ABSTRACT/RESUMEN

Abstract:
The present Master thesis seeks to develop an optimization method for the geometry of the horizontal stabilizers of the Airbus aeroplanes. The flight certifications impose a set of requirements in terms of stability and control that any aircraft has to comply with. The trapezoidal planform and the area of the stabilizer are constrained by these requirements, as they have a critical influence over the handling qualities of the aircraft. The optimization consists in finding the best stabilizer of the design space that allows the plane to pass the certifications.
In order to perform this optimization without actually flying the aircraft, we use an Airbus tool, E-Motion, that simulates handling quality criteria, outputting the feasibility of the tested stabilizer.
The objective function minimized is a combination of the weight and the drag of the stabilizer. An Airbus preliminary design tool, EP-EH, is used to evaluate this objective.
The implementation of this method is made through the simulation tool I-Sight that provides the engineers with a set of sampling, approximation and optimization methods that can be chosen in function of the needs.
This report presents the construction and the results of this method in the particular case of the Airbus A380. The weight and drag reductions theoretically achieved on the A380’s HTP are respectively of 115Kg (1,9%) and 0,58 drag-count (8,4%).

Resumen:
Este presente Proyecto Fin de Carrera trata de desarrollar un método de optimización para la geometría de los estabilizadores horizontales de los aviones Airbus. Ensayos en vuelo imponen un conjunto de requerimientos sobre la estabilidad y el control que los aviones tienen que cumplir. La forma en planta trapezoidal y el área del estabilizador son restringidos por estos requerimientos, porque tienen una influencia crítica sobre las calidades de manejo de los aviones. La optimización consiste en buscar el mejor estabilizador del espacio de diseño que permite al avión que pase las certificaciones.
Para realizar esta optimización sin realmente volar con el avión, utilizamos una herramienta de Airbus, E-Motion, que calcula criterios de calidad de vuelo, dando en salida la factibilidad del estabilizador probado.
La función objetiva minimizada es una combinación del peso y de la resistencia aerodinámica del estabilizador. Otra herramienta de Airbus, EP-EH esta utilizada para evaluar este criterio.
La implementación de este método se hace con la herramienta de simulación I-Sight que provee a los ingenieros de un conjunto de métodos de muestras, aproximación y optimización de los cuales se puede elegir según la necesidad.
Esta memoria presenta la construcción y los resultados de este método en el caso particular del Airbus A380. Las reducciones de peso y de resistencia teóricamente conseguidas son respectivamente de 115Kg (1,9%) y 0,58 drag-count (8,4%).
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1 GLOSSARY

**AMC**: *Aerodynamic mean chord*. For a lifting surface, it is the width of an equivalent rectangular wing in given conditions.

**Airfoil**: Shape of the wing as seen in cross-section.

**Attitude**: The attitude of an aircraft is its orientation in a defined referential. Attitude can be defined by the pitch, yaw and roll angles.

**Baseline**: A baseline value, aircraft or component refers to a reference used as a starting point for comparisons.

**CFD**: *Computational Fluid Dynamics*. CFD is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows.

**CG**: The centre of gravity of the aeroplane. It is usually given in percentage of the wing AMC.

**CG envelope**: Two-dimensional diagram (aircraft weight vs. CG) featuring the domain in which the airplane must be able to fly in any condition.

**Dihedral**: Angle formed by any lifting surface (wing, HTP) and the horizontal plane.

**DOE**: *Design of Experiments*. I-Sight’s driver for executing a process with various sets of inputs that can be user-provided, randomly generated, or regularly arranged in the space.

**Downwash**: Deflection of the airflow caused by the aerodynamic action of the wings.

**Drag-count**: $1.10^{-4}$ variation of the drag coefficient. This unit is used to study the relative effects of different tradeoffs over the aircraft drag.

**EASA**: *European Aviation Safety Agency*. European agency promoting the common standards of safety and environmental protection in civil aviation in Europe.

**FAA**: *Federal Aviation Administration*. Agency of the US Department of Transportation with authority to regulate and oversee all aspects of civil aviation in the U.S

**Feasible space**: Refers to the part of the design space where all the constraints of the optimization problem are satisfied. A feasible point satisfies all the constraints whereas an infeasible point infringes at least one.

**Fuselage**: Aeroplane’s main body section that holds crew and passengers.
**HTP**: *Horizontal tailplane* (also horizontal stabilizer). Small lifting surface whose purpose is to stabilize and control the aeroplane longitudinally.

**MAC**: See AMC.

**NACA**: (National Advisory Committee for Aeronautics) U.S. federal agency founded in 1915 to undertake, promote, and institutionalize aeronautical research.

**NLR**: *New Long-Range*. Airbus project of long-range airliner replacing the A340.

**OAD**: *Overall Aircraft Design*. Airbus department in charge of assembling the main components of an aeroplane during the design phase.

**Planform**: Shape of the wing as seen from above.

**Tunnel**: A wind tunnel is a tool used in aerodynamic research to study the effects of air moving past solid objects.

**Trim**: To trim an aircraft is to equilibrate it in pitch using the horizontal tailplane.

**VLM**: *Vortex-Lattice Method*. Relatively simple and fast CFD method, neglecting the thickness of the lifting surface and the effects of viscosity.

**VTP**: *Vertical Tailplane*. Also called vertical stabilizer, it has the same role as the HTP but for the lateral stability and control.

**Wetted area**: Area of a wing in contact with the external airflow. It has a direct influence over the overall drag of the aircraft.
2  PREFACE

The choice of doing this master thesis with a company was motivated by the wish of putting in application the knowledge and know-how I have acquired during my years of engineering studies in the world of industry. It was, as well, guided by the attractiveness of contributing to a European-scale challenge, the development of transportation aeroplanes with the world leader in the domain, Airbus. Having already had a good working experience with EADS, and a natural fondness for the world of aerospace, I took Airbus’s offer of a six-month internship at Future Projects Office in Getafe.

Airbus S.A.S., founded in 1970 as *Airbus Industrie*, designs, develops, builds, sells and maintains around half of the world’s jet airliners. Airbus employs 57,000 people and had 27,5 billion Euros in revenue in 2008. It is established in sixteen sites in England, France, Germany and Spain. Airbus is 100% owned by the group EADS.

Among the Airbus’s great successes are the first commercially viable fly-by-wire airliner, the A320, and the world’s largest airliner, the A380.

Although the company benefits from decades of experience in plane manufacturing, it always needs to innovate, create and pay attention to new technologies to stay competitive.

In that spirit, this thesis consists of using, combining and improving various tools to explore and compare design options that have not been studied before, in order to improve aircraft characteristics. It studies the sensitivity of handling qualities, weights and drag towards different design variables and develops an optimization method for the aeroplanes’ horizontal stabilizers.
3 INTRODUCTION

In the Airbus world, the planform of the horizontal stabilizers is, as many other characteristics, the result of many years of experience, creating and designing new aeroplanes. The state of the art in horizontal tailplane optimization is, today, the minimization of the area of the stabilizer, which is usually performed during the late phases of design. No calculation is currently made to systematically seek the best geometry, looking at all the variables at the same time.

The objective of this master thesis is the development of an optimization tool allowing the aircraft designer to optimize all the planform variables, minimizing the weight of the stabilizer, rather than its area.

Such an optimization has become possible, as Airbus departments have developed several programs meeting the requirements. We will see that the optimization problem is defined by a set of constraints, resulting from stability and control requirements, while the weight to be minimized comes from load calculations and structural assembly.

The difficulty lies in interfacing a series of components that cover a large range of disciplines, including aerodynamic calculations, flight simulation and weight evaluation. Our aim is to build a flexible and easy-to-use tool that makes it possible to change from one optimization algorithm to another or one aeroplane study to another, without being a specialist in any of the programs intervening in the process.

Another challenge to take up is the adaptation of this method to various degrees of development of the aeroplane. This study was conducted on the case of the A380, a finished aircraft. We will see how different the problem is and what changes are reflected in the optimization method when tackling a plane in its early development.
4 AEROPLANES AND HORIZONTAL TAILPLANES

4.1 Aeroplanes features and characteristics

4.1.1 Aeroplanes main parts

As shown on the following figure, a conventional airliner is composed of three main parts: the fuselage, containing the cockpit and the cabin; the wings, providing the lifting force for the aircraft to fly; and the empennage, consisting of the stabilizers and the rear fuselage.

![Aircraft main components](image)

*Figure 1: Aircraft main components. Source: [15]*

The engines, fixed to the wing (again, in this conventional configuration), provide a thrust force parallel to the fuselage. This force accelerates the plane, which creates a movement of air all around it. The airflow around the wings’ aerodynamic airfoil creates a difference of pressure under and above them: this generates the lift force, which allows the aircraft to fly.

4.1.2 Axes and control surfaces

In flight dynamics, pitch, roll and yaw angles measure both the absolute attitude angles (relative to the horizon/North) and changes in attitude angles, relative to the equilibrium orientation of the vehicle. These are defined as (see Figure 2):

- Pitch - angle of X body axis (nose) relative to horizon.
- Roll - angle of Y body axis (wing) relative to horizon
- Yaw - angle of X body axis (nose) relative to North.

Each angle has an associated control surface (see Figure 3): Roll is controlled by the ailerons, situated on the wings; yaw is controlled by the rudder, situated on the vertical
Horizontal tailplane optimization

tailplane; pitch is controlled by the elevator, situated on the horizontal tailplane. This last one will be at the centre of this study.

Figure 2: Aeroplane’s axes and attitude angles. Source: [15]

(a) Ailerons: Roll control
(b) Rudder: Yaw control
(c) Elevator: Pitch control

Figure 3: Control surfaces. Source: [15]
4.2 Longitudinal stability and control

The horizontal tailplane (HTP), also called horizontal stabilizer, is a small lifting surface located on the tail (empennage) of the aeroplane.

Stability can be defined when the aeroplane is in trim; that is, there are no unbalanced forces or moments acting on the aeroplane to cause it to deviate from steady flight. If the aeroplane is disturbed, stability refers to its tendency to return to the trimmed condition. During a disturbance, or any deviation from the equilibrium, the HTP produces a pitching moment opposed to the deviation, in order to balance the aircraft.

Control refers to the ability of changing the aeroplane’s attitude and position. A HTP has a hinged flap, called an elevator, allowing the pilot to control the amount of lift produced by the HTP. The action of the pilot causes a nose-up or nose-down pitching moment on the aeroplane that is used to control it in pitch (See 4.1.2).
The elevator is used in basic manoeuvres such as banked turns, take-off, etc. (Figure 5).

