this level and the level from before the take-off of the 4th flight is probably under the threshold of filling and the filling is then not detected.

The fact that the consumption estimated with the blue line is in order of 0.06L/h, which is way below from what is expected, shows that a mistake was made by the algorithm. The slopes of the two lines crossing the red points are close to -0.2L/h, which is close to what expected.
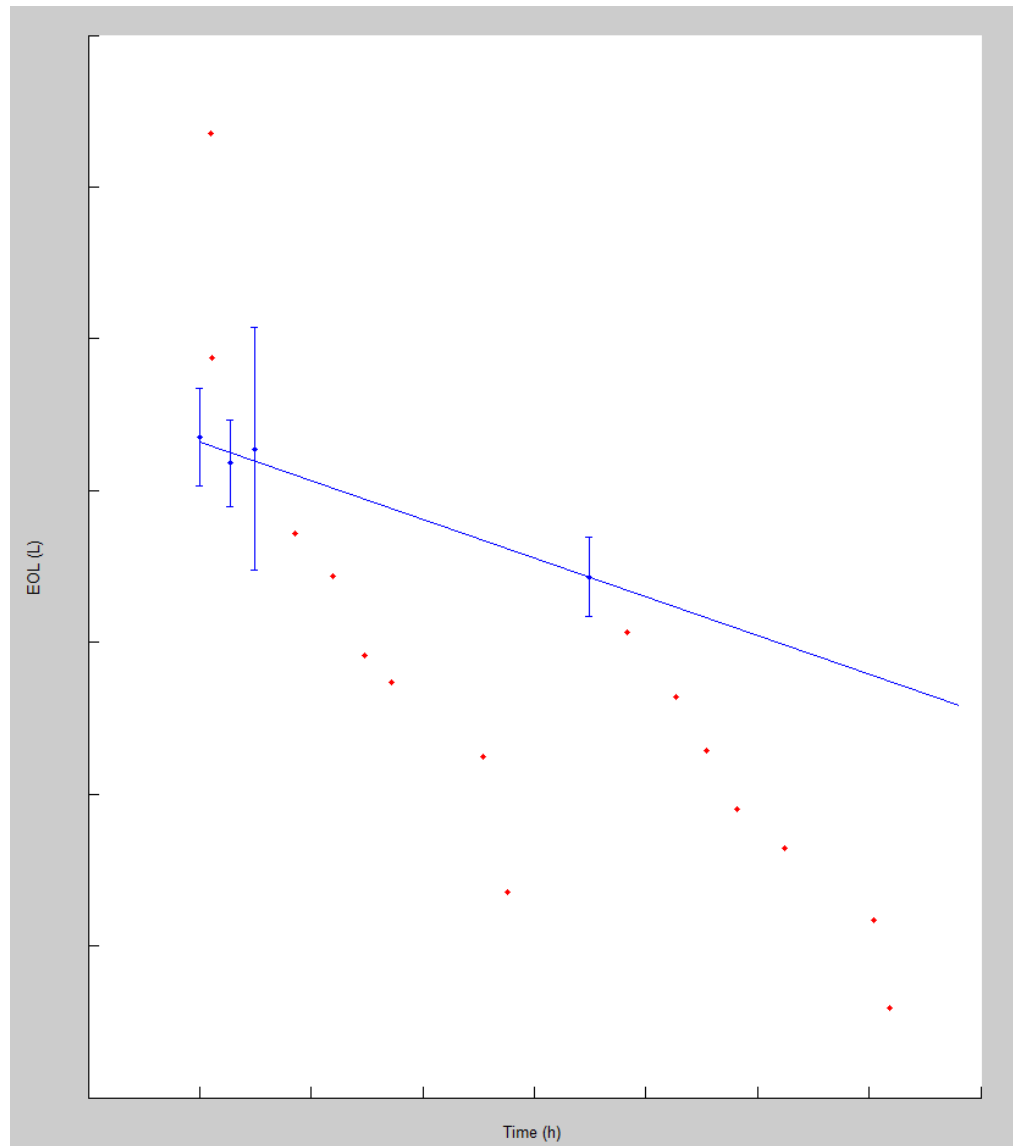
Figure 55, Interest of adding the intermediate points on the detection of the fillings

