POLITECNICO DI TORINO

Master's Degree in AEROSPACE ENGINEERING

Master's Degree Thesis

RAMS- and mass-based optimization of aircraft on-board system architectures during preliminary aircraft design

Supervisors

Prof. Marco FIORITI

Carlos CABALEIRO DE LA HOZ

Jennifer RAMM

Candidate

Feliciano SCARCELLI

DECEMBER 2023

Summary

In this work, various on-board system architectures have been analyzed in order to replicate existent long- and medium-haul aircraft system architectures and possible new architectures related to more and all electric concepts. All methods for designing and modelling the design space have been explored using an internal software for the System Architecture Design, from the most basic concepts to the most complex ones. In this phase of the work the on-board systems analyzed were mainly the Flight Control System and Landing Gear System. The design space was adapted to the necessity of the work including the possible choices for the range of aircraft of interest. The final design space included also Electric Power System and Hydraulic Power System for each aircraft on-board system, a concept introduced to make possible a deeper knowledge of the relations between power consuming systems and power generation and distribution systems. For the current work the focus was mainly on the on-board system itself. Every possible architecture design has been evaluated through a multi-objective optimization tool whose objectives were two: operational reliability and system mass. For the optimization part the Flight Control System has been considered as on-board system case study evaluating a wide range of architectures including different actuation systems and actuator types for each aircraft case study chosen. The work was conducted mainly on HSAs, EHAs, EMAs and Ball-screw. Previous studies conducted to have a deeper knowledge of differences between these actuators highlighted that newer and more electric aircraft are usually heavier but more reliable than the Hydro-Static Actuators. Optimization evaluations were conducted to find the most optimal architectures and define the Pareto front between both objectives. Genetic algorithms were selected due to the nature of the problems and its design variables. The system sizing related to the Flight Control System has been realized integrating in the loop the sizing of the actuators and the components related to them based on the function of each one, according to hinge forces and moments to face. The operational reliability has been developed through a Reliability Block Diagram for the quantitative estimation. Each component time-variable reliability was calculated through a probability function to consider the non-constant failure rate of the components throughout their life cycle

Table of Contents

List of Tables

List of Figures

Acronyms

AC Alternate Current

ADB Automatic Differential Braking

AEA All Electric Aircraft

APU Auxiliar Power Unit

APU-DP APU Driven Pump

ATA Air Transport Association

CDF Cumulative Density Function

DC Direct Current

EBHA Electric Back-up Hydraulic Actuator

ECS Environmental Control System

EDP Engine Driven Pump

EHA Electro-Hydrostatic Actuator

EG Engine Generator

EMA Electro-Mechanical Actuator

EMDP Electric Motor Driven Pump

FBW Fly-By-Wire

FCS Flight Control System

HSA Hydraulic Servo-Actuator

LEHGS Local Electro-Hydraulic Generation System

LGS Landing Gear System

MaD Multiple and Detailed

MEA More Electric Aircraft

MLG Main Landing Gear

MTOM Maximum Take Off Mass

NLG Nose Landing Gear

OBS On Board Systems

PBW Power-By-Wire

PDF Probability Density Function

PTU Power Transfer Unit

RAT Ram Air Turbine

SaD Single and Detailed

SaS Single and Simplified

THS Tailplane Horizontal Stabilizer

WLG Wing Landing Gear

Chapter 1

Introduction

Since the 1960s, technological advancements have led to the development of increasingly larger and more feature-rich systems. This progression prompted experts to explore solutions that could simplify the design, implementation, and operation of these intricate systems. System Architecting, a crucial step in the systems engineering process [1], involves making abstract decisions to address the complexity of a system, ensuring it meets the desired needs and values of stakeholders [2]. In contemporary times, the RAMS (Reliability, Availability, Maintainability, and Safety) concept holds paramount importance, particularly in engineering fields such as the aircraft industry, where a high level of safety is imperative due to the critical operating environment. Reliability, defined as the ability of a specific component or complex system to function without failure under specified conditions, is often quantified as the probability of success within a given time frame [3]. The focus of this work is on Probabilistic Reliability, which pertains to individual components, and the utilization of Reliability Block Diagrams (RBDs) to quantitatively estimate specific systems and systems of systems.

A big quantity of objectives has to be analysed during the preliminary design to understand if it's worth to make a change in a specific architecture and each objective has a different weight in the final evaluation. When these objectives are studied on a system, the system architecting can help the creation of the different combination of architectures. The more combinations are possible, the more architectures can be evaluated for a single architecture. The two objectives of the thesis are the mass system and the system operational reliability and since they are described by discrete variable function, they cannot be evaluated by classical optimization methods like the Gradient-based parameter optimization. A genetic algorithm is necessary for this kind of problem and the output of this work is a Pareto Front, since two objectives are present. The optimization goal of this work is intended to evaluate the trade off between mass and reliability of the Flight

Control System (FCS) actuation system, understanding the possibility of a change for a more electric aircraft. The concepts here introduced are deeper explained in the next section

1.1 Thesis Main Concepts

1.1.1 System Architecting

In the System Engineering (SE) a set of decisions has to be analysed and evaluated from the early stages. As an example, during the Apollo program, NASA conceived a dedicated capsule to descend to the surface of the Moon from lunar orbit, rather than to descend to the surface with the same Module used to bring astronauts to lunar orbit [2]. System Architecting is one of the steps in the systems engineering process [1]. It is an abstract concept used to describe a set of decisions (architecting) made on a complex system in order to fulfil the needs and values wanted by the stakeholder [2]. A complex system is supposed to be composed of subsystems where a defined number of decisions are made on each subsystem: every decision can affect the whole system and some decisions are made in the early stages of the design without knowing exactly the detailed purposes of the system [2]. The design of a system is based on two main topics: the functions of the system and the form, also referred to as components [1]. In this thesis, system thinking is about evaluating all the aircraft on-board systems architectures taking into account the need for a more electric scenario but at the same time the most important goal is to minimize a possible increase in weight and to maximize the overall reliability for the stakeholders.

There are many ways to decompose the aircraft design but in this case, the decomposition is focused on the on-board systems currently powered by the hydraulic system, the electric system and even on-board systems powered in a hybrid way. A function-based decomposition is approached in order to give the possibility of choosing different architectural choices for the same aircraft but also different aircraft sizes to work on.

1.1.2 Reliability, Availability, Maintenance and Safety (RAMS)

RAMS analysis have a vital importance during the design of a system. Reliability is related to the ability of specific component or complex system to fulfil its function in stated conditions without failure and can be referred to as the probability of success at a certain time or over a period [3]. The component reliability can be defined through a probabilistic or deterministic approach while Reliability Block Diagrams (RBDs) are introduced to determine a quantitative estimation of specific systems and system of systems. Availability is referred to as the percentage of time the component or system is in its operating state or ready to operate: it can be defined as the ratio between the sum of operating period of time and system life-cycle. Maintainability is the ability of a system to be maintained: it is related to the ease, accuracy, safety and economy in the performance of maintenance actions. Maintainability can be expressed in terms of maintenance frequency factors, maintenance times and labour-hour factors, and maintenance cost. Safety is a term that concerns the theory, investigation, and categorization of flight failures, and the prevention of these failures through regulation, education and training. Safety means that the system of interest is free from unacceptable risk, where an unacceptable risk is "a risk that can not be justified except in extraordinary circumstances [4]".

1.1.3 Optimization Methods

Optimization Methods are introduced when problems need for a solution whose objective is the maximum or minimum described by the objective function. Often there are more than one objective function: the multi-objective optimization (MOO) is described by more objective function whose object operations can be the minimization or the maximization [5]. Gradient-based parameter optimization (GBPO) methods are widely used when an optimization methods since they converge much faster than optimization methods that do not use gradient information [6]. However, since the optimization problem is about discrete-variable functions, GBPO methods cannot be used as they are referred to continuously differentiable functions. Optimization algorithms are extensively used lately instead of GBPO to obtain a Pareto Front since multi-objective‘problems usually don't show a unique solution but a restricted number of feasible solutions. NSGA-II and Bayesian optimization are two of the most used optimization algorithms gradient-free. NSGA-II is a evolutionary algorithm that simulates the process of evolution described by the Darwin´s Theory and whose optimization trend depends on statistical properties. Bayesian Optimization is a Surrogate-Based Optimization that train a regression model of the design space through the Gaussian Process by estimating mean μ and uncertainty σ.

1.2 Thesis Chapter Breakdown

The next chapters of this work are three. On-Board Systems State of The Art includes a literature review of the main on-board systems and studies for more-electric and all-electric solutions. Main focus is on Flight Control System (FCS) and Landing Gear System (LGS) but a quick review is done also on Environmental Control System (ECS), Ice Protection System (IPS) and the Generation and Distribution Systems: Electric Power System, Hydraulic System and Pneumatic

System. A short description of the theory for the RAMS analysis is also present in On-Board Systems State of The Art.
The Metodology chapter describes the methodology used to model the design space with ADORE (system architecting software) and the methods used for the definition of the two objectives and their implementation in the optimization phase in order to obtain the Pareto front.
One chapter is about the results and it shows the outputs obtained from the work and the analysis of what they represent. In the 5, some thoughts are explained about what we have learnt from this work and the future needs and perspectives.

Chapter 2

On-Board Systems State of the Art

In this chapter the state of the art of aircraft on-board systems, the reliability methods are analysed. The past and recent studies about More Electric Aircraft (MEA) and All Electric Aircraft (AEA) are also presented.

On Board Systems (OBS) are as much fundamental as the airframe to permit the accomplishment of a civil or military mission. Aircraft systems can be divided into two categories [7]:

- Utility systems: enable the aircraft to continue to fly safely throughout the mission;
- Avionic systems: enable the aircraft to fulfil its operational role.

These two categories of aircraft are interconnected: avionic systems need to be powered and to be cooled while the utility systems need to be connected to the human-machine interface in the cockpit.
Avionic Systems are divided into two groups: basic avionics and mission avionics. Basic avionics include the following functions: Communication, Identification and Surveillance, Navigation, Flight Control and Vehicle Management. Mission avionics, generally related to military aircraft, include the functions of defence and weapons management and attack.
Utility systems contain: Propulsive System, Propellant System, Ice Protection System, Environmental Control System, Landing Gear System, Flight Control System, Hydraulic Power Systems, Electric Power Systems and Pneumatic Power Systems. These are the main important utility systems which are identified from the ATA (Air Transport Association) Chapter: the systems-dedicated section goes from ATA 20 to ATA 50 (each chapter in this range is shown in Table 2.1).

ATA Number	**ATA Chapter name**
ATA 20	STANDARD PRACTICES- AIRFRAME
ATA 21	AIR CONDITIONING AND PRESSURIZATION
ATA 22	AUTO FLIGHT
ATA 23	COMMUNICATIONS
ATA 24	ELECTRICAL POWER
ATA 25	EQUIPMENT / FURNISHINGS
ATA 26	FIRE PROTECTION
ATA 27	FLIGHT CONTROLS
ATA 28	FUEL
ATA 29	HYDRAULIC POWER
ATA 30	ICE AND RAIN PROTECTION
ATA 31	INDICATING / RECORDING SYSTEM
ATA 32	LANDING GEAR
ATA 33	LIGHTS
ATA 34	NAVIGATION
ATA 35	OXYGEN
ATA 36	PNEUMATIC
ATA 37	VACUUM
ATA 38	WATER / WASTE
ATA 39	ELECTRIC AND ELECTRONIC PANELS AND MULTIPURPOSE COMPONENTS
ATA 40	MULTISYSTEM
ATA 41	WATER BALLAST
ATA 42	INTEGRATED MODULAR AVIONICS
ATA 43	EMERGENCY SOLAR PANEL SYSTEM (ESPS)
ATA 44	CABIN SYSTEMS
ATA 45	ONBOARD MAINTENANCE SYSTEMS (OMS)
ATA 46	INFORMATION SYSTEMS
ATA 47	INERT GAS SYSTEM
ATA 48	IN FLIGHT FUEL DISPENSING
ATA 49	(AIRBORNE) AUXILIARY POWER UNIT
ATA 50	CARGO AND ACCESSORY COMPARTMENTS

Table 2.1: Aircraft Systems ATA Chapter

In this thesis, the main focus is on Flight Control System (FCS) and Landing Gear System (LGS). Secondly, Environmental Control Systems (ECS) and Ice Protection System (IPS).

In Figure 2.1 an OBS breakdown is shown.

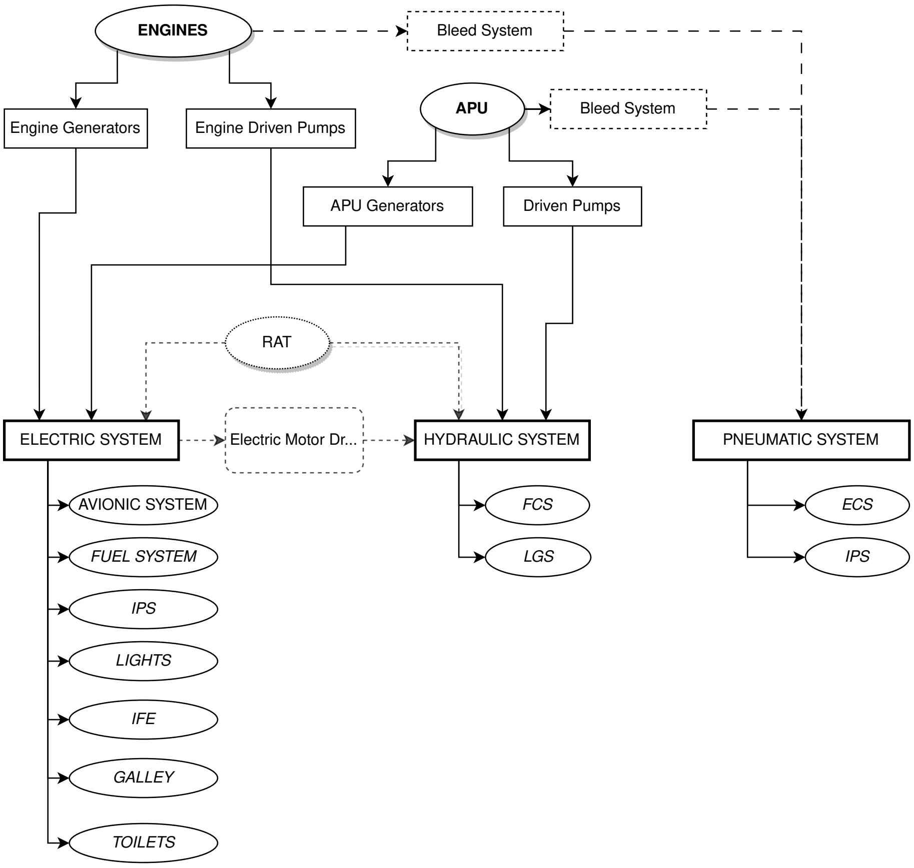


Figure 2.1: Power Generation Components and Systems Connection of a conventional aircraft

The connections and power generation components that a conventional aircraft needs between all the systems are shown in a simplified way.
Aircraft OBS can also be divided into three categories:

- Power Generation Systems: Engine Generators (EGs), Engine Driven Pumps (EDPs), APU Generators (APU-Gs) and APU Driven Pumps (APU-DPs) that provide electric or hydraulic generation from engine power;
- Power Distribution Systems: Electric System, Hydraulic System and Pneumatic System deliver power to all the users;
- Power Consuming Systems: the various forms of power are delivered to the users at the end.

Hydraulic Power is the form of power used to feed Primary FCS actuators and LGS actuators. There have been studies to introduce the electric power system to

feed these actuators and they will be discussed in the next sections. Electric Power is used for some Secondary FCS actuators and part of the Primary FCS actuators introduced in aircraft like A380, A350 and B787. Electric Power is also used for the Avionic System, Fuel System, part of the Ice Protection System and Cabin Utilities. Pneumatic Power System generally feeds the Environmental Control System and part of the Ice Protection System.
Hydraulic Power is generated by Engines and APU (Auxiliary Power Unit) driven pumps; electric generators mounted by engines and APU generate Electric Power; Bleed System is used for pneumatic generation.

Ram Air Turbine (RAT) is extracted in case of emergency and it feeds hydraulic and electric systems. Electric Motor Driven Pumps (EMDPs) become active if Engine and APU Driven Pumps fail. EMDPs power the hydraulic systems and they are controlled by electric motors (which cannot be powered by RAT in case of emergency).

2.1 Flight Control System (FCS)

Flight Control System executes the following functions:

- Acquire flight data that can be divided into air data and aircraft attitude;
- Compute flight data, directly related to the acquisition. FCS compute air data and attitude;
- Manage flight control surfaces. This function consists of acquiring commands, transmitting them to control surfaces, measuring control surfaces positions and providing control surfaces feedback;
- Alleviate pilot workload; this function is related to managing aircraft stability and controlling autonomously control surfaces;
- Inform the pilot by showing attitude, air data and engine performance.

To fulfill these functions actuators move the Flight Control Surfaces. Although through the years different and hybrid flight control surfaces have been designed, the most adopted flight control surfaces are divided into two categories:

- **Primary Flight Control Surfaces**, they provide pitch, yaw and roll control. The most common surfaces for commercial aircraft are:

  - *Elevator*, which perform pitch control. Usually, there are 4 elevator sections (2 in smaller aircraft);

- *Tailplane Horizontal Stabilizer (THS)*, which performs the pitch trim function. Usually, there are 2 synchronous THS surfaces;

- *Ailerons and Spoilers* perform roll control. The number of surfaces depends on the size of the aircraft;

- *Rudder* is used to control yaw and there are typically two or three sections that fulfill it;

- **Secondary Flight Control Surfaces** provide useful functions to make more comfortable flights for passengers and easier manoeuvres in some flight phases for the pilots. The most common surfaces for commercial aircraft are:

- *Inboard Spoilers* that provide speed brake function in flight;

- *Spoiler in Ground Spoiler* or *Lift Dump* function during the landing;

- *Flaps* and *Slats* to increase wing lift.

High Lift Device Systems have their own ATA chapter (ATA 27) but they are still flight control systems. Most common way to actuate slats and flaps is through a central power distribution unit that is mechanically connected to ball-screw actuators that move the corresponding control surfaces. These central units can be hydraulically or electrically powered on each slat or flap. In Figure 2.2 the A320 Flight Control System whose actuators are all powered hydraulically is shown [8]. Military Aircraft have different Flight Control System surfaces to guarantee different requirements in terms of manoeuvrability. A fighter aircraft is shown in Figure 2.3 and it can be composed (but other hybrid control surfaces have been adopted over the years) of:

- **Primary Flight Control Surfaces**

- *Moving Canard* or Foreplanes can control pitch. They are positioned close to the nose and render unstable the aircraft but at the same time more manoeuvrable the aircraft. Foreplanes also provide roll control when they are differentially moved;

- *Flaperons* augment roll control;

- *Rudder* provide yaw control in the same way it does in a conventional aircraft;

- **Secondary Flight Control Surfaces**

- A combination of flaperons and leading edge slats fulfil the high lift control;

- Flaperons can also be used the improve aerodynamic characteristics of the wing during landing approach;

- Leading Edge Flaps are also actuated during combat in order to increase wing camber and lift.

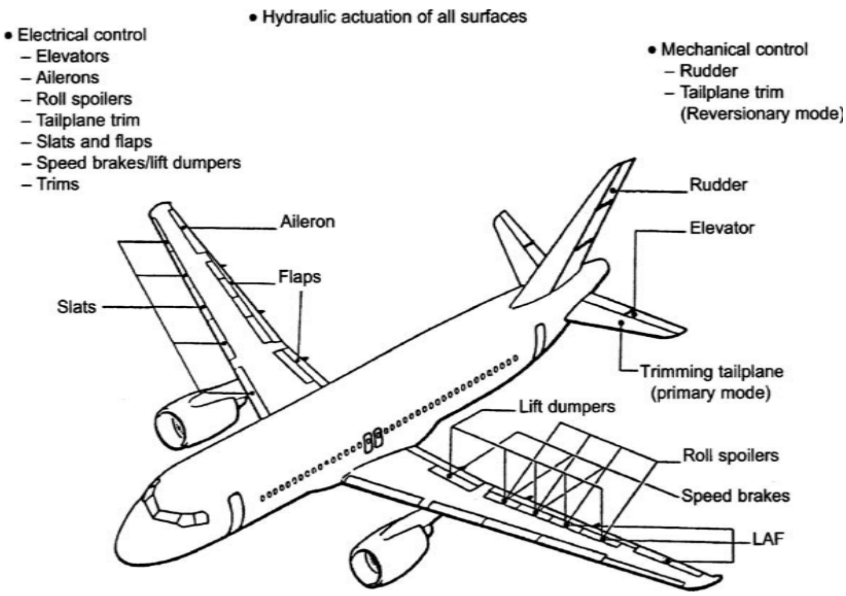


Figure 2.2: FCS of a Conventional Aircraft (A320) [8]

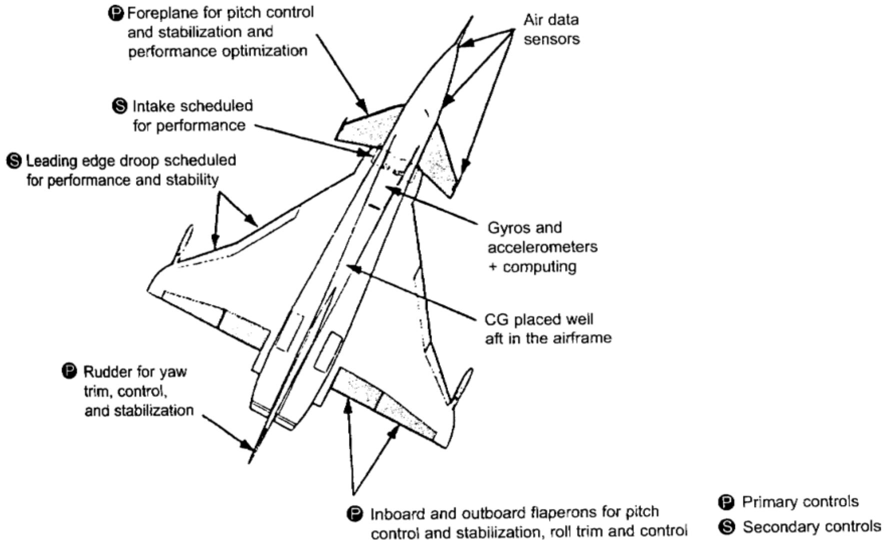


Figure 2.3: FCS of a Military Aircraft (EAP) [8]

Different concepts have been developed over the years. Early aircraft were manually operated using mechanical parts to connect the cockpit to the respective flight surfaces and to transmit forces applied by the pilot. This method of controlling aircraft became problematic over the years due to the technology evolution: aircraft became faster and bigger and the pilot workload also became larger. Mechanical control is currently used in small aircraft. Hydraulically powered control surfaces were introduced to overcome limitations related to mechanical control. It consisted of a mechanical circuit used to link cockpit control to hydraulic circuits and a hydraulic circuit which provided power to the actuators. The hydraulic pressure was then converted by the actuators in surface movement. Hydro-mechanical flight control system needed the introduction of artificial feel devices because the hydraulic circuit changed the perception of the load on the surfaces [9].
In the late 1970s Fly-By-Wire (FBW) flight control systems were introduced: this concept was based on analogue electronics. In the 1980s first Digital FBW Flight Control Systems were introduced. Among the main benefits, there are: the removal of the complex mechanical control runs and linkages, replaced by wires; the computer connects the pilot´s command to control surfaces and permits to obtain artificial stability of the aircraft; motion and air data sensors help the computers give feedback and information. Redundancies became more effective thanks to computers and their utilization for fault and failure detection. Figure 2.4 shows an example of a FBW flight control system where redundancies are omitted for clarity [10].

From the 80s to these years a lot of concepts based on Fly-By-Wire flight control system have been developed. In the latest years, two more concepts have been

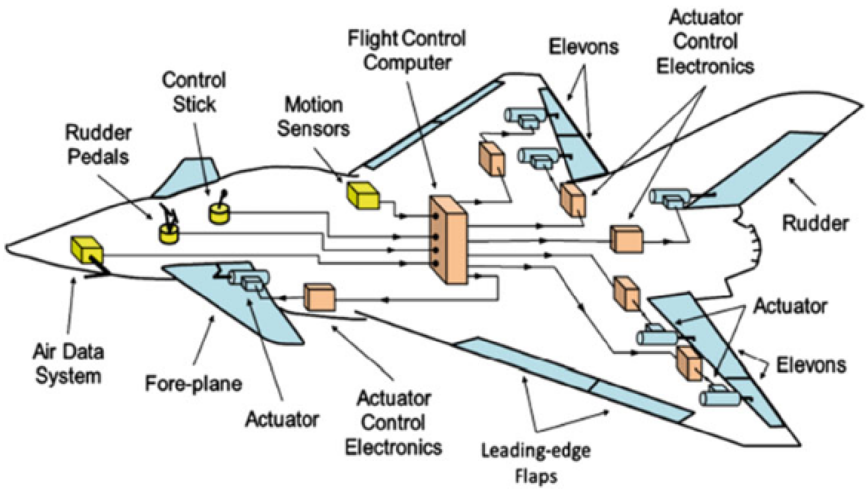


Figure 2.4: Basic elements of a Fly-By-Wire FCS [10]

developed: Fly-By-Light and Power-By-Wire (PBW).
The first one is an evolution of the Fly-By-Wire which consist of fiber optic cables instead of wires and is convenient in term of weight but currently, it could not be implemented due to the technology gap. The second one, PBW, is developed from FBW but power for the actuator is provided only by the electrical system: hydraulic are only present inside the actuator to transform electric power into mechanical power in order to move the surfaces (electro-hydrostatic actuators case) [9].

The actuators themselves play an important role in the Flight Control System, they are crucial components in order to reach an accurate flight surface position. In the Figure 2.5 the state-of-the-art actuators are shown: current aircraft manufacturers trend is towards more electric aircraft. To be as electric as possible, electric-powered actuators (EHA, EMA) are needed and then a PBW concept has to be pursued. It is possible to distinguish four different concepts:

- **HSA**: Hydraulic Servo-Actuator is the conventional actuator. It´s powered by the hydraulic system (one or more hydraulic lines) and controlled by a servo-valve. The servo-valve is controlled by low-powered electronics in an accurate way while high-powered hydraulics deliver the necessary forces to move the piston and consequently the cylinder (Figure 2.5a) [11];

- **EHA**: Electro-Hydrostatic Actuators move the piston through hydraulic pressure but, in this case, every actuator has its own hydraulic circuit that is supplied by an electric motor. As a consequence, the actuator does not need to be supplied by a central hydraulic line. Usually, the motor is a high and variable speed electric motor that drives a fixed or variable displacement pump (Figure 2.5b) [11] [12].

- **EBHA**: Electric Back-up Hydraulic Actuator is a combination of a HSA and EHA. This kind of actuator operates as a conventional actuator in normal mode. In case of a hydraulic failure, the power supply is switched and it operates as an EHA (Figure 2.5c). In this way, only one hydraulic line is needed for HSA, the redundancy is represented from the EHA mode. A zoom into this actuator is shown in Figure 2.6;

- **EMA**: Electro-Mechanical Actuator removes the hydraulic circuit and replaces it with a gearbox assembly. In Figure 2.5d two different EMAs are shown: Gear Drive Type has a gearbox assembly that connects the electric motor and cylinder; Direct Drive Type has no gear and the electric motor integrated into the cylinder [11].

Redundancies also assume a crucial role in keeping a safe flight, especially in case of fault or failure of some components.

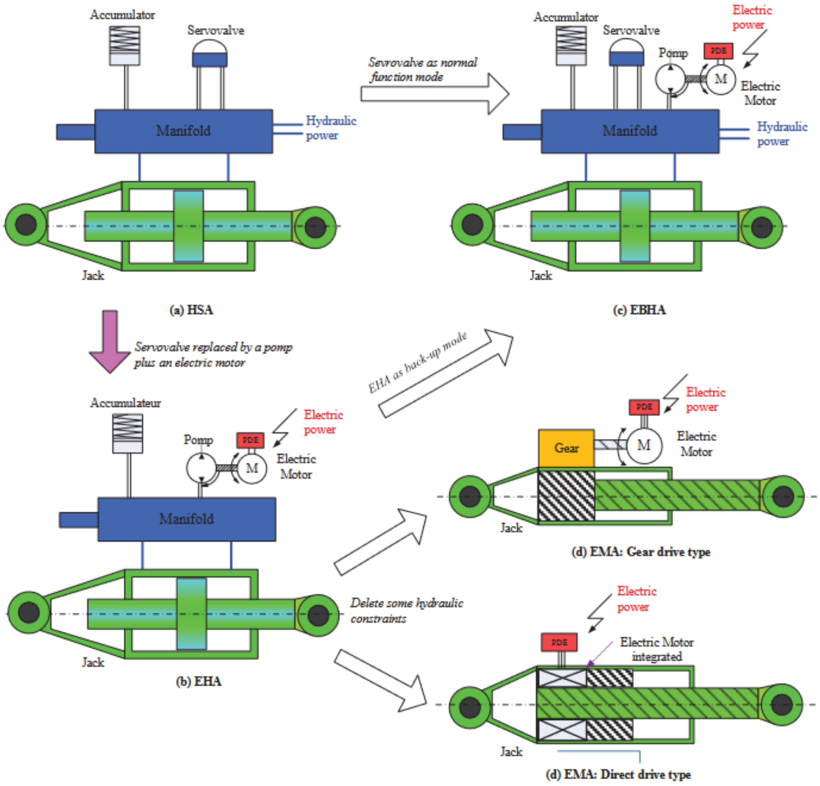


Figure 2.5: Schematic of actuator servo-control [11]

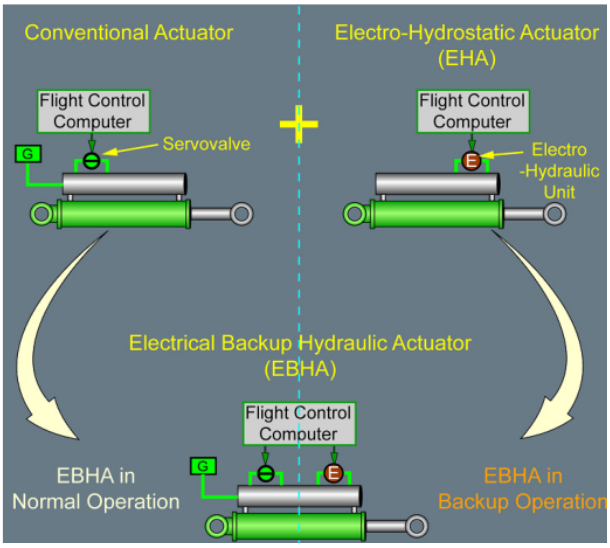


Figure 2.6: Schematic of EBHA combination

There are three types of redundancies used by aircraft manufacturers on FCS actuators. In figure 2.7a the internal redundancy is shown: only one actuator arm is moved by a single actuator driven by different power paths (as in EBHA). in figure 2.7b is possible to see an example of actuator redundancy which is the most common redundancy for primary flight control system: two different actuators and each actuator has one actuator arm and both act on the same flight surface. They can be actuated in two modes: active/active or active/standby. The difference between these two modes is basically related to the fact that in active/active mode both the actuators are used while in active/standby mode either one is active and the other one is in standby until the first one fails: in active mode, the actuators count maintenance time while in standby mode the maintenance time is counted differently. The redundancies mode is a safety crucial concept regarding the failure of one actuator: flutter must be avoided. The last one (figure 2.7b) is the surface redundancy: in this case, there are more surfaces fulfilling the same function and each surface has one actuator. This kind of redundancy is typical of High lift device systems, this kind of redundancy sometimes is also compulsory. There are some aircraft with two ailerons per wing because one single aileron could break due to the high loads.