**4.3 Stabilizers geometry and properties**

**4.3.1 Parameterization of the planform**

The HTP planform can be considered a trapezium although its actual geometry is more complicated (at the tip and at the joints with fuselage). Mathematically, a trapezium is defined by four independent parameters. In the Airbus world, the four parameters that are commonly used to define the HTP planform are:

- The reference area ($S_{ref}$)
- The aspect ratio ($AR$)
- The taper ratio ($TR$)
- The quarter chord sweep angle ($\Lambda$)

![Figure 6: Geometry of the HTP planform. Source: own](image)

**Equation 1: Aspect ratio and taper ratio**

\[
AR = \frac{\text{span}^2}{S_{ref}} \quad TR = \frac{\text{tip chord}}{\text{root chord}}
\]

Other very useful parameters directly derive from those, and are of great use in certain aerodynamic or mechanical contexts. For instance:

- The span
- The root and tip chords
- The aerodynamic mean chord (AMC)
Equation 2: Derived geometric parameters

\[ \text{span} = \sqrt{S_{\text{ref}} \cdot AR} \]

\[ \text{root} = 2 \cdot \frac{S_{\text{ref}}}{(1 + TR) \sqrt{S_{\text{ref}} \cdot AR}} \]

\[ \text{tip} = 2 \cdot TR \cdot \frac{S_{\text{ref}}}{(1 + TR) \sqrt{S_{\text{ref}} \cdot AR}} \]

\[ \text{AMC} = \frac{2}{3} \cdot \frac{1 + TR + TR^2}{(1 + TR)^2 \sqrt{S_{\text{ref}} \cdot AR}} S_{\text{ref}} \]

### 4.3.2 Other geometric properties of the HTP

As any lifting surface, the HTP has an aerodynamic airfoil. It is not the purpose of this study to look for the optimal one, as this task can be done independently. A critical parameter of the airfoil is its thickness-to-chord ratio, which has a great influence over lift, stall and drag effects. It usually is around ten percent.

![Figure 7: Typical HTP airfoil. Source: Airbus](image)

It is also important to mention that horizontal stabilizers are not actually horizontal as they usually are set with a dihedral angle that is a critical factor in the stability of an aeroplane about the roll axis: The dihedral effect is a rolling moment resulting from the vehicle having a disturbed yaw angle.

![Figure 8: Dihedral angle on a plane. Source: Wikipedia](image)
As a windmill blade, the aerodynamic airfoil of the HTP does not face the airflow with a uniform angle of incidence. This variation of angle along the span is a characteristic called the twist. It allows the redistribution of the lift along the wing, which often has the purpose of ensuring that the wing tip is the last part of the wing surface to stall.

![Wing tip twisted down](image)

*Figure 9: Twisted wing. Source: Wikipedia*

Like the airfoil, the twist and dihedral angles will not be studied in this thesis. However, they are important parameters of the programs we use in our simulations.

### 4.4 Aerodynamic coefficients

#### 4.4.1 Aerodynamic forces

As any wing shape, the HTP is designed to generate aerodynamic forces. When set in airflow, a distribution of overpressure appears all around its airfoil. This field of pressure results in one global force, applied to the centre of pressure of the HTP. The amplitude of this force, its orientation, and the position of the centre of pressure depend on the setting of the HTP (angle of incidence $\alpha_H$), the setting of the elevator (angle of deflection $\delta q$) and the velocity of the airflow (through the Mach number $M$).

![Distribution of pressure and aerodynamic force on an airfoil](image)

*Figure 10: Distribution of pressure and aerodynamic force on an airfoil. Source: Wikipedia*
The projections of this force are, in the airflow direction, the drag $F_X$, and in the orthogonal direction, the lift $F_Z$ (Figure 10).

From these forces can be defined the associated aerodynamic coefficients:

$$\text{Equation 3: Aerodynamic forces on the HTP}$$

$$F_X = \frac{1}{2} \rho v^2 S_{red} C_X (\alpha_H, \delta q, M)$$

$$F_Z = \frac{1}{2} \rho v^2 S_{red} C_Z (\alpha_H, \delta q, M)$$

But the real goal of the HTP is not to produce lift, as it is for the wings. The HTP has a stabilizing and controlling role. The lift force generates a moment around the Y-axis. This moment allows the stabilization and the control of the pitch angle of the aeroplane (see Figure 3c).

$$\text{Equation 4: Pitching moment created by the HTP}$$

$$M_Y (\alpha_H, \delta q, M) = F_Z (\alpha_H, \delta q, M) \times L_H (M)$$

$$= \frac{1}{2} \rho v^2 S_{red} C_Z (\alpha_H, \delta q, M) \times L_H (M)$$

A new parameter appears: the lever arm $L_H$. The moment $M_Y$ is calculated at the reference line of the plane, which is located at the 25% of the wing aerodynamic mean chord. The variable part of the lever arm depends on the position of the centre of pressure of the HTP (that depends on the Mach number).

$$\text{Equation 5: HTP Lever arm}$$

$$L_H (M) = L_H^0 + x_{\text{pressure}} (M)$$

![Figure 11: HTP Lever arm. Source: [17]](image)
4.4.2 Linearization

In order to simulate the aircraft’s static equilibrium, we need to calculate the pitching moment $M_Y$. As we saw, it depends directly on the aerodynamic coefficient $C_Z$. This coefficient has various linear parts and a nonlinear part, what enables us to decompose its expression (thus, to simplify its calculation):

\[
C_Z(\alpha_H, \delta q, M) = \frac{\partial C_Z}{\partial \alpha_H}(M)(\alpha_H - \alpha_H^0(M)) + \frac{\partial C_Z}{\partial \delta q}(M)\delta q + C_Z^{NL}(\alpha_H, \delta q, M)
\]

The Mach number influences critically the slopes of the coefficient’s linear parts towards the angle of incidence and the elevator deflection. When entering the transonic regime, compressibility effects become strong.

**Figure 12:** Lift curve slope on classical NACA airfoils. Source: [7]

**Figure 13:** Typical HTP lift coefficient at a certain Mach number. Source: Airbus
The nonlinear term depends on the Mach number through the stall angles. The nonlinear parts at the negative stalling and at the positive stalling are different (the function is not odd), which is due to the dissymmetry of the HTP airfoil (see Figure 7).

So one can decompose the nonlinear term this way:

Equation 7: Nonlinearity of the lift coefficient

\[ C_{Z}^{NL} (\alpha_{H}, \delta q, M) = \begin{cases} C_{Z}^{NL+} (\alpha_{H} - \alpha_{H}^{stall+} (M), \delta q) & \text{if } \alpha_{H} > 0 \\ C_{Z}^{NL-} (\alpha_{H} - \alpha_{H}^{stall-} (M), \delta q) & \text{if } \alpha_{H} < 0 \end{cases} \]

Equation 7 contains a very important parameter that critically affects the handling qualities of the plane: the stall angle of the HTP, \( \alpha_{H}^{stall} \). If the angle of incidence exceeds this value, turbulent effects appear causing the separation of the flow, a diminution of the lift and an increase of the drag. Stall must be always avoided to keep the plane safe. Stall angles depend a lot on the planform, the airfoil, the Mach number and the deflection of the elevator.

Figure 14 features the lift coefficient of a NACA airfoil, for different values of elevator deflection. The stall angle varies from 12° to 20° depending on the elevator deflection.

Figure 14: Lift coefficient for different deflections of the elevator. Source: [16]
4.4.3 Tabulation of the coefficients

The important thing to keep in mind in this model is that it is intended to reduce as much as possible the dependencies of the basic coefficients in use. These coefficients are stored in aerodynamic tables so that their values can be interpolated for any set of \((\alpha_H, \delta q, M)\) by an external program, such as an aerodynamic model. We could store the entire lift coefficient \(C_Z\) in the database, in form of tables, but two problems would arise:

- It would be a huge volume of data as \(C_Z\) depends on three variables.
- If we had to slightly modify the HTP, we would need to compute again the whole three-dimensional table, whereas by separating the different components of the function we also isolate the physical phenomena.

The conclusion is that the aerodynamic behaviour of the HTP can be described by a set of tabulated coefficients depending on the planform and other parameters:

\[
\frac{\partial C_Z}{\partial \alpha_H}(M), \frac{\partial C_Z}{\partial \delta q}(M), \alpha_H^0(M), \alpha_H^{\text{stall}+}(M, \delta q), \alpha_H^{\text{stall}^{-}}(M, \delta q), x_{\text{pressure}}(M)
\]

We can observe that, for a given HTP geometry, most of those parameters depend only on the Mach number. This is not the case of the lift coefficient \(C_Z\).
5 INDUSTRIAL PROBLEMATIC

This Master thesis does not intend to design an individual and independent product for a certain target market. Its goal is to satisfy a company’s need of improving a component, part of a bigger product.

Therefore, it does not make sense to include certain classical sections, usually featured in more conventional thesis of the ETSEIB, such as a market study section. For this same reason, other issues will be treated in a slightly unusual way, like the costs, benefits and budget part.

Nevertheless, we will expose in this chapter Airbus’s interest for this thesis, its energetic and ecological consequences, and finally, the different costs and benefits linked directly or indirectly to this study.

5.1 Reasons for optimizing the HTP

Optimization can be defined as “the design and operation of a system or process to make it as good as possible in some defined sense”.

Airbus has been designing and manufacturing aeroplanes for years, with no real optimization of the planform of their horizontal stabilizers. For years, having an “optimal HTP” (and in general, “an optimal aircraft”) was not an important need nor was it reachable with the available algorithms and design tools. But the problematic has been changing. Costs have grown critical; noise and energetic efficiency have become sensible issues. At the same time, technology evolved and new tools are now available, making possible the simulations of aircraft evolutions, structure design, or weights evaluation, along with the quick calculation of aerodynamic forces and moments around airfoils.

Optimization is therefore not only technologically possible but is also an economical need.

What’s more, optimization does not have to be seen as an additional burden to be included in the process of the aircraft design. In fact, developing optimization tools allows engineers to reduce a lot the time needed to design the aircraft. Whereas before they would try various configurations and use separate tools to look for a best possible set of parameters, now, optimization allows them to calculate and size whole parts of the aircraft automatically. Optimization not only makes better aeroplanes, it also contributes to make the process faster and more rational.
5.2 Energy consumption and environmental impact

5.2.1 The Breguet range equation

The Breguet range equation evaluates the range of an aircraft in function of basic parameters.

\[
R = \frac{C_L}{C_D} \frac{V}{SFC} \ln \left( \frac{W_L + W_F}{W_L} \right)
\]

- \(R\): Range (miles)
- \(C_L/C_D\): Glide ratio (–)
- \(V\): Cruise velocity (miles/h)
- \(SFC\): Specific fuel consumption (l/h)
- \(W_L\): Landing weight (Zero fuel) (tons)
- \(W_F\): Fuel weight (tons)

For airliners, the glide ratio is usually between 15 and 20. The range, the landing weight, the cruise velocity and the specific fuel consumption usually are design parameters and do not change in case of a modification of the HTP.

Actually, such a change will only affect directly the gliding ratio. And indirectly, to keep the range constant, it will affect the weight of fuel contained inside the aircraft.

For instance, to compensate an increase in drag coefficient of 1%, the term \(\ln \left( \frac{W_L + W_F}{W_L} \right)\) has to increase too of 1%. Logically, increasing the drag implies bringing more fuel.

This simple observation has various economical, energetic and environmental consequences.

5.2.2 Consequences

The first immediate consequence of the Breguet equation is that seeking a HTP of minimal weight is not fully satisfying. Indeed, if the optimal HTP is very light but requires loading the aeroplane with a lot more fuel, we do not make a real gain.

This is why we need to introduce a different objective function. The choice made in this project is to combine the structural weight of the HTP with the drag produced by the HTP.
Taking the baseline design as reference point, we define the equivalent weight of the HTP as the sum of:

- The structural weight of the HTP
- The variation of fuel load brought to keep the range constant (calculated with the Breguet equation and the drag coefficient)

Modifying the HTP then means burning a different amount of fuel and bringing a different payload (thus, a different number of passengers). This has various effects on the airline companies’ costs. To evaluate these consequences, we need to calculate the amount of additional fuel burnt to compensate the drag created by the HTP.

