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# MASTER THESIS REPORT
# Preliminary assessment & optimization process for the operational concept of a fleet of high-speed civil aircraft

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## 0.1   Acknowledgements

I'd first like to thank my parents for the constant support in these endless 19 years of school, and for teaching me just enough cooking for me to barely survive in Toulouse.

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Finally, i must thank everyone at ONERA i played Tarots with, because it is probably the main reason that would make me do it all over.

## 0.2   Glossary

- MDA = Multi-disciplinary Design Analysis

- MDO = Multi-disciplinary Design Optimization

- DOE = Design Of Experiment

- ZEHST = Zero Emission High Speed Technologies

- LAPCAT = Long-term Advanced Propulsion Concepts and Technologies

- ISP = Specific Impulse

- B = Billion(s)

- M = Million(s)

- h = Hour(s)

- MJ = Mega Joule

- GHG = Greenhouse gasses

- HST = Hypersonic speed travel

- FC+B = First class plus business class

- DOC = Direct Operative Costs

- IOC = Indirect Operative Costs

- Pax = Passengers

- VoT = Value of Time

- L/D = Lift to drag ratio

- T/O = Take off

- MTOW = Maximum Take Off Weight

- OEW = Operative Empty Weight

- AOCTF = Airline Operational Cost Task Force

- IEP = Item Explained Previously

- ASK = Available seat * km

- ES = Emplaned seats

- TSFC = Thrust specific fuel consumption

- TRL = Technology Readiness Level

- NASA = National Aeronautics and Space Administration

- ONERA = Office National d'Etudes et de Recherches Aérospatiales

- GUI = Graphical User Interface

# Part I

# Introduction

# Chapter 1

# Thesis presentation

## 1.1  Stage goal

Since the beginning of aviation, the main goal has always been to increase productivity. It was brought forward in many ways: by expanding the number of routes available and the flights on each route, by always striving for better performances and increasing the number of passengers of each aircraft.

Each company has fought with the competition to take a bigger share of the market with each new product released, always aiming higher.

However, only recently another trend has taken hold, and that is to diminish the impact on our planet. Indeed, since it became common knowledge that the climate change affecting the earth not only is real, but is highly affected by human activities, one way after the other has been studied to understand how to counter it, or even just limit it.

This master thesis and stage places itself exactly in the middle of these two trends, combining them together: it studies concepts with much higher speed and cruise altitude than the civil aircraft that are used right now, therefore increasing productivity and helping solve the airspace traffic problem experienced in the last years. This part is in line with the first trend, however there is a second aspect to it: the analysis carried out are with the aim of trying to minimize the cost, of course, but also the climate impact that a fleet of this kind would have, which is clearly in line with the second trend.

Its main goal is therefore to create a **Preliminary assessment & optimization process for the operational concept of a fleet of high-speed civil aircraft**. This process will have to analyze at the same time:

- **Flight time**

- **Ticket price**

- **Climate impact**

of said high speed civil aircraft fleet, and evaluate which choices would allow to optimize them.

But, before going deeper in the contents of this thesis, it is imperative to have a little context to better understand everything.

## 1.2   Context

As the title of the thesis says, it studies high-speed civil aircraft, but what does that mean?

First, the term civil civil indicates private, commercial and government owned aircraft primarily transporting cargo and passengers, in this case it is thought for passengers. It is in opposition with military, that includes state-owned aircraft engaged in transport, training, security and defence.

Secondly, high-speed indicates that the concepts involved will be either supersonic or hypersonic. The condition of supersonic flight occurs when the flight speed of the vehicle exceeds the speed of sound in that specific atmospheric condition. In that case, two compression waves will be generated at the beginning and end of the airplane, forming the sonic boom phenomenon.

From Mach = 1 (speed of sound) to Mach = 4 (four times the speed of sound) approximately, it is considered as supersonic, while for higher Mach than 4 it becomes hypersonic, as the air dissociation and heat loads effects begin to become significant. In this particular thesis, only hypersonic concepts will be taken into consideration.

That said, it is important to understand that, until now, no hypersonic civil aircraft have ever been actually created, for different reasons, the main of which is the lack of the necessary technology. That is why, throughout this thesis, only theoretical concepts with their estimated data will be considered.

The only high-speed civil aircraft to have ever been designed, produced and used as such in history are the Concorde and the Tupolev Tu-144: both were supersonic airliners with a maximum speed of approximately M = 2.

Both were also retired for reasons linked to various incidents, to the rising price of fuel that made the profit from the flight lower than the fuel cost, and to the restriction of supersonic travel, that could not go faster than the speed of sound above land or the sonic boom effects could cause problems to the population underneath.

However, even if no hypersonic civil aircraft exists, multiple project on this topic have already been carried on.

## 1.3   Previous works

### 1.3.1   HIKARI project

The HIKARI project [1], that stands for "*High speed Key technologies for future Air transport - Research & Innovation cooperation scheme*", was born from the collaboration of all the hypersonic initiatives in Europe and Japan.



Figure 1.1: HIKARI collaborating partners
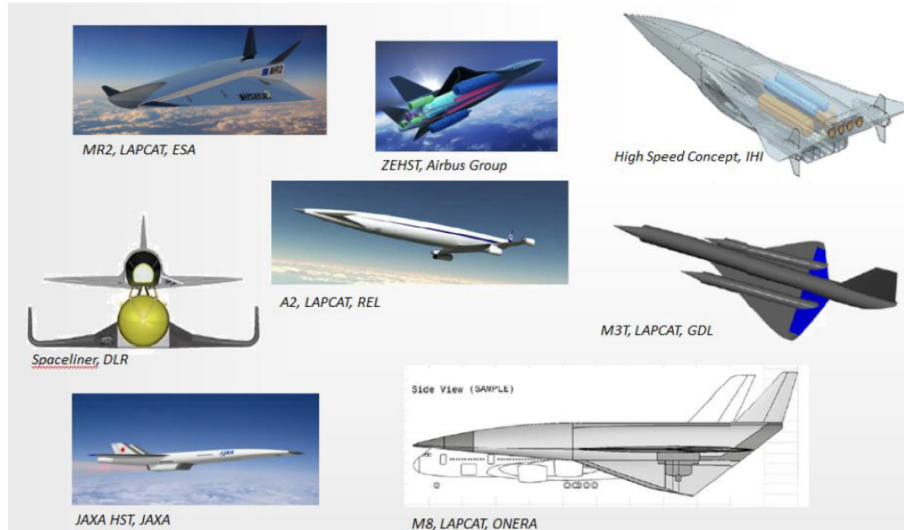
Figure 1.2: HIKARI concepts

Developed between 2012 and 2015, its goal was to drive the convergence of all their concepts and roadmaps. Thanks to the hard work of all the different partners, it has created a common path towards a joint design for high speed transport, paving the way for all future studies on the subject.

From this very project some of the necessary data to develop this thesis was taken, in particular:

**Network traffic estimations**

As HIKARI project treats hypersonic civil concepts, it's horizon is set to to be far in the future. Therefore to evaluate which concept would be better in said future, a network of 490 city pairs between 42 airports was selected, and all the relative traffic data was estrapolated:
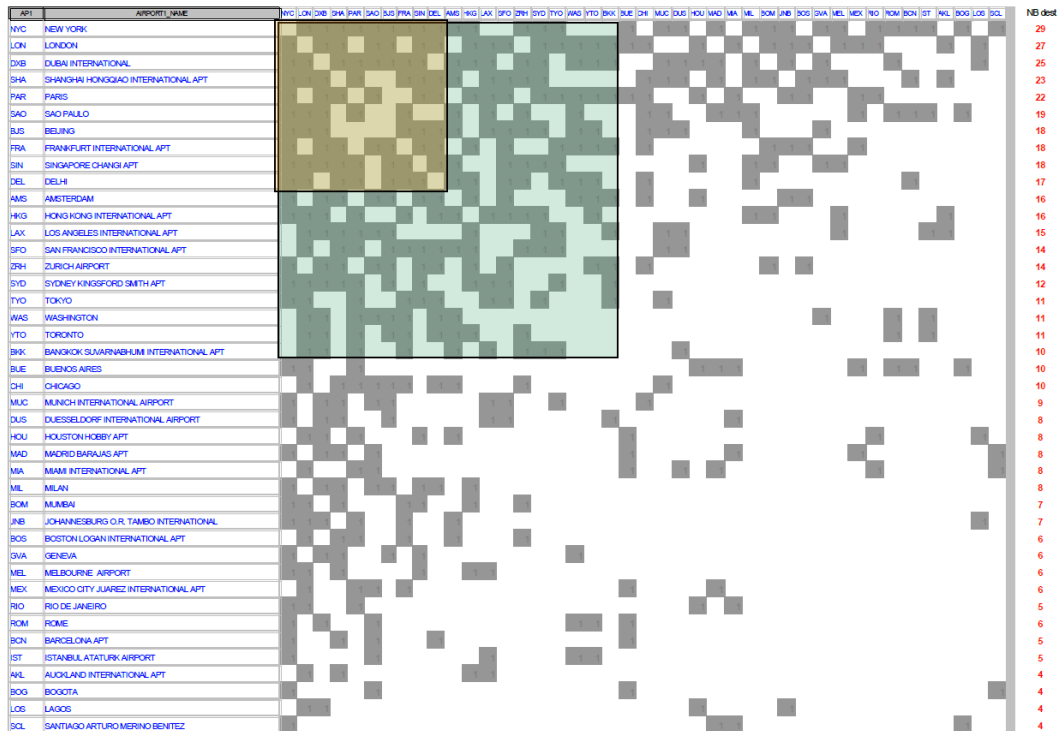


Figure 1.3: City pairs [1]

Thus, for each city pair, both the ground distance and the FC+B (see glossary here 0.2) passengers estimated to fly on them monthly were evaluated, using as horizon the year 2031.