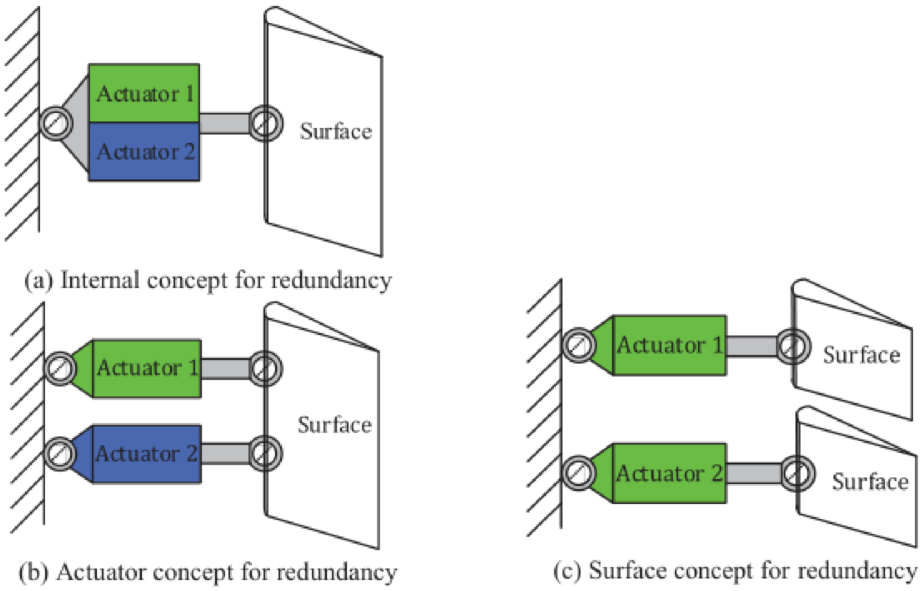


Figure 2.7: Redundancy Configurations

In the next paragraphs some examples of Flight Control System Conventional Architectures are shown. Each aircraft manufacturers adopted a different schematic for number of surfaces, redundancies and also power supply is structured in different ways. A320 family, ERJ-190 and ATR-42 FCS architectures are the object of this part.

FCS Conventional Architectures: A320
A320 FCS, shown in Figure 2.8, is powered by three different hydraulic power lines indicated as green, blue and yellow.

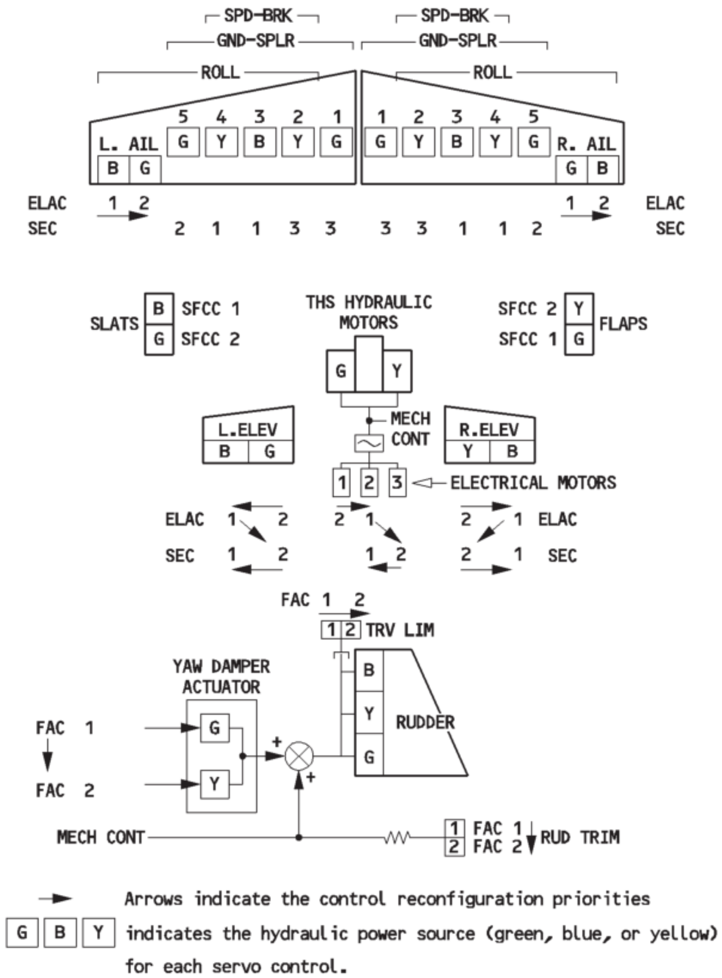


Figure 2.8: A320 Flight Control System Architecture

For the pitch control, there are two elevator surfaces with two actuators per surface and the trimmable horizontal surface (THS). The elevator surfaces are all actuated by HSAs while the THS has a screwjack system powered by two hydraulic

motors. The two actuators on each elevator surface work in active/damping mode: if the active HSAs fail then the two actuators switch their mode (damping/active).
Roll Control is fulfilled by ailerons and spoilers. Spoilers are also used for speed brakes and ground spoiler functions. Each spoiler surface is moved by one actuator and each wing has a total of five spoilers while there is only one aileron per wing and every surface is moved by two actuators. It can be seen how ailerons require the double-actuator redundancy while spoilers do not since there are five per wing and the required safety levels are already guaranteed. All the roll control actuators are HSAs. In case of failure of a spoiler surface, the symmetric one is inhibited.
Yaw Control is different from the other control systems. Yaw Dumping and Turn Coordination functions are executed automatically while pilot control is executed through the rudder pedals (hydro-mechanical control). The automatic functions are fulfilled by three HSAs that are actuated in parallel on the same surface and are powered by the blue, yellow and green lines at the same time [13].

FCS Conventional Architectures: ERJ-190
ERJ-190 has a FBW Flight Control System, only the ailerons are driven by conventional control cables moving hydro-mechanical actuators. Almost all the actuators are HSA except for the THS which is actuated by EMA. The number of control surfaces and actuators and hydraulic supply lines is almost the same as A320. The rudder is actuated by two HSAs instead of three. Figure 2.9 shows ERJ-190 high lift device systems.

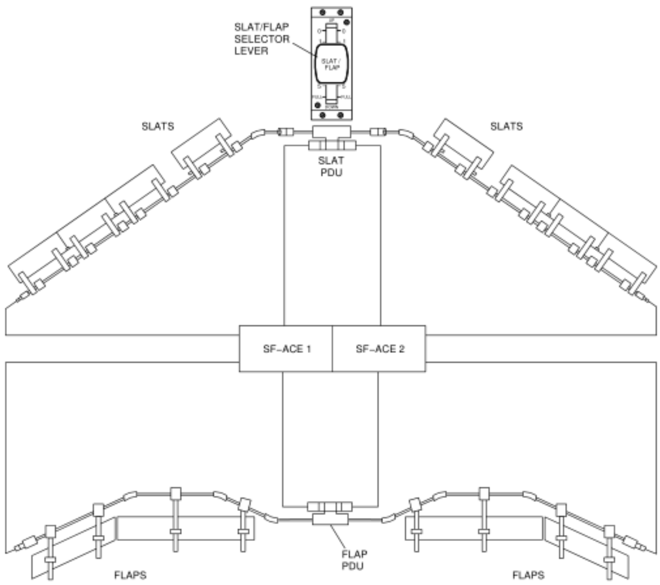


Figure 2.9: E190 high lift device system

This aircraft uses electrical power to move flaps and slats: one slat power driver unit and one flap power driver unit control respectively all the slats and all the flaps. The central units are electrically powered and control the ball-screw actuators through a mechanical line consisting of tubes and gearboxes [14].

FCS Conventional Architectures: ATR-42
ATR-42 primary FCS are actuated mechanically like the majority of old regional aircraft: the mechanical actuation is possible due to the size of the aircraft that is lighter and smaller than the other examples. Spoilers and flaps are hydraulically actuated (HSAs). Some studies of more-electric versions of this aircraft are currently explored making the ATR42 one of the most interesting case-study for the MEA transition [15].

2.2 Landing Gear System (LGS)

Landing Gear System fulfils the following functions:

- Support the aircraft during ground operation: this function includes the support of vertical and horizontal forces, preservation of aircraft ground clearances and the maintenance of aircraft stability;
- Control the aircraft during ground operation;
- Reduce aircraft speed on ground and landing gear drag during flight;
- Facilitate take-off and landing operations.

According to the size and design of the aircraft, it is possible to see different LGS architectures. The LG structure is relevant for support forces while the positioning is important to maintain the aircraft stability; LG length is very important to preserve aircraft ground clearances. In order to control the aircraft during ground operation: wheels allow aircraft movement while the steering system change aircraft direction. A shock absorber is necessary to reduce vertical speed and the braking system permits to reduce horizontal speed. It is needed to minimize the aircraft drag and the landing gear system generates additional drag, this is the reason why a retraction/extraction system is needed. LG bays are also needed in order to allocate the LG inside the fuselage and sometimes inside the wings. These bays need actuators that can open and close them (open bays also generate drag).
In a preliminary analysis, a Landing Gear System is characterized by its architecture and its subsystems. In the years a lot of LGS architectures have been created depending on the size and characteristics of the aircraft (bicycle, taildragger, non-conventional), in Figure 2.10 some of them are shown.

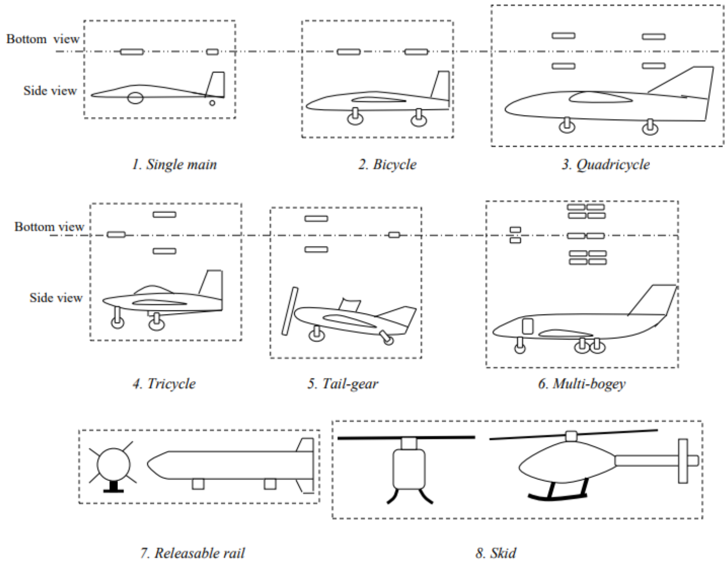


Figure 2.10: Examples of Landing Gear Layout [16]

Civil aviation adopted some decades ago the tricycle configuration and this configuration is still the most optimal. Similar configurations can have different struts which are vertical structures containing shock-absorbing mechanisms. Each strut can have a different number of wheels. In Figure 2.11 the schematic with all the possible choices for a tricycle configuration is shown: obviously bigger aircraft need 3 types of struts.

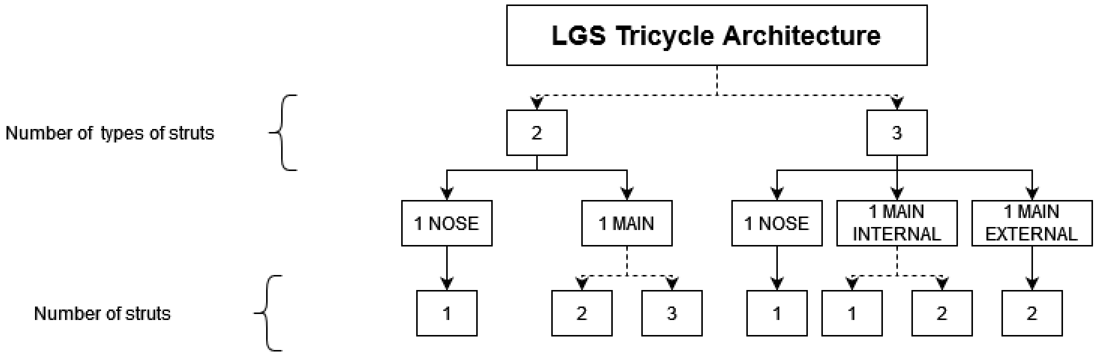


Figure 2.11: Schematic of possible choices in the design of a Tricycle Landing Gear System

Usually, the external main structures are extended under the wings and their bays are located in the fuselage. The number of structures for the main landing gear is also a design choice. Usually, every strut has an oleo-pneumatic shock absorber.

Lighter civil aircraft don´t need all the actuation systems that are installed on heavier civil aircraft. Small aircraft are likely to use mechanical steering systems which consist of direct control of the pilot through rudder pedals without powered assistance. Older or Lighter aircraft use a mechanical system also for the retraction system [17]. The analysis in this thesis examines medium and long range civil aircraft which need power systems. The actuators in the system are used for different functions: extraction, retraction, steering and opening/closing door bays. The most used actuators in modern commercial aircraft Landing Gear Systems are:

- **Steering Actuators**: deflection of the pedal or steering wheel is transduced in a variation of pressure on both cylinders that consist of a differential mechanism. This kind of actuator is always present in the nose landing gear of commercial aircraft and sometimes it is installed on the main landing gear of very large aircraft. Usually, the nose gear is controlled by a cable system while, if present, main gears are actuated through electrical signals that control an electro-hydraulic valve and actuator [17]. Each pair of steering wheels has one actuation system. In the Figure 2.12, steering actuation system of Boeing B777 is shown.

- **Retraction Actuators**: the mechanical retractable landing-gear system is present in some older aircraft while is present as an emergency extension system on many light aircraft. Modern light aircraft often use electrical retraction systems consisting of electric motors specific for this function and some mechanical links that permit them to open and close the doors. The most common power system used for retraction is the hydraulic retraction system [17]. Usually, one actuation system per strut is used. In Figure 2.13 a hydraulic retraction system is shown.

- **Doors Actuators**: doors can be operated mechanically through links with the strut or hydraulically. Every strut usually has two doors: nose-gear doors are composed of a forward door and an aft door while main-gear doors are composed of an outboard door and an inboard door. A typical situation sees the forward door and inboard door operated hydraulically while the aft door and outboard door are linked to the respective gear [17].

In general, the remaining components that are hydraulically actuated are door latches, bungee cylinders and brakes [17]. The most used brake assemblies for transport aircraft are: Segmented rotor-disk brakes, Carbon Composite Brakes and Multiple-Disk Brakes. Three types of brake systems are used on aircraft:

1. Independent Brake Systems: used on small aircraft, they are independent of the aircraft´s main hydraulic system. A small independent hydraulic system fulfil the brake function;

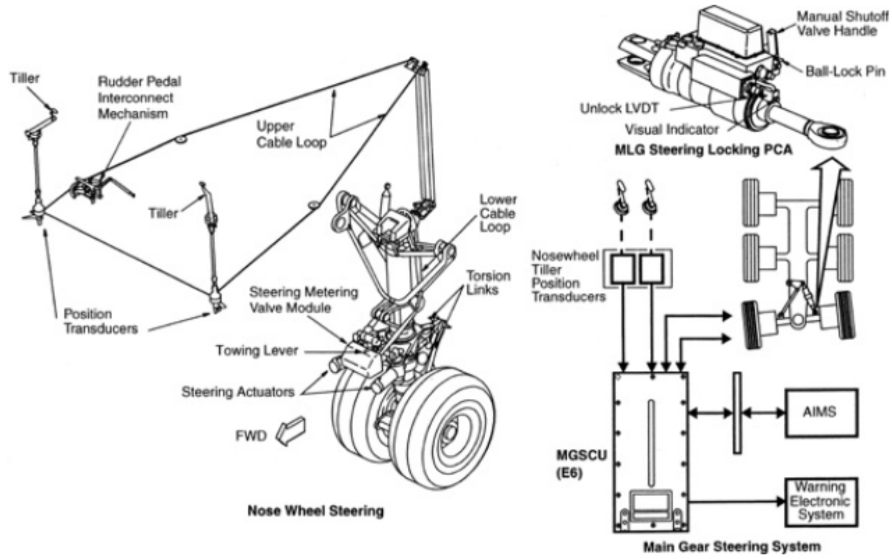


Figure 2.12: Nose wheel and main gear steering (Boeing Aerospace Co.) [17]

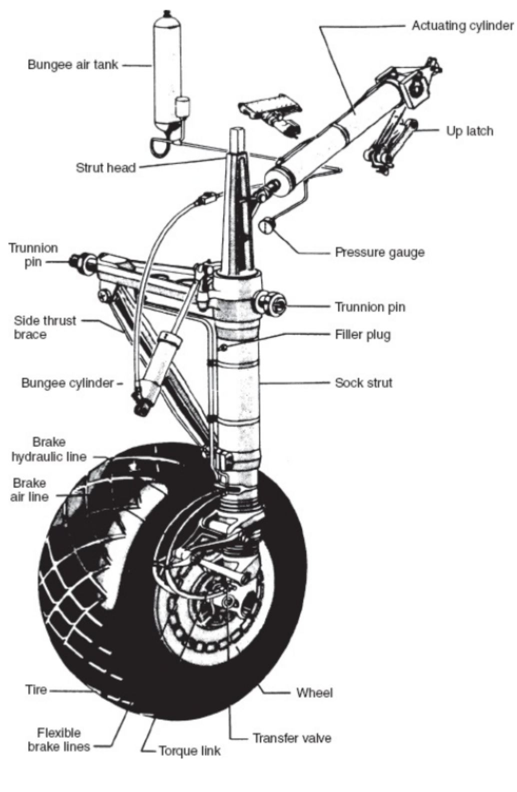


Figure 2.13: Retractable main landing gear [17]

2. Power Boost Systems: used on high landing speeds aircraft or for which are too heavy for an independent brake system. The system operates the brakes through the hydraulic system pressure;

3. Power Brake System: used on large aircraft that need huge amounts of hydraulic pressure. This is the brake system that will be analysed for our study cases.

LGS Conventional Architectures: B777
B777 is a long-range wide-body airliner. This aircraft landing gear system has a tricycle configuration with a six-wheel truck on each main landing gear and a two-wheel gear on the nose landing gear. In addition to the nose landing gear, the two aft wheels in each main landing gear strut have the steering function. Besides the door actuators and the retraction actuators some other actuators are present in the main landing-gear retraction system. MLG drag brace and MLG brace down lock actuators are used when the MLG has to be retracted: pressure goes to these actuators that start retracting and consequently, the gear down locks are retracted. This pressure also goes to some valves of the system and to the MLG truck positioner actuator which is extended to the STOW position. Pressure permits to retract also the MLG door lock actuator in order to unlock the main gear door and the MLG door actuator gets extended pressure through the MLG door priority/relief valve. When the MLG door is almost open, a sequence valve transfers the pressure to the MLG retract actuator to retract the gear. When the MLG is into the bay some locking valves are actuated and the door is closed through the same actuator previously used to open it [17]. In Figure 2.14 the B777 main-landing gear retraction schematic is shown. The same components are used in order to extend the main landing gear. If normal extension fails, Landing Gear can be extended using the hot battery supplies that control the extension and power it through an electric motor that pressurizes fluid from the central hydraulic system. Brake Assembly installed on B777 are Multiple-Disk Brakes. The assembly is a rotor-stator unit powered by hydraulic pressure. Rotors and stators are carbon disks and they are compressed between the pressure plate and the end plate assembly to slow or stop the airplane. Pistons apply to the pressure plate brake system hydraulic pressure. The example is shown in Figure 2.15.

LGS Conventional Architectures: A320
The analysis of A320 and A380 verges on a deeper understanding of the various power systems that feed each subsystem. A320 Landing Gear System consists of two two-wheeled main gear and a two-wheeled nose gear. A320 has three hydraulic systems: green, yellow and blue. Blue Hydraulic System can be considered the emergency hydraulic line. The green hydraulic system actuates all gears and doors during the retraction cycle.

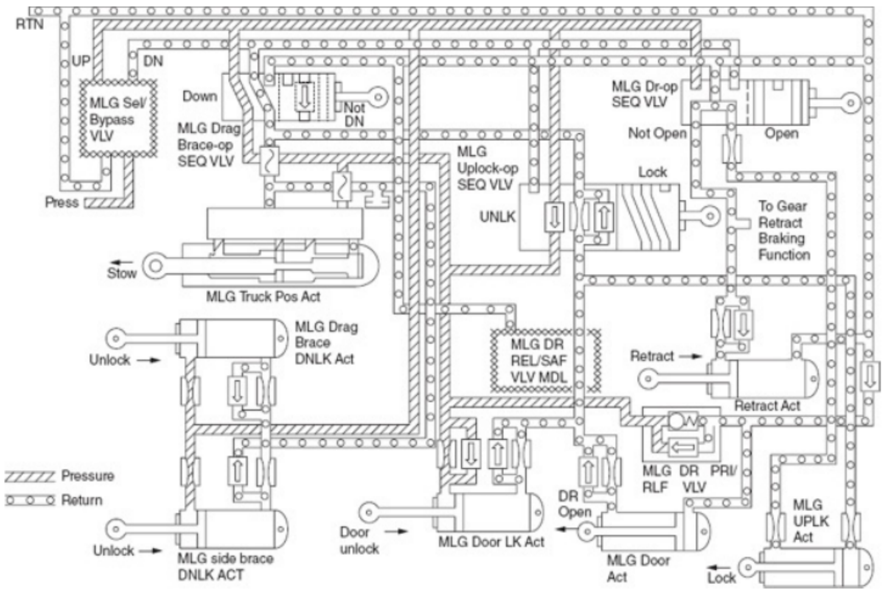


Figure 2.14: Main landing gear B777 retraction scheme [17]

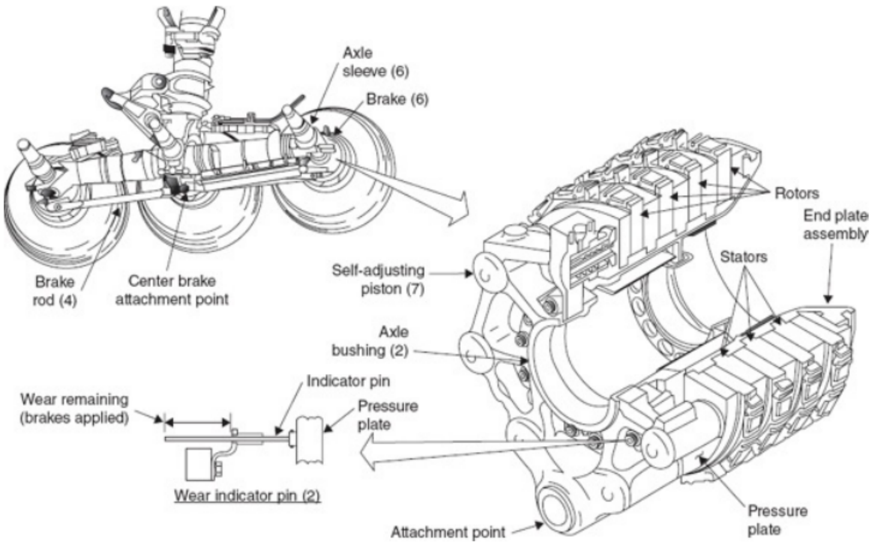


Figure 2.15: Multiple-Disk Brakes Assembly [17]

If the normal system (hydraulic actuation) fails, the landing gear can be extended through gravity and aerodynamic forces while the gear doors remain open. The steering function is fulfilled only by the nose landing gear. Also in this system, the green hydraulic system supplies pressure to the nose wheel cylinder but the steering function doesn´t work if the system is in emergency mode. Multi-disc brakes are installed on the main wheels: the normal system uses green hydraulic pressure while the alternate system uses the yellow hydraulic system backed up by a hydraulic accumulator [18].

LGS Conventional Architectures: A380

A different configuration can be found on the A380 LGS (Figure 2.16): one two-wheeled Nose Landing Gear (NLG), two four-wheeled wing landing gears (WLG) and two six-wheeled body landing gears (BLG). In normal operation, the landing gear hydraulically extends and retracts: NLG and WLG and related doors are powered by a green hydraulic system while BLG and related doors are powered by the yellow hydraulic system. In emergency mode, gravity-assisted landing gear extension can be performed. The braking function is fulfilled by the wing landing gears and the four most forward wheels of each body landing gear. In normal braking mode, WLG brakes are supplied by green hydraulic system and BLG brakes are supplied by yellow hydraulic system. LEHGS and brake accumulators are used in the other braking mode. LEHGS (Local Electro-Hydraulic Generation System) is an independent hydraulic power source that is composed of an electrically-powered pump, a hydraulic reservoir and an assigned control unit. The steering system consists of a green hydraulic system powered Nose Wheel Steering in normal mode (LEHGS power in Alternate Mode) and a yellow hydraulic system powered Body Wheel Steering. BWS is used only during taxi, pushback and towing and it is about the two aft wheels of each body landing gear, as in the B777 main wheel steering [19].

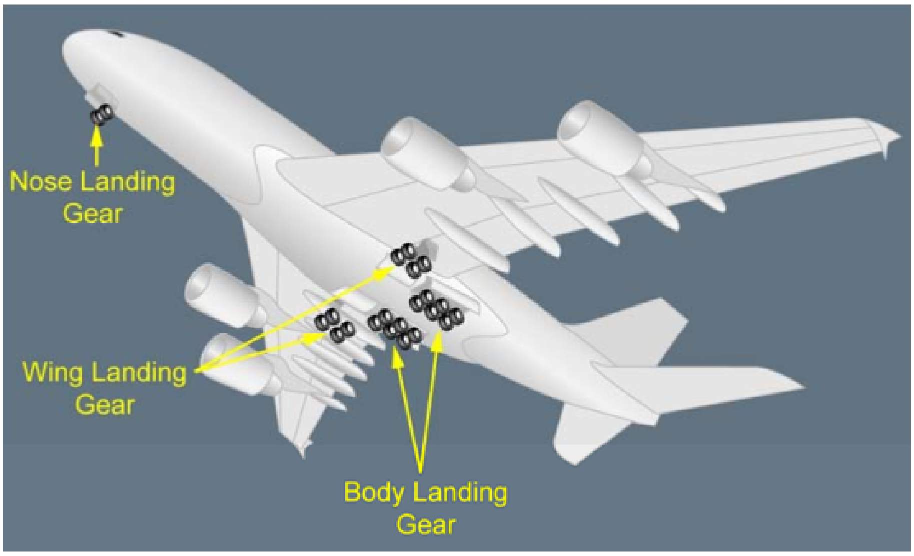


Figure 2.16: A380 Landing Gear Configuration

LGS Conventional Architectures: A350

A350 Landing Gear System consists of one two-wheeled nose landing gear and two four-wheeled main landing gears. In Figure 2.17 doors and gears are indicated with the respective actuation mode (colours refer to the hydraulic system).

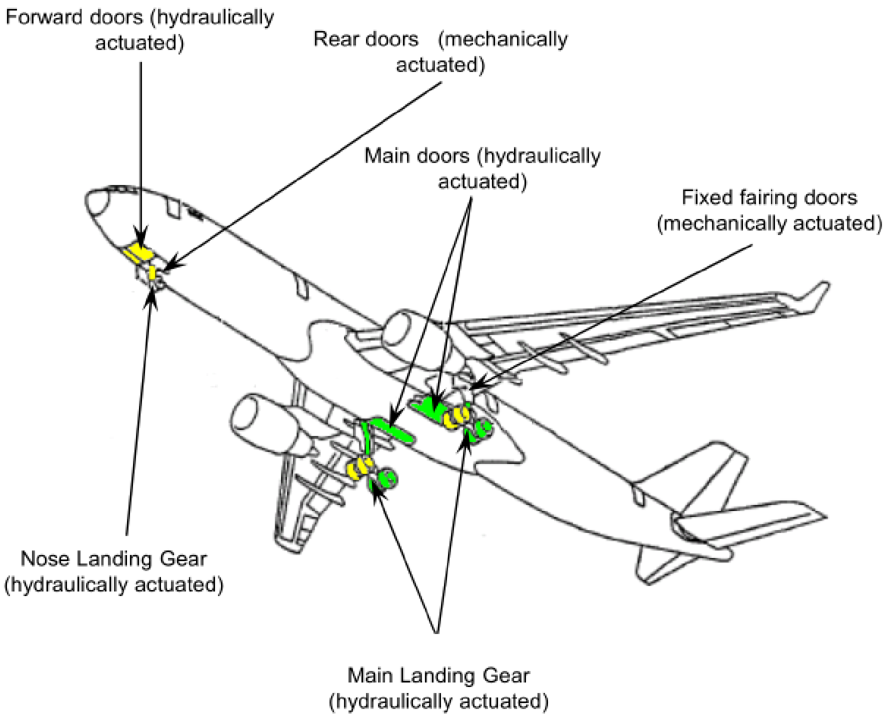


Figure 2.17: A350 Landing Gear Configuration

About the Extension and Retraction System, the green hydraulic system power the MLG and associated doors and the yellow hydraulic system powers the NLG and associated doors. In case of emergency, as in the other extension systems, a gravity-assisted landing gear extension can be performed. Braking system is present in the main landing gear: front MLG wheels are supplied by yellow hydraulic system and rear MLG wheels are supplied by green hydraulic system during normal brakes. Two ACCUs power the brakes in the other modes. Steering system is provided by the nose landing gear in normal mode. The NWS is powered by yellow hydraulic system. In backup mode, the Automatic Differential Braking (ADB) permits a limited steer: the green MLG brakes are used [20].

LGS Conventional Architectures: ERJ-120

E120 has a two-wheeled nose landing gear and two two-wheeled main landing gears.

The green hydraulic system supplies retraction and extension of main and nose landing gears, door opening/closing and nose wheel steering. Alternate extension is provided by an electrical override system while there is also the emergency free-fall extension system. Normal brake is operated by the hydraulic systems: the outboard pair of wheels are supplied by green hydraulic while the inboard ones by the blue system. The emergency braking system is also operated by the blue hydraulic system.

LGS Conventional Architectures: ATR-42
ATR42 has a two-wheeled nose landing gear and two two-wheeled main landing gear. Landing gear extension and retraction is supplied by the green hydraulic system while doors are actuated mechanically. There is also an emergency gravity-assisted extension. Nose wheel steering is powered by the blue hydraulic system. The green system supplies the brake system (main landing gear) on normal mode while in emergency and parking modes see the brake system powered by the blue system [15].

2.3 Hydraulic System

Hydraulic Power System is among the Distribution Power Systems. Currently, this system is used for the on-board systems that need high power actuation. In Figure 2.18 the main hydraulic power users are shown.