### 5.2.3 Energetic and environmental impact

**Energy needed:**
To take into account this energetic repercussion, we consider the Breguet equation (Equation 9) with the baseline parameters. The cruise speed, specific consumption and lift coefficient are not affected by the change. The range and the sum $W_L + W_F = W_T$ are also supposed to be constant (We study a constant maximum take-off weight on a constant range; what changes is the proportion of fuel in this weight). Equation 10 shows the variation of fuel brought to compensate the variation of drag, as done in [10]:

\[
1 = \frac{C_D + \Delta C_D}{C_D} \ln \left( \frac{W_L + W_F}{W_L} \right)/\ln \left( \frac{W_L + W_F}{W_L + \Delta W_L} \right)
\]

\[
\iff -\frac{\Delta W_F}{W_L} = \frac{\Delta W_L}{W_L} = \frac{W_L + W_F}{W_L} \exp \left( \ln \left( \frac{W_L + W_F}{W_L + W_F} \right) C_D + \Delta C_D \right) - 1
\]

\[
\iff \Delta W_F = -W_L \times \left( \frac{W_L}{W_L + W_F} \right)^{\frac{\Delta C_D}{C_D}} - 1
\]

In the case of the A380:
- $W_L = 386$ tons
- $W_F + W_L = 560$ tons
- $C_D = 0.03$

Equation 10 thus tells us that an increase of one percent of the drag coefficient implies to trade 1.43 tons of payload for the same quantity of fuel.

The aviation fuel (Jet A1) having an energetic content of 43.15 MJ/kg ([6]), the additional energy needed is (still in the case of a 1% increase of $C_D$):

---

Eric Leibenguth
\[ \Delta E = 1430 \text{ kg} \times 43,15 \text{ MJ/kg} = 61,9 \text{ GJ} \]

**CO₂ emissions:**
The environment is affected during the whole life of the aircraft, from conception to recycling. But the main impact occurs during the commercial activity the aircraft, that is, when it regularly flies and burns fuel.

Indeed, the energetic consumption, gases or waste emissions during the fabrication or transport are insignificant compared with the total volumes of gases emitted by the engines during the life of the aeroplane.

Carrying on the previous example, if the A380 gains 1% of \( C_D \), this means 1,43 tons of extra fuel burnt during every “typical” flight. To evaluate the subsequent gas emissions is complicated but we make here a few approximations permitting to have an idea of it.

Kerosene is part of the chemical class of liquid complex carbon hydroxides. In general, the composition is a mix of 8 to 20 alkanes, depending on the type of kerosene. To have an order of magnitude of the amount of the additional CO₂ emissions, let’s consider a 100% decane (alkane C₁₀H₂₂) fuel, and its combustion:

\[ C_{10}H_{22} + \frac{31}{2}O_2 \rightarrow 10CO_2 + 11H_2O \]

The combustion of one mole of decane produces ten moles of carbon dioxide. Decane is 142,3 g.mol⁻¹ and CO₂ is 44 g.mol⁻¹. Thus, the mass of carbon dioxide released in the atmosphere because of the additional drag is:

\[ \Delta M_{CO2} = \frac{10 \times 44 \text{ g.mol}^{-1}}{142,3 \text{ g.mol}^{-1}} \times 1,43 \text{ tons}_{C_{10}H_{22}} = 4,43 \text{ tons}_{CO2} \]

The environmental impact seems to be huge, but on the other hand, a 1% increase of the total aircraft drag is a big number, since we will only slightly change the HTP planform. We will study in the result section how much emissions will really produce the optimized stabilizer of the A380 that come out of the project.

### 5.3 Costs and benefits

The economical question of the costs and benefits of the HTP optimization is too wide to be entirely treated is this thesis. We will only enumerate the main economical repercussions, and focus on a few costs for which we are actually able to set up and use a simple model.
Two main categories emerge:
- The costs and benefits on the Airbus side.
- The costs and benefits on the airline company’s side. These actually have repercussions on the first ones. Indeed, a plane with smaller operating costs can be sold a higher price to the airline companies, which implies benefits for Airbus. However, we will not study this price repercussion.

5.3.1 Costs and benefits for Airbus

Airbus is economically influenced in various ways by the optimization of the stabilizer. There is, first, the actual cost of this thesis. But what really significantly changes is the cost of fabrication.

**Cost of the master thesis:**
The cost of carrying this project is made of:
- The cost of the software used: The only commercial code in the project is I-Sight.
- The cost of employing the student.

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Unitary cost</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-Sight Runtime Gateway license</td>
<td>6 months</td>
<td>200€/month</td>
<td>1.200€</td>
</tr>
<tr>
<td>I-Sight Design Gateway license</td>
<td>6 months</td>
<td>2000€/month</td>
<td>12.000€</td>
</tr>
<tr>
<td>Student grant</td>
<td>6 months</td>
<td>1000€/month</td>
<td>6.000€</td>
</tr>
<tr>
<td><strong>Total cost</strong></td>
<td></td>
<td></td>
<td>19.200€</td>
</tr>
</tbody>
</table>

**Benefits of the HTP optimization:**
The cost of producing a horizontal tailplane has to include every cost from the construction of the factories, the design of the parts of the HTP (fixed costs) to the costs of the salaries, the materials, the energy and the transport (variable costs).

The money saved thanks to the optimization is the difference between the cost of the baseline design and the cost of the optimal design. To calculate precisely such a cost in this thesis is, of course, out of the question. However, a common acceptable approximation is to assume that the cost of production is directly proportional to the weight of the HTP. In the case of the A380, the ratio is around 1.000 dollars per kilogram.

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Unitary cost</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production costs saving (for 1kg saved)</td>
<td>1kg/aircraft</td>
<td>1000$/kg</td>
<td>1.000$/aircraft</td>
</tr>
<tr>
<td><strong>Total benefit (for 1kg saved)</strong></td>
<td></td>
<td></td>
<td>1.000$/aircraft</td>
</tr>
</tbody>
</table>

A 100kg saving on the A380’s HTP then means an approximate 100.000$ saving per plane for the company (the price of an A380 is 325.000.000$). We will evaluate this economical repercussion in the result section (when we know how much weight is saved).
Other benefits may result from the change of the plane’s price. If the new design allows the airline companies to save money, the plane can be sold at a higher price, or in greater numbers. However it is impossible to evaluate this kind of benefit at this level.

5.3.2 Costs and benefits for the airline company

Operating costs:
As exposed in [11], the direct operating cost per trip for airline companies is the sum of:
- The fuel cost.
- The flight desk and cabin crew cost.
- The aircraft maintenance cost.
- The landing and navigation fee.
- Depreciation, interests and insurance.

Among these, all can be slightly affected by the HTP optimization. Indeed:
- As it reduces the fuel consumption, the fuel cost is lowered.
- As the payload/number of passengers grows, the cabin crew cost rises.
- The weight of the empty aeroplane is reduced, which decreases maintenance costs and slightly influences the other costs.

The energetic study on the A380 made in 5.2.3 showed that a one-percent reduction of drag implied a reduction of 1.43 tons of fuel and a gain of 1.43 tons of payload. This observation means that the same one-percent drag reduction triggers a reduction of the fuel cost and an augmentation of the cabin crew cost.

Taking a typical fuel price of 800$ per metric ton, we obtain a saving of:
\[1.43\text{tons} \times 800$/\text{ton} = 1147$\]

The other cuts in the costs are too complicated to be calculated here, but anyway, the biggest gain lying in the operating costs is due to the fuel cost saving.

Benefits:
The saving of 1.43 tons of payload corresponds to approximately 14 passengers (depending on the company), which means a significant increase of the incomes. It is too complicated to evaluate this economical repercussion in detail, as the airline company can choose from many strategies to impact this gain. But one can easily observe that 14 additional passengers on a 500$-ticket flight is definitely interesting for the company.

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Unitary benefit</th>
<th>Benefit ($/trip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel costs saving (for 1% drag reduction)</td>
<td>1,43 tons/trip</td>
<td>800$/ton</td>
<td>1.147</td>
</tr>
<tr>
<td>Passengers gain (for 1% drag reduction)</td>
<td>14 pas./trip</td>
<td>500$/ticket</td>
<td>7.000</td>
</tr>
<tr>
<td>Total benefits (for 1% drag reduction)</td>
<td></td>
<td></td>
<td>8.147</td>
</tr>
</tbody>
</table>
6 HANDLING QUALITIES CRITERIA

6.1 Origins and history of Handling Qualities

6.1.1 Definition

In 1969, test pilots George Cooper and Raymond Harper defined handling qualities as “those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.”

Handling qualities involve the study and evaluation of the stability and control characteristics of an aircraft. They have a critical bearing on the safety of flight and on the ease of controlling an aeroplane in steady flight and in manoeuvres.

This project treats only the optimization of the HTP. Therefore, it only deals with longitudinal stability and control, which are part of the aircraft handling qualities.

6.1.2 Certifications

In order to be authorized to do commercial flights, an aircraft must pass the certification step. The European Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA) are respectively the European and American institutions that grant certifications to the airliners manufacturers, authorizing their aircraft to fly in their continents.

Both publish books of norms and specifications that the airliners must comply with. Handling quality requirements are evaluated during flight tests. These tests are varied and cover all the critical situations in which the aeroplanes can reasonably be.

Here is an example from [9]:

(2) Longitudinal control, flap extension, § 25.145(b)(1).

(i) Configuration:
   - Maximum landing weight or a lighter weight if considered more critical.
   - Critical CG position.
   - Wing flaps retracted.
   - Landing gear extended.
   - Engine power at flight idle.

(ii) Test procedure: The airplane should be trimmed at a speed of 1.4VS. The flaps should be extended to the maximum landing position as rapidly as possible while maintaining approximately 1.4VS for the flap position existing at each instant throughout the manoeuvre. The control forces should not exceed 50 lbs.
maximum force for short term application that can be applied readily by one hand) throughout the manoeuvre without changing the trim control.

These procedures can evolve, but they generally keep the same philosophy. American and European specifications have the same kind of formulation, although the procedures can be slightly different. To understand the concept of “critical CG (center of gravity) position”, we must introduce the notion of CG envelope:

The CG envelope is drawn on a graph showing the way the center of gravity may vary with the gross weight of an aircraft. Any combination of weight and center of gravity position that falls within this envelope is an approved loading condition for that aircraft.

![Figure 15: CG envelope for the Airbus A350-900. Source: [17]](image)

For a conventional commercial transport aeroplane, the centre of gravity should usually be located between 15% and 40% of the aerodynamic mean chord (AMC):

![Figure 16: Centre of gravity extreme positions. Source: [17]](image)

A key idea in flight tests is that the aircraft shall always be put in the worst possible configuration. That means, among other things, that the centre of gravity should always
be located at the most forward or backward authorized position, depending on the performed manoeuvre.

6.1.3 Flight simulations

Of course, the flight tests take place when the airliner is fully designed. So, if it fails this certification step, the consequences in terms of redesign of the aircraft must be as small as possible. On the other hand, aeroplanes cannot be conceived with gigantic margins of safety; better manoeuvrability calls for bigger control surfaces, which means higher weights and higher costs. Then, the manufacturer’s objective must be to design the aircraft so that it complies with the safety specifications with the smallest costs, which usually means with the smallest margins towards the handling quality requirements.