Adding the intermediate points should then allow to detect fillings which were not detected before but also to get rid of fillings detected wrongly (see Figure 56).
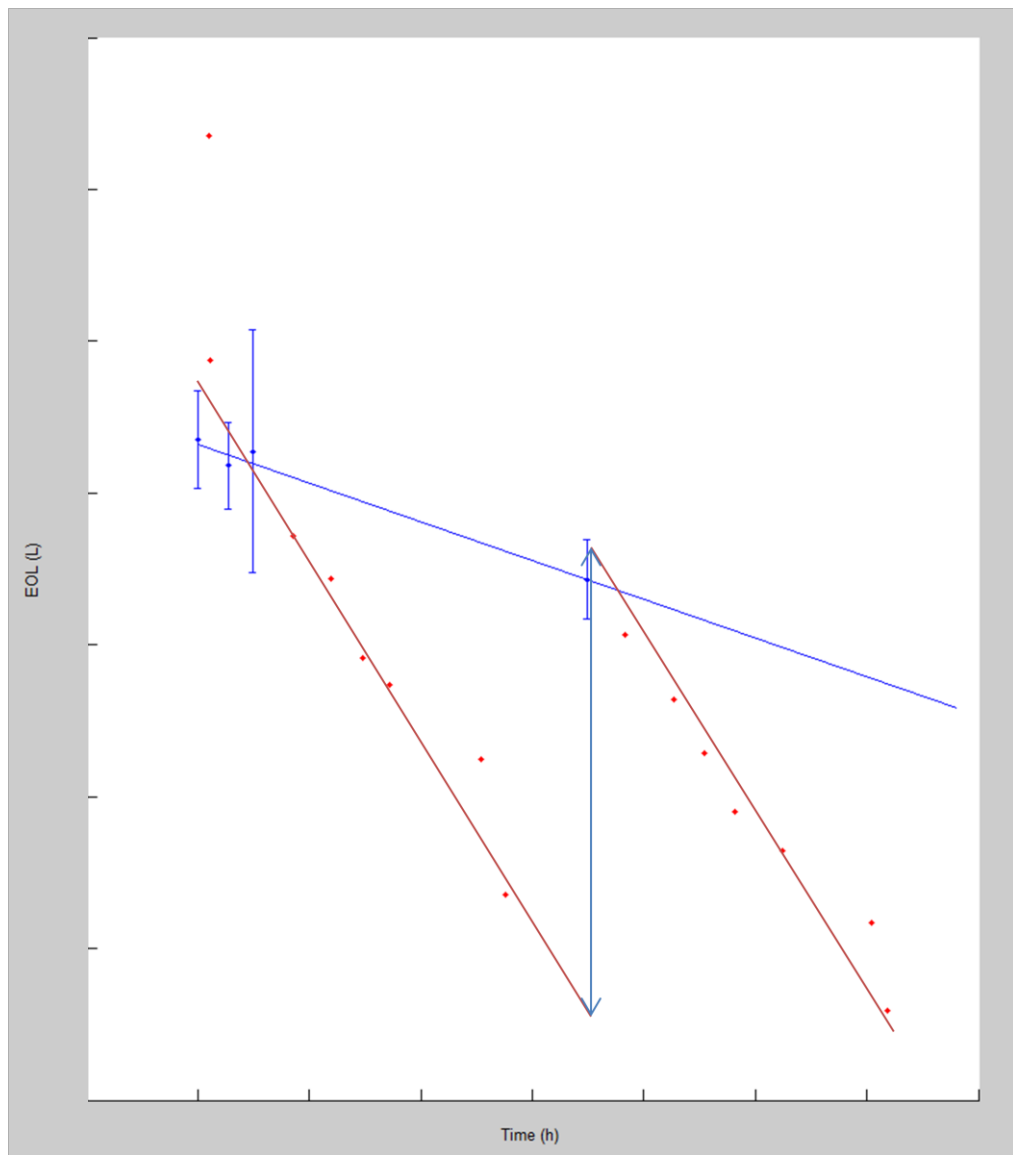
Figure 56, Filling detected thanks to the intermediate points