Those values were then taken over and used for the completion of this thesis.

**Empirical and statistical equations**

In multiple occasions some of the simplified equations used by this project were also used to complete the models developed.

**Hypersonic concepts**

From the different collaborating partners came also different hypersonic concepts developed by them, and were used in this project to evaluate different scenarios with different part of the fleet taking up a share of the market. In this thesis some of them were also used for a similar purpose and will be cited throughout this report.

In particular, the concepts that will be mentioned more often are the ZEHST and MR2, which are relative respectively to the EADS ZHEST and ESA LAPCAT MR2 concepts shown in the table below:

| Aircraft type | Cruise Mach | Cruise altitude (m) | Maximum range (km) | Maximum seats | Engine_Type | Fuel of design |
|---|---|---|---|---|---|---|
| GDL ATLLAS M3T | 3,5 | 25000 | 10186 | 200 | Combined cycles | Jet-A, LCH4 |
| EADS ZEHST | 4 | 25000 | 10200,816 | 60 | Combined cycles | Jet-A, LH2, LOX |
| DLR LAPCAT M4 | 4,5 | 26500 | 15997,576 | 202 | Combined cycles | Jet-A |
| IHI ZEHST-LIKE | 4,5 | 25000 | 9000,72 | 100 | Combined cycles | Jet-A, LCH4, LOX |
| JAXA HST | 5 | 25000 | 8700,696 | 100 | Precooled turbojet | LH2 |
| LAPCAT A2 | 5 | 26500 | 18699,644 | 300 | Precooled turbojet | LH2 |
| ONERA LAPCAT II | 8 | 35000 | 16199,444 | 300 | Combined cycles | LH2 |
| ESA LAPCAT MR2 | 8 | 32000 | 18223,68 | 300 | Combined cycles | LH2 |
| MBDA AXISYMETRIC | 8 | 33000 | 15000 | 300 | Combined cycles | LH2 |

Figure 1.4: Hypersonic concepts [2]

## 1.3.2 STRATOFLY project

In the same way, the STRATOFLY project [3] has continued the previous HIKARI project work, with the goal of evaluating the potential of a high speed civil aircraft configuration to reach TRL 6 by 2035, developing a MR3 configuration from the aforementioned ESA LAPCAT MR2.

More precisely, its aim was to offer a solution to the presently congested flight paths, while at the same time minimizing environmental impact both in terms of greenhouse gasses and emitted noise.

# 1.4 Main tool: WhatsOpt

This assessment process is a software based on Python language, within the OpenMDAO framework developed by NASA, coupled to the WhatsOpt [4] GUI developed by ONERA. The latter was developed precisely to be used for multidisciplinary design analysis.

Along this document, there will often be images of WhatsOpt conceptual maps, therefore it is necessary to explain a bit better how this graphic interface works, and how to interpret the different parts.
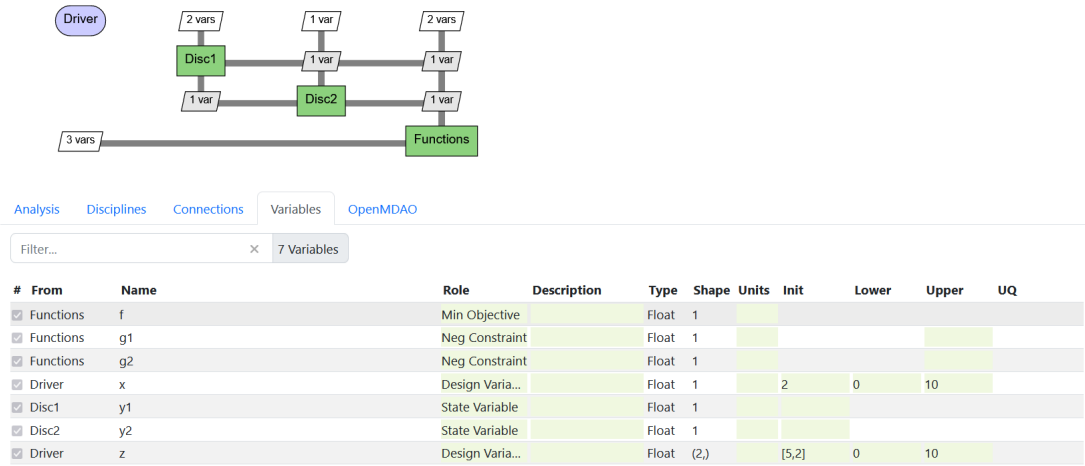
Figure 1.5: Basic WhatsOpt model

From the conceptual map in figure 1.5, it can be seen that there are three types of structures:

- Driver: starting module in every WhatsOpt model, and it contains all the data that will be used as an input.

- Modules: they are the green squares, that will take some variables as an input and using the defined equations, give other variables as an output. Those equations will be defined in the python files generated by the interface.

- Variables: they are the white and grey rhombuses. If they are linked to a module by a vertical line, they are inputs to that module, else they are outputs. If an output is on the left of the module, it means it will be a feedback to the module above it, however if it is placed under the Driver, it wont be a feedback, but a model's output variable.

Additionally, all variable defined in the Driver can be:

1. A parameter: it is a fixed value, which means that the optimizations or the design of experiments than can be implemented with the program will only use the initial value of said parameter.

2. A design variable: it is a variable that can be changed within given bounds to study the effects of said variable on the outputs of the model.

3. An uncertain variable.

For each of them it is possible to set:

- An initial value: it is the value that will be used in the MDAs.

- A lower value: it's the lower limit used in the MDOs and DOEs.

- An upper value: it's the higher limit used in the MDOs and DOEs.

Other variables can be simple response variables, min/max objectives (thus the optimization will try to minimize/maximize it respectively), a constraint (to keep the optimization between specific bounds), etc.

# Part II

# Process and models structure

**In this part the general process and the two different models will be explained shortly, leaving the details to the annexes**

# Chapter 2

# Process

The goal of this thesis, as the title shows, is to make a first assessment on a hypothetical fleet of hypersonic civil aircraft, evaluating its feasibility and its impact on the world.

Therefore it is necessary to start by looking at the big picture and to develop a process to achieve said goal, then use that process to create a model, and finally improve the model until the wanted degree of precision is reached.

After researching thoroughly, a first conceptual map of the process is developed:
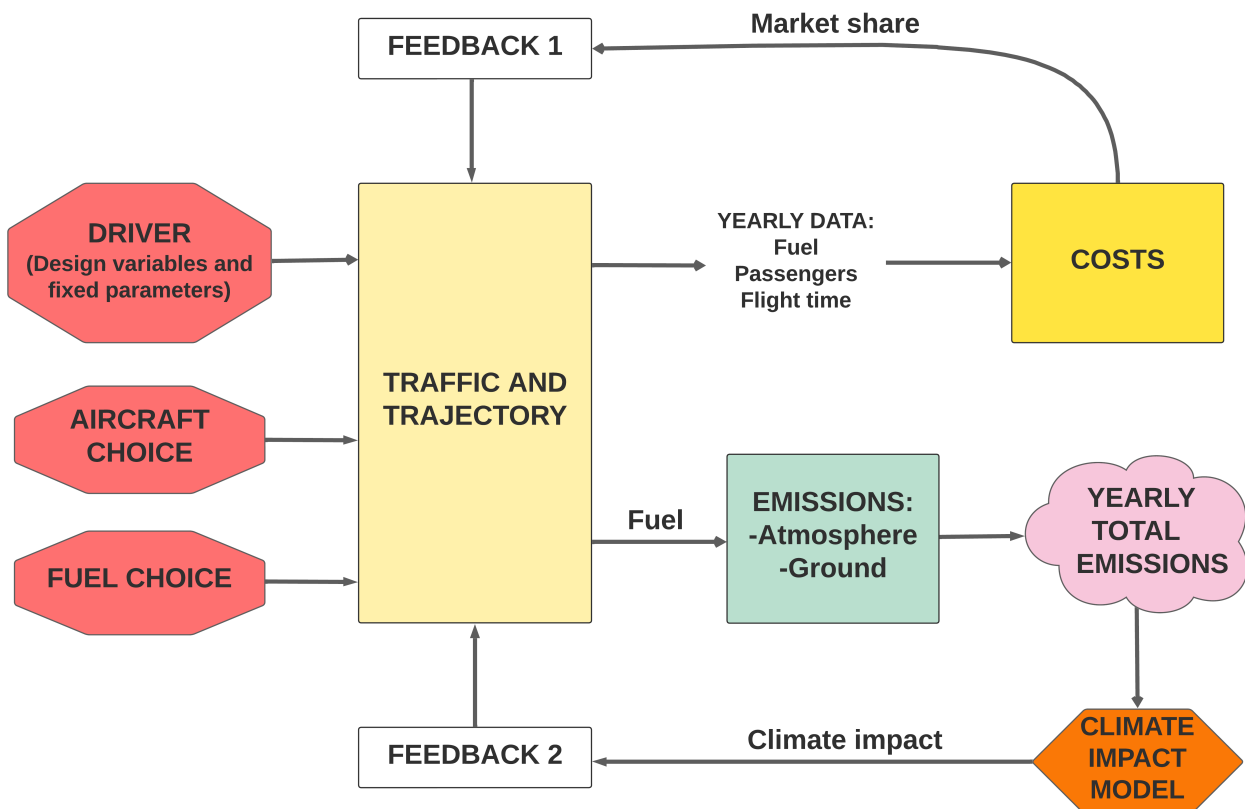