This implies that, during the design phase, the engineers must know as much as possible how the aircraft will respond during the flight tests. Reproducing the flight tests conditions numerically allows the engineers to size the control surfaces with the smallest acceptable dimensions.

This is the idea of E-Motion, the Airbus tool for handling quality optimization. E-Motion performs “handling qualities criteria” simulations, which reproduce the critical conditions that the aeroplanes will face during their certification. It allows the engineers to test the performances of the aircraft varying key parameters, such as the surface of the HTP.

6.2 Handling qualities criteria

6.2.1 Definition of a criterion

The principle of E-Motion is to put a virtual aeroplane into a set of critical situations, called criteria, which reproduce the exigencies and requirements of the certifications. A criterion can be very complicated and advanced, or, on the contrary, quite simple. The level of complexity depends on the precision and realism of the simulation. A more accurate simulation will not be necessarily more restrictive; but it will provide a more reliable result.

In the first version of E-Motion (the one used in this study), the criteria simulations are made of static equilibrium of the aircraft.

A static criterion, as those of the first version of E-Motion, is defined by a set of parameters (e.g. flap configuration, HTP setting, elevator setting, etc.) and a set of unknown variables (e.g. altitude, speed, angle of incidence, extreme centre of gravity position, etc.). The flight equations constitute a solvable system, and its solutions can be compared to the requirements to evaluate the handling qualities. Typically, the extreme
position of the centre of gravity is calculated and compared to the CG envelope of the plane (Figure 15). If the extreme CG computed is inside the envelope, it means the aircraft is not fully controllable or stable in a certain domain of the envelope, and then it will fail passing the certification at some point.

6.2.2 Typical longitudinal criteria

We will only describe here a few typical criteria. Others exist and these can actually have many variants. These descriptions come from [2]:

**Trim the aircraft:**
It is a series of criteria consisting in trimming the aircraft. They are performed through the entire flight domain with the elevator deflection at the 0° position and the HTP in the most penalizing deflection. The aim of those criteria is to find the maximal/minimal CG position with which the aircraft can be trimmed without using the elevator (elevator deflection at 0°) and keeping the trim deflection in the maximal deflection range.

- “Trim glide” (Trimming at low speed)
- “Trim idle” (Trimming with no thrust)
- “Trim stall” (Trimming at stalling angle of attack)
- “Trim take off” (Trimming at take off)
- “Trim turn idle” (Trimming during a 45% turn)

**“Push over”:**
Manoeuvre in which the pilot has to abruptly dive in the approach phase (he pushes the stick forward), causing negative loads on the plane. To compensate this and to equilibrate the aircraft, the HTP is set with a very negative angle of deflection. This criterion makes sure that the HTP angle of attack does not become higher than its stall angle.

**“Manoeuvre point”:**
This criterion makes sure the aircraft can be trimmed and equilibrated at high speed, where dynamic instability can appear and become a serious issue. The bigger the plane, the more critical becomes this problem. Thus, it is the sizing criterion for the A380.

**“CEV”:**
The CEV is flight case in which the HTP is not well trimmed and is stalling. The criterion makes sure that the aircraft has enough control power to come back to a safe angle of incidence.

6.2.3 Computation of the criteria

The criteria are not all computed the same way; they all have their own process. But they all seek a common goal: finding the extreme CG position in order to compare it to the CG envelope.
To do so, E-Motion calculates a series of equilibrium from which the most sizing case is kept. Typically, E-Motion will compute the criteria for a given set of aircraft masses. A few criteria also require a sampling towards the Mach number, or other parameters.

The principle of equilibrium calculations lies in the resolution of the fundamental dynamic equations (sum of the forces and sum of the moments):

\[ \dot{x} = \frac{1}{m} \sum F(x, \dot{x}, \theta, \dot{\theta}, u) \quad \text{and} \quad \dot{\theta} = \frac{1}{I} \sum M(x, \dot{x}, \theta, \dot{\theta}, u) \]

\( x \): position of the aircraft
\( \theta \): attitude of the aircraft
\( F, M \): external forces and moments on the aircraft
\( m, I \): mass and inertia of the aircraft
\( u \): command vector (thrust, deflection angles, etc.)

The resolution is performed using the state vector and its derivative:

\[
X = \begin{pmatrix} x \\ \dot{x} \\ \theta \\ \dot{\theta} \end{pmatrix} \quad \dot{X} = \text{statedot}(X) = \begin{pmatrix} \dot{x} \\ \frac{1}{m} \sum F(X, u) \\ \dot{\theta} \\ \frac{1}{I} \sum M(X, u) \end{pmatrix}
\]

Depending on the criterion, certain variables are known and others are unknown. In the same spirit, some commands are known and others are unknown (thrust, deflection angles, etc.). The position of the centre of gravity can be inferred directly or indirectly from the resolution.

**Figure 17: Architecture of E-Motion. Source: own**
6.3 From Handling Qualities to design spaces

The design space, for the HTP, is the space of all the possible geometries that can have the HTP. Given an aircraft and all its characteristics, the design space can be divided in a feasible space, in which all the flight tests can be performed successfully, and an infeasible space, in which it is not the case. Optimizing the HTP consists in choosing the “best” point inside the feasible space.

In E-Motion, we compute a set of criteria with different masses, we find the extreme CG positions for each couple (criterion, mass) and we compare them with the CG envelope. If a point is inside the envelope, it means a criterion fails for at least one mass: this is an infeasible HTP.

The distance between the CG position and the CG envelope defines a margin. A margin can be defined for every couple (criterion, mass). If all the margins are positive, no criterion has failed: the HTP is feasible.

![Figure 18: CG envelope of the A380 with criteria. Source: [1]](image_url)

The CG margins are natural mathematical inequality constraints of our optimization problem. Every criterion performed by E-Motion is a constraint, and the value of this constraint is the minimal (most restrictive) margin among the computed mass cases.

The calculation of the constraints is half of the optimization problem, the other half being the calculation of the objective function, which in our case is the equivalent weight of the HTP.
7 WEIGHT CALCULATIONS

In the aerodynamic industry, the weights are critical; it is always necessary to take them into account when designing or modifying parts of an aeroplane. The lighter an airliner is, the cheaper it costs and the further it flies.

In this project the structural weight of the HTP is part of the function we want to minimize. It is therefore necessary to calculate it as we calculate the handling quality margins.

However, finding a way of performing this calculation is not among the objectives of this project, as Airbus already disposes of a tool able to do this task. This tool, programmed in Fortran 77, runs in approximately six seconds and is named “EP-EH” (Evaluator de Peso – Empennage Horizontal). We will briefly describe this tool in this section in order for the lector to be able to understand where the weight calculations come from.

The important thing to keep in mind is the basic architecture of EP-EH:

![Figure 19: Architecture of EP-EH. Source: own](image)

**7.1 Aerodynamic calculations**

The first step in the process is the calculation of an aerodynamic database for the aircraft and its tail. A module named “EP-AERO” performs this task. The next module needs this data in order to run simulations of load cases.

As inputs, EP-AERO needs a few geometry files and parameters (wings and HTP airfoils, twist distributions and planform parameters). EP-AERO is based on a vortex-lattice method (VLM).

The VLM is a numerical computational fluid dynamics (CFD) method, used mainly in the early stages of the aeroplane design. The VLM models the lifting surfaces, such as an aircraft wing, as an infinitely thin sheet of discrete horseshoe vortices (see [14]), to
compute lift and induced drag. The influence of the thickness, viscosity and other effects, is neglected.

Figure 20 shows the discretization of a wing. The enlarged panel shows how the vortex horseshoe is positioned in respect to the collocation point where the boundary condition will be met.

![Figure 20: The vortex lattice method. Source: [14]](image)

The VLM is not as good as finite elements methods, but it has the benefit of running way faster. In the case of EP-EH, which is a preliminary design tool, we are not supposed to seek perfect precision, but rather a quick approximation of the reality that allows us to make more complicated things afterwards. The VLM is a linear method. It cannot generate the nonlinear parts of the coefficients. And it does not seize the compressibility effects appearing in the transonic regime.

To have more reliable data, EP-AERO modifies the results of the VLM with a semi-empirical method using results of tunnel experiments and flight tests. These empirical methods add nonlinear parts to the previously calculated coefficients.

The outputs of EP-AERO are concretely ([3]):

- Wing aerodynamic coefficients \( (\alpha_0, \frac{\partial C_Z}{\partial \alpha}, C_{m0}, x_{ca}) \)
- HTP aerodynamic coefficients \( (\alpha^H_0, \frac{\partial C_Z^H}{\partial \alpha^H}, \frac{\partial C_{m0}^H}{\partial \delta q}, C_{n0}^H, x_{ca}^H) \)
- Downwash coefficients \( (\varepsilon_0, \frac{\partial \varepsilon}{\partial \alpha}, \frac{\partial \varepsilon}{\partial n}, \frac{Q_T}{Q}) \)
- Stall angles
- Spanwise aerodynamic distributions

All of them are tabulated in function of the Mach number. Usually, 15 to 20 values of Mach number are used.
7.2 Evolutions and loads

7.2.1 Load cases

The EVOL module mission is to perform the loads calculation through the simulation of evolutions (load cases). This module simulates aircraft equilibriums during critical flight cases. It calculates all the loads along the wing and HTP spans for each case. For the sizing procedure, only the most critical load case will be used. That is to say, the dimensions of the components (skin thickness, spars and ribs resistance...) depend on the worst load situation that can reasonably happen.

The loads cases are a set of certain manoeuvres that the aeroplane shall be able to perform. On top of the variety of these manoeuvres, they are simulated in numerous configurations of: mass and centre of gravity position, altitude and thrust.

Typical manoeuvres are:

*Pitching, rolling and yawing:* When in cruise flight, the lift generated by the HTP is small, if not nil. But when the aircraft is turning or otherwise manoeuvring, the lift increases and can become critical. Especially because of the extra lift created by the elevator.

*One Engine Off (OEO) manoeuvres:* In order to certificate an airliner, it must be proven that it is able to fly and perform certain manoeuvres with one inoperative engine. This condition is more critical for the vertical stabilizer (VTP), because it must compensate a huge moment caused by the thrust dissymmetry. However, these manoeuvres also affect the HTP and must be taken into account.

*Gust manoeuvres:* Air turbulences cause changes in direction and speed (velocity) and these will create gust loads on the aircraft, within a short duration of time. If these rapid loads exceed the maximum load factor an aircraft, they can cause buckled skin or worse.

7.2.2 Loads

EP-EVOL module values the empennage loads in terms of:

- Shear force
- Bending moment
- Torque moment

The calculations are made through a discretization of the HTP in various sections. Figure 21 shows the HTP and the calculated forces and moments.
For each manoeuvre the aircraft is trimmed. That is to say the deflection angle of the HTP $i_H$ is calculated in order to balance the aeroplane for the given evolution. Then the loads are calculated along the span. The most critical load set is transmitted to the following MASS module.

### 7.3 Sizing of the HTP

When the most critical manoeuvre has been identified, and the associated loads calculated, the MASS module evaluates the weight of the HTP. To do so, it virtually assembles its constitutive elements, sizes them, and calculates their weights.