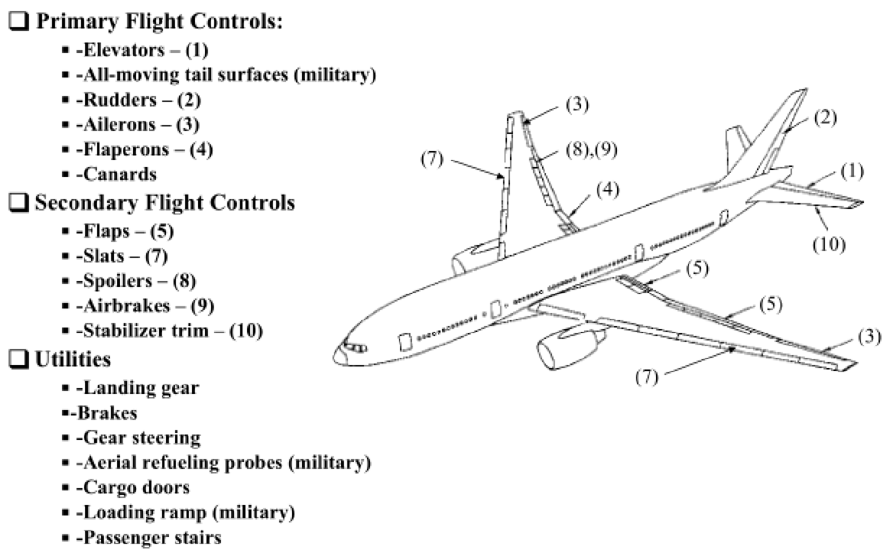


Figure 2.18: Main Hydraulic Users Schematic [8]

Usually, a hydraulic system is composed of pumps which are moved by engines, APU or RAT through gearboxes, a reservoir, a filter to keep clean fluid, a multiple redundant distribution system, pressure and temperature sensors, a mechanism for hydraulic oil cooling and a means of storing energy such as an accumulator [8]. Multiple paths with different pumps, reservoirs and pipes in a hydraulic system are necessary to permit continuous feed to the users even in case of a single failure. The degree of redundancies is regulated by specifications and mandatory regulations with many differences between civil and military aircraft.

A320

This aircraft has three operating hydraulic systems that are shown in Figure 2.19:

- Green Hydraulic System: the system is pressurized by Engine Driven Pump that is powered by Engine 1. The fluid is provided by a green reservoir;

- Yellow Hydraulic System: this system is pressurized by an Engine Driven Pump (Engine 2) and an Electric Driven Pump for ground servicing operations. The fluid is provided by a yellow reservoir;

- Blue Hydraulic System: the system is pressurized by a electric-driven pump and the RAT in emergency case.

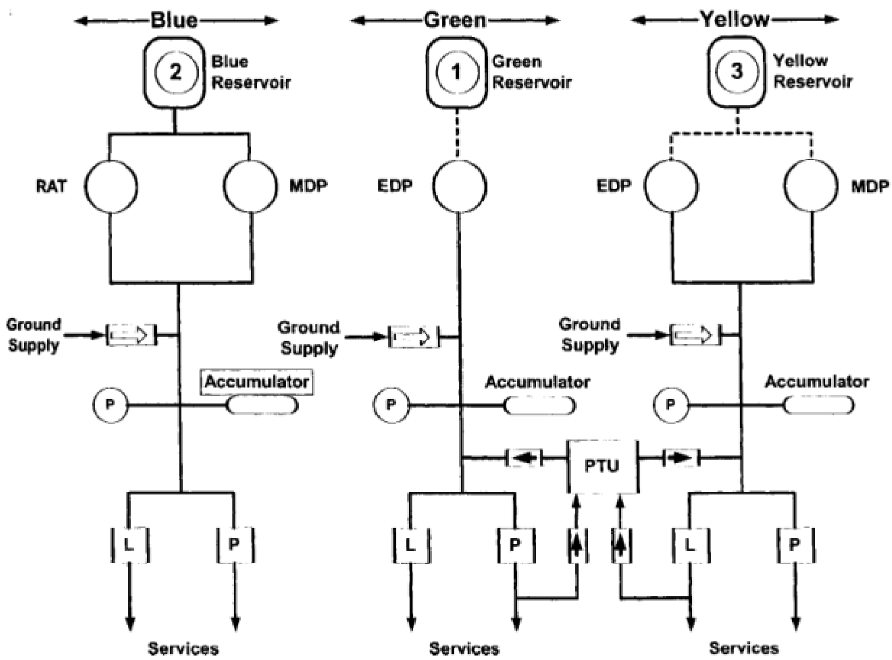


Figure 2.19: A320 Hydraulic System Schematic [8]

A bi-directional Power Transfer Unit permit Green and Yellow systems to power each other by transferring fluid when one of them fails. When the aircraft is on the ground the PTU make hydraulic power available for green users through the electric-driven pump of the yellow system. Each system has a Ground Supply channel used on ground when the engines are off, an accumulator in order to keep a steady supply of pressure during transients, a leak measurement valve and a priority valve in case of low hydraulic pressure. Each engine has a fire shut-off valve to isolate the engine from the hydraulic system. Some crucial functions are provided also by the accumulators which are used when the hydraulic lines fail and during the transients [8].

A380

A380 Hydraulic System consists of two hydraulic circuits: yellow and green systems. They are identical and independent; the power generation is provided by four engine-driven pumps (1 and 2 for the green hydraulic system, 3 and 4 for the yellow hydraulic system) and the fluid is provided by the reservoir present in each system. Two electric pumps provide hydraulic power on ground. If one or both hydraulic systems fail, hydro-electrical backups remain available for the flight control system (EHAs and EBHAs) and braking and steering (LEHGS). Valves, cooling systems and accumulators are installed in the systems in a similar way to A320 hydraulic system.

A350

Like the A380 hydraulic system, the A350 hydraulic system has green and yellow hydraulic circuit. The components contained in this system actually are the same as the A380 hydraulic system components. The only difference between these two systems concerns backups related to landing gear users: instead of LEHGS in A350 landing gear the independent hydraulic accumulators are used for braking while the Automatic Differential Braking (ADB) and the hydraulic accumulators are used for steering.

B787

B787 hydraulic system consists of three hydraulic systems: the left one and the right one have one engine-driven pump and one Electric Motor Driven Pump, the central system has three electric motor-driven pumps. B787 hydraulic system has more electric power proposal related to B777 Hydraulic Power Generation but the most important improvement brought in this aircraft is the capacity: the maximum flow of EMPs (electric motor-driven pumps) is the same as EDPs while in the B777 the maximum flow of EMPs was lower [21].

2.4 Electric Power System

Electric power systems have evolved over the years in order to provide electric power to more and bigger users. In Figure 2.20 the evolution of electric power generation is shown.

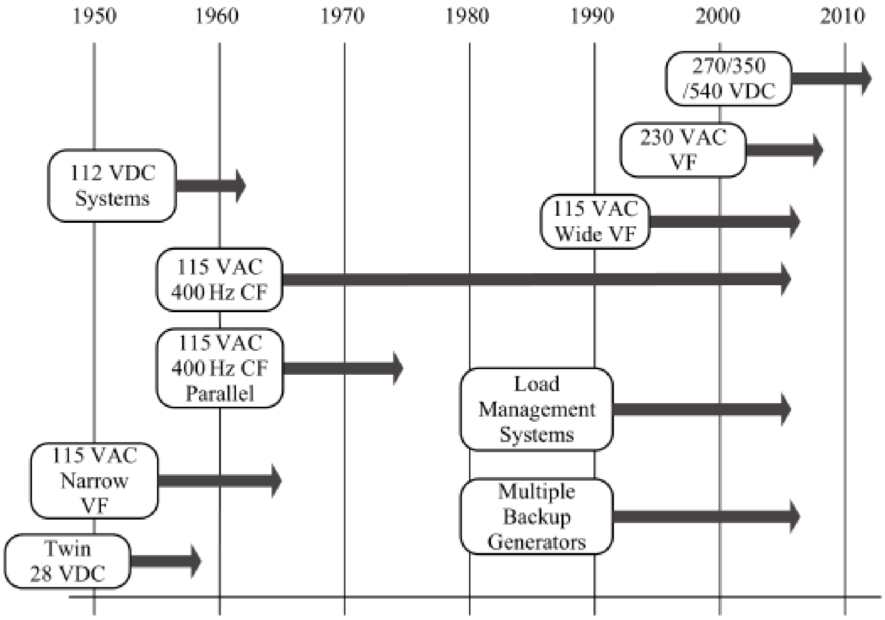


Figure 2.20: Electric System Evolution [8]

Some components have been present in almost every electric power system over the years:

- Generators: different types of generators have been developed over the years (currently present in almost every aircraft in service);
- Inverters: these devices transform DC power into AC power (usually from 28VDC to 115VAC single phase or three phases);
- Transformer Rectifier Units (TRUs): these devices transform AC power into DC power (usually from 115VAC to 28VDC single phase or three phases), TRUs dissipate a lot of heat and consequently they need air coolers;
- Auto-Transformers: they may be used for a step-up or step-down conversion from AC to AC;
- Battery Chargers: their function is to charge the aircraft battery in a controlled way;

- Batteries: they provide DC power to essential users in emergency situations.

There are some other devices: contactors, high power electromagnetic used for power switching; circuit breakers and solid state power controllers are used for load protection. Electrical power generation can be obtained through the following types:

- The Constant Frequency (CF) 115 VAC, three-phase, 400 Hz generation types. The Integrated Drive Generator (IDG), Variable Speed Constant Frequency (VSCF) Cycloconverter and DC Link options typify it;
- Variable Frequency (VF) 115 or 230 VAC, three-phase power generation (termed also Wild Frequency). Although this power generation type is a relatively inexpensive form of power generation, in some cases it can require motor controllers;
- 270 VDC systems are the military target;
- 28 VDC generated by Permanent Magnet Generators (PMGs) are used as emergency electrical power for high-integrity, systems.

The main generators used nowadays consist of Constant Frequency (CF) using an IDG, Variable Speed, Variable Speed Constant Frequency (VSCF) options. The CF/IDG is expensive to purchase and maintain mainly due to the hydro-mechanical Constant Speed Drive. VF is the simplest and more reliable form of power generation but the variable frequency could penalize the performance of some aircraft subsystems. VSCF has not been proven yet in the transport market. In this case, the frequency is electronically converted to constant frequency [8]. The power generation can be obtained through Engine Generators, APU generators and RAT generators. Some generators can be also starter generators.

B787

The following description is related to the B787 electrical power system and it´s one of the latest transport aircraft EPS. The primary generators are 230 VAC VF starter generators, two for each engine and two APU starters/generators and one RAT generator. Studies proved that the increase in voltage by a factor of 2:1 affects positively the electrical distribution system by decreasing the feeder losses and allowing significant wiring reduction. Electrical power is also converted into 115 VAC by ATU, 28 VDC by ATRU and 270 VDC to feed with the appropriate voltage and ampere all the subsystems that need electrical power. EPS of B787is left-right symmetric: on each side are present 2 230 VAC busbars, 2 270 VDC bus bars, 1 115 VAC bus bar and 1 28 VDC bus bar (fig 2.21) [22].

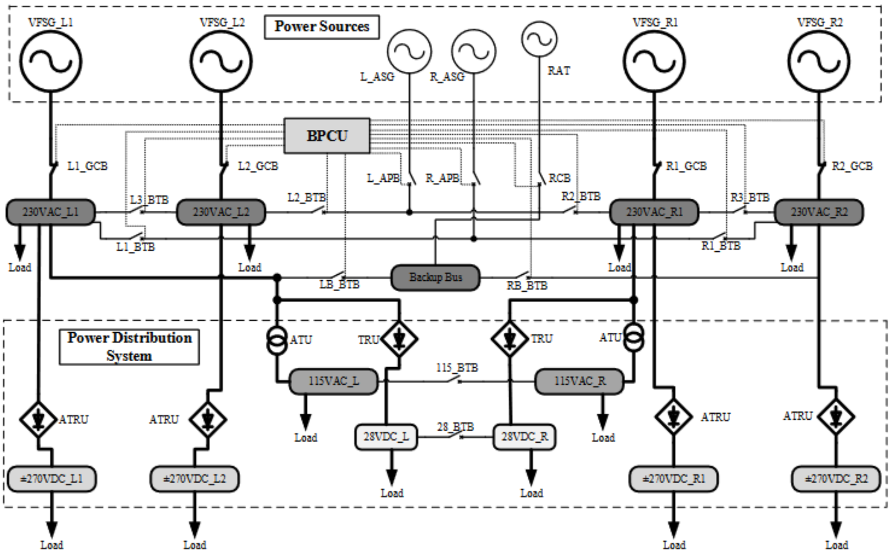


Figure 2.21: B787 Electric Power System [22]

2.5 Environmental Control System

Different typologies of ECS have been developed over the years by various aircraft manufacturers. The main functions of ECS are:

- To keep proper pressure and temperature levels within the cabin and systems compartments;
- To keep proper humidity levels and air chemical composition within the cabin

In the case of small aircraft, the cabin is not pressurized: the ECS will have open loop cycles. In not pressurized cabin, ECS has a simple venting system capable of regulating temperature within a limited range. Venting is provided by ram air intakes on the fuselage or venting. It is possible to heat through the air coming from the engine shroud. In a pressurized cabin, the aircraft would have to manage a high level of structural load if in cruise sea level pressure is kept. Consequently, the cabin simulates an ascent up to 2500 m while temperature is maintained within the range 18°C-25°C. A short description of all the different pressurized aircraft ECS is done in this section.
The first subsystem is the Bleed Air System whose functions are to take the air directly from the atmosphere and to provide it at high pressure and temperature to the Air Conditioning System. Usually, the air is bled from the engine and in case of failure, it can be extracted from the APU. On ground the air is provided by a high pressure ground connection.

Lately the bleedless configuration is a growing concept but for now this concept has been adopted only for Boeing B787. The Air Conditioning Systems conditions the air that comes from the Bleed Air Systems and delivers it to the cabin. The subsystem itself can be divided in: Air Conditioning Packs, Mix Manifold, Recirculation System, Air Distribution System and Ram Air System. A focus on the different Air Conditioning Packs adopted over the years follows. Figure 2.23a shows the Simple Air Cycle: the air directly goes through the heat exchanger and then to the turbine. This concept has been adopted only on Fokker 100 due to its high inefficiency. In Figure 2.23b the Two Wheel Bootstrap Cycle is shown: a compressor is present before the heat exchanger in this case but a ground fan is also present to fulfill the ram air generation on-ground.

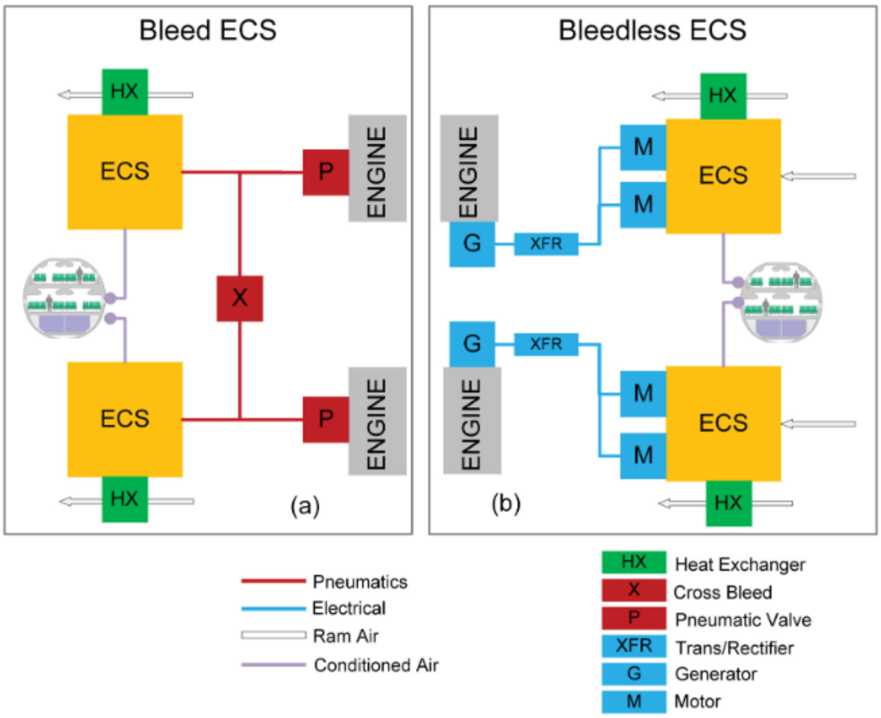


Figure 2.22: Bleed and Bleedless configuration [23]

The ground fan is transferred on the turbine and compressor shaft in the Three Wheel Bootstrap Cycle while a second turbine is introduced in the Four Wheel Bootstrap Cycle. In conditions of high percentage of humidity, the air could freeze. This is why two solutions: low pressure bootstrap cycle (non-subfreezing) which uses a water extractor after the turbine and this restricts the minimum temperature in the turbine to 2 or 3 degrees; high pressure bootstrap cycle (or subfreezing) has a water extractor before the turbine that makes the cycle more efficient thanks to the possibility for the turbine to reach lower temperatures [12].

A open loop cycles pressurized cabin is usually linked to pneumatic system (but can be also bleedless) where the ECS takes high-pressure and high-temperature air. The Cold Air Unit (CAU) regulates air flow according to the cabin requirements and an outflow valve regulates the air to be discharged while the relief valves balance the inside and outside pressures. The closed loop cycles recycle cabin air through filters. Compressors are used to fill cabin with new air while vapour cycle CAU regulates temperature.

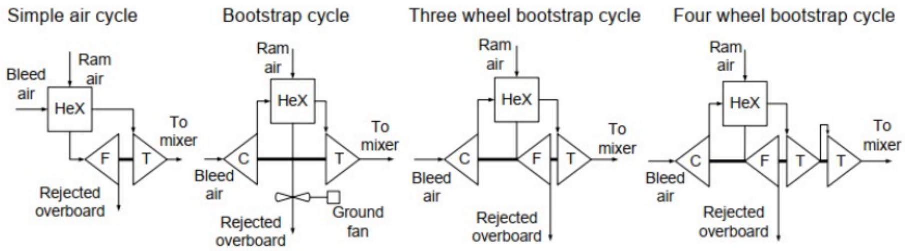


Figure 2.23: Air Packs [24]

2.6 Ice Protection System

Ice Protection and De-Icing systems are fundamental to permit the proper functioning of the aircraft and all its systems. Generally, there are three different powering forms for IPS: pneumatic system, electric system and direct engine bleed. Chemical de-icing systems are also used but they have a negative environmental impact. Thermal anti-icing and de-icing systems have been adopted but the amount of air bled from the engine is very high while an electro-thermal solution needs a large amount of energy. Mechanical de-icing systems are used and these systems are commonly powered by electric or pneumatic systems. The usage of the pneumatic system has a negative impact on the aerodynamic performance [25].
More specifically, Electro-Mechanical Expulsion De-icing System (EMEDS) is one of the concept: in this case, electromechanical actuators are moved through electric impulse and their movement causes high frequencies that detach the accumulated ice from the surface interested [26]. Electro-Impulse De-icing System (EIDS) destroys ice accumulation through rapid deflection of the skin surfaces: electromagnetic forces are created using coils slightly separated from the surface. The current induces eddy currents on the surface that are repulsive to the coil current and thus the surface deflects [27]. Electro-Thermal IPS (ETDS) is based on the concept of heating the surface through electrical energy in order to keep the surface temperature above freezing temperature. ETDS is a high-level power consumption concept with also the problem related to the runback icing. Pulse

Electro-Thermal De-Icing System (PETDS) decrease the demanding power of the system by dividing the elements into parting strips and shedding zones: the parting strips are energized with constant power density while the shedding zones receive periodic short impulse of power. Thermo-Mechanical Expulsion De-icing System (TMEDS) is a combination of EMEDS and PETDS mounting the heater of PETDS in the stagnation zone and the actuators of EMEDS to chordwise ribs: firstly the heater reduces the ice adhesion on the surface and then the actuators remove all the ice [27]. Nowadays, the state of the art for the Ice Protection Systems can be resumed as follows:

- For wing, horizontal and vertical tails protection: bleed air, pneumatic de-icing boots(via bleeding or dedicated compressor), Electro-Impulse (EIDS), fluid de-icing (passive de-icing, ice-phobic coating), Electro-Thermal(ETDS), Pulse Electro-Thermal (PETDS), Electro-Mechanical (EMEDS), Thermo-Mechanical (TMEDS);

- For engine nacelle protection: bleed Air, pneumatic de-icing boots(via bleeding or dedicated compressor), fluid de-icing (passive de-icing, ice-phobic coating), Electro-Thermal(ETDS) and Electro-Mechanical(EMEDS);

2.7 Pneumatic System

A short description of the pneumatic system follows as has been highlighted its use in the previous sections. High pressure air is bled from the engine to be transferred at the correct pressure to all the users while for the engine starting is commonly adopted the medium-pressure bleed air either using air from a ground power unit (GPU), APU or cross-bled from another engine. The Pneumatic System present in conventional aircraft usually fulfills the following functions:

- Cabin pressurization and Environmental Control Systems;

- Anti-ice protection for wing and engine;

- auxiliary functions like hydraulic reservoirs pressurization, hot air providing for rain dispersal from the aircraft windscreen, water and waste system pressurization;

- Data indicators are mostly based on pneumatic principles.

The pneumatic system is composed of: air pumps, pneumatics safety systems, valves, filters and regulators.

2.8 More Electric Aircraft

Climate change and the need for an alternative form of power to the fossil one in every industry is pushing also the aviation industry towards a more environmentally friendly development of transport aircraft. Recent studies have been done to understand how it is possible to change the primary power generation (in other words the engines) towards a carbon net zero emissions. Some challenges and new concepts have started over the last decades for on-board systems. A More Electric Aircraft (MEA) is an aircraft where electric power is used to feed on-board systems or subsystems at present fed by hydraulics and or pneumatic. MEA is an evolving concept because of the technology evolution: some MEAs introduced over the last years could become conventional aircraft if all the aircraft manufacturers move in that direction. An All-Electric Aircraft (AEA) is the most difficult challenge for a transport aircraft. In this case, all on-board systems are powered by Electric Power System (EPS): this is the way the AEA concept is intended conventionally but a totally AEA concept needs also an electrically powered engine or hydrogen-powered one. Another goal pursued by the aviation industry consists of the development of a main shaft engine integrated starter-generator that could make possible less fuel consumption as a consequence of the drag penalty due to the accessory gearbox currently connected to the starter-generators. The improvement in technology makes it almost impossible for now to have commercial transport aircraft with an AEA concept because of the big amount of electric power needed while small aircraft like the new concepts named Air Taxis, in a bigger context called Urban Air Mobility (UAM), can: many startups and companies are working on the certification of their electric small aircraft that can host a few people (usually not more than 10-12 people) for a very short range flight between two close cities or places (about 100 km).

Since the work concerns commercial transport aircraft systems, in this section the focus will be on the development of on-board systems powered mostly by the EPS. The first aircraft built in history were almost all developed with electric powered on-board systems. The increase in aircraft weight and size for transport purposes asked for a change in the powering: the development of hydraulic systems made it possible to build bigger aircraft with good performance [28]. This caused a change of direction towards a greater development of hydraulic systems rather than electric ones in the world of aviation.

The usage of MEA concepts on military aircraft showed some benefits in fuel savings according to some studies: the introduction of the electric actuation would have had between 0.5-1% benefit while an electric-powered air conditioning could save over 3% of fuel [28]. A full AEA/AEE concept predicted over 7% of fuel savings. Aircraft weight is another characteristic that can widely affect performance. Real changes in aircraft weight due to the introduction of electric actuation have to be studied. It is known that EHA´s weight is around twice the HSA´s weight while EMA´s weight is around 1.6 the HSA´s weight [28]. A deeper knowledge of overall weight change can be achieved by studying also the distribution system weight change due to the electric transition of these systems. Pipelines and hydraulic motors are replaced by electric motors and electric lines. Current trends for MEA expect the removal of an IDG in case of AC generation: this lead to a higher system power density. Afterwards, the power is transformed into a high-voltage DC. A high-voltage distribution system with a consequent lower current allows to reduce the cable weight. Furthermore, in DC systems there is no reactive power or skin effect [29]. A Regional AEA would be overall heavier and more fuel efficient due to the lack of hydraulic and pneumatic system [30]. EMAs and EHAs also need a power converter and a control system that must be designed with fault-tolerant capabilities as it is currently in the HSAs: power converters are usually designed using a redundancy approach while electric motors are designed to make themselves fault tolerant [29]. EMAs could be controlled by the motor but jamming issues in an EMA could be critical for a primary flight control surface: in order to use more EMAs benign failure mode must be guaranteed [31]. Electric regeneration from electric actuators should be studied to improve the effectiveness of MEA/AEA [29]. In Figure 2.24 the conventional schematic and the MEA 1 schematic are shown. This kind of MEA concept replaces the hydraulic system by feeding FCS, Landing Gear, Brakes and Steering Systems through the Electric Power System. The Pneumatic System has the same functions as in the conventional concept.

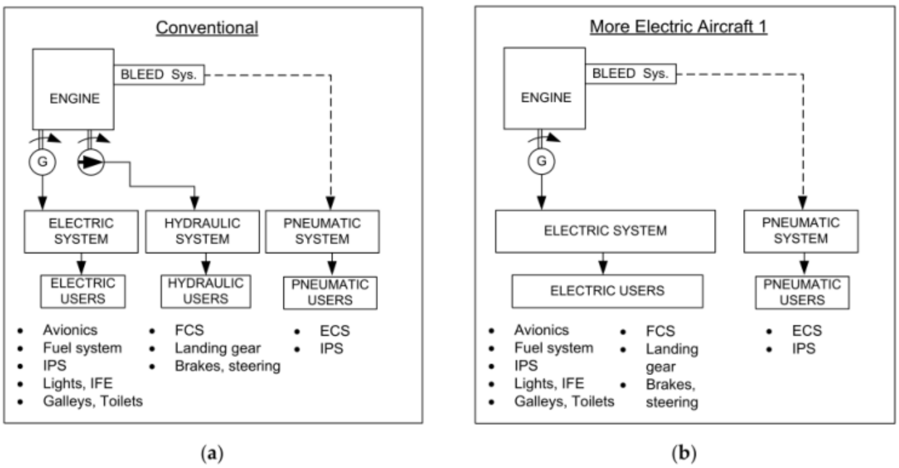


Figure 2.24: (a) Conventional Schematic; (b) MEA 1 Schematic [32]

In fig. 2.25 on the left the MEA2 concept is shown: in this concept, the power generation is electric and consequently there is no need for an engine bleed system

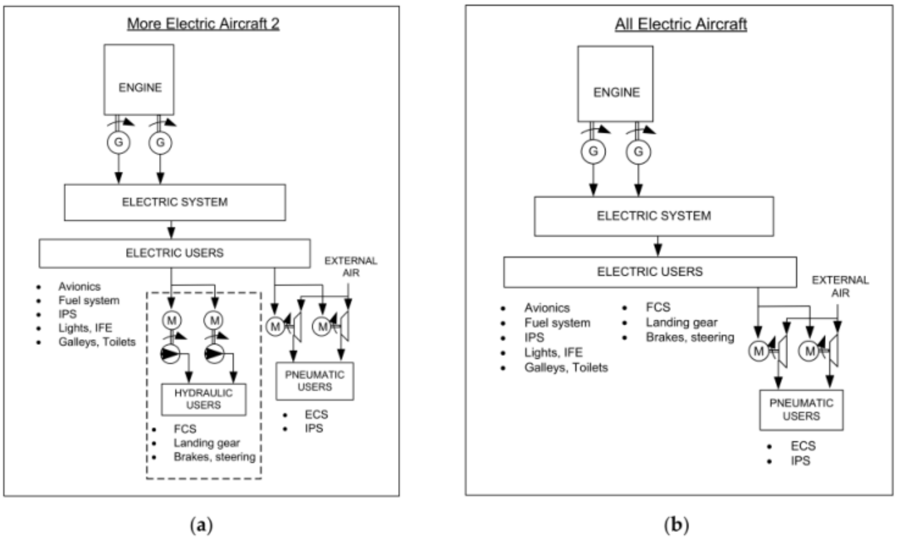
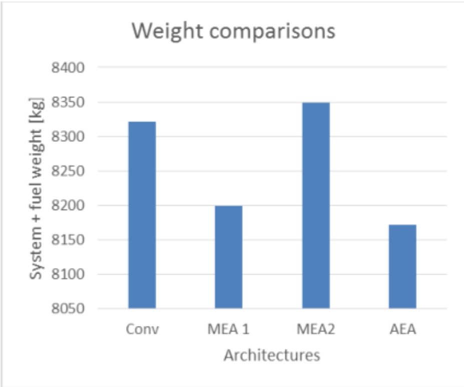


Figure 2.25: (a) MEA 2 Schematic; (b) AEA Schematic [32]

while are necessary electric-motor driven pumps to move hydraulically FCS, Landing Gear, Brake and Steering Systems. The pneumatic users (ECS and IPS) are fed by centrifugal compressors powered by an electric system. On the right of Figure 2.25 the AEA is shown: as in the MEA2 there is not the Engine Bleed System and the pneumatic users are fed by electrically powered centrifugal compressors but in this case, FCS, Landing Gear, Brakes and Steering Systems are fed directly by Electric System as in MEA1. Definitely, in case of electric to hydraulic conversion turbo-compressors are needed; in case of electric to pneumatic conversion electric motor driven pump are needed
Flight Control System has very different load requirements that can go from a few KW for the edge slats up to 50-60 KW for the rudder and horizontal stabilizer [29]. It is understandable that is not possible a direct skip from a Conventional Architecture to an All Electric one: this change concerns a lot about aircraft safety and reliability and optimisation of the aircraft's performance that is related to the current technologies. These are the reason why the latest aircraft built have some More Electric features and the manufacturers are following a step-by-step philosophy.
Some studies have been conducted over the years analysing various characteristics and optimisation variables. One of these has been conducted to investigate the overall costs of every possible architecture on a regional aircraft: the cheapest choices in all the architectures resulted being the ones with a bleedless configuration that allows a massive save of fuel although they have higher acquisition costs. The operating cost is strongly affected by pneumatic system technology;

the on-board system procurement cost is related to FCS actuators technologies. Focusing on weight assessment, FCS actuator technologies play a primary role in the overall onboard systems' weight. Not only high voltage power generation could reduce the system's weight but also high-pressure power generation. The bleedless configuration weighs more but there is less fuel consumption [30]. The results of this study are shown in the Figure 2.26.