Figure 2.1: General process

The idea behind it is that there would be two main branches: The **Costs** branch, to calculate the ticket price, and the **Climate impact** branch.

Both those branches of course need specific data to work, that comes from the common **Traffic and Trajectory** module. Thus the latter has two tasks: calculate all necessary data to implement the two branches, and of course estimate the third and last output needed for the multi-objective optimization: the flight time.

Finally, the process has two feedback loops: Their task is to take back the outputs of the branches and use them to evaluate the number of passengers that will actually fly with the designed fleet of hypersonic aircraft. For example, for the second feedback it's intuitive that a higher climate impact of the fleet would push more people towards greener alternatives. In the same way, a higher ticket price would mean that less people would be willing to pay it just to waste less time flying.

The problem was, of course, how to implement those two feedback loops.

Let's start with the feedback coming from the Costs branch. As you can see from the previous conceptual map, the variable returning to the Traffic and Trajectory module is not the ticket price, but the market share. But what is the market share and how does it works? As it's a complex matter, not usually seen in the aerospace domain, it will be explained in detail in the next section.

## 2.1 Market share concept and cycle

It is important to specify that when talking about average person or client in this section, it will be the average **First class or Business class client**, as high speed travel will still have pretty expensive tickets and therefore it is taken for granted that people that usually fly with Economy will not be interested. To even be more clear, the acronym FC+B will be added when it is felt that there could be some misunderstanding, to indicate the fact that only first and business class passengers are taken into consideration.

The Market share is a concept introduced in [5], and it is defined as the **percentage of the market interested in the product**, therefore if the market share of a certain product is 30%, it means that 30% of the market pool is likely to buy that specific product instead of one of the competitors.

In this case it originates form the fact that it was evaluated that, by looking at the comparison from the hypersonic ticket price and its subsonic (FC+B) counterpart, and by comparing the time gained, it would be possible to estimate the percentage of people that would choose hypersonic transport.

Therefore Airbus, with the help of Oxford Economics, generated an empirical law that, given as an input the hypersonic and subsonic reference (FC+B) ticket prices and flight times, will return the percentage of the (FC+B) market that will be taken over by high speed travel:

$$Market_share = \frac{1}{1 + \exp b0 + b1 * time_ratio + b2 * fare_ratio} \tag{2.1}$$

With:

- b0, b1 and b2 are empirically derived coefficients.

- The time ratio is the ratio between hypersonic flight time and its equivalent subsonic reference's flight time.

- The fare ratio is the ratio between hypersonic ticket price and its equivalent subsonic reference's ticket price.

But how was it possible to insert in the law the time gain? How can a time quantity be evaluated economically? By using the concept of Value of Time (VoT).

The value of time is a concept studied in different domains, that in this case gives the quantity of money that people are willing to pay to save an hour of flight. For example, if the medium passenger was willing to spend 100 € more to buy a flight that lasts two hours less, his VoT would be 50 €/h.

For the HIKARI project this value was taken from two studies:

1. A study that quantifies the VoT for executives using private jets [6].

2. A Concorde-based estimated of the VoT by Oxford Economics and Airbus, on the New York - Paris route.

These studies both take into consideration only people with a certain income, but that's correct because, as said previously, this type of clients were the one targeted by the network traffic study, as they will be the only ones that can afford HST travel. Adjusting the value calculated from those two studies to the network chosen, that is significantly different from Concorde, a value of 890 €/h was returned.

Then, how does the Market share cycle work? It can be summarised by the following conceptual map:
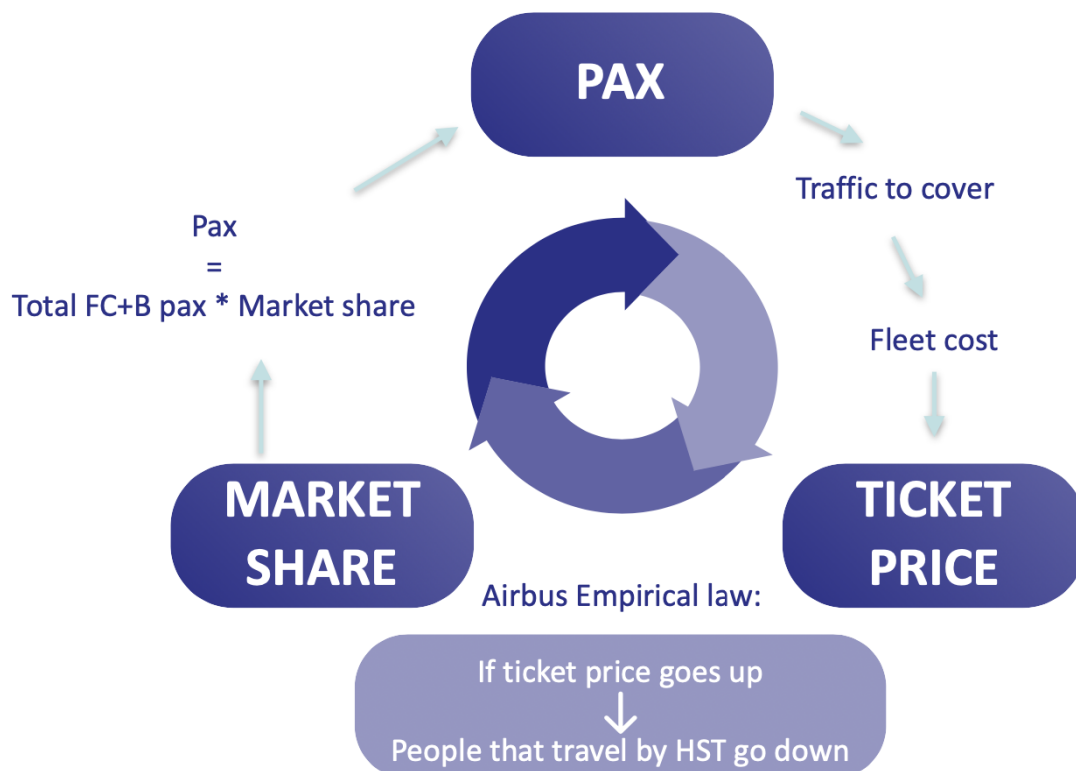


Figure 2.2: Market share cycle

Basically, the cycle starts with an initial market share hypothesized, that will be used, with the total number of passengers in the market pool, to find the effective number of people wanting to fly with HST in a year. Having then the total number of client to be flown, and the aircraft data in input as shown, it is possible to calculate the total number of yearly flights, and the total costs derived from

fuel, maintenance, etc. All those costs added together will return the total fleet costs. Finally, by inflating the total costs to have a profit, and by dividing them for the total number of passengers displaced, the ticket price can be found, and from it the market share, using the empirical law developed by Airbus and Oxford Economics. The cycle then restarts, and iterates until the market share arrives at a point where it converges on a certain value, obtaining the Market Share Equilibrium, with relative hypersonic ticket price, costs and passengers.

As for all the equations and variables that will be implemented to generate a model from this process, they will be discussed in detail in the annexes.

Finally the second feedback loop, as can be seen from the general process figure, should bring back the climate impact as global temperature increase, influencing the initial modules. However, after researching thoroughly, no existing climate impact model was found for this application, not even ones that could be modified and interpolated to adjust them accordingly.