Figure 22 shows the architecture of the structure of a horizontal stabilizer. The MASS module can design such a structure and create a layout of the components, following a set of rules.
Figure 22: Horizontal tailplane architecture. Source: [8]

Figure 23 features the following constitutive elements of the HTP structure:
- **Skin panels**: the external part in contact with the airflow.
- **Wing ribs**: transversal parts supporting the skin (regularly set along the span).
- **Spars**: longitudinal components supporting the ribs (only two: front and rear spars).
- **Other structural items**

Figure 23: Horizontal tailplane elements. Source: [5]
Design parameters of this architecture are very important in the weight calculations: For instance, the points of the chord where the rear and front spars are, or the distance between two consecutive ribs. During this study, these are fixed as parameters of the model. But they could, and actually must, be the result of an optimization process. The code that designs the HTP is complicated and it is not the purpose of this project to study its details. It uses material properties (mass, resistance, etc.) and the sizing loads (shear force, bending and torque moment) to determine the minimal size of each component. Then it values these sizes in terms of masses, whose sum constitutes the structural weight of the HTP.

7.4 Equivalent weight

As exposed in 5.2, minimizing the weight of the horizontal stabilizer is not enough. We are interested in taking into account the drag created by the HTP. For this purpose, we introduced the equivalent weight, sum of the structural weight and the fuel load needed to compensate the drag created by the HTP.

The weight of this fuel is calculated through the Breguet Equation (Equation 9), and more precisely, through a coefficient derived from this equation. The idea is to obtain a linear relation between the weight and the drag coefficient. The variation in drag coefficient is quantified in “drag count” (1 drag count = 1.10⁴ variation in C₀).

\[
\text{Equation 14: Linear relation between weight and drag variations}
\]

\[ K = \frac{\Delta \text{weight (kg)}}{\Delta C_D (\text{drag count})} \]

Equation 14 features:
- The variation in weight that we want to calculate.
- The variation in C₀ is the drag coefficient of the HTP.
- K is a constant parameter calculated once and for all with the Breguet equation, from baseline parameters.

The parameter K comes from the differentiation of the Breguet equation:

\[
\text{Equation 15: Differentiation of the Breguet equation}
\]

\[
dR = \frac{V}{\text{SFC}} \left[ d \left( \frac{C_L}{C_D} \right) \ln \left( \frac{W_L + W_F}{W_L} \right) + \frac{C_L}{C_D} d \left( \ln \left( \frac{W_L + W_F}{W_L} \right) \right) \right]
\]

\[ \Leftrightarrow \quad dR = \frac{V}{\text{SFC}} \left[ - \frac{dC_D}{C_D} \frac{C_L}{C_D} \ln \left( \frac{W_L + W_F}{W_L} \right) - \frac{C_L}{C_D} \frac{dW_L}{W_L} \right] \]
\[ \frac{dR}{R} = -\frac{dC_D}{C_D} + \frac{1}{\ln \left( \frac{W_L + W_F}{W_L} \right)} \frac{dW_L}{W_L} \]

Taking \( dR = 0 \) (max range), we obtain:

\[ \frac{dW_L}{dC_D} = \frac{W_L}{C_D} \ln \left( \frac{W_L}{W_L + W_F} \right) = K \]

Taking, for the Airbus A380, the nominal parameters:

- \( W_L \) = Operational Weight Empty + Payload = 277.5 tons + 70.6 tons
- \( W_L + W_F \) = Maximum Take-Off Weight = 560 tons
- \( C_D \) = 254 drag-counts

We obtain \( K = 652 \) kg / drag-count.

The drag coefficient of the HTP is calculated through semi-empirical equations, in view of the fact that the CFD we use is too basic to provide the drag force. The drag can be decomposed in two parts:

- The induced drag (which, ideally, is equal to zero in cruise regime for the HTP)
- The parasitic drag (related to the wetted area, the shape factor and the skin friction coefficient)

We only keep the second part, which gives us:

**Equation 16: Parasitic drag coefficient**

\[ C_D = k.C_f \cdot \frac{S_{wet}}{S_{ref}} \]

with:

- shape factor for swept wings \( k = 1 + 3.52 \frac{L}{c} \times \cos^2 (\Lambda_{0,5}) \)
- skin friction coefficient (Von Karman fit) \( C_f = \frac{0.455}{\log(Re)^{2.58}} \)
- Wetted area \( S_{wet} \) and reference area \( S_{ref} \)

The equivalent weight’s expression is finally:

**Equation 17: Equivalent weight’s expression**

\[ W_{\text{equivalent}} = W_{\text{structural}} + K.C_D^{HTP} \]
8 THE OPTIMIZATION PROBLEM

8.1 Definition

Mathematically, an optimization problem is defined by:

- A set of optimization variables.
- An objective (or criterion) to minimize (or maximize).
- A set of constraints (or restrictions) that may be equalities or inequalities.

Both objective and constraints depend on the variables. The space in which the variables satisfy the constraints is called the feasible space. The point of the feasible space where the objective is minimal is called the optimum.

In our case:

- The variables are the four geometric parameters that define a unique HTP planform: the surface $S_{ref}$, the aspect ratio $AR$, the taper ratio $TR$ and the quarter chord sweep angle $\Lambda$ (plus the minimum angle of deflection of the HTP, $i_{h\min}$).
- The objective is the equivalent weight of the HTP computed by EP-EH (although, depending on the point of view, the objective could also be the surface, the weight or the cost).
- The constraints are the margins of each handling quality criterion computed by E-Motion (if all the margins are positive, the criteria are satisfied: The HTP planform is in the feasible space).
- All the wing and fuselage data of the aircraft that are needed to compute the weight and/or the criteria are parameters. That is to say, they cannot change during the optimization.

8.2 Optimization algorithms

Many methods and algorithms exist to solve optimization problems defined like the previous one. The choice of a well-adapted algorithm is very important, as it will strongly influence:

- The actual convergence to an optimal solution.
- The speed of convergence.
- The knowledge we get of the explored design space.

The regularity of the objective function and the constraints, the number of variables, the desired precision and the speed we want to work with dictate the nature of the optimizer.
In our case, although the functions present macroscopically a linear aspect, they really are not microscopically regular enough to use a linear programming method (like the well-known simplex algorithm).

We mostly use two major types of methods:
- Nonlinear programming based on gradient methods
- Exploratory techniques (Response surfaces or genetic algorithm)

To explain these methods and their field of application, we will study a generic constrained optimization problem defined as:

\[
\text{Equation 18: Generic optimization problem}
\]

\[
\min_x f(x) \quad \text{s.t.} \left(b_i(x) \geq 0\right)_{1 \leq i \leq n}
\]

Equation 18’s problem could be formulated like this:

“Minimize the function \(f(x)\) such that the functions \(b_i\) are positive or nil at the optimum.”

### 8.2.1 Gradient-based methods

These methods are very numerous. We will not study the details of every one of them, but simply expose their common point, and explain in which cases they are adapted to solving our optimization problem.

The general idea of the gradient-based method is, starting from an initial guess point, to evaluate the objective function and the constraints, then to move of a \(\epsilon\) in every direction of the space and then to evaluate the functions again in order to compute their gradients by finite differences. Further on, using other available information on these functions (previous iterations, derivatives of higher order, etc.), move to a better point according to a certain strategy. This process iterates until no improvement can be made.

In the case of the Equation 18’s problem, the process is:

\[
\text{Taking } x_0 \text{ as the initial guess,}
\]

\[
\begin{align*}
\text{compute } \quad & f(x_0), (b_i(x_0))_i, \\
\text{compute } \quad & f(x_0 + \varepsilon), (b_i(x_0 + \varepsilon))_i, \\
\nabla f(x_0) & \approx \frac{f(x_0 + \varepsilon) - f(x_0)}{\epsilon} \\
\nabla b_i(x_0) & \approx \frac{b_i(x_0 + \varepsilon) - b_i(x_0)}{\epsilon} \\
\text{according to a certain descent strategy, move to } x_1 \\
\text{repeat the process}
\end{align*}
\]
Figure 24 shows the iterations of a gradient method in the case of a two-dimension convex function $f(x)$ with two linear constraints $b_1$ and $b_2$.

Figure 24: Gradient descent in 2D space with two linear constraints and a nonlinear function. Source: [18]

The pros of these methods are mainly their speed and their precision. The more regular the functions are, the quicker the algorithms converge. Each of the iterations, in a space of $n$ dimensions, needs $n+1$ calls to the objective functions and constraints. In our case, we evolve in a space of no more than five or six dimensions (the geometric parameters of the HTP planform). That would make supposedly the gradient-based methods perfect when we want to converge quickly to the optimum.

The cons are:
- We gain little information on the space.
- We take the risk of converging to a local optimum.
- The functions need to be regular.

These cons are important. Indeed, in certain cases of our study, we will need not only to find the optimum, but also to gain knowledge of the space. The risk of converging to a local optimum is to be taken seriously too, as our functions present a certain roughness, even if macroscopically they look quite regular.
8.2.2 Exploratory techniques

Exploratory techniques can also refer to many algorithms and techniques. Like in the gradient-based methods section, we will not study in detail the algorithms. We will only expose the pros and cons of two major methods: Genetic algorithms and response surface methods. They share the common point of not following a path, like the gradient methods, but rather globally exploring the optimization space.

**Genetic algorithms:**

The idea of genetic algorithms is to start with an initial random set of points that are spread within the space (that has to be bounded). Then, through a process mimicking natural evolution, new generations of points are generated, improving at each iteration the minimization of the objective and the satisfaction of the constraints.

In the case of Equation 18’s problem, the process is:

\[
\text{Taking } (x_i)_{i \in \mathbb{N}} \text{ as an initial population, compute } (f(x_i), (b_j(x_i)))_i \\
\text{according to a certain evolution strategy: perform selection, crossover, mutation, ...}
\text{repeat the process with the new population}
\]

These methods are particularly well suited to irregular and high-dimension problems, because they do not rely on a descent principle. The algorithms favour points with a high “fit function”, which reflects both feasibility and optimality. Also, if the objective function presents local minima, the fact that the algorithms start from a random population makes them more likely to find the global optimum.

As mentioned before, in some cases we also like the idea of having knowledge of the function. Genetic algorithms widely explore the space, and therefore their results provide a lot of topological information.

The drawback is of course the need to compute the objective functions and constraints many times during the optimization. That makes these algorithms un-suited to our problems: our functions being globally regular but long to compute, the use of these algorithms is not justified.

**Response surface methods:**

These methods are also exploratory, in the meaning that they try to explore the space globally, to have a general view of it. The idea is to sample the space and to build an approximation of the objective functions and constraints based on these samples. Then,
one can easily interpolate the optimum, or run a quick gradient method using these approximations.

There are many ways to sample the space, some being random, some being deterministic, and others being hybrid. When using the response surface philosophy, one shall not expect great precision from the results, as the algorithm will not try to converge to the optimum. This, for the simple reason that what is really sought here is not the optimum, but rather the visualization of the space, and the sensitivity of the functions towards the design variables.

In the case of the previously introduced two-dimensional function, the sampling and the approximation could take the form shown in Figure 25.

![Figure 25: Application of a randomly sampled response surface method on a two-dimensional function with two linear constraints. Source: own](image)

In our case, the functions being globally regular, it is reasonable to approximate them and then guess the optimum by interpolation. If precision is really required, one can run a gradient method to improve it (using the interpolated optimum as an initial guess).

However, optimizing with huge precision does not really make sense in this project, as most of our simulations already make approximations and run with approximated data.