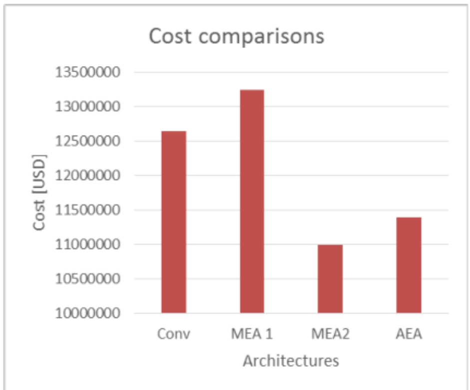


Figure 2.26: Weight and Cost comparison of four on-board systems architectures on a Regional Aircraft [30]

It is possible to see that AEA architecture is the lightest one if we evaluate systems and fuel weight while MEA2 is the cheapest architecture. Conventional and MEA2 are the heaviest ones due to the presence of the hydraulic system even with a weight save related to the usage of HSAs. MEA2 and AEA architectures save weight thanks to the removal of the hydraulic system which is opposed by the increment of electrical power generation; in these aircraft the bleedless configuration makes the aircraft more efficient due to the fuel save. This also produces another effect which is the less fuel required that consequently reduces the operating cost. On the other hand, the conventional and MEA1 require more fuel while having a reduced acquisition cost [30]. Another study has been conducted for the electrification of a small regional aircraft: in this case, the lighter architecture in terms of MTOM was the MEA1, followed by MEA2 and AEA. MTOM and OBS systems are not directly related to each other as shown from this study: considering MTOM, MEA2 achieves only half of the mass saving of MEA1 and AEA. It is clear that the MTOM depends also on the aircraft mission duration due to the fuel consumption: MTOM changes are affected by the size and mission types of the study-case aircraft [32]. Another analysis conducted on small regional aircraft showed that the maximum OBS electrification level does not equal the maximum MTOM reduction due to the introduction of bleedless technologies [33]. Following a More Electric Aircraft, electric power needed will increase. Technology improvement in this field will play

a primary role and the power density target go from 10 KW/kg (short term) to 50 KW/kg (long term) [31].
Last decades have seen some aircraft manufacturers design new configurations to make the aircraft more electric and some examples are shown in the next paragraphs.

2.8.1 MEA architecture: A380 FCS

Airbus made some changes to the FCS architecture that before the introduction of A380 was fully hydraulically actuated. As shown in Figure 2.27, two AC Busbar and one AC emergency busbar. These busbars feed EHAs and EBHAs: EHAs are present on the inboard and middle ailerons and all the elevator surfaces which have an actuator redundancy composed of HSAs and EHAs; spoilers 5 and 6 are actuated by an EBHAs which is formally an internal redundancy. Rudder surfaces are actuated by EBHAs with a mixed redundancy: EBHAs make it possible to have an internal redundancy but every surface has two EBHAs and consequentially there is also an actuator redundancy. The actuator redundancy is also present on the THS with two HSA and one EMA. A380 high lift device system is a hybrid system with both electrical and hydraulic motors, as shown in Figure 2.28

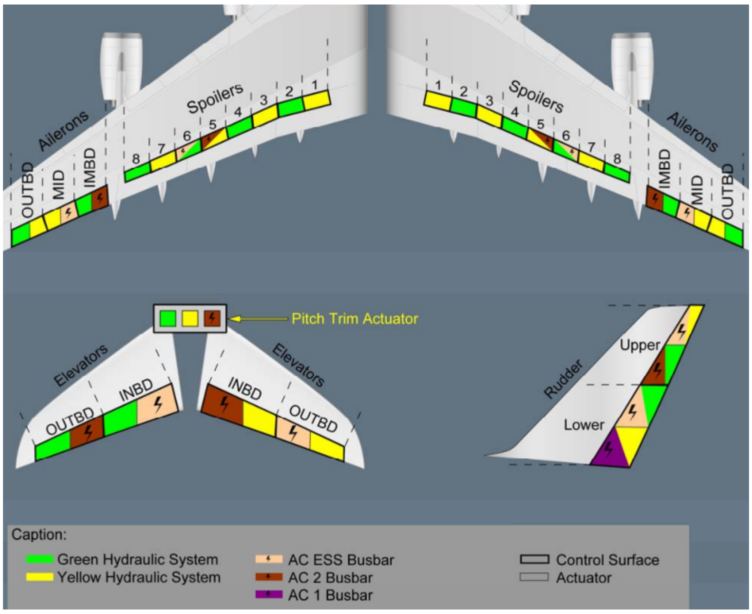


Figure 2.27: A380 Flight Control System schematic

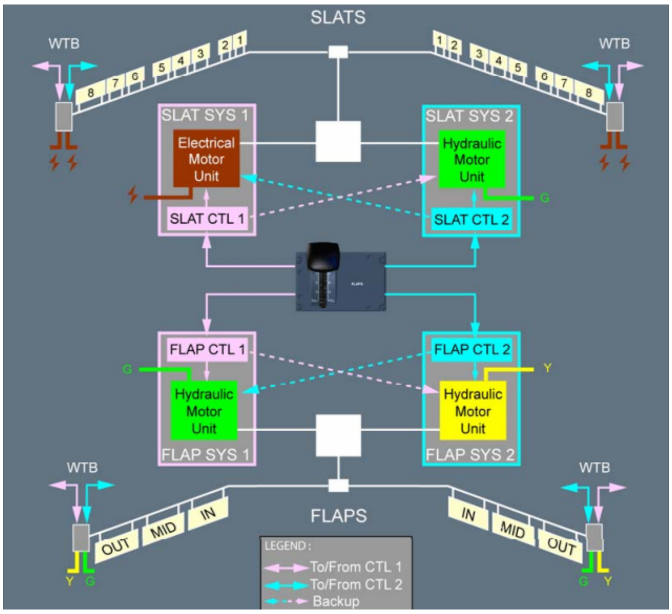


Figure 2.28: A380 High Lift Device System schematic

2.8.2 MEA architecture: A350 FCS

A350 FCS is really similar to the A380 one, the main difference is related to the number of control surfaces because of the different sizes of the two aircraft: the inboard ailerons have actuator redundancy, one EHA and one HSA actuate each surface. One spoiler surface per wing has an internal redundancy through the usage of EBHA.

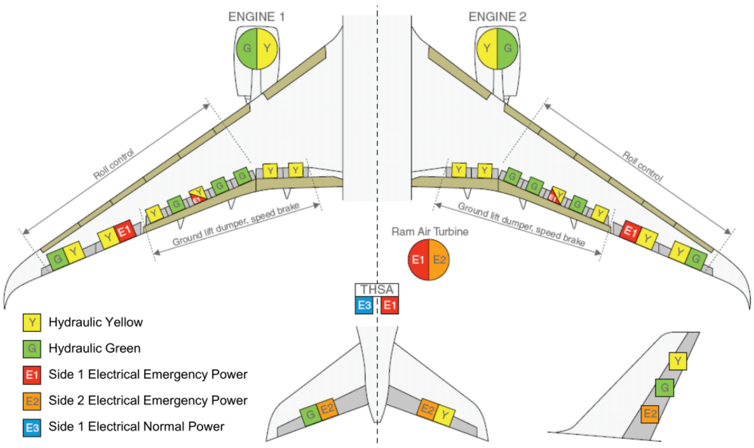


Figure 2.29: A350 Flight Control System schematic

Two elevator surfaces have the same properties of inboard aileron surfaces while the rudder has only one control surface that can be moved by two HSAs and one EHA. THS is moved by two EMAs.

2.8.3 MEA architecture: B787

B787 has introduced some suggestive innovations which will be briefly explained: the Electric Brake System and the Bleedless Systems The introduction of bleedless systems reduced fuel burned of about 3 percent and brought some advantages in terms of maintenance and reliability. In this architecture, the cabin pressurization is provided by electrically driven compressors while the fresh air is brought onboard via dedicated cabin air inlets: these inlets are not present in conventional architectures and consequently this introduction brings an increase of the aircraft drag. Air pressure is adjusted via the compressors while the engine design is much more simple due to the removal of pneumatic system, pre-coolers, control valves and required pneumatic ducting. Unlike the conventional pneumatic systems which develop more power than is needed in most conditions, electric system produces only enough power as needed. B787 also uses an electro-thermal ice protection scheme which consists of heating blankets for wing de-icing protection while engine bleed is present only for engine cowl ice protection and pressurization of hydraulic reservoirs. This aircraft also introduced the electric brake system: the hydraulic actuator, oil and brake piston are respectively replaced by electric actuator, electric field in working medium and EMA. Hydraulic pipelines are replaced by wires and HSA are replaced by motor driver [34].

2.9 On-Board Systems Reliability

The reliability of aircraft systems is a critical study for evaluating the feasibility of a new architecture or the introduction of new technological advancements within the same architecture. RAMS analysis holds fundamental importance in the preliminary design of aircraft. Reliability, described as "the ability of an item to operate under designated operating conditions for a designated period of time or number of cycles" [35], can be assessed through either a probabilistic approach or a deterministic approach. The deterministic approach is intended to be used to understand the reasons for failures through in-depth studies aimed at identifying and preventing failures by conducting tests, analyses, and reviews of field failure reports. The probabilistic approach takes into account the probability of failure of the item during its life-cycle in designated operating conditions. The concept of Availability is strictly related to the Reliability concept: the availability analysis verifies that an item has a satisfactory probability of being operational and can be seen as combination of an item's reliability and maintainability. The mathematical explanation of availability is defined by the fraction of the operating condition time in relation to total time [35].

2.9.1 Probability of Failure of single component

The probabilistic approach was chosen for this work. In order to obtain the probabilistic trend of a system during its life-cycle, the probability of failure of the single component and its match with the other components in the system is needed. Different probability theories have been created over the years and many mathematical functions to describe these trends. Weibull distribution, Exponential distribution, Gaussian distribution and log-normal distribution are the most common theories used to describe the failure rates of a component over is life-cycle. Combination of these theories or combinations of different parameters of the same theories have been used to create more complex rates models, like the bathtub curve. In the Figure 2.30 the most common models are shown.

Wear-out characteristic			Prevalence among aircraft components	Best mathematical model	Alternate possible models
A		Bathtub curve	4%	3 Weibull distributions	
B		"Pronounced wear-out region"	2%	Weibull	
C		"Gradually increasing"	5%	Weibull with extended tail	
D		"Low... followed by a quick increase"	7%	Weibull	
E		"Constant probability of failure"	14%	Exponential	Weibull with $\beta = 1$
F		"Infant mortality"	68%	Weibull	
G		Pronounced wear-out region characterized by fatigue life	Most structural components	Weibull	Lognormal, but very similar to Weibull

Figure 2.30: Common failure rates model [36]

The infant mortality model presents a trend that takes into account the built-in region, where more failures are possible mostly due to the errors in manufacturing or mounting the items in the system: this model can be described through the Weibull theory with the shape parameter under the unity value. The Low rate built-in region followed by a quick increase, described through Weibull with a value over the unity, is a more accurate model when the component manufacturing and mounting is well studied and defined over the years. The constant probability of failure is really common in case of high uncertainty on the failure rate of the item and can be described by the exponential model or Weibull defined with the unity value for the shape parameter. The combination of 3 different shape parameters in the Weibull distribution defines the Bathtub Curve: the built in is described as in the infant mortality curve, the region in the middle is described as in the constant probability of failure curve and the wear-out zone is described with the shape parameter bigger than the unity. A pronounced wear-out zone is very common for structural components.

Some concepts are used to describe well a component probability of failure over the time: failure or hazard rate, probability density function (PDF), cumulative density function (CDF). The reliability of the component over the time is then described by a function that is the complementary function of the CDF. For instance, hazard rate, PDF, CDF and reliability function in the Weibull model are shown:

$$f(t) = \frac{\beta}{\eta}(\frac{t}{\eta})^{\beta-1} \exp(-\frac{t}{\eta})^{\beta} \tag{2.1}$$

$$F(t) = \int_0^t f(t)dt \tag{2.2}$$

$$R(t) = 1 - F(t) \tag{2.3}$$

$$h(t) = \frac{\beta}{\eta}(\frac{t}{\eta})^{\beta-1} \tag{2.4}$$

f(t) is the probability density function (PDF), F(t) is the cumulative density function (CDF), R(t) is the reliability function and h(t) is the hazard rate (or failure rate) function. The definition of F(t) and R(t) is the same for every probability distribution chosen. The probability density function represents the failure statistical distribution over the time; the cumulative density function is obtained by integrating over the time the PDF; the reliability is strictly related to the CDF since the CDF represents the cumulative probability of failure over the time while the reliability function define the probability that a system performs a required function under given conditions for a given time interval β is the shape parameter while η is the scale parameter; t represents the time in hour. In Figure 2.31 the different PDF and Failure Rate depending on different shape parameters are shown. As it was described before, the exponential distribution is described by $\beta = 1$, and the related failure rate is constant. Generally, the exponential distribution describes random failures of an item. This distribution describes also the MTBF (Mean Time Between Failures) as the reciprocal of the failure rate

The analysis of the reliability of each component must be integrated in the system analysis. Different Reliability prediction methods have been developed over the years, empirical methods are used to estimate failure rates of components in different operating conditions through corrective coefficients applied on the failure rates known for specific conditions. Part Stress Analysis method and Parts count method are the most used model for estimate the reliability of electronic component: the first one is meant to be used in the late stages since a big amount of data is necessary, the second one is a simplified model useful in the early stages.

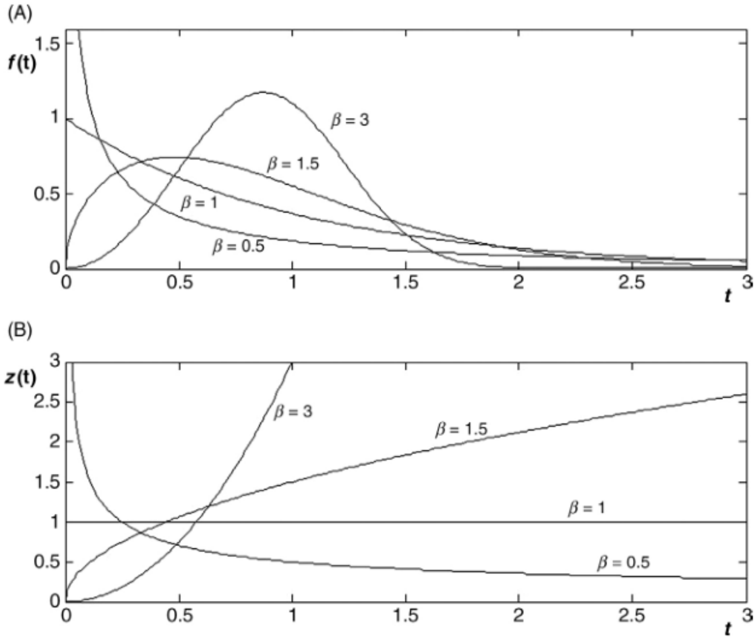


Figure 2.31: Weibull distribution with different shape numbers: (A) Probability Density Function, (B) Failure Rate [37]

2.9.2 Reliability Block Diagram

System Reliability Estimation can be fulfilled through Reliability Block Diagrams (RBD). The RBD represents the logical relations between components included in a system. Different logical connection can be used to describe the system reliability: series, parallel, Bayes and Active-Standby network.
A series network means that the system works properly if all the blocks work (Figure 2.32). The reliability of a series network is described by the following formula:

$$R_S = \prod_{i=1}^{n} R_i \tag{2.5}$$

The reliability of a parallel network (Figure 2.33) is necessary when redundancies

Figure 2.32: Series network [37]

are present and is used to study safety and mission reliability:

$$R_S = 1 - \prod_{i=1}^{n}(1 - R_i) \tag{2.6}$$

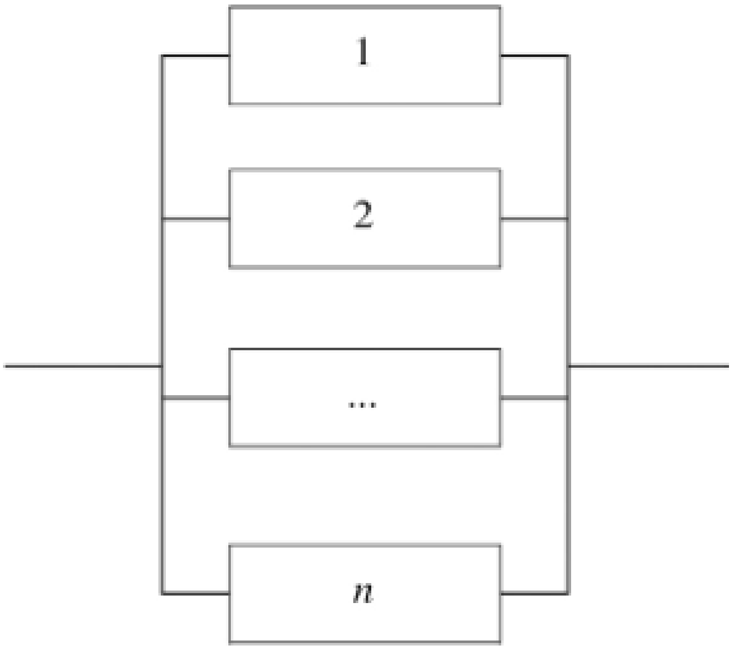


Figure 2.33: Parallel network [37]

Bayes models are used when some logical connections cannot be described by neither series nor parallel network. Another model is the m-out-of-n model where m elements out of n elements are operating:

$$R_S = 1 - \sum_{i=m}^{n}[\binom{n}{i} {R_c}^i (1 - R_c)^{n-i}] \tag{2.7}$$

Stand-by redundancy (Figure 2.34) is a logical concept present in the FCS where one or more components do not operate on the system but are used when the primary component fails. There are three different concepts for stand-by components [38]:

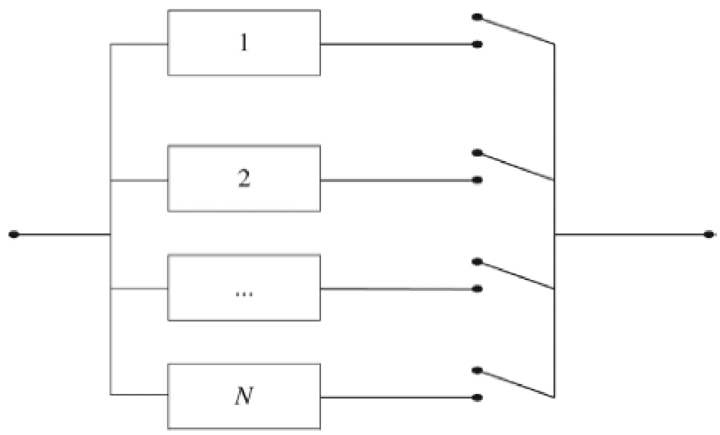


Figure 2.34: Parallel network with active and standby components [37]

- Hot Stand-by: the component is working and has the same probability of failure but is not used for its function;
- Cold Stand-By: the component does not work until the active component fails, the probability of failure are zero until that moment;
- Warm Stand-by: the component is ready for the switch and working but not at the same level of the active one, the probability of failure is less than the active component.

Last model can be described in this way:

$$F(t) = \begin{cases} F(\gamma(t)), 0 < t <= \tau \\ F(t - \tau + \gamma(\tau)), t > \tau \end{cases} \tag{2.8}$$

In this case τ is the switching time, it indicates the moment when the active component fails and the standby component is switched; γ is the aging factor that is multiplied with the time to change the probability trend of the component in warm standby.

2.10 Science Gaps & Research Questions

New solutions have been designed in the last years also thanks to the innovative electric technologies introduced and some benefits have been shown. An electric brake system has a higher reactivity in the response and fewer maintenance needs than a hydraulic system; a more electric FCS could bring benefits in maintenance tasks and in terms of weight if the electric generation and distribution are designed in a proper way; bleedless ECS and IPS could save a lot of fuel. If the direction decided is the one that sees in the future all electric transport aircraft, it will be necessary to mix all these innovations: big changes in the electric generation and distribution system are expected and the most important thing is to achieve higher density power to allow it. The technology gap present now does not allow us to design an AEA for transport purposes. Consequently, small steps towards AEA are needed and to achieve every little step it is important to understand how much it is convenient from every possible point of view. One question on each main topic of this work are necessary. The first is about System Architecting: the estimation and evaluation of every feasible architecture has consequences on the computational cost and every possible choice increase exponentially the possible design spaces. How can be possible to find an optimum in terms of System Architectures for every case study? The second is about the reliability studies and is made of more little question: what is the impact of different failure rates model? What is the impact of the redundancy level and model of a system on its reliability? Which type of reliability is the most useful one at this stage of design?

For the overall design one last question must be defined: what is the best way to connect everything inside the same framework to perform a multi-objective optimization achieving traceability from the system architecting phase to the optimization results?

Chapter 3

Methodology

In this chapter, all the tools and methodologies exploited are explained. The work could be divided into four phases: the system architecting, the mass estimation, the reliability estimation and the optimisation phase. Different tools are used to fulfil the various needs and a few attempts have been made to reach a more accurate representation of the system studied (the aircraft and its subsystems) and to create an optimization method that could have been as efficient as possible. Actually the two phases are continuously exchanging data since every generation of the system architecting phase is involved in the multi-objective evaluation to permit the trend prevision of the algorithm used for the optimization phase. A generic flow of the work is shown in the Figure B.1.

3.1 System Architecting

The system architecting phase was fulfilled by ADORE [1], a DLR in-house tool developed in Python by Jasper Bussemaker. ADORE is a new tool under continuous development in order to give the possibility to build all the possible system architectures: during the phase of system architecting various attempts have been made to create first the most accurate model and in the end to create the most useful model for the thesis purpose taking into account in both cases the need for a limited computational cost because the overall computational cost could increase drastically in the following phase, the optimisation phase.
The Architecture Design Space Graph (ADSG) can be built only after the design space definition. The design space contains all the information to create the ADSG and all the information are contained in the elements definition and the connection between them. The elements present in the design space are the following [1]:

- Function: a function defines what a system should do when it is a boundary function. A function also can be solution-specific if induces any bias towards some fulfilment solutions otherwise, it is called solution-neutral.

- Component: a component fulfils functions and it may need functions. Different components can fulfil a function
- Concept: a concept connects a solution-neutral to a solution-specific function
- Function decomposition: by creating a function decomposition it is possible to match one function with more functions
- Non-fulfillment: this element means explicitly that is not possible to fulfil a function in the way described
- Multi-fulfilment: a multi-fulfilment means that a function can be fulfilled by multiple components
- Port: a port specifies accurately what is the pattern connection between input and output components which means components that need a function (input) and components that fulfil that function (output)
- System: a system is composed of different elements and can be instantiated for different times (defining the possible instances)

The component instances are defined in the component and system details; the Quantity of Interest (QOI) is a quantifiable input or output associated with functions or components. Every component can have attributes to whom the attribute values can be connected. It is possible to link external elements to the design space, inspect and link architecture, manually create architecture instances (helpful to test the design space) and define design problems (understandable by optimization algorithms) [39]. Different design spaces will now be described in the next paragraphs.
Different concepts have been created during the System Architecting phase. Since the software is quite new, a deep exploration of the ways to define the design space were necessary before the definition of the best concept for this work. A deep understanding of the potential of the software to relate different aircraft systems were also necessary. Three different concepts are now presented with different level of detail of description of each system: each of the concept can be useful for future works, their usefulness is based on the specific objective of each work

3.1.1 Design Concept: Single and Detailed (SaD)

The Single and Detailed concept consists of the most complete model conceived for this work. At first, it was meant to be used for this work and to be useful for future works in analog fields of interest. The model is based on the following choices:

1. All the system is held under one single main function in order to have an overview of the system
2. The power consuming (aircraft system) considered is connected to its powering systems (power generation and distribution systems)
3. It is possible to power each system through a single power system or two or more (if it is possible and realistic) power systems;
4. The presence of the ports makes it possible to know how busy is every line and how many generators are connected to each line.

The model is supposed to be very detailed but the limits behind the current development of ADORE does not permit the total implementation: the size of the model increases drastically due to the number of the possible port connections between actuators and line. For instance, even if the design space is created with half of the system components (with the hypothesis of a symmetric design for the components), 21 maximum connections for line where necessary if all the actuators were powered by the same line. After the implementation of all the pitch related functions in the FCS model was not possible to save the subsequent model development. The FCS model developed with the SaD concept shown in Figure B.2.
As it is almost impossible to read what is written in the box in Figure B.2, a more detailed explanation of the various part will follow. The next figures (Figures 3.1, 3.2, 3.3 , 3.4, 3.5) explained and related to this concept are a zoom in of the Figure B.2: the FCS first design and the two power generation and distribution systems first design are shown. The first part analysed is the definition of all the pitch functions. In Figure 3.1 it is possible to see that the pitch control is decomposed into two more functions:

- Trim Pitch Attitude: this function is fulfilled by the horizontal stabilizer which can be moved by a screw-jack driven by two or three hydraulic motor otherwise the Horizontal Stabilizer (THS) can be moved by an actuation system which can consist of one, two or three actuators. The number of actuators and hydraulic motors depends on the aircraft type and the level of redundancy related. The actuators can be EHA, EMA or HSA and it is possible every combinations of them;
- Change Pitch Attitude: the function is fulfilled by elevator that can be only moved by two or four actuators. All the options are related to the actual FCS architectures present on civil aircraft. In this case two or four actuators are meant to be intended as the total number of actuators per side, this assumption can be done thanks to the symmetry of the elevator but it is also

true that the connection to the various line can be different on the symmetric actuator. Per instance, A380 has four actuators (two per each elevator surface) per side and all the symmetric ones are connected to different lines. If the SaD concept has to be used for some future works, this must be taken into account to create an high fidelity concept.

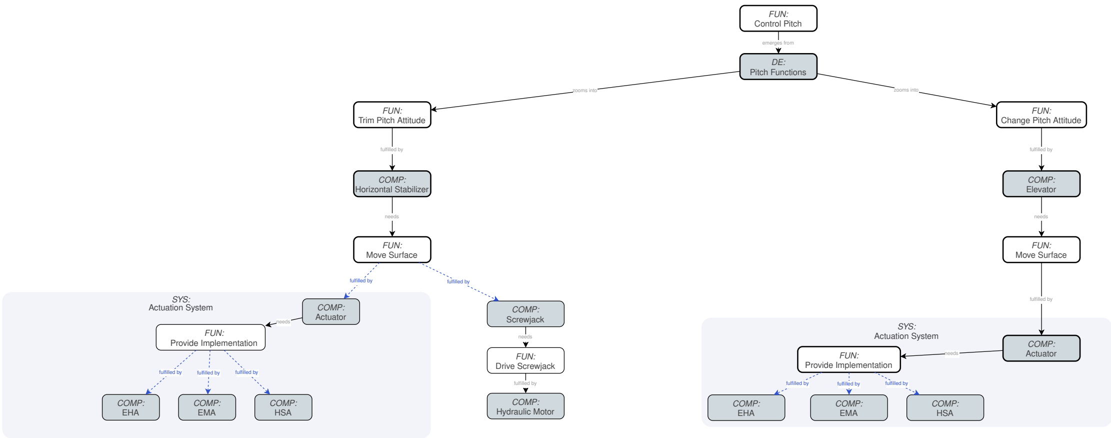


Figure 3.1: Pitch Control in FCS model, SaD concept

Of course, the model could reach the maximum accuracy by excluding the symmetric assumption but the development needed to support a certain accuracy brought the decision of include that assumption.
The second zoom into the FCS design space (SaD) is for the other control functions of the FCS (Figure 3.2) whose objective was to develop in the same way as the Pitch Control. The arrow that aims to the left is connected to the Control Pitch function.

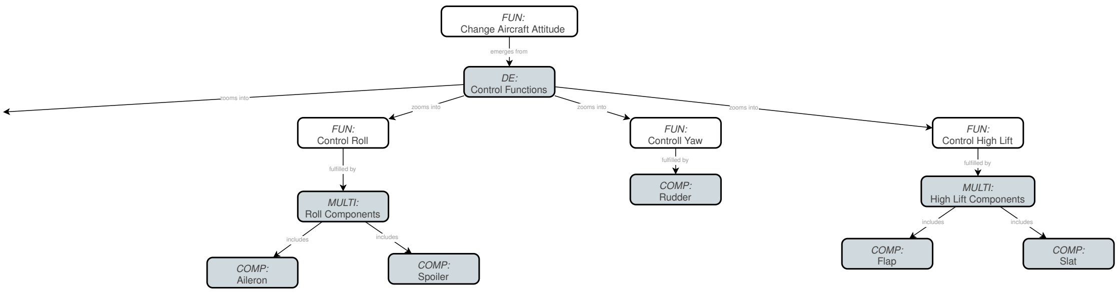


Figure 3.2: Control Functions in FCS model (except Control Pitch), SaD concept

It is possible to notice that the High Lift Device Systems are not created for this Design Space but they are designed in the last (and definitive for this work) concept: some components and functions are designed in the latest stages since the presence

of some elements was neglected for different reasons in the early stages.
All the actuators and motors are connected to the 'Provide Electric/Hydraulic Power to the Actuator' functions, fulfilled by Normal Line or the multi-fulfilment that includes Normal and Emergency Line. Figure 3.3 shows the Electric Distribution and Generation. In addition to the functions, it is now possible to see the introduction of the ports: for instance, the Normal Electric Line Port connects the electric-powered actuators (which are also the ones connected to the parallel function 'Provide...'), EHA and EMA, to the Normal Electric Line which consists of one or two possible instances. The Emergency Electric Line consists of one or two possible instances. The Lines are subsequently connected to the Generation System that consists of one Engine Generator (EG: 2,3 or 4 possible instances), one APU generator and the RAT. The RAT is connected to the emergency electric and hydraulic emergency lines. In this Distribution and Generation model, something is missed and a more accurate space design is realized in the next concept that will be described. In Figure 3.5 the Normal Electric Line Port detail is shown: every actuator that can be hypothetically present can be connected to only one line per time (dot arrows indicate it) while every line can be connected with all the actuators, giving the possibility of having all the actuators connected to the electric line if only one electric line is instantiated, this is the way chosen to design every line port (except when it is specified a different way). Actually in the literature review is possible to find actuators designed to be connected to two lines at the same time but this would have been problematic for the number of combinations obtainable and subsequently for the computational cost. The Normal Distribution System makes it possible to connect each line to one or two generators and every generator can be connected to only one line at a time. The hydraulic system has been developed in analogy to the electric power system and it is shown in Figure 3.4: the decision about the presence of a Power Transfer Unit is missing here but is created later. Some changes have been made to the ports in the newer concepts to get closer to all the aircraft models.
This concept is really good when it is necessary an accurate knowledge of all the connections between actuators, lines and generators. The all-in-one ADORE model is useful if the whole aircraft system has to be analysed. Indeed, the computational cost is high and the detail of this concept was unnecessary for this thesis's purpose.