## 2.2 Climate impact

Let's go a bit deeper in the climate impact topic, to really understand why it was not possible to find or implement a climate impact model. First of all, to evaluate the impact, usually a temperature gradient is used, as the main consequence of the greenhouse effect is a rise in the total planet temperature. That is why normally this $\Delta T$ would be one of the three main model's output results. To find this gradient, a phenomenon called Radiative Forcing (RF) is used, as they are linked by this formula:

$$\Delta T = \lambda * RF \tag{2.2}$$

Therefore they are proportional, as $\lambda$ is a constant called climate sensitivity parameter, usually with units $\frac{K}{W/m^2}$. RF, usually measured in $\frac{W}{m^2}$, describes the change in energy flux caused by different factors, in this case greenhouse gasses. With a positive RF there will be an increase in temperature, therefore negative consequences.

The problem is that this difference in radiation energy entering/being reflected into the lower atmosphere and radiation energy exiting/being reflected out of the lower atmosphere is extremely difficult to estimate, as it greatly changes with chemical species, altitude, latitude and many other parameters. Thus it is only possible to calculate it having the specific data for a certain chemical specie, a certain altitude and latitude, by having already collected a lot of data in those conditions. Therefore, even if some climate impact model exists, they mostly are for subsonic altitudes, as for subsonic flights. For example for kerosene, all the necessary data is collected from the different flights that take off everyday. However for higher altitudes, like the ones taken into consideration in this thesis (As subsonic flights usually don't fly higher than 13 km of altitude, while all concepts taken into consideration here fly higher than 25 km of altitude, deep in the stratosphere), all the necessary data is not available. Additionally, even if the subsonic data is available, it is mostly about the european zone, where the majority of the flights take place. HST, however, is almost necessarily made of intercontinental flights, as for lower ranges the time saved by flying faster would not be compensating the longer climb phase to arrive at Mach > 4 and a cruise altitude higher than 25 km, therefore even by trying to interpolate subsonic data for higher altitudes would not be enough to cover all latitudes needed. And that is without taking into consideration that an interpolation would not really be possible as the lifetime of some chemical species like water vapour in the stratosphere is still not clear to this day.

In conclusion, a feedback of this kind was not possible to implement in a working module by the author of this thesis, but the process is still valid and could be taken over in case a suitable climate impact model will become available at some point.

As a result of this problem, to successfully generate a functioning model from this process, the best way to take into consideration the pollution caused by the fleet in the estimation of the effective number of HST clients was to implement a **GHG tax**. This way, the tax derived from those emission would increase the total fleet costs, therefore increasing the final ticket price and lowering the market share as explained before, all without the need for a climate impact model. The mechanics on how this tax was implemented will be better explained in the chapters about the two different models, and in the annexes, where the majority of the models equations are shown in detail.

## 2.3 Introduction of the models

From this process, two different models have been developed:

- A **Fixed concepts** model: it will take as input already existing hypersonic civil aircraft concepts, and apply the aforementioned process to evaluate them.

- A **General concept** model: instead of receiving as input already existing concepts, this model will estimate the aircraft main characteristics with an additional design module, with simplified empirical equations. Therefore it will be useful to judge beforehand in which direction a more detailed design process should focus to achieve the optimal process outputs.

# Chapter 3

# Fixed concepts model
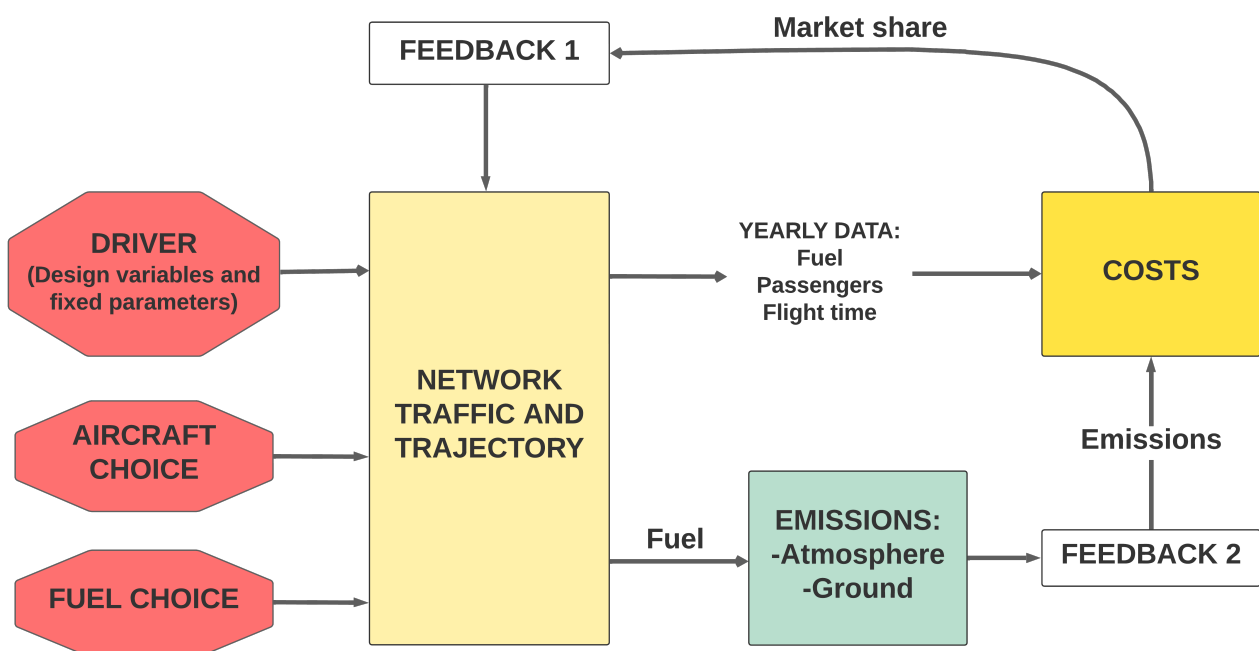


Figure 3.1: General structure

## 3.1 Model limitations

Of course, the goal of this stage being only a preliminary assessment, both the models will have some limitations, some in common and some not.

The common limitations are:

1. The **lack** of a **climate impact model**, therefore it was chosen to evaluate just the total life cycle emissions instead.

2. The **fuel consumption** and **atmosphere emissions** are calculated with the hypothesis that the entire flight time can be approximated as being only **cruise phase**. Therefore the total mass of fuel burned will be returned using the Breguet equation, as explained in annex 1 (V). Moreover, all the emissions deriving from flight fuel combustion will be considered as being released at

cruise altitude because the altitude at which those emissions are effectively doesn't matter if a climate impact model is not available.

3. The **lack of a multiobjective optimization tool**, making it impossible to optimize all three goals of the thesis (Flight time, ticket price and climate impact).

4. It is only accurate enough for hypersonic concepts with cruise Mach not too far from 4-8. That is because all the cost empirical equations are specific to this kind of concept.

5. The fact that **different fuels** are evaluated **without** considering the effective **structure and aerodynamic changes** that would have to be made on the aircraft to accommodate said fuel. Therefore all fuels are considered drop in fuels. The different analized fuels are:

   - **0 - Green LH$_2$:** liquid hydrogen produced using electrolysis, and with a price per kg as of september 2022.

   - **1 - Actual LH$_2$:** liquid hydrogen produced using methane combustion as an energy source, and with a price per kg as of september 2022. It's the main way of producing it right now.

   - **2 - Kerosene:** Jet-A1, principal used aviation fuel as of now.

   - **3 - Methane:** liquid methane fuel.

   - **4 - Future LH$_2$:** liquid hydrogen produced using electrolysis, and with a price for the year 2031 hypothesized as 1.5 €/kg by the author of this thesis.

Of course many of these limitations are about the model, **not the process**. The process itself can be taken and used largely outside the limitations, as long as the equations in the different modules are tailored for the wanted application. The equation here are just to validate the process, showing that with the right equations it can easily allow to make a first assessment and give different useful information.

### 3.1.1 Advantages and disadvantages

Other than the common limitation, there are some others that are more like disadvantages, as they will be compensated a bit by the second model developed.

In particular the Fixed Concepts model has the following advantages over the General Concept model:

- It is more precise, as it uses less empirical equations, that when combined can cause the model to exit physical bounds, and takes into consideration the climb and descent phase in the flight time calculations (but not in the fuel consumption computation).

- It is more stable, as it doesn't have the design cycle, that can diverge for certain conditions (See here 6.2.1).

While still having disadvantages:

- It is less flexible, because having fixed aircraft concepts to choose from takes away the possibility to study many interesting parameters, for example cruise Mach.

- It is less self sufficient, as it needs a lot more data in input and if no concepts already created are available, it cannot work.

## 3.2   Inputs and outputs

Main outputs wanted:

- Flight time.

- Ticket price.

- Emissions masses.

Other interesting outputs that could be evaluated are the total profit in a year (€), and the market share (explained here: 2.1).

And main design variables taken as input:

- **Load factor**: the load factor is a value that indicates the degree of fullness of an aircraft. It is used because one cannot hypothesize that every flight with every aircraft of the fleet will be completely full, especially when we are considering hypersonic flights, that will have a particular slice of the market. Therefore with this value it is possible to take into consideration flights without 100% passengers on board, which is more realistic. It is set as a design variable, as it is interesting to see its effects on the outputs of the model, and set to vary between 60% and 100%, but in general it would be reasonable to set it at 75%, therefore it is the initial value. It could be useful to use higher load factors for smaller payload aircraft, as it is much easier to fill 60 seats than 300.