The Handling Quality criteria calculator, E-Motion, can work in an optimization mode (to minimize the HTP area $S_{ref}$), and it uses a response surface technique. Figure 26 shows a view of the E-Motion optimization interface. The algorithm consists in sampling the space on a 3x3 grid (9 points) and then interpolating the function inside this grid. The green area is the feasible space bounded by the interpolated constraints. The blue point is the optimum: it is the point of the feasible space with the smallest $S_{ref}$.

Eric Leibenguth
Figure 26: E-Motion optimization interface. Source: [1]
9 SIMULATION AND OPTIMIZATION

9.1 The I-Sight environment

9.1.1 What is I-Sight?

I-Sight is a software by Dassault Systèmes that provides engineers with a suite of visual and flexible tools for creating simulation process flows, consisting of a variety of applications, including commercial CAD/CAE software, internally developed programs, and Excel spreadsheets, in order to automate the exploration of design alternatives and identification of optimal performance parameters.

In this project, I-Sight is used to run together different programs, interfacing them and treating automatically the input and output data. It contains a very useful library of optimization algorithms, and numerous sampling methods (Design Of Experiments). What’s more, I-Sight facilitates the debugging of the simulation process, and it allows a very convenient flexibility of use. Thus, I-Sight is particularly adapted to the resolution of our optimization problem, and it allows us to save time and to explore further on the model capabilities.

9.1.2 The design gateway

The design gateway is the software that allows the user to build his model. “Build” possibly meaning the following tasks:

- Insert and configure “drivers”, the main elements heading the execution of a sub-process of components. Among them:
  - Task (runs a sub-process once).
  - Optimization (Performs an optimization by iterating a sub-process computing an objective function and a set of constraints).
  - Design Of Experiments (Performs a user-defined or random sampling of a design space explored through a sub-process).

- Insert and configure “components”, the elementary bricks composing the simulation process. Among them:
  - Simcode (Launches an executable program)
  - Excel sheet (Loads data in an excel sheet, performs the included computations, and extracts the outputs).
  - Data Exchanger (Writes or reads parameters in text files, which typical purpose is to interface simcodes).

- Define the execution flow and the data flow, that is to say:
  - To define the order of execution of the components; this also includes adding loops or tests, for conditional executions of components during the simulation process.
To define the *mappings* of the parameters, which means to direct or dispatch the parameters to the inputs of the components, and the outputs to the associated parameters.

Figure 27 shows an example of a simple arrangement of a few elements inside the Design Gateway. The arrows represent the execution flow. We see a typical task process (executed once) that runs: first an Excel sheet, passing the outputs to the next component, a program (simcode), which as well transmits its results to the last component, a calculator.

![Diagram](Figure%2027.png)

*Figure 27: A basic process in the I-Sight Design Gateway. Source: own*

### 9.1.3 The Runtime gateway

The Runtime Gateway provides execution control and monitoring options for a model, displays execution related results and information, and can be used to create approximations for components.

In this project, this tool is very important as it is used to follow the process of optimization and to visualize all the results and the design space. It is very useful to understand the decisions of the optimizers, and thus, to debug the process and to choose the best possible settings for the model.

We will also see that the approximation tool included in the runtime gateway can easily build analytic functions approximating the equivalent weight (objective function), or the margins of the Handling Quality criteria (constraints functions).

Although these approximations implicate a minor loss of precision, they turn out to be of great use because they do not require much data and are very quick to compute, compared to the real functions that require running a relatively complex and long simulation process.

Figure 28 shows the workflow tab (a), where one can follow the process, the parameters history (b), where one can see the parameters values, the 2D diagrams (c), where one can
see the different points plotted in various dimensions, and a view of the approximation tool (d), where one can visualize and work on analytic approximations.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figs/08_02.png}
\caption{A few views of the Runtime Gateway. Source: own}
\end{figure}

\subsection*{9.2 Linking and interfacing the components}

In I-Sight, interfacing is key. Building models precisely consists in having programs communicating with each other. Certain codes can have dozens of potentially variable inputs, and others way more. Therefore, a proper handling of the dataflow is crucial to ensure no mistake is made.

The first step of dataflow analysis is the identification of the inputs and outputs of the components we use:

\begin{itemize}
\item E-Motion, to compute the Handling Quality criteria (See 6.2).
\item EP-EH, to calculate the weight of the HTP (See 7).
\item EP-AERO, to calculate the aerodynamic coefficients (See 7.1).
\end{itemize}
9.2.1 Inputs and Outputs of the programs

_E-Motion inputs and outputs:_

presents E-Motion’s architecture. E-Motion requires various input files that must be filled and provided by I-Sight. They contain all the information needed by the program to simulate flight manoeuvres, to compute the extreme CG positions and to calculate the CG margins (see 6.2.3). These five input files are:

- _The Handling Quality data file._ It contains many variables of various natures. These variables are used in the aerodynamic model to compute the aerodynamic coefficients. A few of them are to be modified during the simulation. For instance, the data file contains the reference surfaces of the wing and HTP. As the HTP area is one of the most significant variables, it is mandatory to update its value at every modification of this parameter. See A.1.1 for more details.

- _The aerodynamic model._ It is a dll-file that is unique for one aircraft. It contains a function that returns the six main aerodynamic coefficients \((C_X, C_Y, C_Z, C_L, C_M, C_N)\) in function of the parameters contained in the aerodynamic database, and of the aircraft flight variables (Mach number, angle of attack, HTP setting, elevator, flaps, spoiler, etc.). This model cannot be modified in I-Sight; it is not variable during a simulation. It may be manually modified out of I-Sight to change the aircraft model, although this generally implies making corresponding changes to the aerodynamic database. The tool used to edit and save the aerodynamic model, works in Scilab and is named AME. Figure 29 shows a few code lines of an aerodynamic model in AME.

![Figure 29: Aerodynamic model in the editor. Source: own](image)
The aerodynamic database. It is a long file containing the aerodynamic coefficients of the aircraft (e.g. Equation 8) in function of many possible variables (typically Mach number, flap configuration, elevator deflection...). This file has to be updated when the aircraft is modified. For instance, if a simulation generates a new planform, we need to modify the associated coefficients in the database. And, as the format of the file is quite complicated, updating it implies a lot of re-formatting. If this change is to be made automatically within I-Sight, it means using a heavy interface to treat the data.

The engine database. It contains the characteristics of the engines, in form of tables. As we never change anything of the engines, this table is absolutely constant and not to be modified. See A.1.1 for more details.

The nvu criteria file. The criteria are programmed in E-Motion and cannot be modified. But this file gives access to a few settings and to the option of activating or deactivating the computation of the criteria by E-Motion. This file can be modified manually and does not require a complete interface. Generally it will be set once and for all before running an optimization. See A.1.1 for more details.

The outputs of E-Motion are numerous, but in our case we really need only one thing: the list of the margins for the Handling Quality criteria. As E-Motion does not originally build output files (the results are only visualized through the graphic interface), a series of modifications had to be made in order to obtain the margins in a file readable by I-Sight. Details of this modification can be found in A.1.2

Inputs and outputs of EP-EH:

EP-EH, “Evaluador de Peso, Empenaje horizontal” is the code that computes the weight of the HTP (It is described in 7). It requires a relatively big amount of input files. However, most of them are not variables in our study, and we will only introduce the most important of them:
A main input file, containing data of very different natures: general aircraft parameters (speeds, dimensions...), engine properties, wing and HTP geometries, mass load cases to be computed and miscellaneous parameters (more details in A.2.1).

- Wing and HTP airfoils, and twist angle distributions, given in formatted tables.
- Other tables of coefficients (for instance, a few lateral coefficients are required for certain manoeuvres)

**Input and outputs of EP-AERO:**

EP-AERO is the aerodynamic module of EP-EH (see 7.1). We use a standalone version because we need to generate aerodynamic data for E-Motion (see 6.2.3). EP-AERO requires fewer inputs than EP-EH. As it only performs aerodynamic calculations, what it needs is basically the complete geometry of the lifting surfaces (wings and HTP). EP-AERO does not only calculate the HTP aerodynamics. It calculates as well the wings coefficients, also needed by EP-EVOL (the next module in EP-EH, see 7.2).

The input files are:

- The main input file, containing mostly geometric parameters of the HTP and the wing.
- The HTP and wing airfoils and twist distribution, as in EP-EH.
- The list of Mach numbers for which we want to compute the aerodynamic database.

The outputs of EP-AERO that we need are files of aerodynamic coefficients (Figure 31). EP-AERO performs a Mach number loop in which it runs the Vortex-Lattice Method (see 7.1). Therefore, in the output files, all the coefficients are tabulated in function of the Mach number.

![Figure 31: Extracts from EP-AERO's outputs. Source: own](image-url)
9.2.2 Simplified optimization of the A380’s HTP

The A380 is a finished and commercialized airliner. Every data, every detail required by our codes is available. That makes the A380 the perfect aeroplane to experiment our optimization method.

First, we introduce a simplified version of the optimization problem defined in 8.1. In this version we do not consider the planform as a variable. Only the HTP reference area \(S_{ref}\) varies. To simplify the problem again, the objective function does not take into account any weight, or cost: We simply minimize \(S_{ref}\).

The problem can be summarized in a simple formulation: “We minimize the surface of the HTP, such that the margins of the Handling Quality criteria are positive or nil”.

Figure 32 summarizes the structure of the I-Sight model.

As the planform does not change, the whole aerodynamic database stays unchanged. The only input of E-Motion that is a variable is the Handling Quality data file. However, a variation in the HTP surface implies secondary changes; for instance the lever arm of the HTP (that has a critical influence over the handling qualities, see 4.4.1) has to be modified.
In order to perform these secondary modifications, we need to use an Excel sheet as an interface. More details about the Excel file interface can be found in B.2.2.

Finally, our I-Sight model for this simplified problem as the following form:

9.2.3 Complete optimization of the A380’s HTP

We are now going to expose the optimization model integrated in I-Sight, as we introduced it in 8.1. To sum up the problem formulation:

- We minimize the equivalent weight, calculated by EP-EH.
- With respect to the planform variables: the surface $S_{ref}$, the aspect ratio $AR$, the taper ratio $TR$ and the quarter chord sweep angle $\Lambda$, and the minimum angle of deflection of the HTP, $i_{h_{min}}$.
- Such that the margins of the Handling Quality criteria are positive or nil.

Figure 35 summarizes the structure of the model:
The structure of the I-Sight Model is therefore made of two main blocks, one running E-Motion, the other EP-EH. Both blocks are integrated in an optimization loop.

**The E-Motion block:**

Not as in our previous simplified example, the aerodynamic database now has to be partially updated, as we modify the planform. That means we have to calculate the aerodynamic coefficients of the HTP at every call of E-Motion and replace them in the database (as the wings and fuselage do not change, a large part of the database does not have to be updated).

The tool we use to calculate the HTP coefficients and to update the database is EP-AERO, previously introduced in 7.1 and 9.2.1. At this point, two problems emerge:

- EP-AERO does not provide exactly the same coefficients that E-Motion uses.
- EP-AERO is supposed to update a very precise database (results from tunnel and flight test experiments) with data of relatively poorer quality.