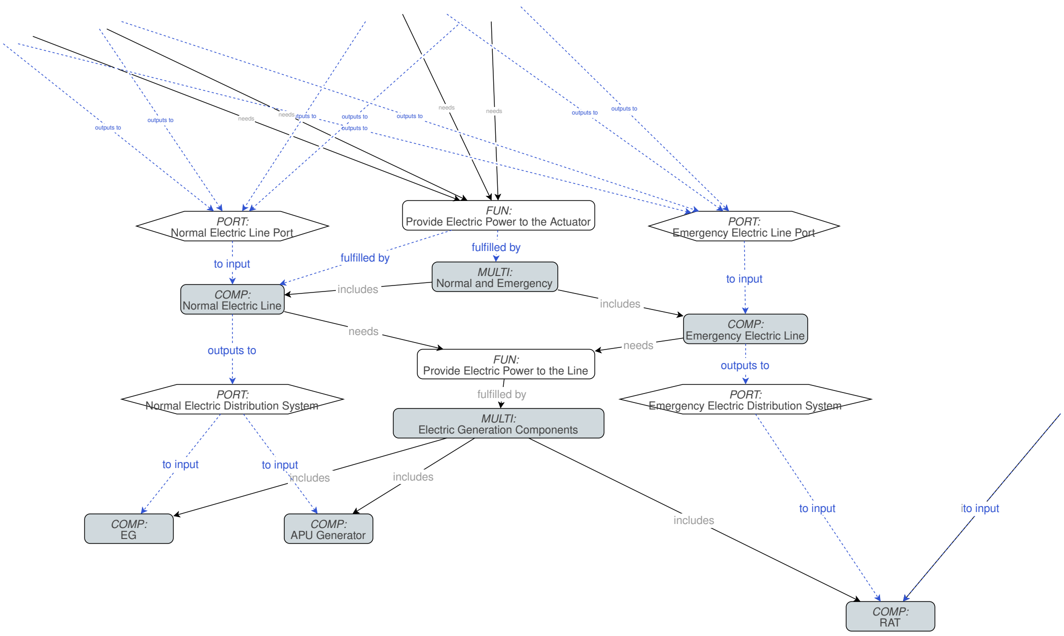


Figure 3.3: Electric Power Generation and Distribution, SaD concept

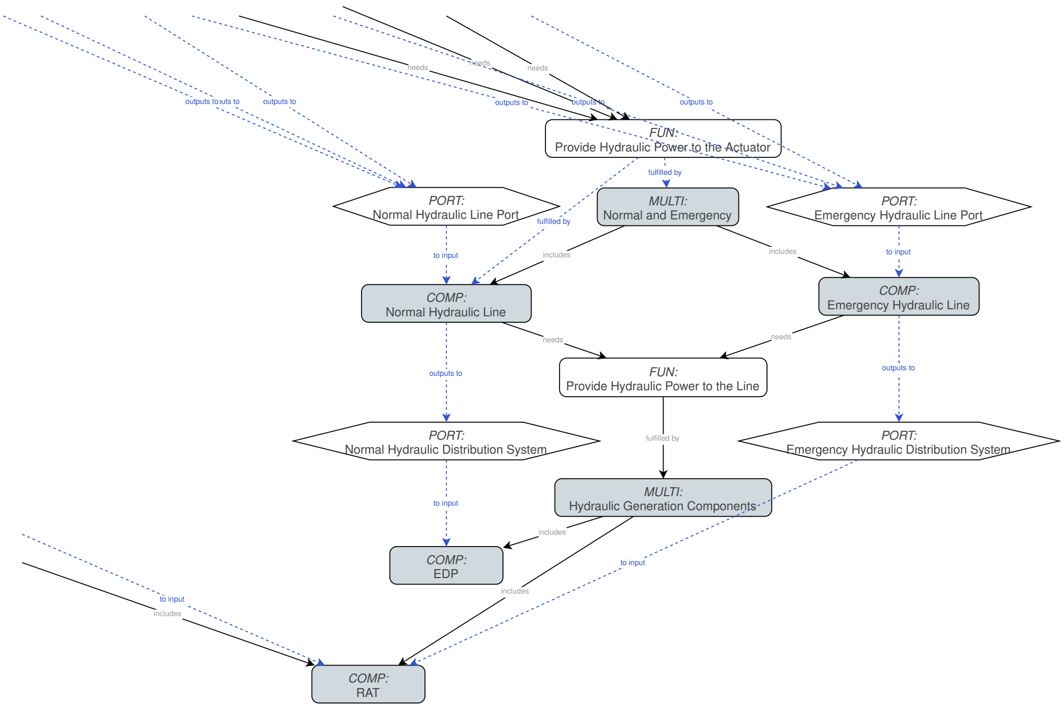


Figure 3.4: Hydraulic Power Generation and Distribution, SaD concept

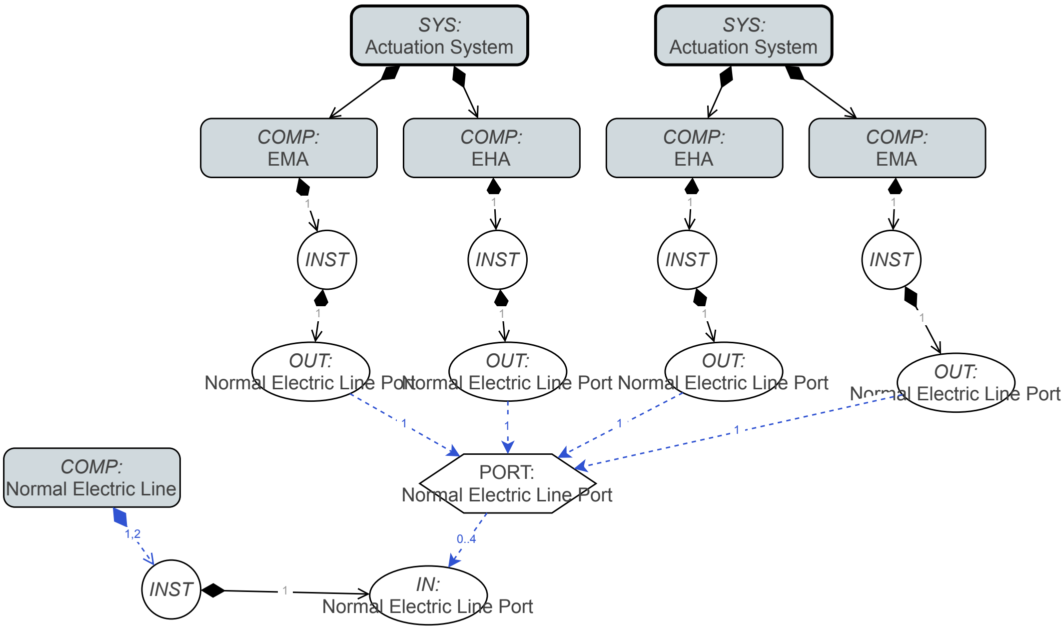


Figure 3.5: Normal Electric Line Port , SaD concept

3.1.2 Design Concept: Multiple and Detailed (MaD)

The MaD concept was created after the computational issues that the SaD concept showed. In this case, each subsystem function of an aircraft system is designed into a specific ADORE model: with this decision, it is possible to create a detailed version of every function of an aircraft system including all the possible architecture choices, also the ones related to the long-range aircraft like A380 but it is not possible to represent in one model the whole system. The cons can be seen in the difficulties of analysing and optimising the whole aircraft system: the subsystems should be analysed one per time and then an overall analysis must be conducted. Consequently, the paradox could be seen in the increasing computational cost of an overall aircraft system optimization due to the necessity of simplifying the ADORE design phase. The MaD concept can be a useful concept for the analysis of only one particular function of an aircraft system: in that case, a specific analysis can be done with a deep knowledge of the interaction between the subsystem and the power system. A description of the FCS and LGS follows in this subsection.

Flight Control System - MaD

FCS is divided into different types of control surfaces: horizontal stabilizer, elevator, aileron, spoiler and rudder. Except for the horizontal stabilizer and rudder, the other surfaces are considered symmetric to lower the computational cost due to the drastic growth of the possible decisions. For the same reason, the spoiler definition is divided into two models: the 'Inboard Spoiler' which has a constant number of 4 spoilers and the 'Outboard Spoiler' with a variable number of spoilers (1,2 or 4). The stabilizer and elevator are designed in the same way as the SaD concept, the only variation is about the actuation system (subsystem) that has been lighted thanks to further development (Figure 3.6). Some updates have been made to the electric and hydraulic systems. Concerning the electric generation system (Figure B.3), the Engine Generator is now linked to the Hydraulic System since it provides the electric power necessary to feed the Electric Motor Driven Pump. About the hydraulic system, it is possible to include in the system architecture the Power Transfer Unit (PTU) (Figure B.4).

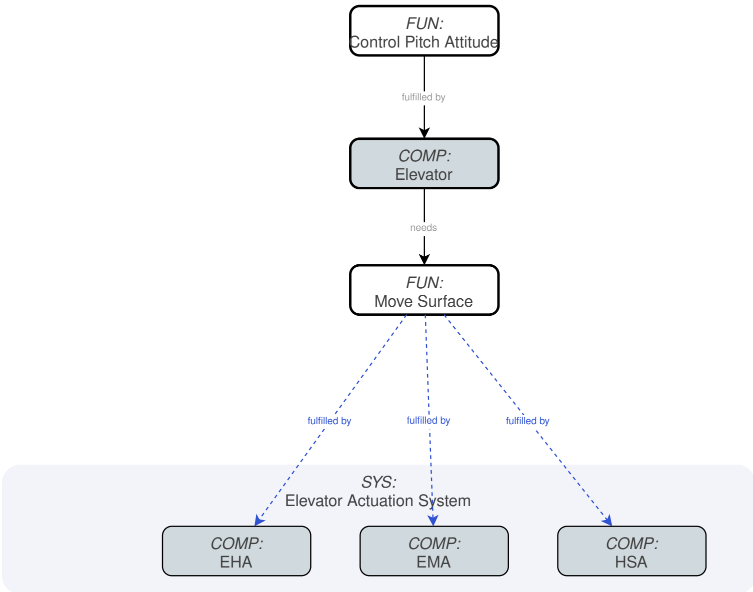


Figure 3.6: Elevator related function, MaD concept

All the control surface space designs are shown in figures 3.7, 3.8, 3.9. The Yaw Control can instantiate 2,3 or 4 actuators: 2 or 3 if only one rudder surface is present on the aircraft and 4 if the aircraft is designed with 2 rudder surfaces. The Roll Control is exploited by spoiler (previously described) and aileron: 2 (1 aileron surface) or 4 actuators (2 aileron surfaces) are present for the aileron, for the computational cost it was not possible to include the aileron architecture of A380 which is composed of 3 aileron per wing with 2 actuators per surface. Only the 'inboard spoiler' concept is shown but the outboard one differs only for the reason previously explained.

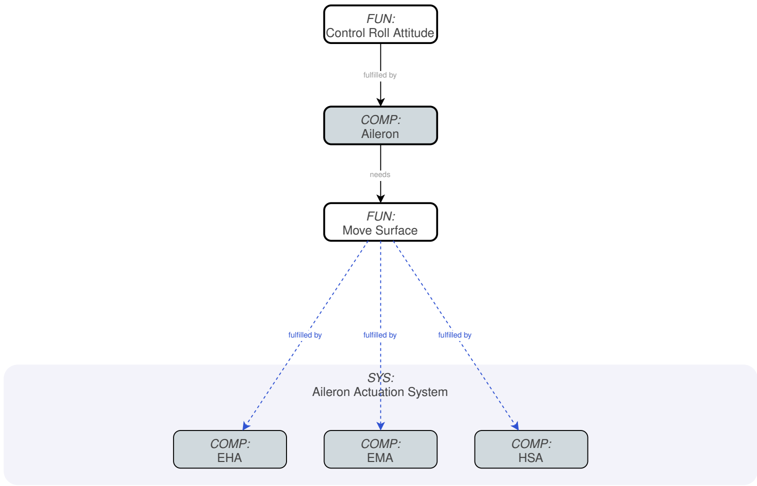


Figure 3.7: Aileron related function, MaD concept

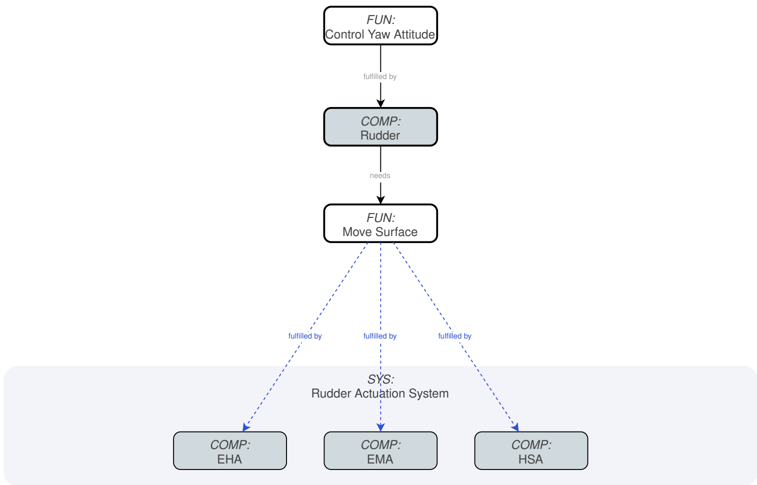


Figure 3.8: Rudder related function, MaD concept

These models have been used to test the ADORE-Python match for a simple attempt of obtaining the optimisation results before moving to the final concept, the one actually used for the optimisation phase.

Landing Gear System - MaD

A first attempt to exploit all the LGS functions in ADORE was made by using the MaD concept. In order to lower the computational cost some assumptions were necessary:

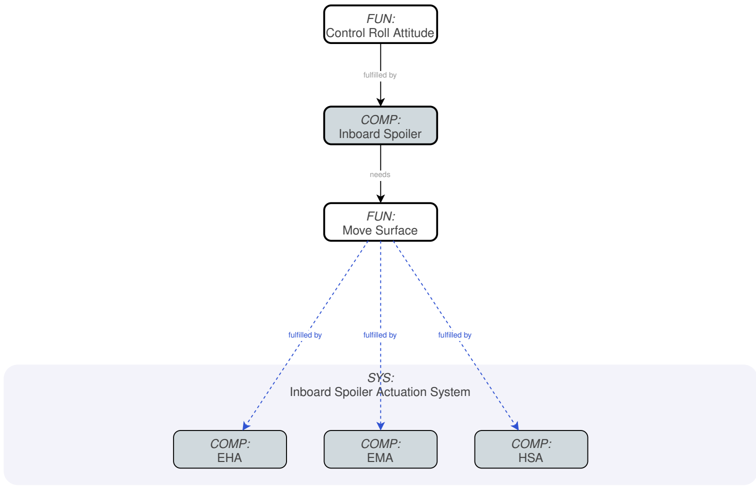


Figure 3.9: 'Inboard Spoiler' related function, MaD concept

- the system has been divided into four subsystems: brake system, door actuation system, retraction system and steering system;
- the symmetric components have been considered in the same way as they have been considered for the Flight Control System;
- for the high number of actuators driving the pistons, the brake system has been considered composed of black boxes representing each landing gear. After that, the optimisation part can consider a number of pistons matching each box during the Python translation.

Some differences were present in the Generation and Distribution system: since often the landing gear system is linked to some additional emergency lines, the electric distribution has the option for a combination of normal lines, emergency lines and a battery (Figure B.5) while the hydraulic distribution can combine normal, emergency, accumulators (1 or 2) and LEHGS (Local Electro-Hydraulic Generation System) in different ways (Figure B.6). In this case the PTU has not been introduced to highlight the combination of the various distribution components but it was introduced in the SaS concept in the same way as was done in the FCS MaD concept.
The brake system (Figure 3.10) has a number of black boxes subordinated to the choice of the concept: in this case it´s not possible the choice for a hybrid brake system that could be much heavier than a single concept (electric or hydraulic). The system is considered symmetric and it is possible to instantiate 1 or 2 symmetric brake gear: one if the brake system is present only in the main landing gear while two represents the case of bigger aircraft with brake system located in the wing

landing gear. The Electric Brake System is a young concept currently present only in the B787 and this means that the related design space has to be defined yet: only a few informations are reported in the literature about the concept introduced by Boeing.
The door actuation system (Figure 3.11) has two options: a multi-fulfilment composed of nose and main doors actuation and the option to actuate only the main doors. The choice depends on the design of the aircraft: if the aircraft is supposed to have doors mechanically linked to the retraction system then it is not necessary to include actuators. The main doors are symmetric and can be 1 or 2 (overall of 2 or 4), it depends on the size of the aircraft. The actuators are defined in the same way of the FCS actuators and this is the same for the other subsystems analysed, starting from this.
The retraction system (Figure 3.12) differs from the door actuation system only for the constant presence of a retraction system for the nose strut.
Last subsystem is the steering system (Figure 3.13), composed of two pistons every two wheels: if there is only the nose steering system, only one actuation system will be instantiated. There is also the possibility for three pairs of wheels with the functions of steering if the aircraft is bigger (for instance A380) and a steering system in the rear wheels of the main landing struts is necessary.

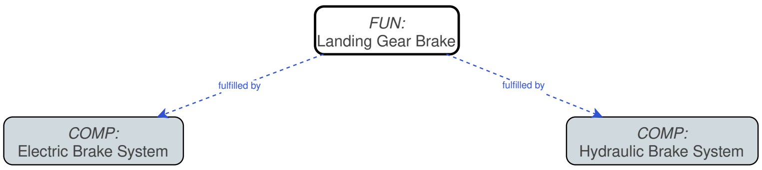


Figure 3.10: Brake function, MaD concept

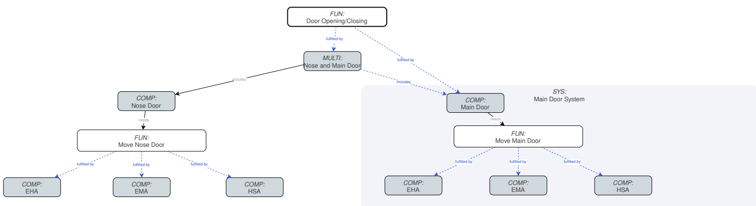


Figure 3.11: Door Actuation function, MaD concept

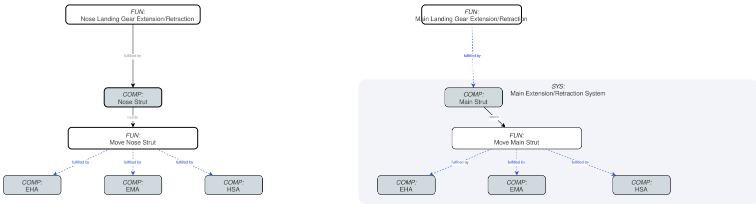


Figure 3.12: Retraction function, MaD concept

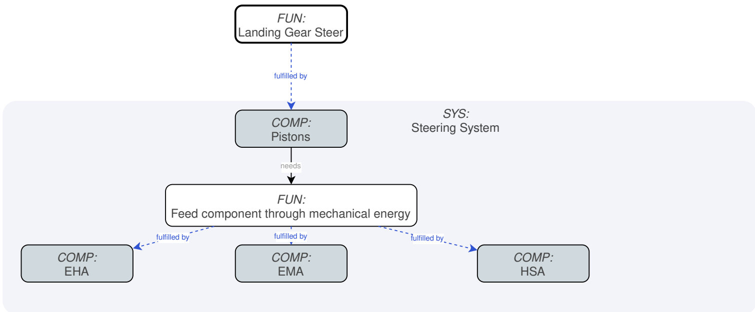


Figure 3.13: Steering function, MaD concept

3.1.3 Design Concept: Single and Simplified (SaS)

The last concept is the Single and Simplified Concept (SaS) and it was developed specifically for the purpose of the thesis: each model has all the functions related to one aircraft system and then the connections with hydraulic and electric systems. The ports are removed since the accurate connection between the elements is not necessary for the optimization phase of this thesis. If the architecture choice related to a long-range aircraft demanded a huge number of instances for a specific function, that number of possible instances was removed. This choice made a big contribution to the decrease of computational cost and pushed the focus of this thesis mainly on short- and medium-range aircraft. The models of FCS and LGS are shown in the Figures B.7 and B.8: it is easy to notice in the FCS design space the red arrows that indicate the incompatibility constraint, in this case the incompatibility is dictated by the logical decision to use the same actuation system for slats and flaps, in case both are present. A last change in the FCS design space has seen the removal of the Power Generation and Distribution Systems: since the thesis' work focused on the actuation system and not on the relation with the Power Distribution and Generation Systems the existence of components not oriented to the objectives would have increased drastically the possible combinations without changing the results of the objectives if the different actuation systems had the same combinations.

3.2 Objective and Design Problem Definition

The objectives of the optimization can be defined in different ways, depending also on the problem and the results we want to get actually. In the case of objectives, these are defined through the Quantities of Interest (QOIs). The Objective (OBJ) QOIs can be minimized or maximized: the OBJ is recalled during the translation of the Design Space in Python. The evaluation of the OBJs in each architecture generated is done in the translation file and can also be related to QOIs of the various components in the Design Space but this is not a rule: sometimes the knowledge of the various connections and the numbers of the different components can be used directly by the translator to evaluate the objective. In the Design Space of the Flight Control System two objectives are present: the first objective is the minimization of the system mass while and the second objective is the maximization of the operational reliability ratio. Both the objectives and their evaluation are deeply discussed in the following sections.
The design problem has been defined in ADORE by fixing some decisions related to the generic architecture of each aircraft case study: four design problems have been created in ADORE, respectively A320, A330, ERJ-190 and ATR 42.

3.3 Mass Estimation

The system mass is the first objective of the optimization phase: the flight control system sizing methodology developed previously by Carlos Cabaleiro de la Hoz and Marco Fioriti [40] has been integrated in the tool. The starting point of this design problem is the hinge moment estimation: the higher fidelity models for the hinge moment evaluation are based on computational fluid dynamics (CFD) analysis. During the preliminary design a good compromise in terms of fidelity and computational cost is chosen: Roskam's method was selected for modelling of ailerons, elevators and rudders [41]. The inputs required for Roskam´s method are really detailed for this stage of the design. For instance, the hinge moment is calculated experimentally and some mission data are not defined during the preliminary analysis. Among the various ways to evaluate the hinge moment, the reverse engineering is one of the most used. The nominal stroke and the maximum deflection angle are the inputs for the moment arm while actuator's stall load with a safety margin are the inputs for evaluating the force. In general, the Roskam's method has some assumptions regarding the geometric relations and the flow around the surfaces that is supposed subsonic everywhere. This method is based at first on the calculation of the hinge moment coefficient:

$$C_h = C_{h_0} + C_{h_\alpha} \cdot \alpha + C_{h_\delta} \cdot \delta + C_{h_{\delta_t}} \cdot \delta_t \tag{3.1}$$

Coefficients are calculated following the Roskam's instructions while the various angles are estimated for the whole mission profile. The method for the evaluation of the hinge moment coefficient is the same for spoiler,slats and flaps, the only difference is that those surfaces are not active during the whole profile mission. The hinge moment estimation for primary control surfaces is reached through this equation:

$$M_{hinge} = q \cdot S_w \cdot c \cdot C_h \tag{3.2}$$

q is the dynamic pressure, S_w is the wing surface and c is the surface´s standard mean chord. Spoilers, flaps and slats hing moment are sized in different ways since the assumptions are quite different. The spoiler hinge moment is evaluated through the flat plate model that consists of an assumption: the spoilers are low aspect ratio flat plates. The equation for these surfaces is:

$$M_{hinge} = q \cdot S_{spoiler} \cdot C_{d_{spoiler}} \cdot arm_{spoiler} \tag{3.3}$$

Flaps and Slats hinge force estimation is obtained through the normal load calculation:

$$N_f = 1.2 \cdot C_{N_{flap}} \cdot S_{flap} \cdot q \tag{3.4}$$

These methods have been calibrated with the A320 and B787-200 FCS references. After the calibration, a surrogate model have been developed. The surrogate model permits to calculate the hinge moment of each control surface with the only knowledge of the maximum take-off mass (MTOM) for ailerons and elevators, the fin surface for the rudder, wing surfaces for spoilers, flaps and slats. The surrogate model is then used for the mass and power estimation considering different mass and power for different actuators and the necessary proportions for component related to ball-screw for flaps and slats. In the Figure 3.14 the estimation for the conventional A320 with HSA and ball-screw is shown.

Component	Number of components	Mass of one component (kg)
Aileron actuator	4	9.6
Elevator actuator	4	6.2
Rudder actuator	3	9.4
Spoiler actuator	10	9.6
Flap ball-screw actuator	8	13
Flap gearbox	8	12
Flap corner gearbox	4	13.3
Flap torque limiter	2	5.5
Flap PDU	1	57.7
Flap tubes	all tubes	3.7
Slat ball-screw actuator	20	3.35
Slat gearbox	20	6.14
Slat corner gearbox	2	6.7
Slat torque limiter	2	2.8
Slat PDU	1	29.1
Slat tubes	all tubes	2.6
Total	-	**756**

756 is the exact value summing the previous components with all the decimals. Since the previous components have been rounded in the table, the summ is a bit less. Significance would be 2.5 kg or 0.33%.

Figure 3.14: A320 estimated FCS component mass [40]

The model has been integrated and validated by comparing the results obtained by the author of this methodology for A320, A330, ERJ-190 and ATR 42 conventional architectures. The model is sensitive to changes in the number of surfaces and the number of actuators per surface and also on a component level can reach a decent estimation of the single mass and the power required. The mass and power estimation are matching the level of detail reached by ADORE.

3.4 RAMS Estimation

The RAMS estimation has been developed specifically for the Reliability part. The Operational Reliability has been evaluated: Aircraft Operational Reliability (OR) is the reliability of the aircraft during flight missions [42]. In the specific case of an aircraft system, the system operational reliability is studied and it is influenced by different factors: design, manufacturing, operating, maintenance and operational environment. This analysis intend to study the chances in operational reliability based on design (different actuators combinations), operating (different analysis based on the flight hours) while different probability function are used to simulate the different manufacturing and operational environment. Some assumptions are needed:

1. the time step is not fixed: each time step is based on the duration of each route in the random routes vector (explained in details below);

2. None of the components present in the architecture fails during the Flight Hours (FH) simulation of the OR. This assumption is selected in order to evaluate the different architectures in ideal operating state;

3. Spoilers have been considered in the Primary FCS loop (except for ATR 42, generally it is a secondary input choice) since flight spoilers could be used during cruise;

4. Secondary Flight Control System (flaps, slats and spoiler in specific cases) are evaluated for a total time of 40 minutes for each route if the current route last more than 40 minutes, otherwise the total flight of the route (same as Primary FCS).

There are different modes to analyse the OR, in this work the evaluation is done through the RBD connecting components reliability. The components are connected through active/stand-by parallel network and series network to be as similar as the real system architecture. The single components reliability is based on the Weibull probability function with the selection of the parameters related to the mean failure rate of each component obtained from the Nonelectronic Parts Reliability Data (NPRD-2016). Different evaluations of the operational reliability of each aircraft are done: the most massive evaluation has the Weibull probability function of each components described as the exponential probability function.
The number of actuators is fixed by the design problem of each aircraft case study in order to evaluate the different reliability with the same number of components. The estimation is done over the time where the unit of measure is expressed in Flight Hours(FH). The time step is variable and it is based on the flights. A random choice from a wide selection of possibles routes for each aircraft case study fill a vector until the FH requested as inputs are reached. The tables (3.1, 3.2, B.2, B.2) for each aircraft case study are shown: the routes are obtained analysing active aircraft that have flown in the air traffic lately.

The total Reliability is calculated by the series network of the Primary FCS Reliability and the Secondary FCS Reliability (High Lift Systems). All the actuation systems are active/active for the massive evaluation: this means that the aging factor is equal to the unity for all the components. The possible RBD schematic of each aircraft FCS architectures is shown in the Figures 3.15, 3.16, 3.17 and 3.18: the primary FCS can be described by one architecture concept that can contain different combination of architectures while two concepts describe the Secondary FCS. The one shown below is the A320 case study.

Different shape parameters have been selected for the other evaluations and the active/standby capabilities of the tool have been tested on some architectures. In the Figure B.9 the calculation flow for this objective in the Python evaluator

Route	FH (h)	FH (m)
OSL-ARN	0	45
CDG-DUB	0	50
BRI-TSR	1	0
CDG-NTE	1	5
MXP-TIA	1	20
HAM-VIE	1	30
BRI-MXP	1	35
MXP-CPH	1	40
LHR-FCO	1	55
MXP-VON	2	0
LHR-HEL	2	20
LHR-OTP	2	35
HAM-ATH	2	40
CDG-CTA	2	45

Table 3.1: A320 routes selected

Route	FH (h)	FH (m)
CDG-TLS	1	0
AGP-DUB	2	45
HNL-LAX	5	0
SMF-HNL	5	15
COO-CDG	5	45
LAS-HNL	6	0
YOW-CDG	6	30
DUB-JFK	7	0
ICN-HNL	8	10
MIA-EZE	8	30
DEL-CDG	9	30
EZE-JFK	10	0
MAD-EZE	12	15
EZE-FCO	13	0

Table 3.2: A330 routes selected

is shown. After the evaluation of the trend of the different RBDs, the tool was changed for its final operational reliability evaluation: the different loops shown in the Figure B.10 demand high computational cost. All the inner loop were then deleted and the only loop that stayed was the one for evaluate the total primary

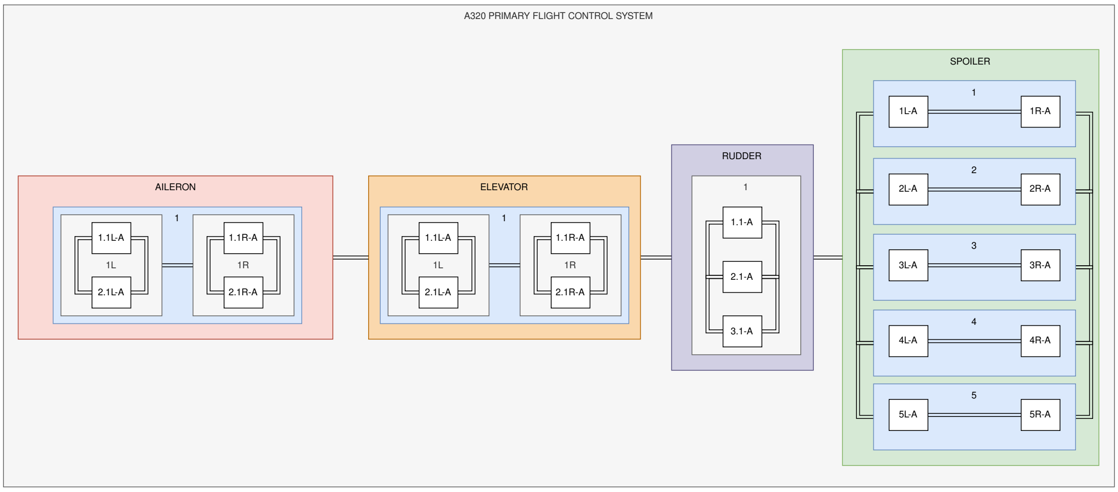


Figure 3.15: A320 Primary FCS logical connection

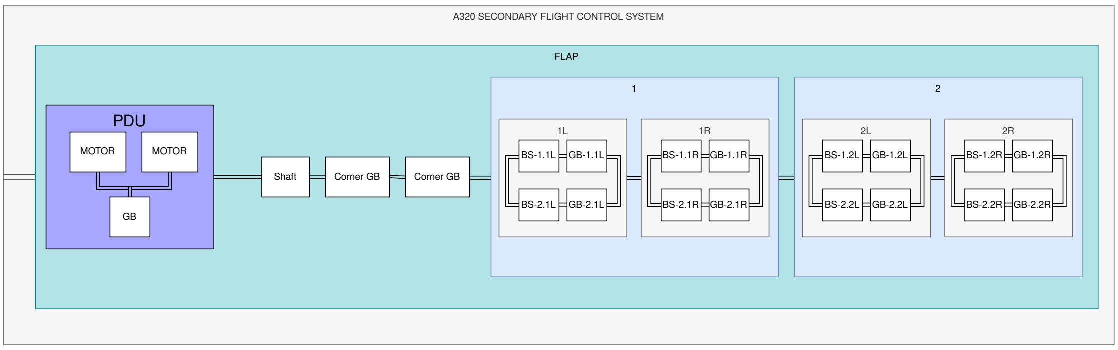


Figure 3.16: A320 Secondary FCS logical connection with ball-screw configuration: flap

and secondary flight hours and then the operational reliability was evaluated ony at the Flight Hour specified as an input. This change avoids the evaluation of each component and sub-system reliability for each time step.