- **Percentual profit**: it sets the percentage of profit wanted in relation to the total cost of the hypersonic fleet. It is set to vary from 10% to 20%, with an initial value of 15%.

- **Annual workload**: maximum yearly hours an aircraft can fly. It is set to vary between 3150 h and 5000 h, with an initial value of 5000 h. This values are taken from the market study done by Oxford Economics and Airbus within the HIKARI project [5].

- **CO2 tax coefficient**: coefficient necessary for the implementation of a carbon dioxide tax.

- **GHG tax coefficient**: coefficient necessary for the implementation of a greenhouse gasses tax.

- **Range interval**: Range interval between set lower and upper limits, to only take into consideration the part of the traffic wanted.

### 3.2.1   Traffic input data

As said before in the previous works section (1.3), both models use HIKARI's estimated traffic data for year 2031.

They take as input all the traffic data from an external excel file (VI), and both a lower range limit and a higher range limit from the driver. Those two last variables together make the aforementioned range interval design variable.

This way, setting a maximum and minimum range, the program will take into consideration only routes with length between those two limits, and not all the network.

It was made because the network contains routes that go from 3000 km to 18000 km, and to create a concept optimized for such a large range difference is not realistic.

Therefore, by only selecting a precise part of the routes, one can evaluate the best options for all ranges, while still using data corresponding to actual airports and routes.
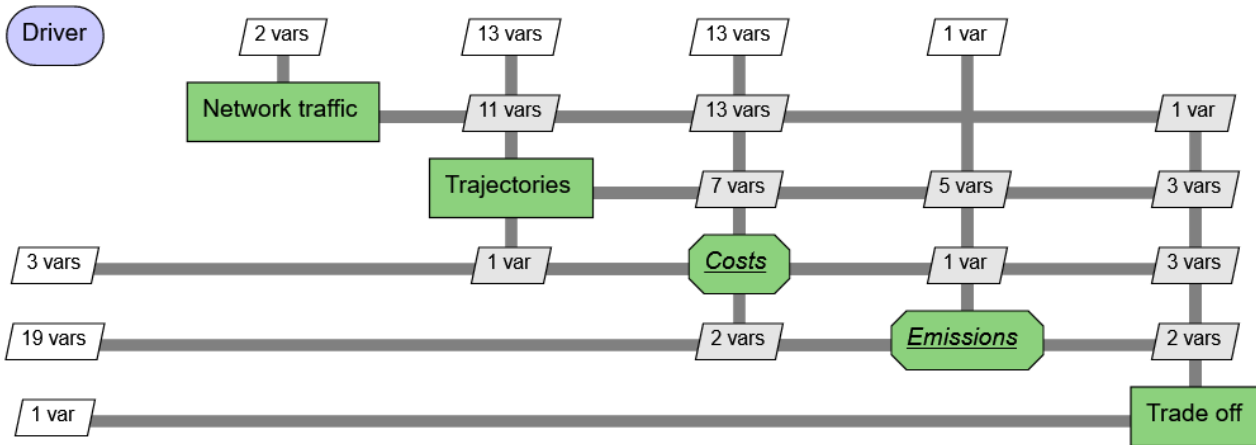
## 3.3    General structure



Figure 3.2: WhatsOpt model structure

The general role and working of each module is described in the following sections, while they will be described in more detail in annex 2 (VI), because the goal of this thesis was to solve a problem, not to create a model. Therefore it was decided that by giving too much space to the model structure, it would outshine the results and conclusions.

### 3.3.1    Common modules

It can be observed from the general structure that, as all WhatsOpt model do, it has a **Driver**, from which all design variables and predefined parameters needed as an input by the model are set. Actually, some of the variables will be taken not from the driver, but from external files, as it is better explained in annex 2 (VI).

The modules that come right after the Driver are Network traffic and Trajectories, that have the specific goal to return all necessary variables to the Costs and Emissions modules, heart of the process.

The **Network traffic** module has the objective to insert into the model all the necessaries variables that cannot be provided by the Driver. Therefore it takes and defines all the general traffic data (as explained before 3.2.1) and the chosen hypersonic concept specifications.

The **Trajectory** module has different objectives: First: defining all the necessary mission trajectory data. Second: using the feedback from the Costs module (that can be seen in the fist image) to define all passengers that will fly with this fleet in a year. This feedback contain the Market share variable, that represents the slice of the market that can be estimated to be taken over by HST.

### 3.3.2 Costs

The Costs submodel is divided in two:

**Ticket cost** aims to calculate the medium ticket price to fly with the hypersonic fleet in the chosen range interval. It first estimates the total operative cost of the fleet in a year, as shown in detail in VI. It was decided to only use the operative costs because, if the range interval is too small, the number of potential clients considered will be also small. Therefore, by introducing development and production costs, they will be shouldered by too little people, making the ticket price too high and diverging the model. As if that were not enough, the actual technology for this kind of travel has yet to be invented, making it extremely difficult to estimate those kind of costs. Then, after having estimated the total yearly fleet costs, the greenhouse gasses tax cost deriving from the emissions feedback is added, and it is increased with the profit wanted. Finally the total sum is divided between the passengers hypothesized flying with HST, obtaining the ticket price (€).
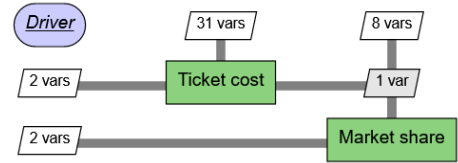
**Market share** then will find the slice of market that is estimated to be interested in flying with HST, in function of the ticket price and time gained (Better explained in 2.1). Later it will go as a feedback to the trajectories module starting a cycle that, if converged, will allow to find an equilibrium.

### 3.3.3 Emissions

Finally the Emissions submodel has the objective to calculate all the emission created by the fleet in a year.

**Atmosphere** will evaluate the $CO_2$, water vapour, $NO_x$ and unburned fuel emissions caused by the fuel combustion during the flight. the last one is due to the combustion efficiency not being 100%. The hypothesis for $CO_2$ and water vapour is that the combustion can be approximated with a simple chemical reactions between the fuel and $O_2$ molecules as shown in annex 1 (V).
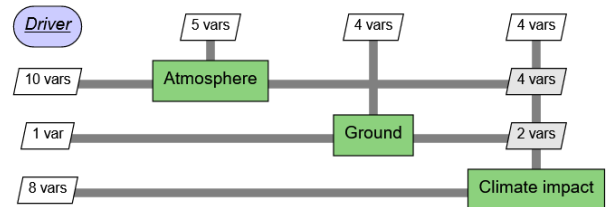
**Ground** however will calculate the equivalent $CO_2$ mass released into the atmosphere with the extraction, refinement, storage and distribution of the fuel used, as better explained here:3.4.

**Climate impact** in theory it should calculate the actual fleet yearly climate impact but, as previously mentioned, it was not possible to implement. Therefore it gives as an output the total mass of GHG or $CO_2$ emissions produced in a year, and the same emissions but per passenger per flown km, to better compare it with different concepts. The feedback from the Emissions submodel to the Costs submodel is to use those total emissions to create a Climate tax, allowing to take into consideration the emissions in the Market Share definition. Even if the outputs are emissions masses, it was still called Climate impact because, even if there is not a climate impact model available yet, the goal of this stage is not to create a finite product, but a process that can be improved in the future, a structure that can be completed and filled.

## 3.4   Life cycle emissions

As aforementioned, the emissions calculated are not only the ones produced by the combustion of fuel during the flight, but also the ones created by the extraction, refinement, storage and distribution of the fuel used.

This last factor is often ignored, as it is much more difficult to evaluate, but it must be taken into consideration when evaluating the overall climate impact. That is because even if some fuels, like liquid hydrogen, are usually considered $CO_2$ free, the entire process that brings said fuel to the aircraft is absolutely not negligible, as it could produce an equivalent $CO_2$ mass comparable with the $CO_2$ produced by the kerosene combustion. Equivalent $CO_2$ because all the energy used to refine the fuel has to be produced somehow, and the vehicles used to distribute it consume fuel, etc. All those processes produce different kinds of pollution, that can be evaluated as greenhouse gasses calculating their Radiative Forcing and therefore the increase in global temperature caused by them. Subsequently this increase in temperature can be compared with the emissions of a certain mass of $CO_2$, obtaining finally the equivalent mass of $CO_2$ that has to be released into the atmosphere to have the same effect of all those processes together. It will be indicated as eq$CO_2$ from now on, or even just $CO_2$.

This eq$CO_2$ is estimated thanks to the studies done in [7] as a mass per MJ. That means that, on average, for every MJ of fuel produced, a certain mass of eq$CO_2$ is liberated into the atmosphere. The fact that this part is not negligible will become obvious from the Results part (III).