11.   DISCUSSION AND CONCLUSIONS

All the operations that have been attempted by the author are presented in this paper. Even if some data had to be removed for confidentially reasons, the methods are explained and allow to follow the reasoning of the author. In this part, it will then be commented all the work that has been done during this internship.

The future work, which will either be done by the author during the last month of his internship, or either by *SNECMA* if they want to go one step further in this line of research, and cannot be included in this report since it had to be finalized one month before the end of the internship, will be discussed in the next part.

11.1 Discussion

In this report, the outputs of each part have already been commented. However, the reader can here find a more global overview of what was done in this report.

For the *FMECA* method, several comments can be done:

- Even if it can be considered that the engines work almost perfectly nowadays (accidents are very marginal in spite of the high number of hours these engines are used), there is still a lot of room for improvement. The result of the *FMECA* study showed that the main failures are already addressed, and with the current architecture that is set, i.e. without adding any components on the current engines, it will be hard, but not impossible, to improve the monitoring of most of these failures;
- For the detection of abnormal oil consumption, which was ranked first at the end of the analysis, it has been seen that it was possible to improve the monitoring. The criteria that the author set to rank the failures and that led him to work on this particular one were thus adequate.

For the normalization of the data from between take-off and landing, what can be said is that:

- The modification of the existing fetching logic appeared to be useful. However, it has still to be determined whether it is worthy to update it on the current calculators or not. It depends on too many criteria such as the cost of this update or even the real benefits of it to judge whether or not it should be done. After the improvement of the detection of the fillings which will be made after the redaction of this report, it will be possible to adjudicate whether or not it is beneficial;
- To normalize the intermediate points, two main approaches have been considered:
    - It has first been considered that the variations of oil levels due to the change of oil temperature were known (even if this model was learnt for a totally different N) and then the variations of oil levels due to the change of N were corrected;
    - The second approach was to learn the variations of oil levels due to the change of N (even if this model was learn in standard conditions of temperature) and then the variations of oil levels due to the change of oil temperature.

    This implies for both techniques that the variations of oil levels with respect to N_2 and oil temperature were totally uncorrelated, which is a main hypothesis that has been made.

    A way to get rid of this would be to have a huge database, with an exhaustive range of N and oil temperature. This way, a model of gulping could be learnt for each set of conditions and the uncorrelation of the parameters would be taken into account.

However, creating this huge database would take a lot of time, and the company cannot afford to wait.

If this model did not change from an engine to another, using the data from different engines would reduce the duration of this learning phase. However, the fact that the model remains the same from an engine to another seems to be an important hypothesis: too many parameters evolve (architecture of the engine, age, dirtiness…);

Regarding the treatment of the normalized data, the following remarks can be made:

- Due to the imprecision of the logs of fillings and the way the fillings are made by the technicians, it is hard to say whether or not the quantization of the fillings has been improved by taking into account the intermediate points;
- The same way, the recalculated consumptions, since they will be in the same magnitude than the previous ones, cannot be judged better or worse;
- The lead that seems promising is the detection of the fillings. Indeed, if it can be shown that fillings can now be detected while it was not the case before, this will have a big impact on the efficiency of the algorithm. This will also have for effect to modify the calculated consumption and to give a more accurate value for this consumption.