3.5 Overall Framework

The overall framework is composed of the Python Translator that runs a GUI Interface: the GUI Interface asks for three input. The first input is the Aircraft Case Study that can be chosen among A330, A320, ERJ-190 and ATR 42; the second input is the probability model that can be the Exponential or the Weibull model; the last one is the Flight Hours (FHs) that are a free choice with the only constraint that this number has to be integer. The shape parameter for the Weibull

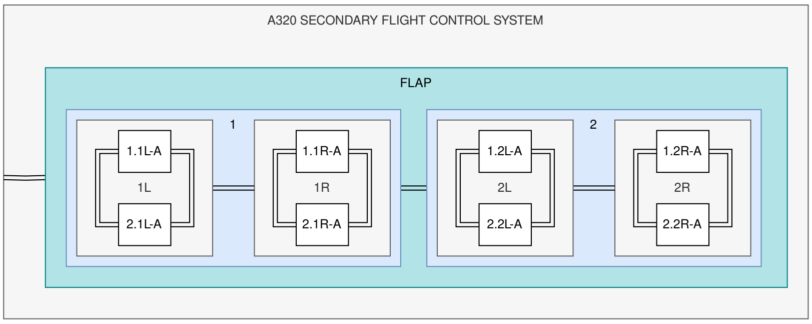


Figure 3.17: A320 Secondary FCS logical connection with EMAs configuration: flap

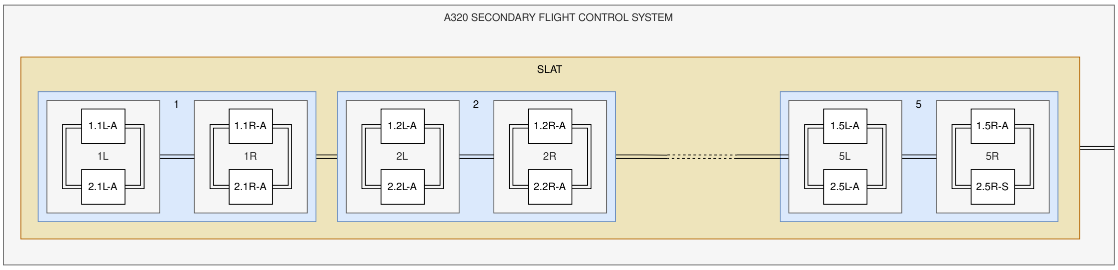


Figure 3.18: A320 Secondary FCS logical connection with EMAs configuration: slat

function has to be selected into the Python code while the Exponential functional is actually the Weibull function with the parameter tuned for the exponential. In the fig. 3.19 the GUI selection is shown. The Python Optimizer is used for the Optimization run and includes the selection of the optimization algorithm: in this work the NSGA-II was selected. In the Optimizer the architectures population size and number of generation can be chosen and the results are saved in a specific folder. The results are saved in a Excel file where it is possible to see all the architectures generated; a plot for visualizing the output of the design problem is done at the end of every run. At the end the post-processing phase consists of the evaluation and the save of the architectures on the Pareto Front and the plotting of the Pareto Front line.

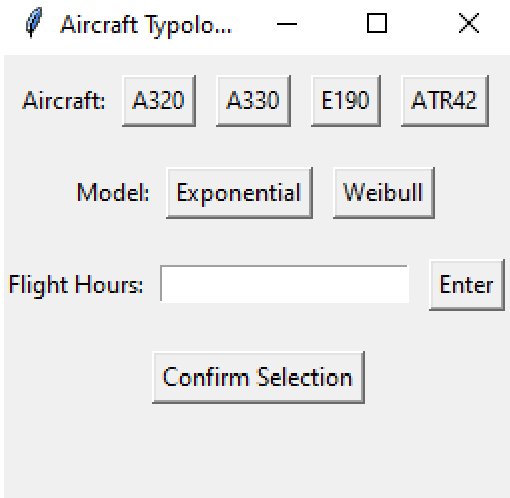


Figure 3.19: Graphic User Interface for Optimizer Input

Chapter 4

Results

In this chapter the output from the analysis of the single component reliability are shown. This part of study aimed to a better understanding of the influence of each parameter in the component reliability evaluation: shape parameter shows the trend of the failure probability while scale parameter is strictly related to flight hours since it scales the failure probability function. Once the parameters have been selected, the multi-objective optimization results are shown: different Pareto Front obtained from the combination of different component failure probability function, flight hours and aircraft case study. All the features present in the optimization loop have been used to validate their integration: different aircraft case study with their TLARs, different failure probability models, different flight hours (even if in the results only one typology of flight hours have been chosen), different redundancy modes (active/active and active/standby).

4.1 Preliminary Reliability Results

In this section the reason why every parameter for the optimization results has been selected is explained. Three different analysis have been exploited.
The first one is about the classic analysis that is done on this type of components: using the Exponential Probability Function all the aircraft case study have been analysed.
The second analysis is about the uncertainty of the data: since it is quite impossible to find in the literature the probability distribution function of the components analysed, different shape parameters of the Weibull function have been used in order to find out if the Pareto front has the same architectures even if we change the trend. This analysis was done only on the A320. As it is possible to see in the Figures, the PDF, CDF, reliability function and hazard rate (that are explained in the Chapter 2) have been analysed: the exponential function is easy to recognise

since the hazard rate is constant. All the function have the same scale parameter that is the reciprocal of the mean failure rate of each component: the reason of this choice is related to the definition of the exponential function through the Weibull function. An evaluation of the components of the Airbus A320 rudder control systems (Figure 4.3) showed that the curve starts close to 10000 FHs, not taking into account the trend of this curve before that. Indeed, the exponential function can be defined through these Weibull parameters:

$$\eta = \frac{1}{failure\, rate} \tag{4.1}$$

$$\beta = 1 \tag{4.2}$$

Where η is the scale parameter and β represents the shape parameter. The scale parameter has been kept constant while the shape parameter has been changed to obtain four different curves: the constant hazard($\beta = 1$), the infant mortality ($\beta = 0.99$), the quick increase after a low starting failure rate($\beta = 1.01$) and a distribution that can be seen on a midway between the exponential and the log-normal ($\beta = \frac{1}{log(2)}$). In the Figures 4.1 and 4.2 the different Probability Density Function (PDF) according to different shape parameter: the only trend totally different from the other ones is the one defined by $\beta = \frac{1}{log(2)}$. In the Figure 4.2 it is possible to see how the various PDFs tend to converge approaching 20000 hours. In Figures 4.4 and 4.5, even if the $\beta = \frac{1}{log(2)}$ curve still shows a different trend from the others the convergence is reached around 10000 hours and then a divergence trend starts. A similar trend is shown in the Figures 4.8 and 4.9 since the reliability function is the complementary of the CDF. Figures 4.6 and 4.7 show the hazard rate function accomplished through the different shape parameters: $\beta = 0.99$ and $\beta = 1.01$ have a different infant trend but in general not that far from the trend obtained by the $\beta = 1$ that is the exponential function and shows a constant failure rate. The analysis of the different output from each shape parameter applied can be useful to see if the Pareto Front changes by modulating the shape parameter of the single component.

The Flight Hours selected for all the analysis are 3500 FH: the decision was done to analyse the Operational Reliability level after one operating year that usually is between 3000FH and 3500FH for a commercial aircraft. The trend of reliability of the Primary FCS over the time is shown in the Fig.4.10 where the A330 Conventional is plotted. In this case, $\beta = 1$ has been selected.

The last analysis was done on the redundancy level: the first two analysis have all the components in active mode, this one has the active/standby mode. Since the active/active mode is widely used in the aircraft industry for the HSAs, the active/standby has been introduced in the A380 for HSA-EHA: HSAs are usually active while the the EHAs are normally on stand-by mode and become active in

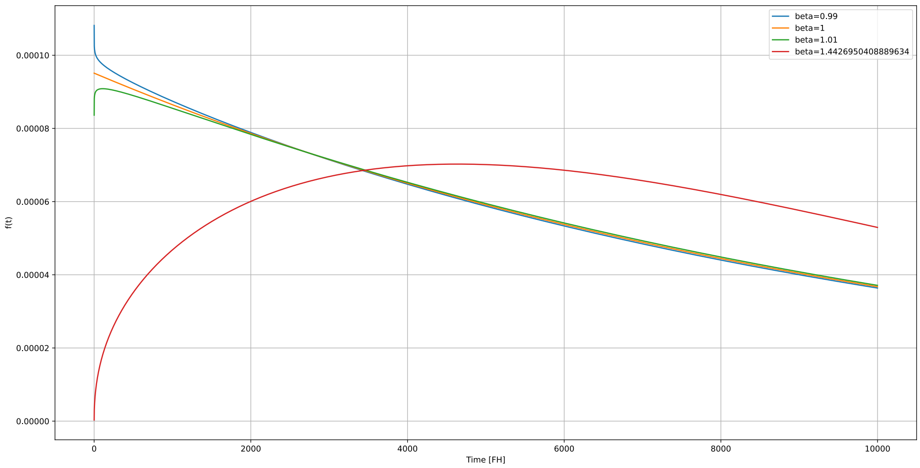


Figure 4.1: Probability Distribution Function (10000 hours)

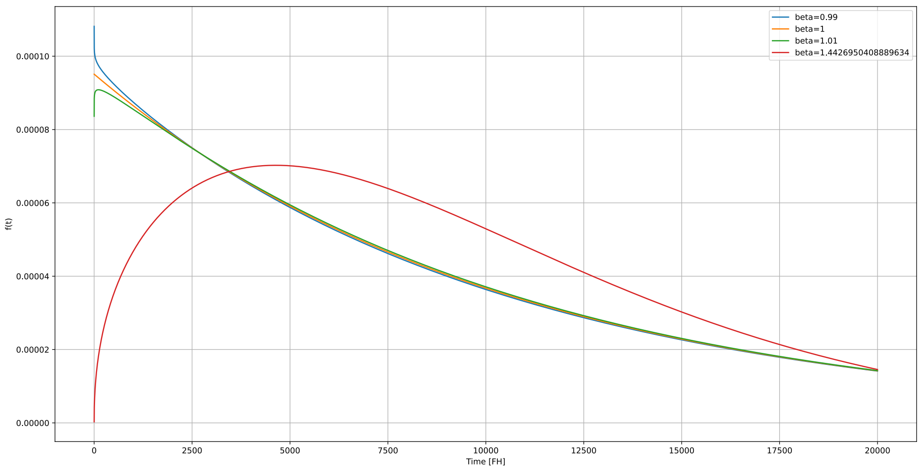


Figure 4.2: Probability Distribution Function (20000 hours)

the event of a failure of the first [44]. The probability function is one more time the exponential and a comparison between active/active and active/standby was done. To understand better what it changes, in Figure 4.11 the Primary FCS Reliability is shown: the redundant actuators have an aging factor $\gamma = 0.5$, this value is between 0, which is used for the hot redundant actuators, and 1, that is used for

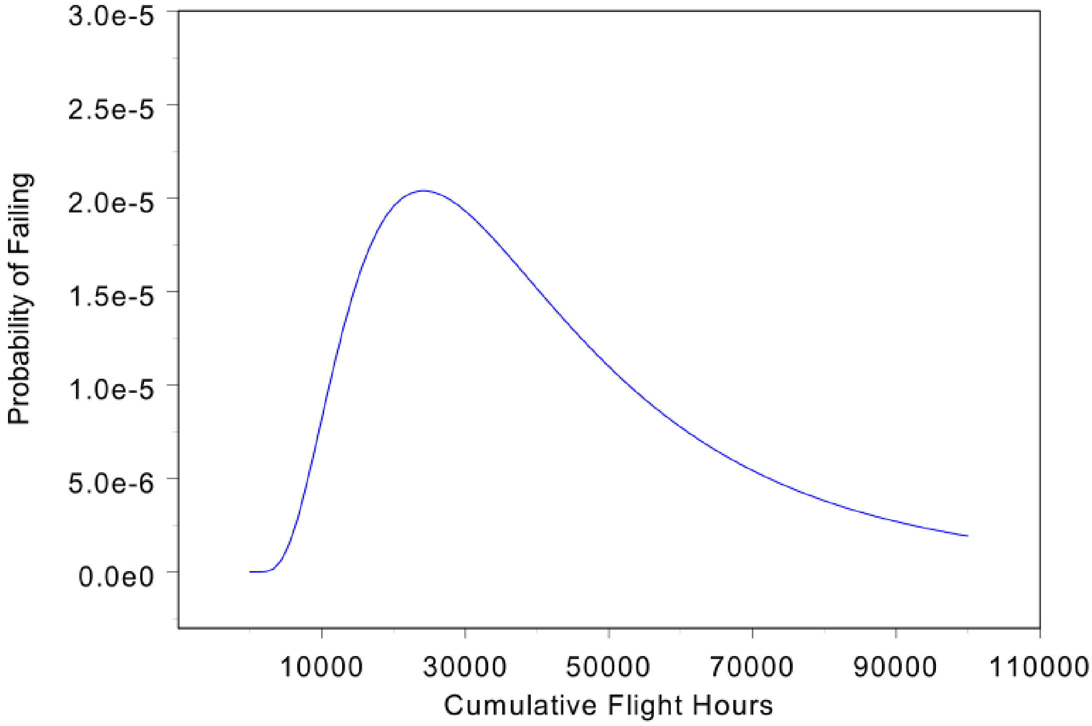


Figure 4.3: FAA A320 rudder - Probability Density Function, from [43]

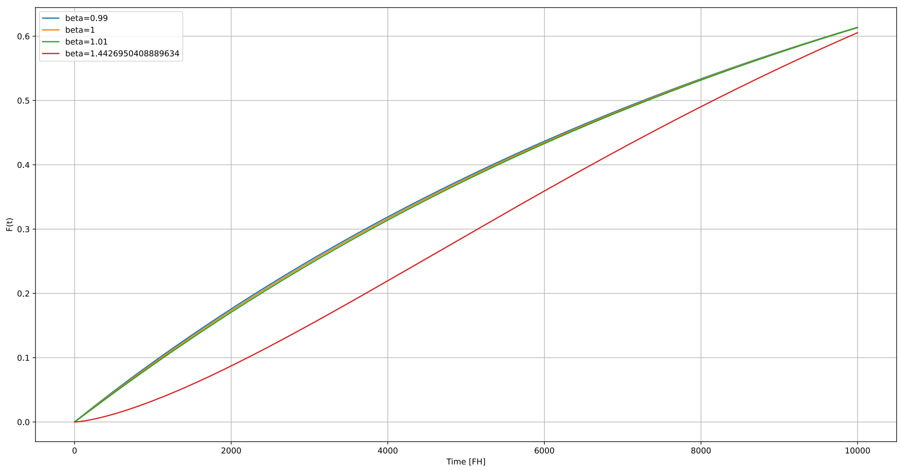


Figure 4.4: Cumulative Distribution Function (10000 hours)

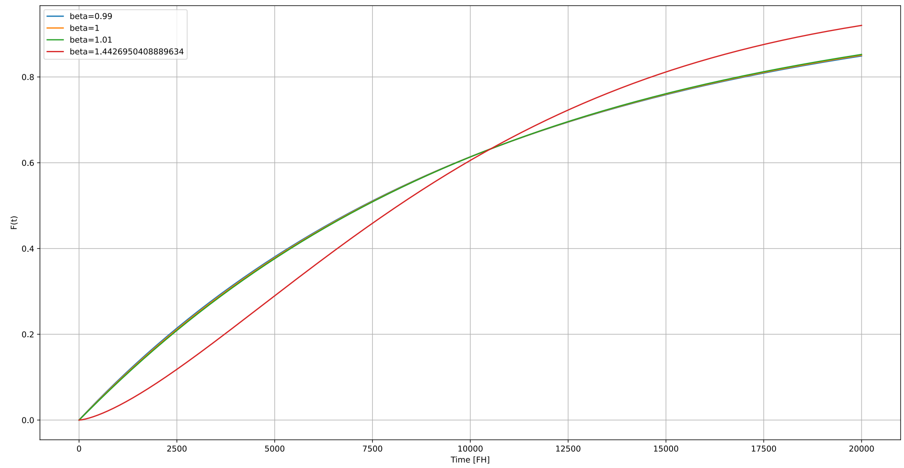


Figure 4.5: Cumulative Distribution Function (20000 hours)

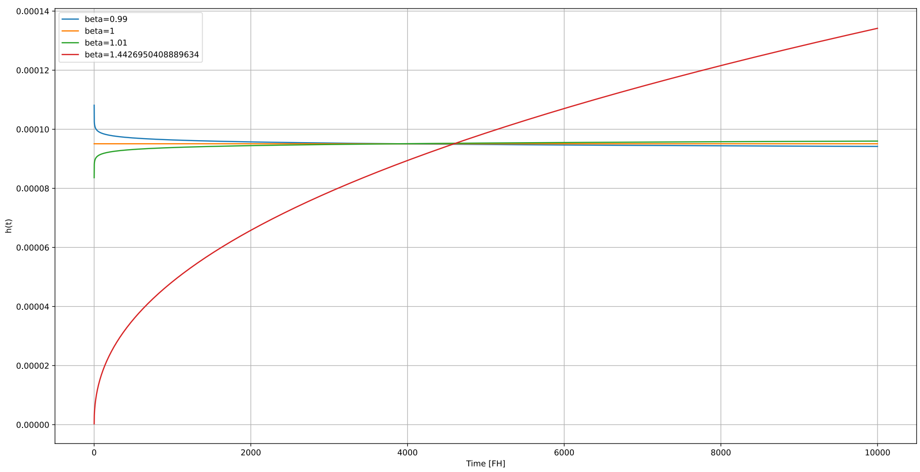


Figure 4.6: Hazard Rate function (10000 hours)

the hot redundant actuators. The reason why the presence of an aging factor is related to the cold start of the standby-actuator: the EHA in standby mode may have to start up in critical operating conditions, like very low temperatures and a permanent heating device (with a own failure probability) should be considered [44]. Concerning HSAs and EMAs, HSAs can have the same problem of EHAs

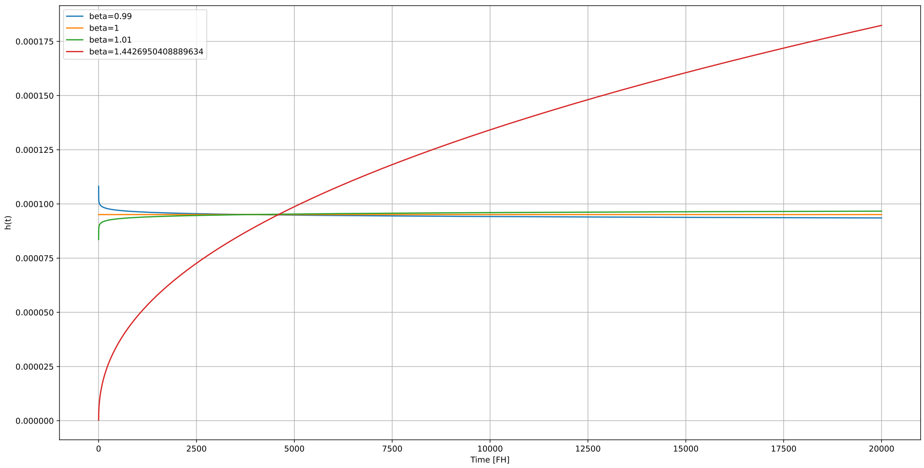


Figure 4.7: Hazard Rate function (20000 hours)

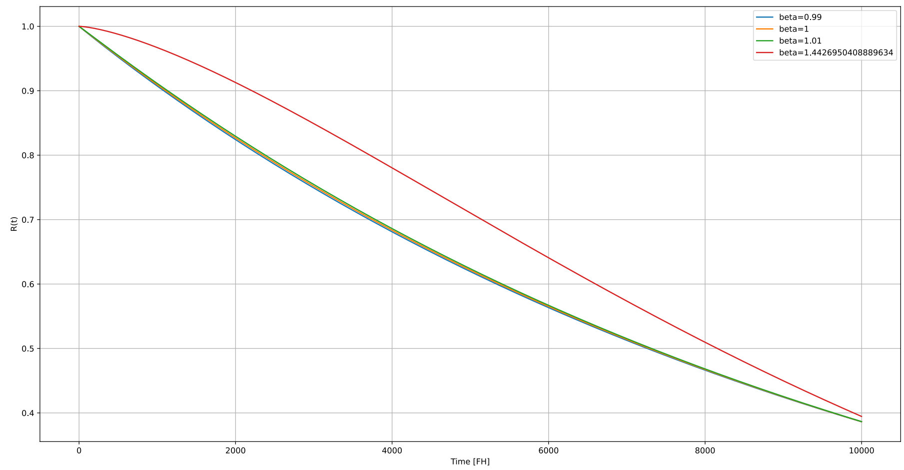


Figure 4.8: Reliability function (10000 hours)

since they have hydraulic circuits; EMAs active/standby mode has been extensively studied over the years since technology improvement for electric motors have been introduced. A big change in terms of Reliability is easily recognizable in Figure 4.11 if compared to the active-active analysis with the same inputs (Figure 4.10).

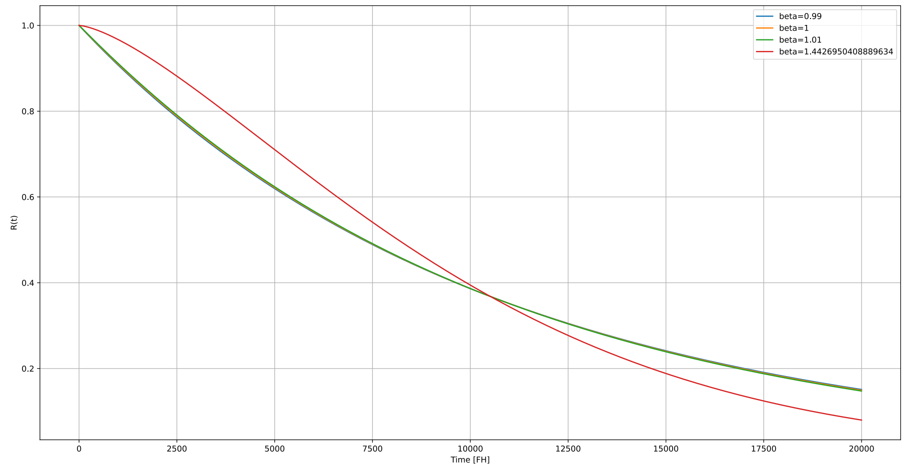


Figure 4.9: Reliability function (20000 hours)

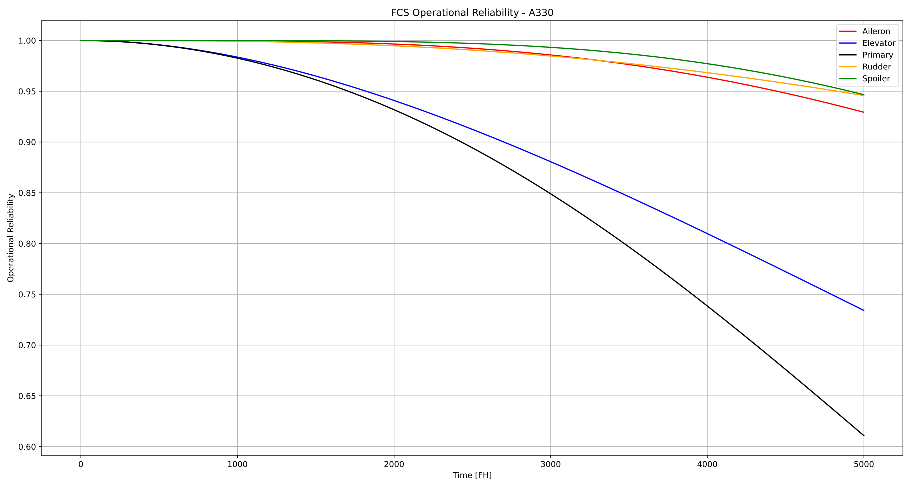


Figure 4.10: Primary Surface and Primary FCS reliability of A330 conventional architecture after 5000 FHs

4.2 Multi-Objective Optimization Results

In this section the three different analysis are shown and the results are briefly commented, as explained in the previous section. Each analysis has a different

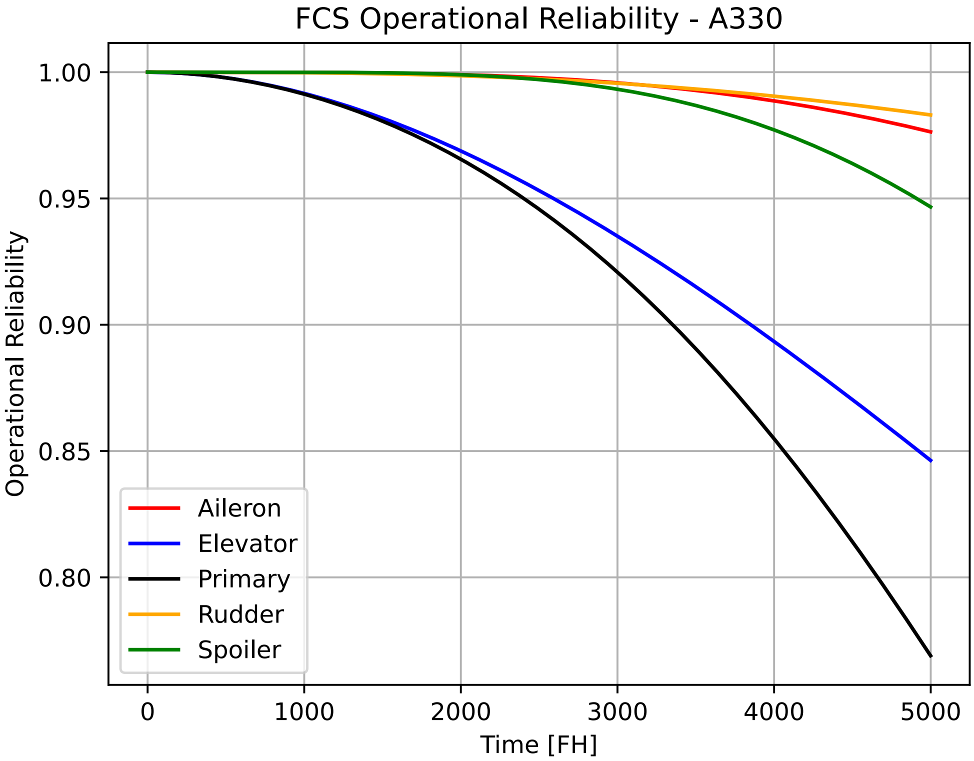


Figure 4.11: Primary Surface and Primary FCS reliability of A330 conventional architecture after 5000 FHs: Active-Standby Configuration

focus and all the inputs and the outputs are shown in two different tables while the pareto front is shown in a plot with all the architectures generated for each run. Each optimization run was done by using the NSGA-II algorithm: 10 to 20 generations where created with a population size of 400. Different number of generations where tested on each analysis to find the right compromise to have almost enough architectures with a non-excessive time of execution.

4.2.1 First analysis: exponential probability density function applied to all the architecture combinations in active-active mode

The first analysis was done on all the aircraft case study, all the inputs are reported in the table 4.1. The results for each aircraft case study show the benefits that EHAs and EMAs can bring in terms of mass and operational reliability.

Aircraft Case Study	A320,A330,ERJ190,ATR-42
Probability Density Function	Exponential($\beta = 1$)
Flight Hours	3500
Actuators Redundancy Mode	Active/Active
Architectures restrictions	None

Table 4.1: First analysis input

A320

The first aircraft analysed is the A320. In the Table A.1 is it possible to see some of the Pareto Front architectures that are shown in Figure 4.12. Some patterns are present in all the aircraft case study analysed: the left population has flap and slat that are actuated by EMAs while the right population ones are actuated by Ball-Screw Assembly; the more reliable the system is the more EHAs are introduced into the system. A trade-off could be necessary according to the necessity: a lower mass needs some HSAs in combination with EHAs, a full EHAs and EMAs system has good compromises in the system.

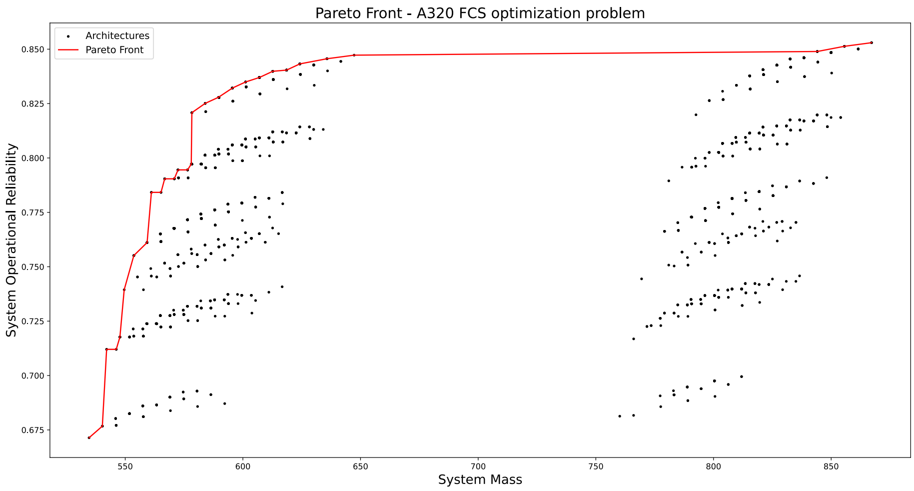


Figure 4.12: A320 first analysis pareto front

A330

A330 has a similar pattern to the A320, the population has a different density and distance. The difference is related to the number of actuators present and to the different size of the aircraft. The system mass is bigger than the A320 and the difference between left side and right side of the pareto is bigger than the A320 since the number of Secondary FCS surfaces are more. The results are shown in Figure 4.13 and Table A.2.

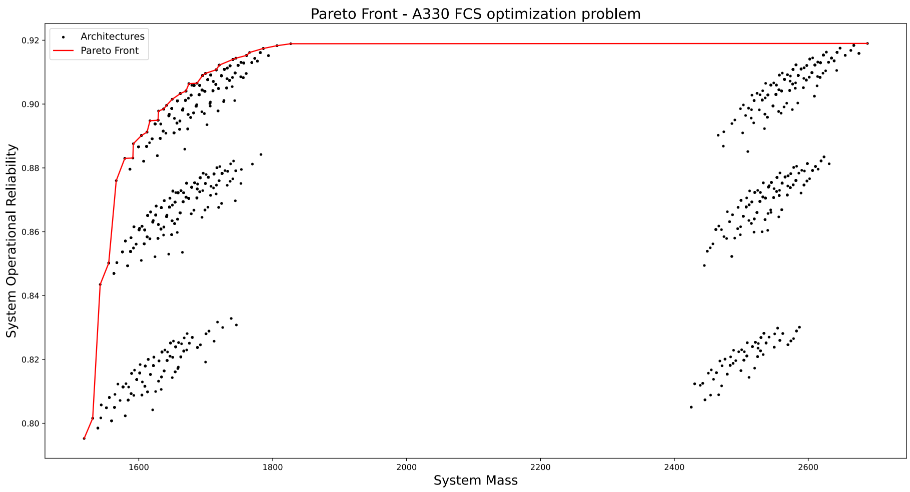


Figure 4.13: A330 first analysis pareto front

ERJ-190

The Embraer 190 is smaller than the A320 and this is reflected into the pareto front and the output datas shown (Figure 4.14, Table A.3). In a similar way to the other aircraft case study, more combinations are done on the spoiler surfaces that are the most likely to have HSAs and EHAs at the same time.