Both problems call for the same solution: An interface of calibration between the two codes. The most adapted tool to perform operations over entire tables is Excel. The idea here is to keep using the high quality information from the database but modified by deltas or ratios computed by EP-AERO. The baseline HTP parameters are a point of reference (the point at which the database is calculated):

**Equation 19: Point of reference**

\[ X_{\text{ref}} = (S_{\text{ref}} = 205m^2; \ AR = 4.5; \ TP = 0.38; \ \Lambda = 33.5^\circ; \ \eta_{\text{min}} = -10^\circ) \]

When the HTP planform is modified (during a new iteration), the coefficients given to E-Motion become:

**Equation 20: Deltas and ratios**

\[ C(X) = C_{\text{DataBase}} + \Delta_{\text{EP-AERO}}(X) \quad \text{with} \quad \Delta_{\text{EP-AERO}}(X) = C_{\text{EP-AERO}}(X) - C_{\text{EP-AERO}}(X_{\text{ref}}) \]

or

\[ C(X) = C_{\text{DataBase}} \cdot \eta_{\text{EP-AERO}} \quad \text{with} \quad \eta_{\text{EP-AERO}} = \frac{C_{\text{EP-AERO}}(X)}{C_{\text{EP-AERO}}(X_{\text{ref}})} \]

For instance, the HTP lift curve slope uses a calibration by ratio:

**Equation 21: The lift curve slope calibration**

\[
\frac{\partial C_Z}{\partial \alpha_H}(M) = \frac{\partial C_Z}{\partial \alpha_H} \bigg|_{\text{DataBase}} (M) \cdot \eta_{\text{EP-AERO}} = \frac{\partial C_Z}{\partial \alpha_H} \bigg|_{\text{DataBase}} (M) \cdot \frac{\partial C_Z}{\partial \alpha_H} \bigg|_{\text{EP-AERO}_{\text{reference}}} (M)
\]
Figure 36 shows the different curves in function of the Mach number (EP-AERO results, reference curve and output curve).

![Figure 36: Calibration of the lift curve slope. Source: own](image)

More information on the calibration interface can be found in B.2.3.

Figure 37 shows the E-Motion block in I-Sight. It contains four components: geometry calculations (Excel), aerodynamic calculations (EP-AERO), calibration interface (Excel), and handling quality calculations (E-Motion).

![Figure 37: The E-Motion block. Source: own](image)

**The EP-EH block:**

The EP-EH block is quite simple. The component running EP-EH just needs a couple of Excel sheets to process the inputs and outputs of the component. The first Excel sheet is the same we use before running EP-AERO (See B.2.2), with additional features for drag
coefficient calculations. The second uses the total weight of the HTP and the drag coefficient to calculate the equivalent weight, as defined in 7.4.

Figure 38 shows the EP-EH block in I-Sight. It contains three components: geometry calculations (Excel), weight calculations (EP-EH) and equivalent weight calculations (Excel).

![Figure 38: The EP-EH block. Source: own](image)

Figure 39 shows what the complete model looks like in I-Sight. The model features the two previous blocks inserted in an optimization loop, which is inserted in a task driver. Indeed, a few initialization components need to be run before the optimization. More details are showed in B.1.

![Figure 39: Complete I-Sight model. Source: own](image)
10 RESULTS

10.1 Optimization of the A380’s horizontal stabilizer

The A380 and its handling quality properties are well known. The sizing criterion for the HTP is the “manoeuvre point” (see 6.2.2). However, Airbus is aware that the A380’s HTP is slightly oversized: Running E-Motion in optimization mode tells us that the baseline surface of 205m² could be reduced to approximately 197,5m² without even changing the planform.

What’s more, the planform has not been optimized. Therefore, it is known that a better one can be found. In the case of the A380, our challenge is to find a better feasible HTP, and more generally, to study the influence of the geometric parameters on the handling quality constraints and on the equivalent weight.

10.1.1 Two-dimensional test: Confirming E-Motion results

The first natural and logical test that has to be made, in the case of the A380, is to run the model with the same optimization variables that E-Motion originally handles. Getting the same result is mandatory to confirm the validity of our method. The I-Sight model used here is the one introduced in 9.2.2.

E-Motion is able to optimize the HTP area $S_{ref}$ and the minimal angle of deflection $\theta_{\text{min}}$, while minimizing the area. These are the two parameters that we have to set as optimization variables in I-Sight. To start with a simple and transparent algorithm, we use a gradient method, counting on a small number of iterations, as the problem is only two-dimensional. The initial point is set to the baseline values ($S_{ref} = 205\text{m}^2$; $\text{AR} = 4,5$; $\text{TR} = 0,38$; $\Lambda = 33,5^\circ$; $\theta_{\text{min}} = -10^\circ$).

![Table](image)

(a) Optimizer settings (b) Optimization variables (only 2)
Horizontal tailplane optimization

The optimization is then run: A result is reached after a few iterations. Iterations last approximately 45 seconds each, which is the time needed to run E-Motion and perform four criteria with three mass cases.

The optimization converges to a surface of 198m², which was almost the same result obtained with E-Motion, which confirms the validity of our model. However, the planform does not change during this optimization, so we cannot conclude anything about the well functioning of the aerodynamic part of the model. Indeed, in this optimization, the aerodynamic data is always the same (equal to the baseline data) because only the surface is optimized.

The gain of this optimization is relatively small. The surface is reduced by less than 4%, which does not make a big difference.

Figure 42 shows the same optimization performed in E-Motion. E-Motion samples the two-dimensional space on a 3x3 grid centred on the baseline values. The feasible space is...
bounded by the coloured lines representing the interpolated zero-margin points of the design space.

![Diagram showing optimization of A380 HTP surface in E-Motion](image)

*Figure 42: Optimization of the A380 HTP surface in E-Motion. Source: own*

**10.1.2 All variables in: bad convergence**

This time, we set all the design variables as actual optimization variables. We keep using the gradient method, as it worked fairly enough in the previous example. What’s more, we minimize the equivalent weight instead of the reference area $S_{ref}$. The model used is the one presented in 9.2.3.
This time, the convergence is longer, which is logical as it takes more time to compute the gradient (this time the space is five-dimensional). Iterations last about one minute each, which is the time needed to run both E-Motion and EP-EH. The algorithm rapidly succeeds in “saturating” (equalling to zero) the manoeuvre point constraint; however, it cannot find quickly the optimal point and shows an incoherent behaviour, which seems to indicate that the gradient is not well calculated.

Figure 43: I-Sight settings (5D test). Source: own

Figure 44: Path of the gradient-based optimizer. Source: own
Various phenomena confirm the bad-convergence problem:

- When starting the optimization from another initial point (a point close to the previous solution), it converges to a different solution.
- The algorithm “changes in mind” during the optimization: It tends to increase the sweep angle at the beginning and then decreases it drastically (see Figure 44c).
- The final solution does not make physical sense (the constraints are not saturated, the variables values are not consistent). This indicates the probable presence of a local minimum (see Figure 44d).

It is also interesting to observe the convergence of the optimizer through the cross-section diagrams provided by I-Sight. Figure 45 shows the paths followed by different variables during the optimization.

![Figure 45: Cross-section diagrams. Source: own](image)

The previous arguments (bad gradients, local minima...) are signs of a high roughness. This roughness is most probably due to the fact that the programs do not act continuously and present small irregularities.

The lack of reliability of the gradient method encourages us to use a more global method, which will not give us an excellent local precision, but a good idea of the aspect of the functions, on a macroscopic scale.

The results also show that the optimization tends to converge to a small sweep angle value. Obviously this is not optimal, as any lifting surface needs sweep angle on a transonic aircraft. This problem is not due to the nature of the algorithm, but rather to the lack of certain physical effects in our model. We will deal with this problem in the interpretation subsection, but for now on, we keep the sweep angle constant, equal to its baseline value (Λ=33,5° for the A380).
10.1.3 Response surface method

The idea of response surface methods is to sample the space at a set of points, and then to build analytic functions that approximate the constraints and the weight functions. Using sampling methods avoids dealing with microscopic effects (like with the gradient-based methods). The information kept is macroscopic: Not only do we find the solution but we also get to know better the aspect of all the functions.

As exposed in 8.2.2, the drawback of these methods is that they usually take more time (the duration increases drastically with the number of dimensions; also, if the functions are very complicated, more points are needed to build a correct approximation).

The model is set to four variables (Area, aspect and taper ratios, \( \text{ih}_{\text{min}} \)), with a random sampling technique (Latin Hypercube). The responses to be analysed are the constraints and the weights (structural and equivalent). The Latin Hypercube technique is used, although a deterministic method would work as well. (See Figure 46)

(a) The optimization driver is changed for a Design of Experiments driver (DOE)

(b) The technique is set to Latin hypercube (random sampling)

(c) Responses to study

(d) Design variables

Figure 46 I-Sight settings (sampling method). Source: own
This technique is not meant to converge to any solution, so we can stop it whenever we think we have enough information. It is then stopped after 100 iterations. As in the previous optimization algorithm, iterations last for about one minute each. Figure 47 shows a few examples of planforms “explored” by the sampling technique. For each of these potential HTP, E-Motion computes the handling quality criteria, testing its feasibility, and EP-EH calculates its weight.

As there is no convergence, the design space is sampled uniformly although we know that some points can obviously not be feasible. But this process allows us to see and apprehend the global behaviours of the functions.

Figure 48 features two cross-section diagrams, red and black dots being respectively infeasible and feasible HTP. In the case of the diagram AR vs. $S_{\text{ref}}$ (a), a clear separation appears between feasible and infeasible space, independently of TR and $i_{\text{min}}$ (the separation is showed by the discontinuous red line). On the diagram TR vs. $S_{\text{ref}}$, there is
no clear separation, but the tendency is that HTP with higher reference area tend to be more feasible (which makes sense: more control surface implies better handling qualities).

![Graph](image1.png)

*Figure 48: The sample points plotted in the cross-sections of the design space. Source: own*

As introduced in 9.1.3, the Runtime Gateway permits to build approximations of the functions. Concretely, analytic functions are calculated to fit the results. Those used by I-Sight are quartic functions. This means that the manoeuvre point constraint, for instance, is approximated by a polynomial function of the fourth order.

![Graph](image2.png)

*Figure 49: 3D approximation diagrams. Source: own*

Figure 49 (a) and (b) show two approximations in which it is striking that the analytic functions are very regular and smooth, almost linear. Indeed, sampling all the design
space and approximating it permits to smooth out all the local roughness that makes the well computation of the gradient very compromised. Figure 50 shows the error made for a few sampled points during the approximation.

![Error on margin (-)](image1)

(a) Error made in the approximation of the manoeuvre point constraint

![Error on eq. weight (kg)](image2)

(b) Error made in the approximation of the equivalent weight

Figure 50: Error functions. Source: own

In both cases, the error does not exceed one percent of the function, which is quite satisfying. Therefore, we dispose of good quality analytic functions, calculable in a few microseconds, instead of one minute for the simulation way.

Finding the optimal HTP is then easy. It can be done by running an optimization algorithm, which quickly converges thanks to these analytical functions. Figure 51 (a), (b), (c) and (d) show the results of a complex hybrid optimization algorithm (“pointer”) that ran 1500 iterations in a few seconds.

![Convergence of the reference area](image3)

(a) Convergence of the reference area

![Convergence of the aspect ratio](image4)

(b) Convergence of the aspect ratio
It converges to a HTP of $S_{ref} = 182 m^2$, $AR=5.5$ and $TR=0.5$ (ih$_{min}$ staying unchanged). Figure 52 shows the planform of the optimal HTP found previously (in black) and the baseline HTP (in red).

The optimal shape is much thinner and slightly longer. The following section will explain how the parameters variations affect the weight and the handling qualities.