# Chapter 4

# General concept model
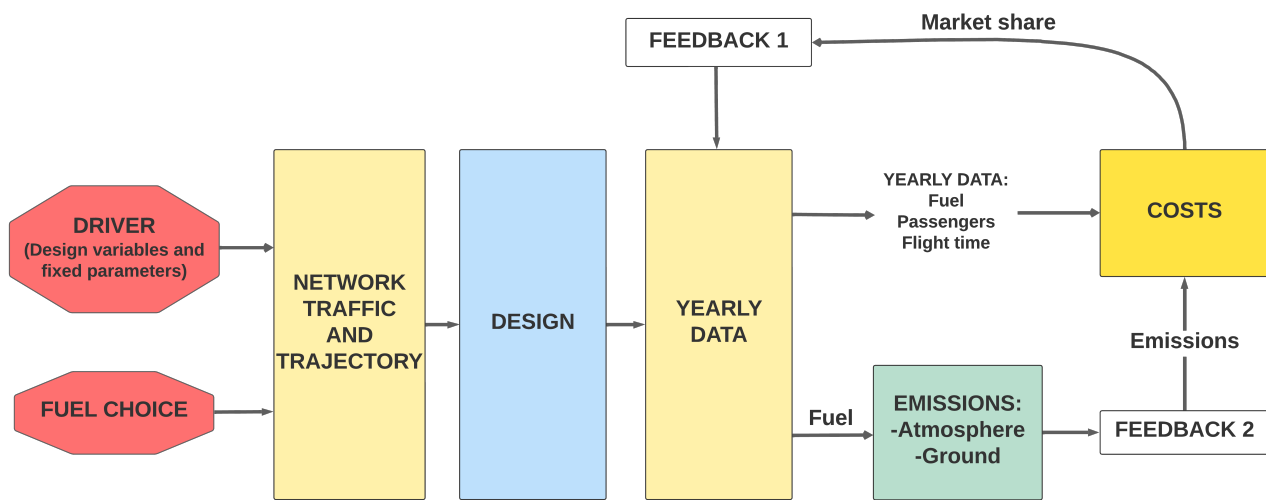


Figure 4.1: General structure

## 4.0.1 Model limitations

The common limitations are the same as the Fixed Concepts model:

1. The **lack** of a **climate impact model**, therefore it was chosen to evaluate just the total life cycle emissions instead.

2. The **fuel consumption** and **atmosphere emissions** are calculated with the hypothesis that the entire flight time can be approximated as being only **cruise phase**. Therefore the total mass of fuel burned will be returned using the Breguet equation, as explained in annex 1 (V). Moreover, all the emissions deriving from flight fuel combustion will be considered as being released at cruise altitude because the altitude at which those emissions are effectively doesn't matter if a climate impact model is not available.

3. The **lack of a multiobjective optimization tool**, making it impossible to optimize all three goals of the thesis (Flight time, ticket price and climate impact).

4. It is only accurate enough for hypersonic concepts with cruise Mach not too far from 4-8. That is because all the cost empirical equations are specific to this kind of concept.

5. The fact that **different fuels** are evaluated **without** considering the effective **structure and aerodynamic changes** that would have to be made on the aircraft to accomodate said fuel. Therefore all fuels are considered drop in fuels.

In this particular model the change in dry mass and volume due to the different masses and densities of fuel is taken into consideration, but not the additional mass or volume due, for example, to the fact that for liquid hydrogen special cryogenic tanks are needed. What's more, with an optimization of the Küchemann tau parameter (explained later) the optimal general shape can be found for each fuel. Therefore even if it's still a common limitation, the impact on this model is lighter.

Of course many of these limitations are about the model, **not the process**. The process itself can be taken and used largely outside the limitations, as long as the equations in the different modules are tailored for the application wanted. The equation here are just to validate the process, showing that with the right equations it can easily allow to make a first assessment and give different useful information.

### 4.0.2   Advantages and disadvantages

Other than the common limitations, there are some other that are more disadvantages, as they will be compensated a bit by the second model developed.

In particular the General Concept model has the following advantages over the Fixed Concepts model:

- It is more flexible, as more parameters can be set as design variables, and even the shape of the concepts is not fixed.

- It is more self sufficient, as it does not have fixed concepts as an input, but only a cruise Mach number, a maximum seats number and a form parameter (Küchemann tau, explained later 4.3).

While still having disadvantages:

- It is less precise, as it uses more empirical equations, and does not takes into consideration the climb and descent phase in the flight time calculations.

- It is less stable, as the design cycle can diverge for certain conditions (See 6.2.1).

## 4.1   Inputs and outputs

Main outputs wanted:

- Flight time.

- Ticket price.

- Emissions masses.

Other interesting outputs that could be evaluated are the total profit in a year (€), and the market share.

And main design variables taken as input:

- **Cruise Mach number**: indicates the cruise speed of the aircraft in relation with the speed of sound.

- **Maximum seats**: maximum number of seats available on the concept.

- **Küchemann tau** ($\tau$): form parameter, influencing the concept's structural design.

- **Percentual profit**: it sets the percentage of profit wanted in relation to the total cost of the hypersonic fleet.

- **Range interval**: Range interval between a set lower and upper limit, to only take into consideration the needed part of the traffic.

## 4.2 General structure
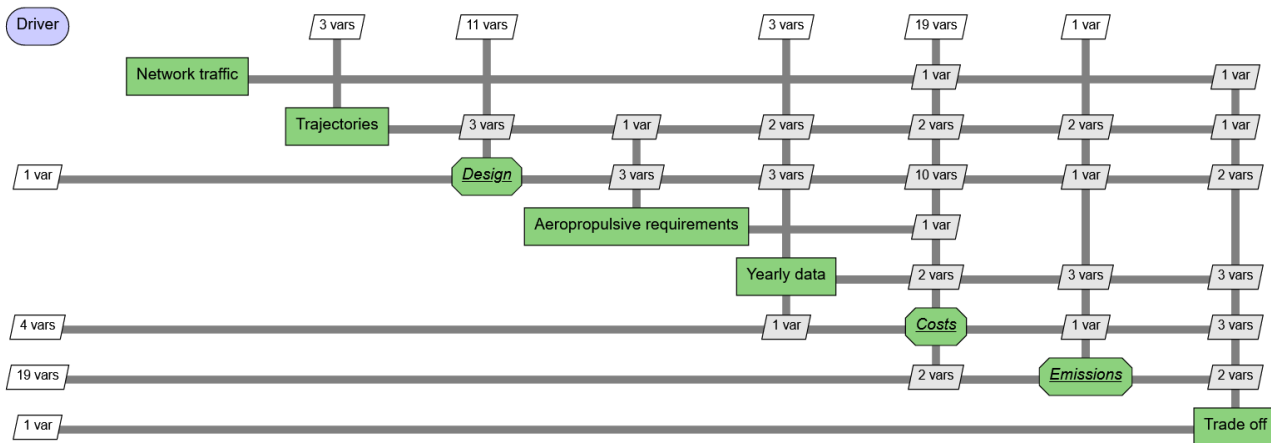


Figure 4.2: WhatsOpt model structure

Every module will be described more in detail in annex02 (VI).

The main difference between this model (more precisely described in VII) and the Fixed Concepts model is the presence of the Design subanalysis, with the aim of defining all the aircraft's characteristics from a few design variables instead of taking them all from an already existing concept. This way the analysis or optimization can also help find the best direction for a later detailed design to focus on, instead of trying every configuration.

In this case therefore the Driver and the first two modules are needed to provide the Design modules with all the information necessary to implement the cycle. As a result of this change, the majority of the outputs that were from those previous modules are now calculated in different Design modules.

### 4.2.1 Design

As it can be observed from the second conceptual map, said cycle is composed by five different modules:

Figure 4.3: Design subanalysis and feedbacks

**Mission**, the first Design module, is obviously needed to compute all variables that define the mission profile that are not already calculated by Trajectories.

**Geometry** is needed to estimate all the form parameters except the $\tau$, that is a design variable. It receives the fuel mass as input from a feedback, because it uses the fuel mass to estimate the fuel volume and then the total volume.
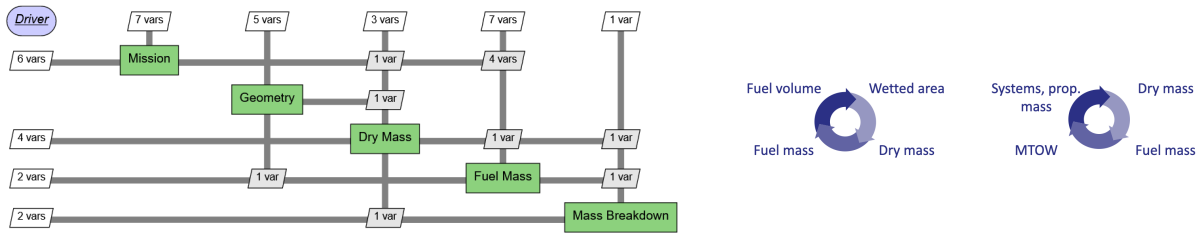
**Dry mass** of course has the task of estimating the concept's dry mass, that will be necessary for the Breguet equation. It receives a feedback as well, as the MTOW is used in this module to estimate airframe, systems and propulsion group mass with different empirical equations.