ATR-42

Last aircraft case study for this analysis is about the ATR-42, the smallest one analysed and also the smallest one in terms of total number of actuators: the Pareto Front in Figure 4.15 makes it clear. In the Table A.4 another important detail is shown: there are two architectures with the same operational reliability but different mass. This is present also in the aircraft case study and it is a way to see the sensitivity of the mass evaluator to the different surface type: the elevator is usually heavier than the aileron but in term of operational reliability if one HSA and one EHA are connected the RBD output will be the same.

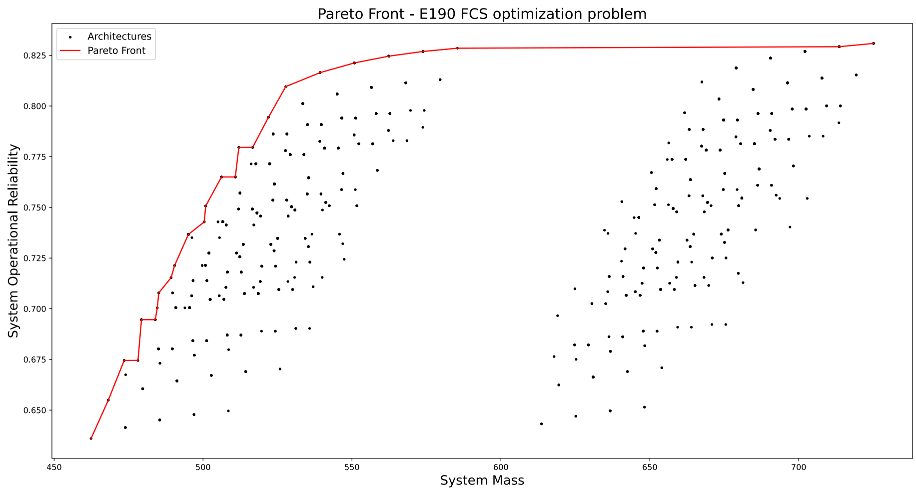


Figure 4.14: ERJ-190 first analysis pareto front

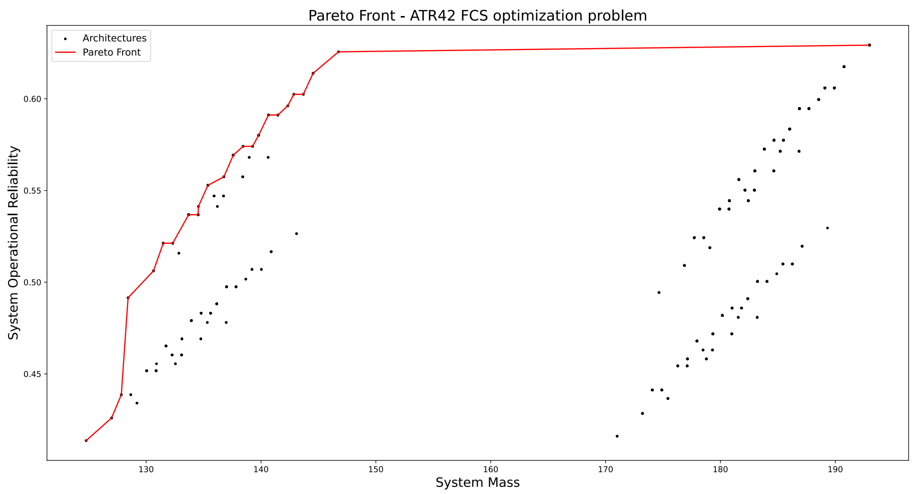


Figure 4.15: ATR-42 first analysis pareto front

4.2.2 Second analysis: variable shape parameter (Weibull function) applied to A320 (architectures with only EMA in sFCS) in active-active mode

This analysis was done on the same aircraft, A320, to understand the changes in the operational reliability due to the different shape parameter chosen for the Weibull function. One more time, all the actuators have been considered active. The architecture generation was restricted, specifying it in the design problem, to all the architectures with only EMA for the Secondary Flight Control System. The inputs can be seen in Table 4.2 while the four different outputs are shown in the Figures 4.16, 4.17, 4.18, 4.19.

Aircraft Case Study	A320
Probability Density Function	$\beta = 0.99, \beta = 1, \beta = 1.01, \beta = 1/\log(2)$
Flight Hours	3500
Actuators Redundancy Mode	Active/Active
Architectures restrictions	EMAs on Flaps and Slats

Table 4.2: Second analysis input

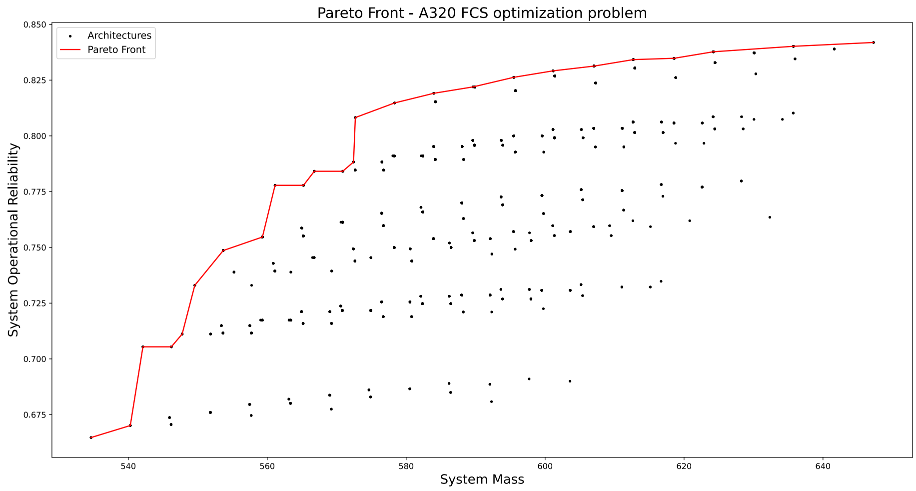


Figure 4.16: A320 with $\beta = 0.99$, second analysis pareto front

This analysis was used to see if there were any changes when the Weibull parameter was changed and, even if the operational reliability of the same architecture with different parameters slightly changes, the architectures in the pareto front are

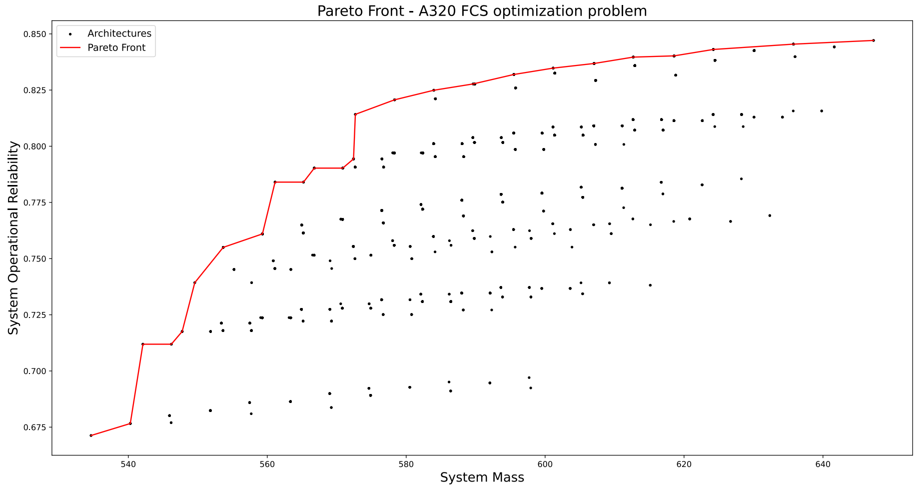


Figure 4.17: A320 with $\beta = 1$, second analysis pareto front

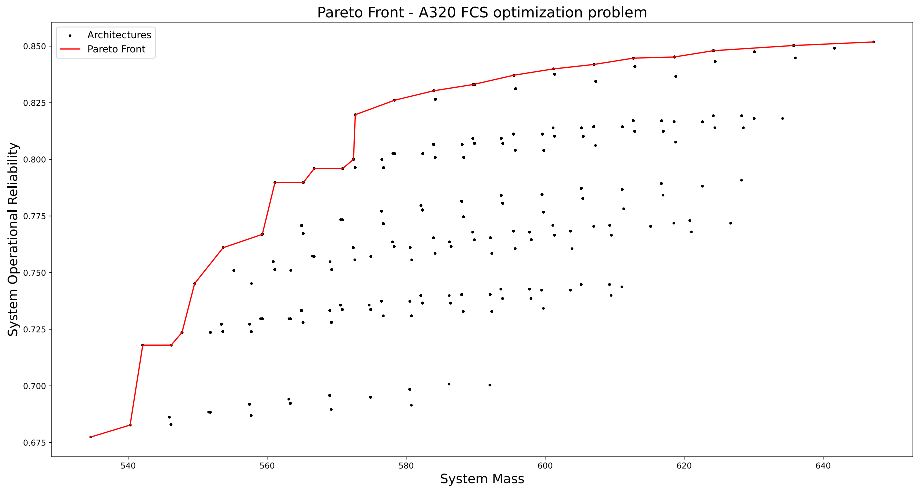


Figure 4.18: A320 with $\beta = 1.01$, second analysis pareto front

pretty the same. It is also visible in the various plots that the pattern created by the population does not show big changes.

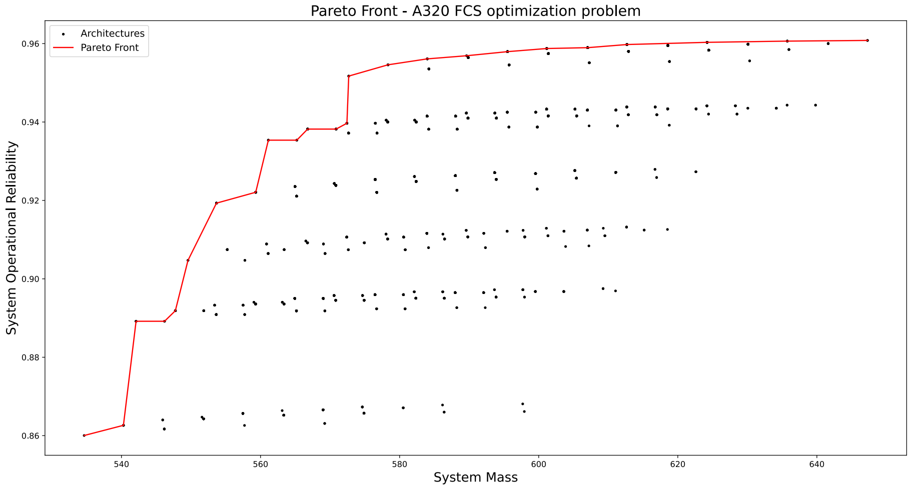


Figure 4.19: A320 with $\beta = 1/log(2)$, second analysis pareto front

4.2.3 Third analysis: exponential probability density function applied to A320 (architectures with only EMA in sFCS) in active-standby mode

The third analysis has the peculiarity of the active-standby mode (Table 4.3), the reason of this analysis is explained in 4.1. The main reason of this analysis is to compare the redundancy concept used for conventional and more-electric architectures. In conventional ones, the HSA do not allow to be left as standy-by, due to the connection with the hydraulic system. However, as expressed by [44], the new EHA concepts allow to leave these actuators in stand-by mode, having a potential benefit in reliability. The exponential function is used again as it was in the first analysis. The results are shown in Figure 4.20 and can be compared with the active/active mode 4.17 that has the same input except the redundancy mode.

Aircraft Case Study	A320
Probability Density Function	Exponential($\beta = 1$)
Flight Hours	3500
Actuators Redundancy Mode	Active/Standby
Architectures restrictions	EMAs on Flaps and Slats

Table 4.3: Third analysis input

Big changes regarding the operational reliability are visible while the shape

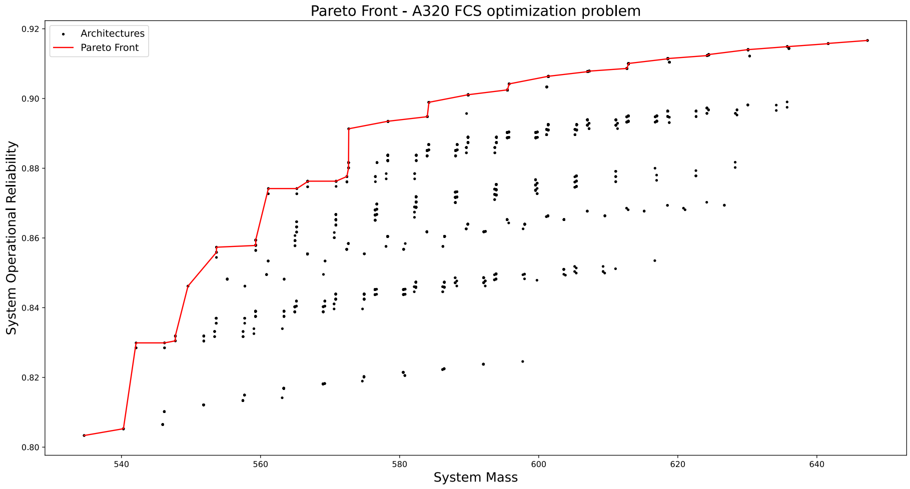


Figure 4.20: A320 active-standby third analysis pareto front

does not change a lot. The presence of more architectures it is explained by the importance that the permutations have now: if a surface have HSA and EHA, then it´s important to know which one is the active actuator (theoretically designed with an aging factor equal to 1) and which one is the standby actuator(aging factor equal to 0.5) since a difference in the operational reliability will occur from the active/active mode. In the end, this analysis shows how can be useful on a reliability side the introduction of active/standby mode in the Flight Control System

Chapter 5

Conclusions and Future Works

This work provides a framework that allows to optimize system architectures in terms of mass and operational reliability. The framework allows to connect system architecting and optimization objectives. During the system architecting phase different aircraft power consuming systems (Landing Gear System and Flight Control System) and power generation and distribution systems (Hydraulic System and Electric Power System) were analysed with different levels of detail. The first optimization objective was the mass: a DLR-PoliTo built-in tool for the sizing of FCS mass and power required was integrating in the optimization loop. The second optimization objective is the operational reliability, defined as the reliability over the missions, analysed with the assumption of no actuator failure during the flight time. Different single component probability density functions, redundancy model and flight hours simulations could be applied on the model to have a wide range of outputs that could be compared. The redundancy mode of actuators connected could be active-active or active-standby, where active-standby means that one actuator is active while the other one becomes active if the first fails; in the active-active both actuators are active. Different trends of probability density function have been included in the study to remove as much as possible the uncertainty related to the absence of experimental data. The output of each run is a plot of the whole population generated with the two objective on the two axis. The optimum population in the plot creates a line called Pareto Front, where all the best architectures are shown and the selection of the best one is based on the trade-off analysis related: the weight of the two objective in the trade-off permits the decision of the best architecture. This work has studied and evaluated the pros and cons of introducing EHAs (Electro-Hydrostatic Actuators) and EMAs (Electro-Mechanical Actuators) in the aircraft Flight Control System. . The electrification of actuators can be a good change in terms of reliability and mass but still more studies on the power required and the safety concerns have to be exploited. EHAs on the primary FCS have already been included in A380, A350 and B787 in hybrid configurations that include EHAs and HSAs, EMAs introduction in flap and slat architectures have to be deeper analysed and tested since the jamming of EMA is still a big issue

Future works can be done by introducing the power analysis and more RAMS parameters analysis in the optimization loop. Also the introduction of more electric components in the other power consuming systems like LGS, ECS and IPS must be analysed to have a total understanding of the improvements that can be done on the aircraft power consuming systems. In the end, the stress and the changes needed on the power generation and distribution system (EPGDS and HPGDS) must be analysed: in this way all the aircraft systems can be deeply studied already during the preliminary aircraft design breaking part of the costs needed for introducing new technologies in the aircraft system. Related to this analysis, a more detailed design space can be done during the system architecting phase in order to have an overall knowledge of the system decisions and combinations, the system architecting is a really useful tool during the preliminary design since all the possibility can be analysed to understand the best change and the best moment to change a technology if the system is then evaluated through enough parameters. A future framework conceived in this way can take into account the different weight of each changes giving the possibility of a depth undestanding of the snowball effect produced by the transformation of a conventional aircraft in a more electric aircraft or by the design of a new more electric aircraft: a change in the systems mass produced by the introduction of electric components instead of hydraulic and pneumatic systems, changes the structure weight and subsequently the overall mass; the overall mass makes change in the fuel required that, according to its density, has a weight and this produces a loop.

Appendix A

First Analysis Results Table

Mass [kg]	OR [%]	Aileron	Elevator	Rudder	Spoiler	Flap and Slat
578.33	82.082	EHA(x2)	EHA(x2)	EHA, HSA(x2)	HSA(x5)	EMA
583.98	82.508	EHA(x2)	EHA(x2)	HSA,EHA(x2)	HSA(x5)	EMA
589.63	82.788	EHA(x2)	EHA(x2)	EHA(x3)	HSA(x5)	EMA
595.51	83	EHA(x2)	EHA(x2)	EHA(x2),HSA	HSA(x4), EHA	EMA
601.16	83.493	EHA(x2)	EHA(x2)	EHA(x3)	HSA(x4), EHA	EMA
607.04	83.699	EHA(x2)	EHA(x2)	EHA(x2),HSA	HSA(x3), EHA(2)	EMA
618.569	84.038	EHA(x2)	EHA(x2)	EHA(x2),HSA	HSA(x2),EHA(x3)	EMA
647.278	84.725	EHA(x2)	EHA(x2)	EHA(x3)	EHA(x5)	EMA
844.09	84.893	EHA(x2)	EHA(x2)	EHA(x3)	HSA(x2),EHA(x3)	Ball-screw

Table A.1: A320 Pareto Front architectures

Mass [kg]	OR [%]	Aileron	Elevator	Rudder	Spoiler	Flap and Slats
1649.94	90.15	HSA(x3),EHA	EHA(x2)	EHA(x3)	HSA(x5),EHA	EMA
1662.04	90.326	HSA(x2), EHA(x2)	EHA(x2)	HSA,EHA(x2)	HSA(x5),EHA	EMA
1670.42	90.406	HSA(x3),EHA	EHA(x2)	EHA(x3)	HSA(x4), EHA(x2)	EMA
1674.81	90.63	HSA(x2), EHA(x2)	EHA(x2)	EHA(x3)	HSA(x4), EHA(x2)	EMA
1695.29	90.897	HSA(x2), EHA(x2)	EHA(x2)	EHA(x3)	HSA(x4), EHA(x2)	EMA
1720.16	91.219	EHA(x3),HSA	EHA(x2)	EHA(x3)	HSA(x4), EHA(x2)	EMA
1826.93	91.889	EHA(x4)	EHA(x2)	EHA(x3)	EHA(x6)	EMA
2688.5	91.898	EHA(x4)	EHA(x2)	EHA(x3)	EHA(x6)	Ball-screw

Table A.2: A330 Pareto Front architectures

Mass [kg]	**OR [%]**	**Aileron**	**Elevator**	**Rudder**	**Spoiler**	**Flap and Slats**
527.77	80.957	EHA(x2)	EHA(x2)	EHA(x2)	HSA(x5)	EMA
539.3	81.646	EHA(x2)	EHA(x2)	EHA(x2)	HSA(x4),EHA	EMA
550.83	82.126	EHA(x2)	EHA(x2)	EHA(x2)	HSA(x3),EHA(x2)	EMA
562.36	82.459	EHA(x2)	EHA(x2)	EHA(x2)	HSA(x2), EHA(x3)	EMA
573.885	82.691	EHA(x2)	EHA(x2)	EHA(x2)	HSA(x1), EHA(x4)	EMA
585.41	82.85	EHA(x2)	EHA(x2)	EHA(x2)	EHA(x5)	EMA
713.6	82.925	EHA(x2)	EHA(x2)	EHA(x2)	HSA, EHA(x4)	Ball-screw
725.13	83.087	EHA(x2)	EHA(x2)	EHA(x2)	EHA(x5)	Ball-screw

Table A.3: ERJ-190 Pareto Front architectures

Mass [kg]	**OR [%]**	**Aileron**	**Elevator**	**Rudder**	**Spoiler**	**Flap and Slats**
141.47	59.116	EHA(x2)	EHA,HSA	EHA, HSA	EHA	EMA
142.32	59.612	EHA(x2)	EHA(x2)	HSA(x2)	EHA	EMA
142.86	60.24	EHA, HSA	EHA(x2)	EHA(x2)	EHA	EMA
143.68	60.242	EHA(x2)	EHA,HSA	EHA(x2)	EHA	EMA
144.54	61	EHA(x2)	EHA(x2)	EHA, HSA	EHA	EMA
146.75	62.56	EHA(x2)	EHA(x2)	EHA(x2)	EHA	EMA
192.97	62.92	EHA(x2)	EHA(x2)	EHA(x2)	EHA	Ball-screw

Table A.4: ATR-42 Pareto Front architectures

Appendix B

Methodology Appendix

Route	FH (h)	FH (m)
ZRH-MXP	0	35
HRG-CAI	0	50
OSL-HEL	1	5
BEI-SSH	1	15
LIS-BCN	1	25
ZRH-NTE	1	30
BOS-CLT	1	40
JAX-BOS	2	10
IST-SSH	2	20
MCO-BOS	2	40
ALA-URA	2	50
SSH-BLQ	3	40
CAI-FCO	4	0
SSH-MXP	4	20

Table B.1: ERJ-190 routes selected

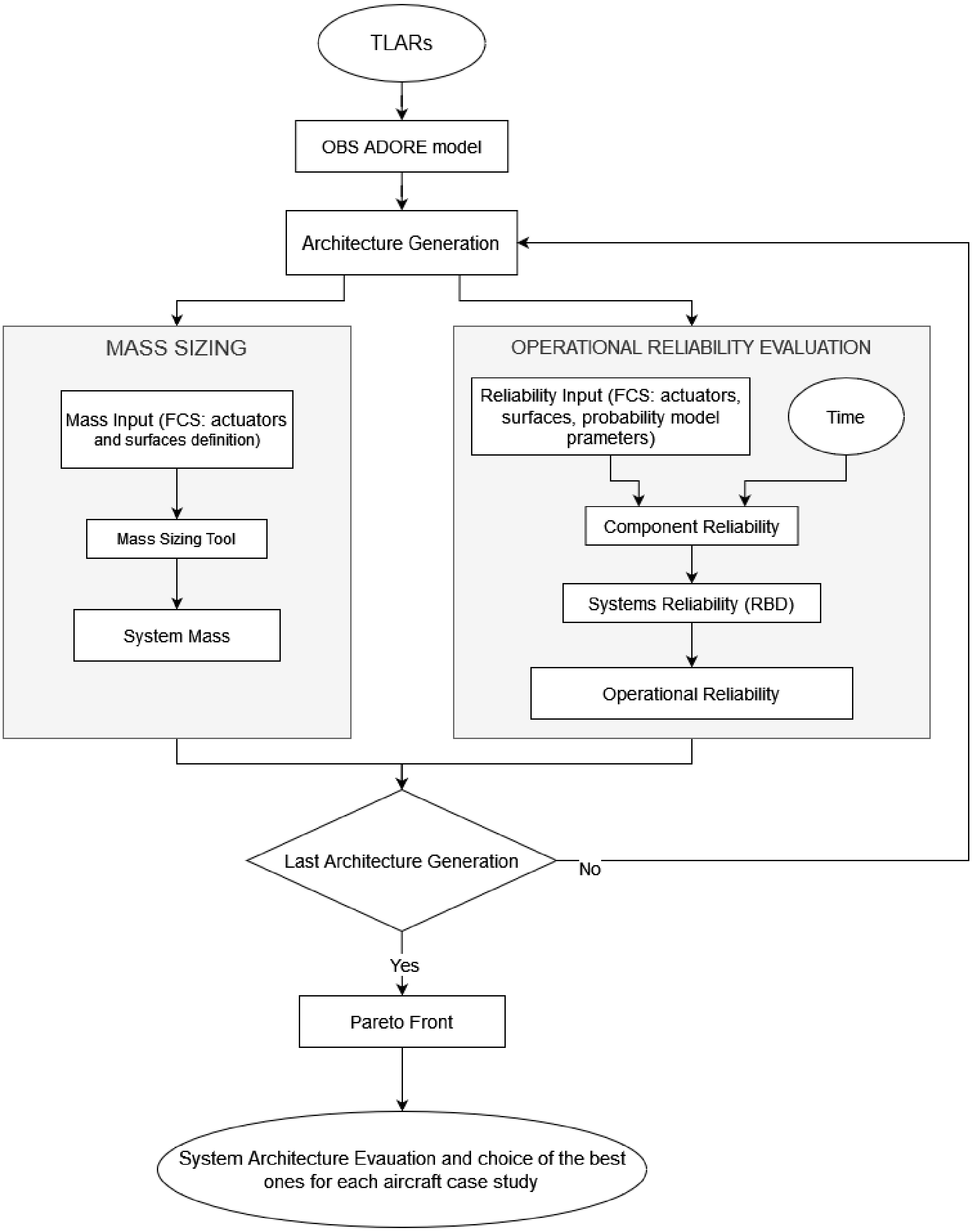


Figure B.1: Flow Chart of the Multi-Objective Tool

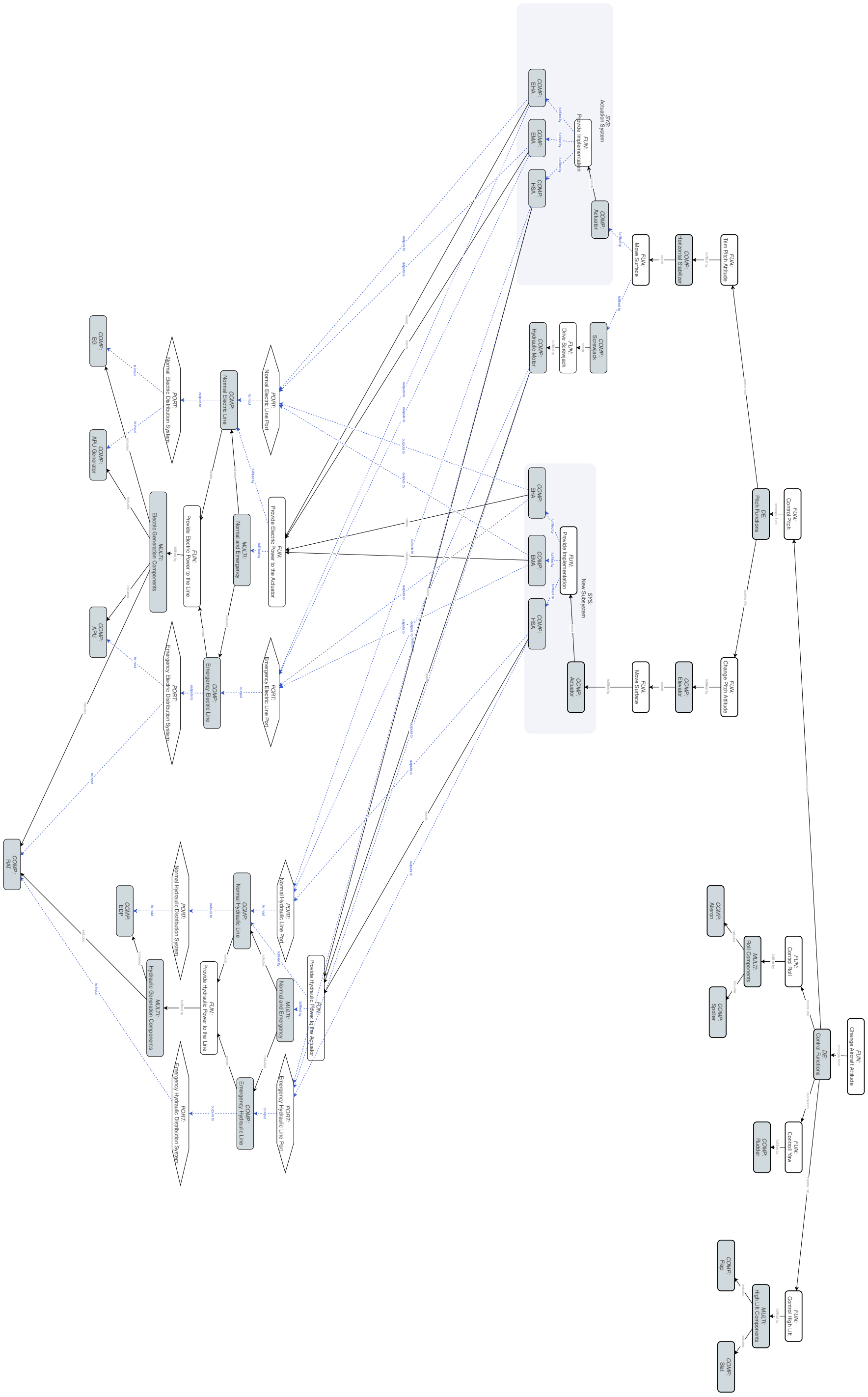


Figure B.2: Overall View of Flight Control System application with SaD concept and only the stabilizer and elevator actuators connected to the Generation and Distribution Systems