10.2 Interpretations and remarks

10.2.1 Sensitivity of the functions

The information given by the previous response surface method calls for a brief sensitivity analysis to understand which parameters affect, and to what extent, the different
functions that intervene in the optimization. For each variable we look at the consequences of a small variation, letting all other parameters unchanged.

**Sensitivity towards the reference area:**
Increasing $S_{\text{ref}}$:
- Increases the structural weight (More skin panels, more ribs and structural elements)
- Increases the drag (Which is directly proportional to the wetted area)
- Increases the handling quality margins (more stability by increasing the lift $\alpha_H$-derivative)

**Sensitivity towards the aspect ratio:**
Increasing AR:
- Increases the structural weight (loads further from the root create more bending moment, which calls from bigger structural elements)
- Increases the drag (smaller chord makes smaller Reynolds number)
- Increases the margins (Bigger lift $\alpha_H$-derivative)

**Sensitivity towards the taper ratio:**
Increasing TR:
- Increases the structural weight (bigger loads near the tip)
- Decreases the drag (bigger chord increases the Reynolds number)
- Increases the margins (higher exposed surface improves the stability; bigger tip increases stall angles)

**Sensitivity towards $i_{h\text{min}}$:**
In this model, $i_{h\text{min}}$ does not affect the weight because it is simply not a variable of the codes. However, it should be the case as $i_{h\text{min}}$ is important in certain load cases and in the weight of the tail.

*Figure 53: Influence of each variable on the shape. Source: own*
Ih_{\text{min}} affects neither the feasibility nor the critical criterion, as the “manoeuvre point” does not depend on this parameter. Its influence in this model is therefore inexistent.

Clearly, the two most influent parameters are the reference area and the aspect ratio. The functions are way less sensitive to the taper ratio because its effects are of second order whereas the area and aspect ratio have a much more direct influence on the aerodynamic coefficients and on the structural elements of the HTP.

Therefore, for every design variable, the optimum is the result of a trade-off between stability, weight and drag. The previous sensitivity analysis can easily be done qualitatively. But obtaining the optimal trade-off quantitatively was the tough part.

10.2.2 Other remarkable properties

**Roughness of the space:**

When observing the analytical surfaces generated by the approximation tool (e.g. Figure 49), we notice that the functions (CG margins, equivalent weight) are very regular, almost linear. Why then wouldn’t the gradient methods converge well? If we look however at the error made by the approximation, we see that the error is small but not insignificant (around one percent of the value for the weight function). This tells us that the functions have a high roughness. This roughness is smoothed out by the response surface method, but it disrupts a lot the gradient methods. A solution could be to increase the step used to compute the gradient (ε in 8.2.1), which does not seem to be possible with the current version of I-Sight. However, the regularity of the functions calls for the use of sampling methods.

**The sweep angle problem:**

As mentioned previously, the optimizer naturally finds a small optimal sweep angle (See 10.1.2). This result is obviously wrong, as wings always need to be swept on transonic and supersonic planes, to avoid a huge increase in drag and instability, due to local sonic waves. This complex phenomenon is not taken into account in our aerodynamic calculations. The model needs to be improved to correct this effect.

Although we did not treat this problem, a solution could be to impose an additional restriction constraining the sweep angle. The following Korn equation links the sweep angle, the divergence Mach number and the ratio thickness over chord ([13]). This means that to optimize the sweep angle, we need to introduce another design variable, the thickness of the HTP.
\[ M_{dd} = \frac{\kappa_A}{\cos(\Lambda)} - \frac{(t/c)}{\cos^2(\Lambda)} - \frac{c_l}{10\cos^3(\Lambda)} \]

\[ t/c: \text{thickness over chord} \]

\[ c_l: \text{cruise lift coefficient} \]

\[ \kappa_A: \text{const. coefficient} \]

10.2.3 Costs savings and emissions reductions

The optimization converges to a HTP of 5826kg with an equivalent weight of 9902kg. This means a drag coefficient of:

\[ \Delta C_D = \frac{\Delta \text{weight}}{K} = \frac{9902 - 5826}{652 \text{ kg / d.c.}} = 6.25 \text{ d.c.} \]

The baseline weights and equivalent weight of the HTP were respectively 5941kg and 10396kg.

\[ \Delta C_D = \frac{\Delta \text{weight}}{K} = \frac{10396 - 5941}{652 \text{ kg / d.c.}} = 6.83 \text{ d.c.} \]

Therefore, the structural weight reduction thanks to the optimization is 115kg (1.9% of the HTP weight) and the drag coefficient reduction is 0.58 drag-count (8.4% of the HTP \( C_D \), 0.23% of the total plane \( C_D \)). This can be translated in terms of cost reductions (see 5.3):

- Manufacturing costs (for Airbus): \( 1000\$/\text{aircraft} \times 115\text{kg} = 115,000\$ \) of savings per aircraft produced.
- Operating cost (for the airline company): \( 8.147\$/\text{trip} \times 0.23\% = 1870\$ \) of savings per trip (considering a typical A380 trip, as in 5.2).

Both of these numbers are gross approximations, but their order of magnitude is big enough to convince us that the optimization of the HTP is a necessary measure, especially because this optimization is costless compared to its benefits.
11 PERSPECTIVES

11.1 The New Long-Range Project

The “New Long-Range” (NLR) is a project of airliner in its early development. Unlike the A380, we do not have much information – aerodynamic or geometric – to work with. Therefore we cannot directly apply our method on this plane. The tough issue here is to decide what data should be used as inputs in our codes.

Of course, in the early development phase, the requirements of precision are lower than what was needed in the case of the A380. What the engineers would like is a quick way to evaluate the weight and the dimensions of the HTP, only knowing a few parameters.

11.1.1 Building an optimal HTP function

The NLR is designed through an Overall Aircraft Design (OAD) loop integrated in I-Sight. The idea of this loop is to design the different parts of the aeroplane in a coherent and unified way. The difficulty is that no component is entirely independent from the others. Therefore, many suppositions and approximations need to be made.

In the case of the NLR, we do not want to compute an optimal HTP for a frozen set of aeroplane parameters; we want to build a function destined to be integrated in the OAD loop. This function would compute an optimal HTP for a set of a few variable inputs. As outputs, it would return the weight and geometry of the optimized HTP.

The challenge is to derive, from the few inputs, all the data needed to run E-Motion and EP-EH; then, to sample the design space of those inputs, and, at each point, to compute the optimal HTP. It will then be easy to build (through the Runtime Gateway, see 9.1.3) an approximation function that returns, analytically, the outputs in function of the inputs, without having to run an optimization every time.

Figure 54: Architecture of the NLR I-Sight model. Source: own
11.1.2 Generation of the inputs

The inputs of E-Motion and EP-EH share common points, because both fundamentally do something similar: planes equilibrium calculations. We will only show a few aspects of the difficulties that we are facing with the NLR project.

The main problem is that we do not have any point of reference, or any baseline aerodynamic database. Of all the inputs of E-Motion, we only have for sure the criteria file. That means we have to generate all the other files (see 9.2.1), which are:
- The aerodynamic model.
- The aerodynamic database.
- The Handling Quality data file.
- The engine database.

**The aerodynamic model:**

The aerodynamic model directly depends on the aerodynamic database. A given set of coefficients has to have an associated model. Once all the coefficients present in the database are determined, it is then easy to build the aerodynamic model once and for all. As we do not care about optimizing the VTP, we will only compute longitudinal criteria. In these criteria, the aircraft stays in the plane XZ (Figure 2), which means we only require a two-dimensional aerodynamic model.

**The aerodynamic database:**

The main challenge is then to generate the aerodynamic database. We know that EP-AERO generates a database from a few parameters. Using this data is the first logical possibility. But, EP-AERO database is generated for HTP calculations purposes, not Handling Quality simulations. That means it is precise enough for the HTP, but relatively poor for the wings and fuselage. What’s more, EP-AERO cannot generate flap, ground, landing gear, flexibility effects and anything nonlinear... And all these effects can be of importance when dealing with Handling Qualities! This is why EP-AERO cannot be used, at least alone, and we need additional data.

**The Handling Quality data file:**

As it can be seen in A.1.1., this file contains various types of data, of very different natures (geometry, engines, mass, speeds...). Some of this data can easily be derived from the OAD inputs, but other parameters have to be estimated.

**The engine database:**

The engine details have little influence over the handling qualities. The OAD loop includes engine calculations that could be used to generate a simplified database for E-Motion.
11.2 Other perspectives

Many possibilities exist to improve the optimization model presented in this master thesis. Here are the most promising.

Improving the optimization algorithm:

In this study, we used only the I-Sight optimizers. We could gain in performance (speed, and precision) by developing an algorithm specialized in the resolution of our problem. To improve the speed, we could think of an algorithm adapting the calculations performed by the codes: for instance, E-Motion does not need to compute every time the criteria for five different masses, as only one is sizing; a couple of iterations could be enough to find the critical mass and then to run E-Motion with it. In the same spirit, the algorithm could limit the calculations to only one or two sizing criteria, after a couple of iterations.

Including more variables in the model:

Many other variables could be added to this model, without changing it drastically. The thickness over chord ratio, for instance, is of great influence over the stall angles of the HTP, and is closely related to the sweep angle (see Equation 22). However, adding new design variables cannot be done without considering new physical phenomena. For instance, the failure of the optimizer to find an optimal value for the sweep angle happens because the model does not take into account transonic phenomena. If we want to optimize the sweep angle, we need to add constraints to the model (the Korn equation could be one).

Improving the components:

The individual components could be improved, in order to gain in precision and flexibility. The aerodynamic code, EP-AERO, is actually very basic, especially concerning the evaluation of the stall angles of the HTP. Improving the precision of the handling quality criteria implies having a better knowledge of the aerodynamic behaviours. Also, the weight evaluation component should take into account more details; for instance, the repercussion over the fuselage of changing the HTP (a lighter HTP means a lighter structure). The influence of the parameter $i_{h_{\text{min}}}$ on the weight should also be taken into account (a large $i_h$ domain means bigger, heavier and more expensive actuators). One could also think of adding a cost module that would include economical considerations currently not taken into account by the weight model.
CONCLUSIONS

The objective of this master thesis was to develop a tool to optimize geometric parameters of the horizontal stabilizers of Airbus’s aeroplanes.

After a time of integration and assimilation of the techniques and technologies used in the company, a few theories and leading ideas were emitted as for the method that was to be followed. The needed codes and programs were linked together and a first optimization was conducted, soon followed by a series of improvements. Applied to the case of the A380, the most emblematic aircraft of Airbus, the method showed very interesting results and proved its reliability for this kind of application.

The weight and drag reductions achieved in this study are respectively of 115Kg (1,9% of the stabilizer’s weight), and 0,58 drag-count (8,4% of the drag produced by the stabilizer). But another benefit is that applying this method to new aircrafts will allow the designers to save time during the process.

This master thesis not only proved the feasibility of a method able to optimize and automate the design of the stabilizers. It provided Airbus with a concrete tool capable of performing this optimization and integrating it in the steps of the aircraft development. It also showed that much more complex optimizations were actually possible and that the current model was still to be developed and brought to maturity.

Many improvements can be made to a method that has already proven itself powerful. The challenge is now to integrate additional physical phenomena, other design variables and new algorithms. The problem of the New Long-Range project will confront the method to certain limits that are currently hard to detect.
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**Additional bibliography**