Finally **Fuel mass** and **Mass breakdown** are of course used to calculate the fuel mass necessary for the mission and the maximum takeoff weight. This subanalysis will the iterate until a convergence is achieved in terms of MTOW.

### 4.2.2 New common modules

The two modules placed between Design and Costs are needed to define all the remaining data necessary for the costs and Emissions subanalysises to take place.

**Aeropropulsive requirements** computates some propulsion parameters, as the takeoff and cruise thrust.

**Yearly data** module contains basically all remaining equations that were in the Trajectory module for the Fixed Concepts model, but that require the aircraft specifications to be determined, which are mostly variable indicating yearly quantities, hence the name.

## 4.3 Küchemann form parameter

The Küchemann $\tau$ is a form parameter often used in supersonic and hypersonic studies, as it combines the volume and the lifting area of the aircraft, allowing it to describe a vast range of configurations.

Tau is defined as:

$$\tau = \frac{aircraft\_total\_volume}{aircraft\_planform\_area^{1.5}}$$
(4.1)

Therefore different tau parameters give different aircraft's shapes:

$\tau = 0.032 \qquad \tau = 0.063 \qquad \tau = 0.104 \qquad \tau = 0.229 \qquad \tau = 0.393$
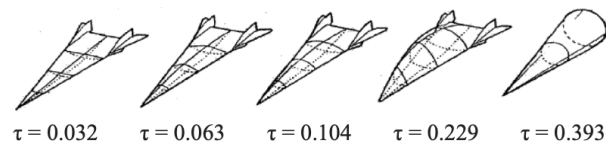
Figure 4.4: Influence on shape of Küchemann $\tau$

Of course those are not the actual limits, that would be $\tau = 0$ for a flat plate and $\tau = 0.7$ for a sphere, but the range between 0.032 and 0.393 is relative to the shapes that would have the physical possibility of flying.

# Part III

# Results

# Chapter 5

# Fixed concepts

## 5.1 Simple analysis

The most basic thing that can be done with this model is a simple analysis of a fixed scenario, without any design variable varying. Two examples are reported here, using the two concepts with the best and worst overall performances:

### 5.1.1 ZEHST

EADS ZEHST is the concepts that arguably has the worst results of all six concepts taken into consideration, as it will be clear in the next sections. This analysis takes as an input the following values:

- Percentual profit = 15%.

- Maximum yearly workload = 5000 h.

- Range interval = 3000 - 19000 km, therefore containing the entire HIKARI network (even if only the routes shorter than ZEHST maximum range will effectively be taken into consideration). This will result in a medium route of 7252 km.

- GHG tax coefficient = 0.1.

- Load factor = 0.75.

The following results are obtained:



Figure 5.1: Market share and ticket price

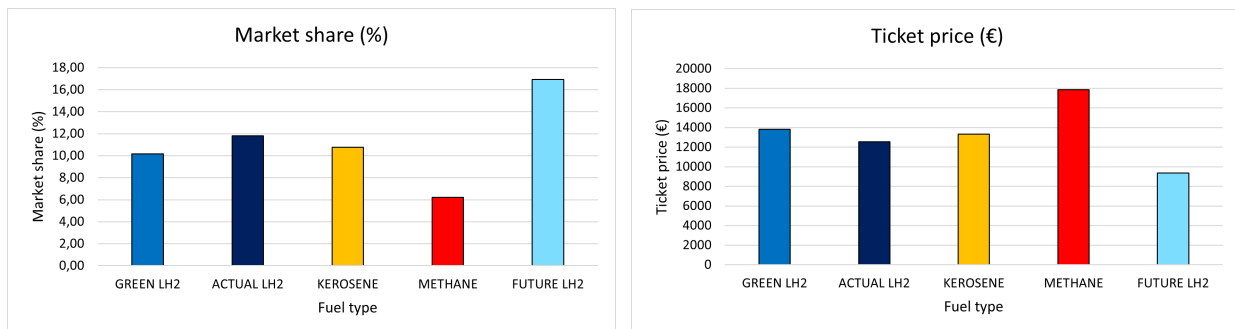As it can be seen, the lowest ticket price, and therefore the highest market share, are relative to the hypothetical future green $LH_2$ fuel. That derives from the fact that hydrogen having a higher heating value than both kerosene and methane, the mass needed for the same flight will be inferior. Hence a lower acquisition cost of the fuel, and also a lower tax GHG as the emissions are proportional to the mass of burnt fuel. Additionally, the future $LH_2$ is produced with electrolysis, thus having less $eqCO_2$ emissions than actual $LH_2$, and has a cost of 1.5 €/kg as opposed to the 3.5 €/kg chosen for the green $LH_2$ fuel as of now.

For the same reasons it is obvious that methane will be the fuel with a higher ticket price and therefore a lower market share, having a lower heating value than liquid hydrogen but also a higher price/kg than jet-A1.

It will be also interesting to confront these values of astronomically high ticket price with the results of the MR2 concept.
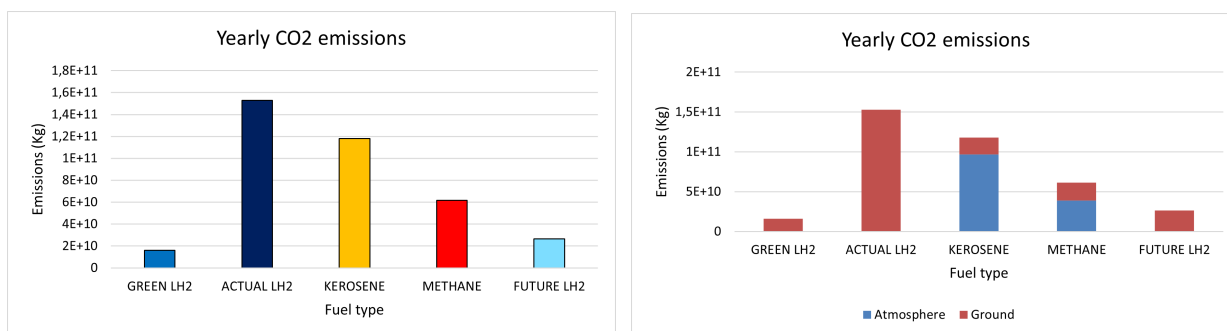


Figure 5.2: $CO_2$ emissions

The figure on the left contains the total $CO_2$ emissions, and of course someone could ask why not only liquid hydrogen powered ZEHST would emit $CO_2$, but the actual $LH_2$ analysis also has the highest production of all. That is because, as it can be seen in the figure on the right, both $CO_2$ from combustion in the atmosphere (equal to zero for hydrogen fuelled aircraft) and ground emitted $eqCO_2$ from the fuel production (estimation by [7]) are taken into account. And the ground produced $eqCO_2$ for the actual $LH_2$ is apparently much higher than the total $CO_2$ produced by the kerosene version, but that could also be due to the higher market share, and thus higher number of passengers transported by the actual $LH_2$ analysis.

That is why a fixed market share analysis was also conducted, to with the following results regarding the $CO_2$ emissions:



Figure 5.3: Fixed MS $CO_2$ emissions

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It can be observed that, fixing a market share of 20% for all fuels, the total $CO_2$ and eq$CO_2$ mass liberated into the atmosphere is still higher for the actual $LH_2$ fuel, proving that when analyzing the climate impact, the entire life cycle of the aircraft has to be evaluated. It would therefore appear that the liquid hydrogen as produced today (with methane combustion) is not the green alternative it is thought to be.
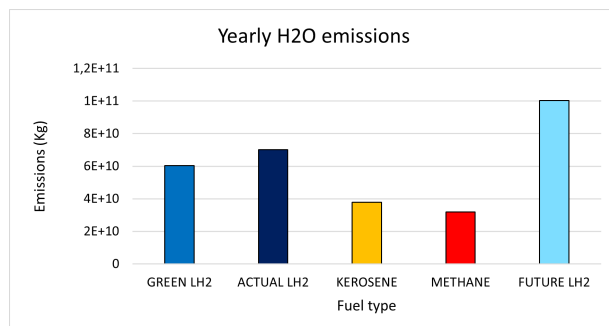