11.2 Conclusions

The initial aim of this study was to improve the way to detect and anticipate the failures by increasing the accuracy of the calculation of the oil consumption. If a better (in a way that it will be closer to the reality) value of the consumption is found for the engines, the company will then be able to increase the rate of detection of the failures. Indeed, it could happen that the failures were not anticipated because the oil consumption calculated by the current algorithm was not out of range. The reliability given to the algorithm will then be increased and the clients will desire to use it more than in the past, which is a benefit for *SNECMA*.

The rate of false alarm can also be decreased. Indeed, when a too high/low oil consumption is detected, an alert is set to check whether a failure is happening. However, one cannot know whether this is synonym of a real failure, or if it just a miscalculation of the algorithm. That is why it is interesting to increase the accuracy of the algorithm in order to avoid the miscalculation and thus to not raise an alarm whereas nothing goes wrong.

The goals of this study have been reached. Indeed, a way to get rid of the influence of the context parameters on the variations of the oil level has been established and the normalized points can be used to improve the current algorithm. Even if the treatment of this points in order to improve the detection of the fillings is not finalized yet due to schedule reason(see above), this seems promising and should provide a real enhancement of the current algorithm.

This internship was interesting in the way that it allowed me to develop my technical skills (for example, I can now say that I understand most of the challenges around the lubrication system of an airplane engine) but also my professional skills (meeting deadlines, be part of a team…). This internship also allowed me to get a better understanding of the functioning of a big company.

Finally, I would say that this internship allowed me to face the field of research, which is what is done when working on the development of preliminary projects. This is quite hard in a way that one should constantly explore new paths, take initiatives and accept to follow paths that might after a certain time appear to be unsuccessful.

12.   RECOMMENDATIONS AND FUTURE WORK

What remains to operate after what was explained in this report is to continue the treatment of the normalized data. The detection of the fillings should be improved, using the intermediate points. Once all the parameters will be estimated (threshold for the detection, rejection of some normalized intermediate points considered as outliers…), this will have to be integrated to the current algorithm.

The method of learning for the gulping should be modified in the future. Indeed, during this study, the author learnt the model of gulping and applied it on the data already used for the learning. This happened to work fine, because the outliers were excluded and did not add default to the model, but a more proper way to learn the model should be applied:

- o Learning of the model on a given period, until the learning base is judged complete and the model judged efficient;
- o From this, application of this model on the new flights;
- o Eventually, improvement under conditions of the model with the new flights.

This would create a more perennial model.

13. TABLE OF ILLUSTRATIONS

14. REFERENCE OF ILLUSTRATIONS

[i] http://www.cfmaeroengines.com/engines/cfm56-7b

[ii] SAFRAN's intranet

[iii] SAFRAN's intranet

[iv] http://www.jet-engine.net/CFM56-3.jpg

[v] http://www.safran-group.com/fr/aeronautique/moteurs-et-nacelles/moteurs-davions

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[vii] http://www.snecma.com/military-engines/combat-and-training-aircraft-engines

[viii] http://www.snecma.com/sites/snecma/files/styles/landscape_medium/public/ajaris/SAF02900_0.jpg?itok=r3ZcLAoI

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[xi] http://code7700.com/turbine_engine.html

[xii] http://code7700.com/turbine_engine.html

[xiii] http://code7700.com/turbine_engine.html

[xiv] Extracted from SNECMA document : engine training: power transmission

[xv] Extracted from SNECMA document : engine training: lubrication system

[xvi] Extracted from SNECMA document : engine training: lubrication system

[xvii] Extracted from SNECMA document : engine training: lubrication system

[xviii] Extracted from SNECMA document : engine training: lubrication system

[xix] Extracted from SNECMA document : engine training: lubrication system

[xx] http://www.vatm.vn/ProductsServices/tabid/175/aid/125/language/en-US/Default.aspx

[xxi] Document from Sagem Défense Sécurité

[xxii] Extracted from SNECMA document : Pratique de conception EOC