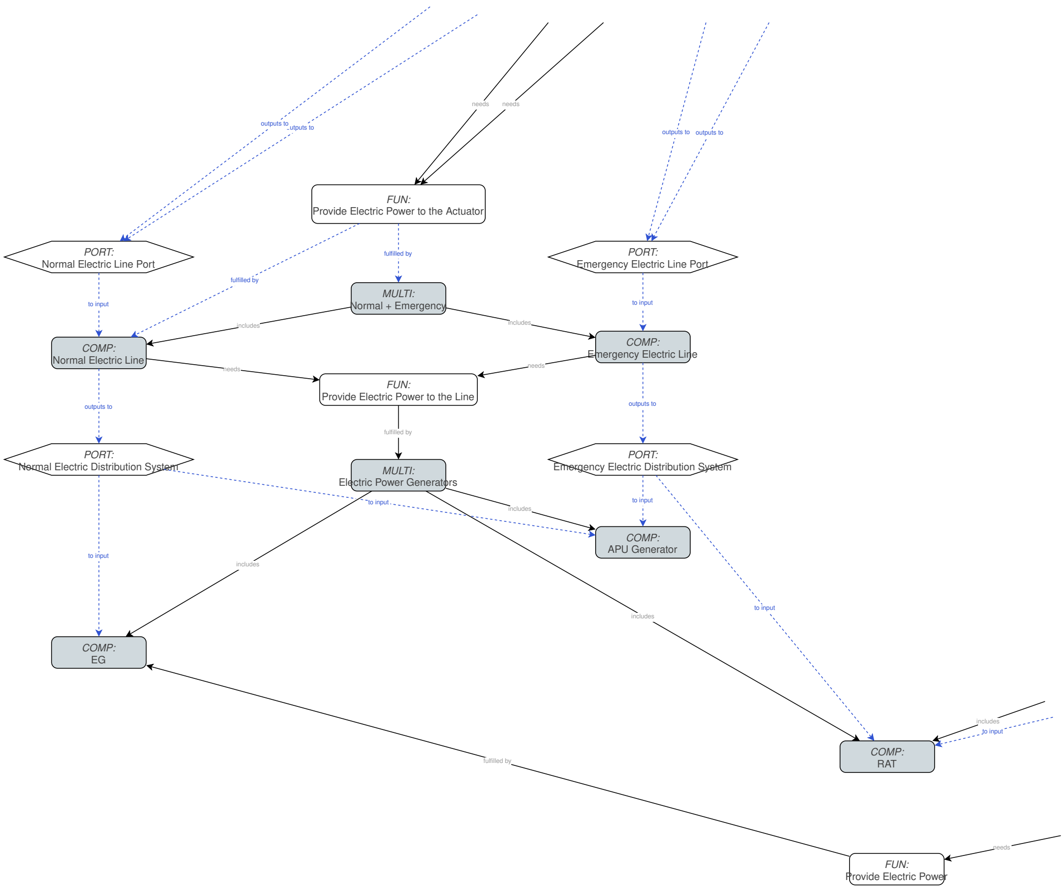


Figure B.3: Electric Power Generation and Distribution in FCS, MaD concept

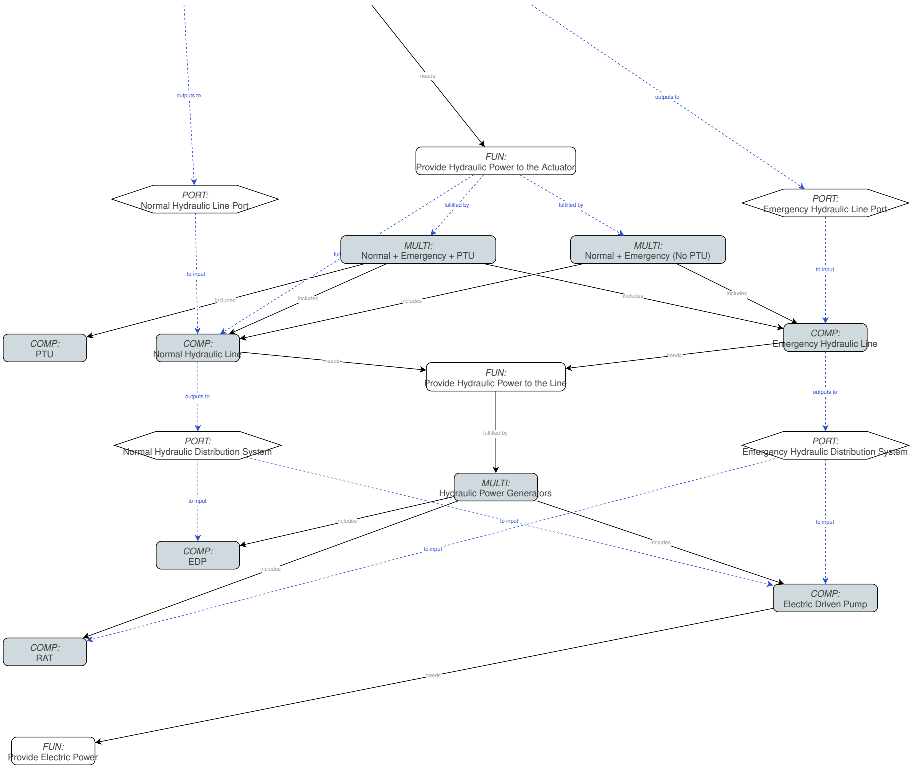


Figure B.4: Hydraulic Power Generation and Distribution, MaD concept

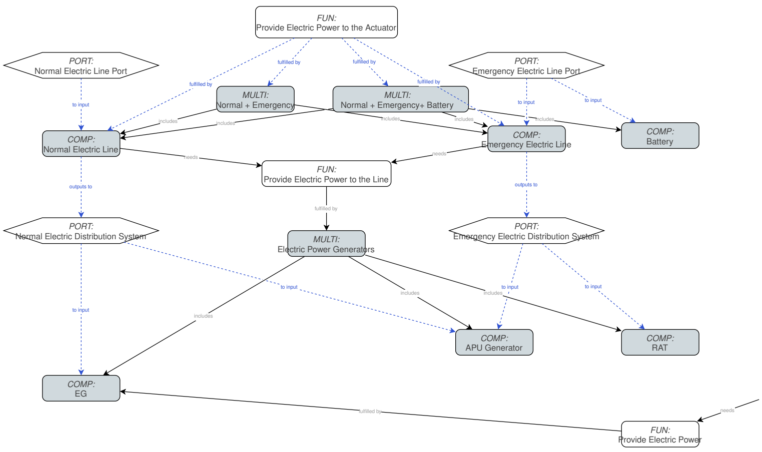


Figure B.5: Electric Power Generation and Distribution in LGS, MaD concept

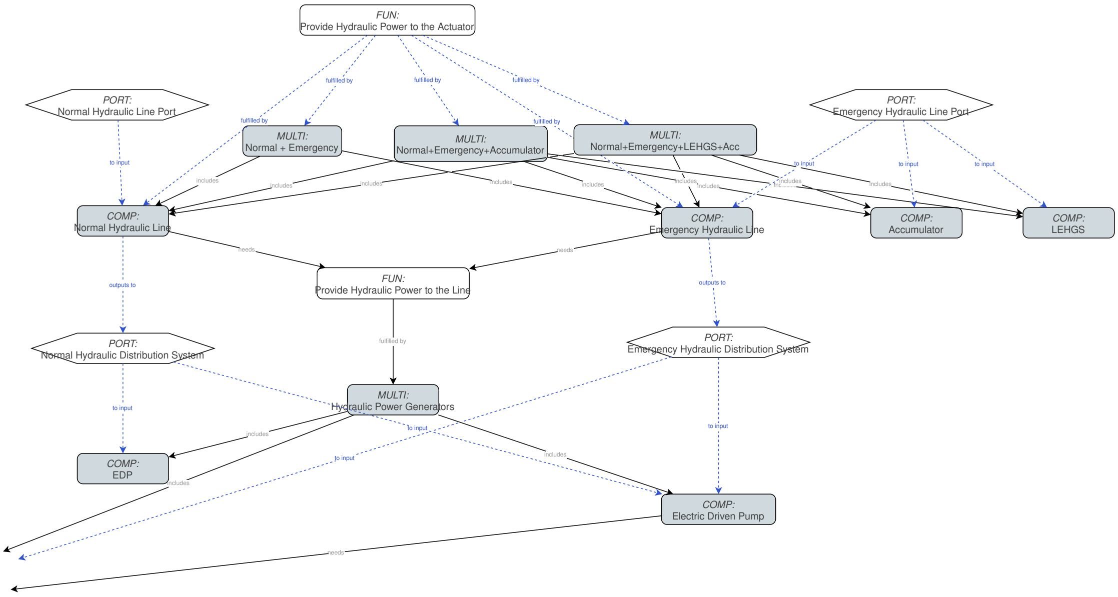


Figure B.6: Hydraulic Power Generation and Distribution in LGS, MaD concept

Route	**FH (h)**	**FH (m)**
STT-STX	0	15
KOI-INV	0	20
ATH-JNX	0	25
ABZ-EDI	0	30
SUV-LBS	0	35
ZTH-ATH	0	45
KOI-EDI	0	50
KKX-KOJ	0	55
ASJ-KOJ	1	0
EDI-LSI	1	5
STI-SJU	1	10
RTA-NAN	1	15
INV-BHX	1	20
SJU-DOM	1	25

Table B.2: ATR 42 routes selected

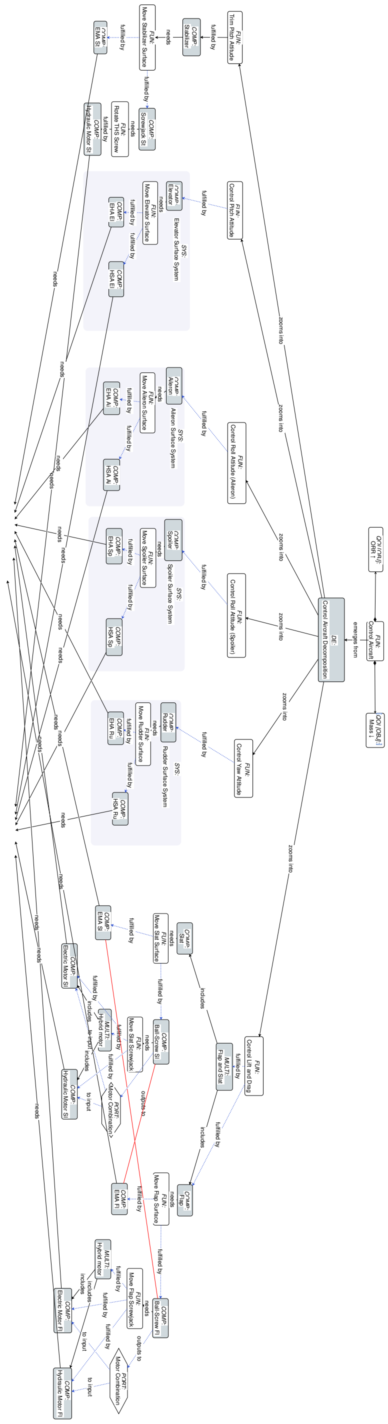


Figure B.7: FCS (the hydraulic and power generation and distribution systems are not shown), SaS concept

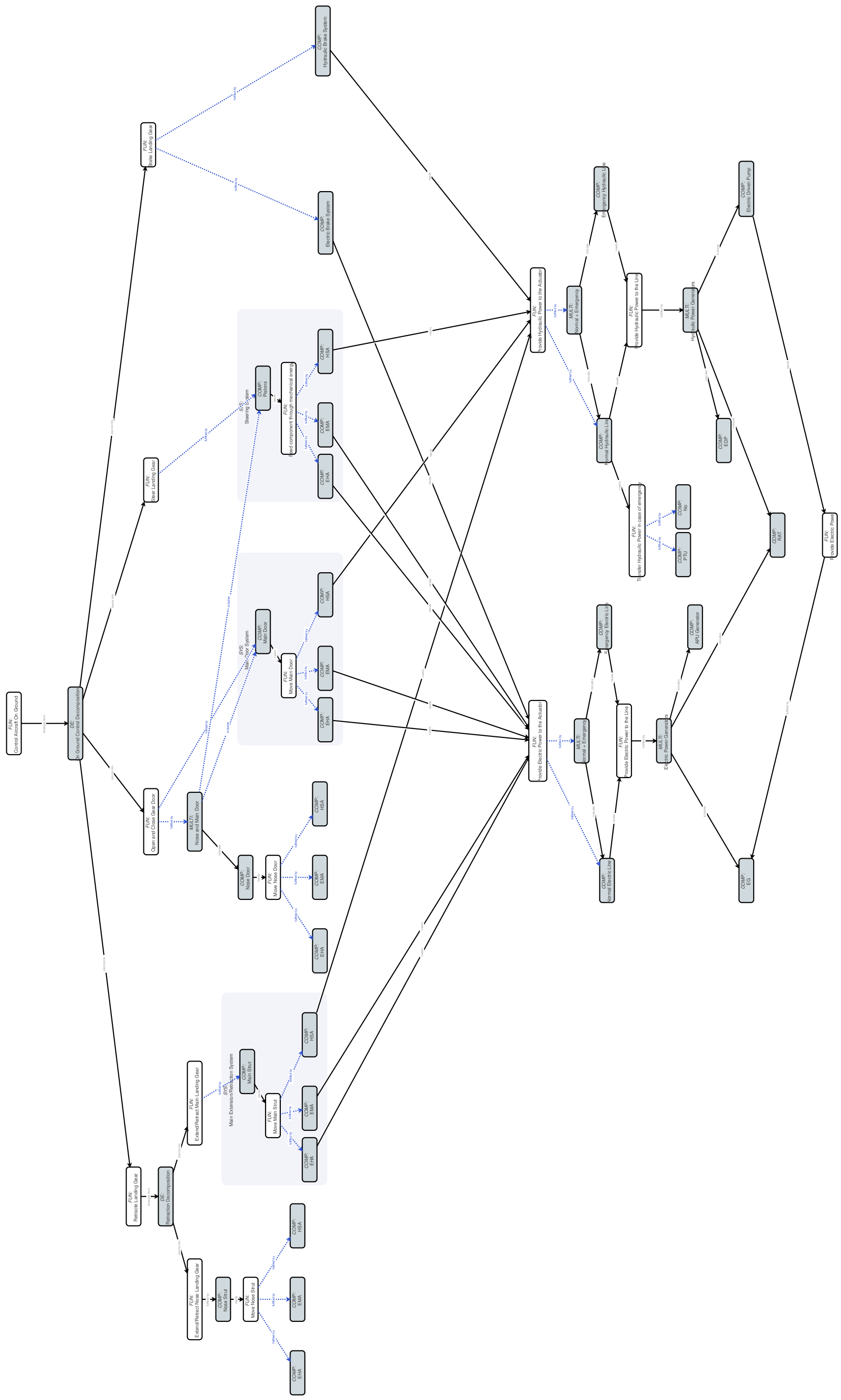


Figure B.8: LGS with power generation and distribution system, SaS concept

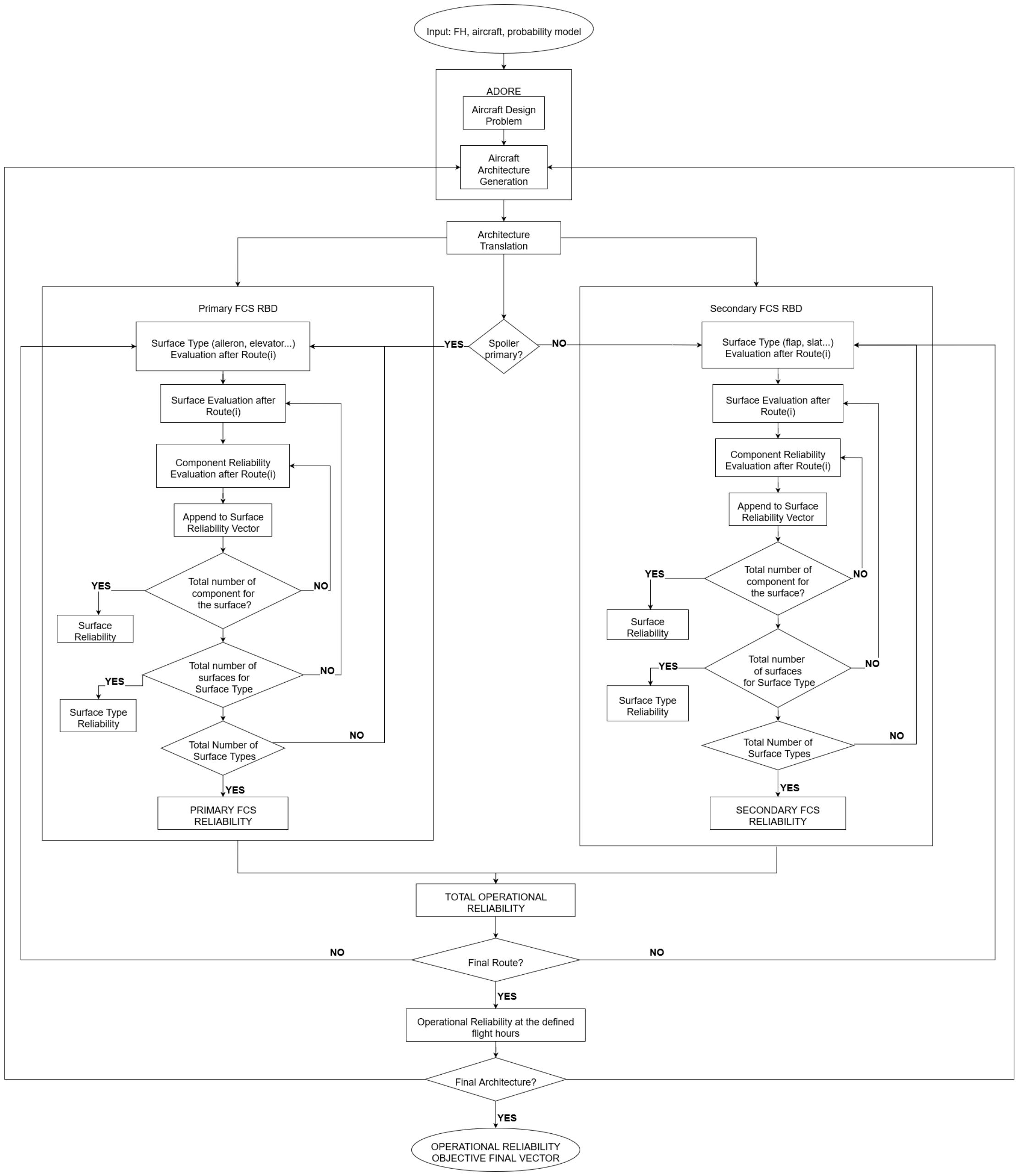


Figure B.9: Operational Reliability workflow for evaluating the best parameters

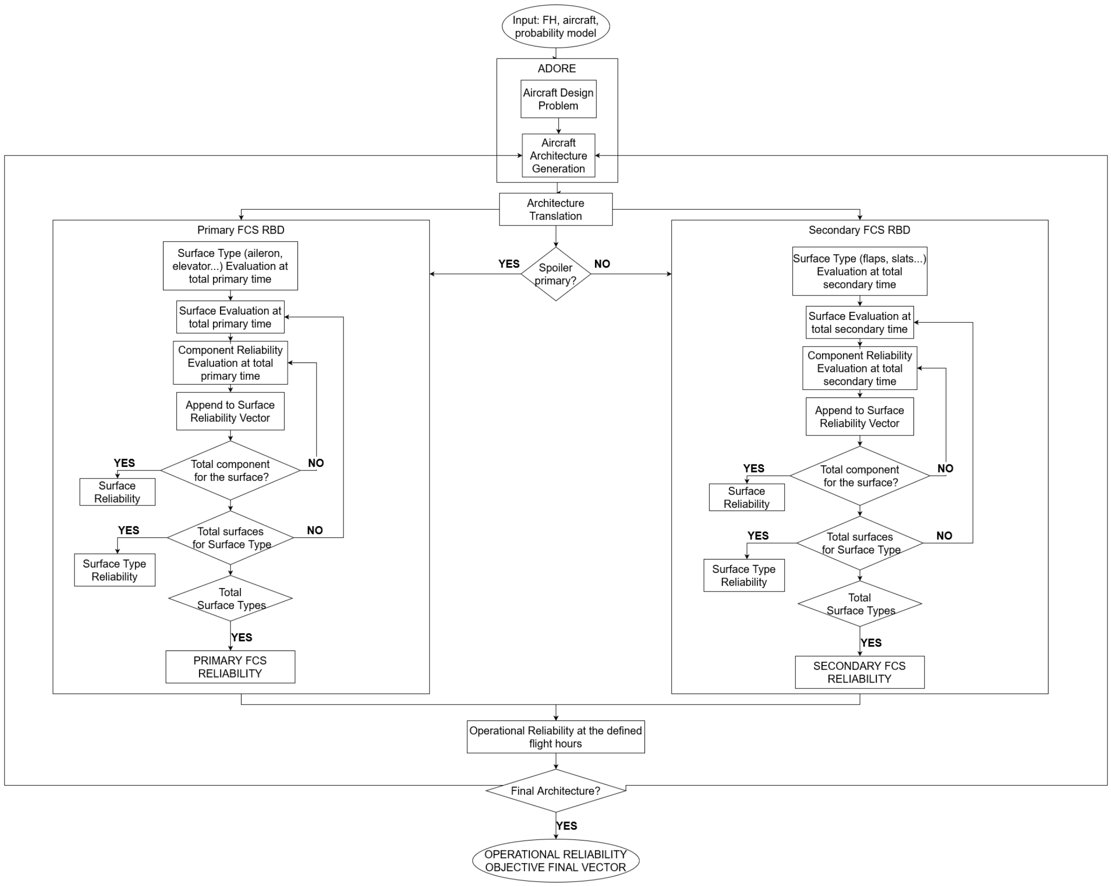


Figure B.10: Operational Reliability workflow for the optimization loop

Bibliography

[1] Jasper H Bussemaker, Pier Davide Ciampa, and Bjoern Nagel. «System architecture design space exploration: An approach to modeling and optimization». In: *AIAA Aviation 2020 Forum*. 2020, p. 3172 (cit. on pp. 1, 2, 47).

[2] Edward Crawley, Bruce Cameron, and Daniel Selva. *System architecture: strategy and product development for complex systems*. Prentice Hall Press, 2015 (cit. on pp. 1, 2).

[3] Patrick O'Connor and Andre Kleyner. *Practical reliability engineering*. John Wiley & Sons, 2012 (cit. on pp. 1, 2).

[4] Marco Fioriti. *Appunti del corso di Gestione dei rischi, costi e supporto logistico integrato dei sistemi aerospaziali* (cit. on p. 3).

[5] Nyoman Gunantara. «A review of multi-objective optimization: Methods and its applications». In: *Cogent Engineering* 5.1 (2018), p. 1502242 (cit. on p. 3).

[6] Edward Wilson and Stephen M Rock. «Gradient-based parameter optimization for systems containing discrete-valued functions». In: *International Journal of Robust and Nonlinear Control: IFAC-Affiliated Journal* 12.11 (2002), pp. 1009–1028 (cit. on p. 3).

[7] Nicole Viola. *Appunti del corso di Sistemi Aerospaziali* (cit. on p. 5).

[8] Ian Moir and Allan Seabridge. *Aircraft Systems: Mechanical, Electrical, and Avionics Subsystems Integration*. 2008 (cit. on pp. 9, 10, 25–29).

[9] MARÉ Jean-Charles and FU Jian. «Review on signal-by-wire and power-by-wire actuation for more electric aircraft». In: *Chinese Journal of Aeronautics* 30.3 (2017), pp. 857–870 (cit. on pp. 11, 12).

[10] Richard PG Collinson. *Introduction to avionics systems*. Springer Nature, 2023 (cit. on p. 11).

[11] Jian Fu, Yongling Fu, and Peng Zhang. «Status and development of electrically powered actuators for aerospace application». In: *CSAA/IET International Conference on Aircraft Utility Systems (AUS 2018)*. IET. 2018, pp. 270–275 (cit. on pp. 12, 13).

[12] Carlos Cabaleiro De La Hoz. *Environmetal Control System and Flight Control System Architecture Optimization from a Family Concept Design Perspective*. 2020 (cit. on pp. 12, 31).

[13] Airbus. *A319-A320-A321 Flight Crew Operating Manual: Flight Control System* (cit. on p. 16).

[14] Embraer. *Embraer 190 - Systems Summary* (cit. on p. 17).

[15] ATR. *ATR-42/72: ATR training and flight operation services* (cit. on pp. 17, 25).

[16] Bereket Kidane. *Design and Analysis of Light GA Aircraft for Agricultural Purpose*. June 2016. DOI: 10.13140/RG.2.1.2889.1766 (cit. on p. 18).

[17] Michael J Kroes and Ronald Sterkenburg. *Aircraft maintenance & repair*. McGraw-Hill Education, 2013 (cit. on pp. 19–22).

[18] Airbus. *A319-A320-A321 Flight Crew Operating Manual: Landing Gear System* (cit. on p. 23).

[19] Airbus. *A380 Flight Crew Operating Manual: Landing Gear System* (cit. on p. 23).

[20] Airbus. *A350 Flight Crew Operating Manual: Landing Gear System* (cit. on p. 24).

[21] Tao Li, Hongxin Wang, Qianting Zhao, Boyang Duan, and Tonggang Wu. «General scheme study for civil aircraft hydraulic power system». In: *CSAA/IET International Conference on Aircraft Utility Systems (AUS 2022)*. Vol. 2022. IET. 2022, pp. 88–92 (cit. on p. 27).

[22] Kelu Xu, Ning Xie, Chengmin Wang, and Xudong Shi. «Modeling and Simulation of Variable Speed Variable Frequency Electrical Power System in More Electric Aircraft». In: *The Open Electrical Electronic Engineering Journal* 11 (Apr. 2017), pp. 87–98. DOI: 10.2174/1874129001711010087 (cit. on pp. 29, 30).

[23] Prince George Mathew. *Model-based system engineering methodology for implementing networked aircraft control system on integrated modular avionics-environmental control system case study*. 2019 (cit. on p. 31).

[24] Michael Sielemann, Tim Giese, Bettina Oehler, and Martin Otter. «A flexible toolkit for the design of environmental control system architectures». In: *Proceedings of the First CEAS European Air and Space Conference*. 2007 (cit. on p. 32).

[25] Marc Budinger, Valrie Pommier-Budinger, Gael Napias, and Arthur Costa da Silva. «Ultrasonic ice protection systems: analytical and numerical models for architecture tradeoff». In: *Journal of Aircraft* 53.3 (2016), pp. 680–690 (cit. on p. 32).

[26] Marco Fioriti, Flavio Di Fede, Sabrina Corpino, Pia Iodice, Giovanni Cerino, et al. «ON-BOARD SYSTEM ARCHITECTURES FOR HYBRID/ALL-ELECTRIC REGIONAL AIRCRAFT». In: *32nd Congress of the International Council of the Aeronautical Sciences, ICAS 2021*. International Council of the Aeronautical Sciences. 2021 (cit. on p. 32).

[27] Qinglin Ma. «Aircraft icing and thermo-mechanical expulsion de-icing technology». In: (2010) (cit. on pp. 32, 33).

[28] RI Jones. «The more electric aircraft—assessing the benefits». In: *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 216.5 (2002), pp. 259–269 (cit. on pp. 34, 35).

[29] Aldo Boglietti, Andrea Cavagnino, Alberto Tenconi, Silvio Vaschetto, and Politecnico di Torino. «The safety critical electric machines and drives in the more electric aircraft: A survey». In: *2009 35th Annual Conference of IEEE Industrial Electronics*. IEEE. 2009, pp. 2587–2594 (cit. on pp. 35, 36).

[30] Marco Fioriti, Luca Boggero, Sabrina Corpino, Alik Isyanov, Artur Mirzoyan, Riccardo Lombardi, and Roberto D'Ippolito. «Automated selection of the optimal on-board systems architecture within MDO collaborative environment». In: *18th AIAA/ISSMO Multidisciplinary analysis and optimization conference*. 2017, p. 3150 (cit. on pp. 35, 37).

[31] Pat Wheeler. «Technology for the more and all electric aircraft of the future». In: *2016 IEEE International Conference on Automatica (ICA-ACCA)*. 2016, pp. 1–5. DOI: 10.1109/ICA-ACCA.2016.7778519 (cit. on pp. 35, 38).

[32] Marco Fioriti, Pierluigi Della Vecchia, and Giuseppa Donelli. «Effect of Progressive Integration of On-Board Systems Design Discipline in an MDA Framework for Aircraft Design with Different Level of Systems Electrification». In: *Aerospace* 9.3 (2022), p. 161 (cit. on pp. 35–37).

[33] Marco Fioriti, Carlos Cabaleiro De La Hoz, Thierry Lefebvre, Pierluigi Della Vecchia, Massimo Mandorino, Susan Liscouet-Hanke, Andrew K Jeyaraj, Giuseppa Donelli, and Aidan Jungo. «Multidisciplinary design of a more electric regional aircraft including certification constraints». In: *AIAA AVIATION 2022 Forum*. 2022, p. 3932 (cit. on p. 37).

[34] Jinsong Liu, Jinri Yang, and Yang Xiao. «Study on electric brake system of civil aircraft». In: *2016 IEEE International Conference on Aircraft Utility Systems (AUS)*. IEEE. 2016, pp. 917–922 (cit. on p. 40).

[35] Mohammad Modarres, Mark P Kaminskiy, and Vasiliy Krivtsov. *Reliability engineering and risk analysis: a practical guide*. CRC press, 2016 (cit. on pp. 40, 41).

[36] Albert F Lowas III and Frank W Ciarallo. «Reliability and operations: Keys to lumpy aircraft spare parts demands». In: *Journal of Air Transport Management* 50 (2016), pp. 30–40 (cit. on p. 41).

[37] He Ren, Xi Chen, and Yong Chen. *Reliability based aircraft maintenance optimization and applications*. Academic Press, 2017 (cit. on pp. 43–45).

[38] Rui Peng, Qingqing Zhai, and Jun Yang. *Reliability modelling and optimization of warm standby systems*. Springer, 2021 (cit. on p. 44).

[39] Jasper H Bussemaker. «Tutorial: Architecture Design Space Modeling using ADORE» (cit. on p. 48).

[40] Carlos Cabaleiro de la Hoz and Marco Fioriti. «New methodology for flight control system sizing and hinge moment estimation». In: *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 236.12 (2022), pp. 2375–2390 (cit. on pp. 59, 61).

[41] Jan Roskam. *Airplane Design: Part 6-Preliminary Calculation of Aerodynamic, Thrust and Power Characteristics*. DARcorporation, 1985 (cit. on p. 59).

[42] Wei-Huang Pan, Yun-Wen Feng, Cheng Lu, and Xiao-Feng Xue. «Adoption of a Bayesian Network for the Operational Reliability Analysis of Aircraft Systems». In: *IOP Conference Series: Materials Science and Engineering*. Vol. 1043. 2. IOP Publishing. 2021, p. 022055 (cit. on p. 61).

[43] Federal Aviation Administration. «Aging Aircraft Evaluation of the Airbus A320 Rudder Control System». In: *CSAA/IET International Conference on Aircraft Utility Systems (AUS 2018)*. FAA. 208, DOT/FAA/AR–07/65 (cit. on p. 70).

[44] Dominique Van Den Bossche. «The A380 flight control electrohydrostatic actuators, achievements and lessons learnt». In: *25th international congress of the aeronautical sciences*. Vol. 1. International Council of Aeronautical Sciences (ICAS) Hamburg, Germany. 2006 (cit. on pp. 69, 71, 80).

Acknowledgements

Un ringraziamento al professor Fioriti, a Carlos, Jennifer e DLR per l'opportunita' di crescita e il continuo supporto durante questi mesi, se il percorso che mi ha portato a svolgere questa tesi e' passato in maniera fluida lo devo anche a voi.

Grazie ai miei genitori e alla famiglia per avere sempre assecondato e cercato di comprendere le mie scelte in questi anni. A Francesca basta ricordare tre parole della nostra infanzia, non serve altro.

Un pensiero a chi mi ha accompagnato nelle diverse tappe, i miei amici. Agli amici di Andria, quelli che ho ritrovato a Torino e quelli che sono dispersi per l'Italia. Agli amici di Torino: l'Artigianelli, il clan perugino e affiliati, Via Belfiore 24. Alla bella gente conosciuta ad Amburgo, in particolare i coinquilini ed i Galletti.

Infine due frasi le meritano anche i luoghi perche' di non-luoghi ne ho visti tanti in questi anni: San Salvario, Santa Giulia, Sternschanze e Grindel, tutti posti in cui ho conosciuto meglio me stesso.