Figure 5.4: $H_2O$ emissions

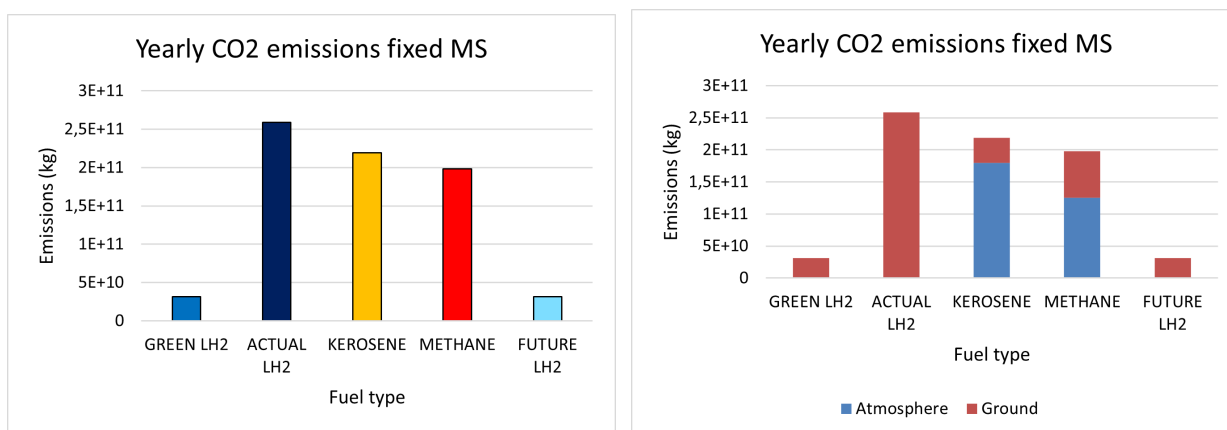It's obvious that higher water vapour emissions will be from hydrogen fuelled aircraft, and more precisely from the future $LH_2$ as it has the highest market share equilibrium, thus more passengers and flights.

Finally the total life cycle GHG emission are calculated, by adding to the $CO_2$ and $H_2O$ emissions also $NO_x$ and unburned fuel:
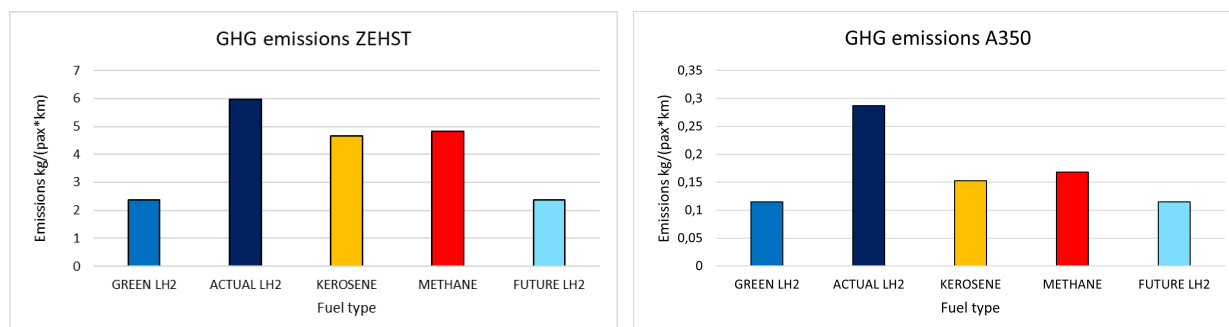


Figure 5.5: Life cycle GHG per pax per km emissions

It was decided to showcase it in the format of kg of emissions per single passenger and km, as it is easier to confront the effective net emissions of every fuel type configurations, and also to confront it with a subsonic reference of choice as for the figure in the right. It is interesting to observe that the ZEHST emissions are at least twenty times higher than the A350, and even the best fuel type configuration (green and future $LH_2$) still has a much higher pollution than the worst fuel type subsonic configuration, raising the question as to whether hypersonic civil transport will really be worth it.

## 5.1.2 ESA LAPCAT MR2

A lot of similar observations can be made for the MR2, with results that are generally better than ZEHST. It is important to note that even if for both the analysis the entire network of routes is taken into consideration, as the MR2 has a much higher maximum range, the routes actually considered will be more, with a higher medium range.

The initial values are respectively:

- Percentual profit = 15%.

- Maximum yearly workload = 5000 h.

- Range interval = 3000 - 19000 km, therefore containing the entire HIKARI network (even if only the routes shorter than MR2 maximum range will effectively be taken into consideration). This will result in a medium route of 8788 km.

- GHG tax coefficient = 0.1.

- Load factor = 0.75.
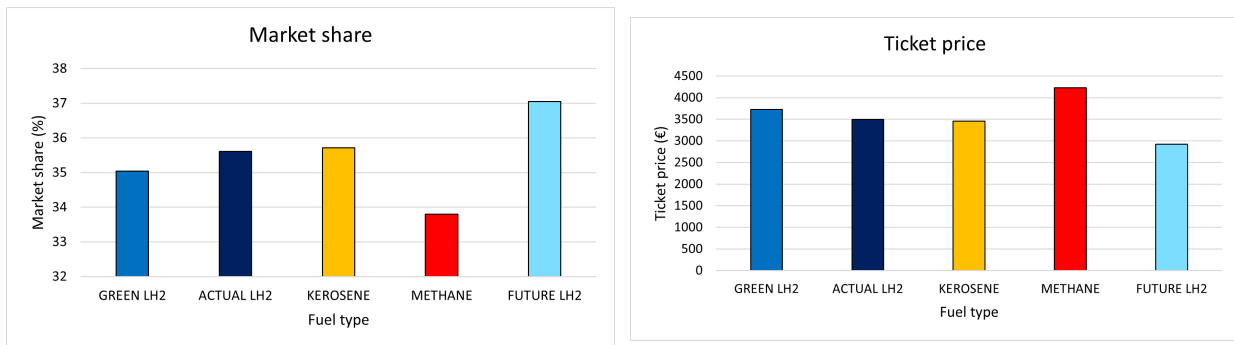


Figure 5.6: Market share and ticket price
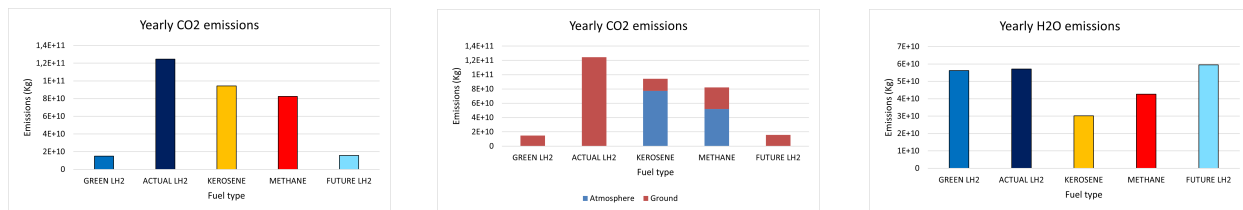


Figure 5.7: $CO_2$ and $H_2O$ emissions
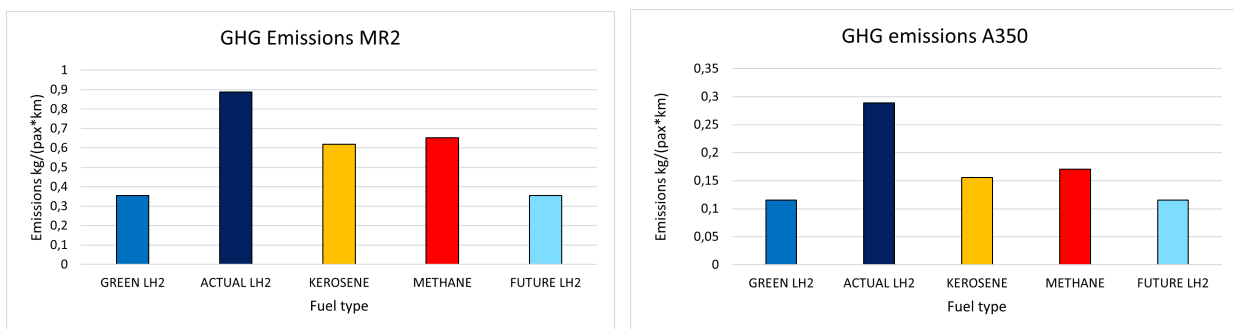


Figure 5.8: Life cycle GHG per pax per km emissions

It is still interesting to see that even the concept with the best results overall has significantly more emissions per pax per km than the subsonic reference, with a factor of approximately three.

## 5.2 Parametric studies

By varying some of the design variables it is possible to analyze the impact on the results and help choose the best configuration for a specific combination of parameters.

### 5.2.1 Varying range and fuels

The fixed values of design variables for this analysis are:

- Percentual profit = 15%.

- Maximum yearly workload = 5000 h..

- GHG tax coefficient = 0.1.

- Load factor = 0.75.

In this subsection the goal is to analyze the impact of the range variation on a single concept, while still using different fuels.

It was therefore decided to take the entire network, with routes from 3000 km to almost 19000 km, and run multiple analysis using slices of 4000 km every time. This way it will be narrow enough to observe which fuel work better for low, mid or high ranges, but it will contain enough network's routes in it to prevent outlier routes to have too big of an impact on the analysis.

For each slice (3000 km - 7000 km, 4000 km - 8000 km, etc) a medium range is calculated as explained in annex 2 (VI), and the analysis is developed:
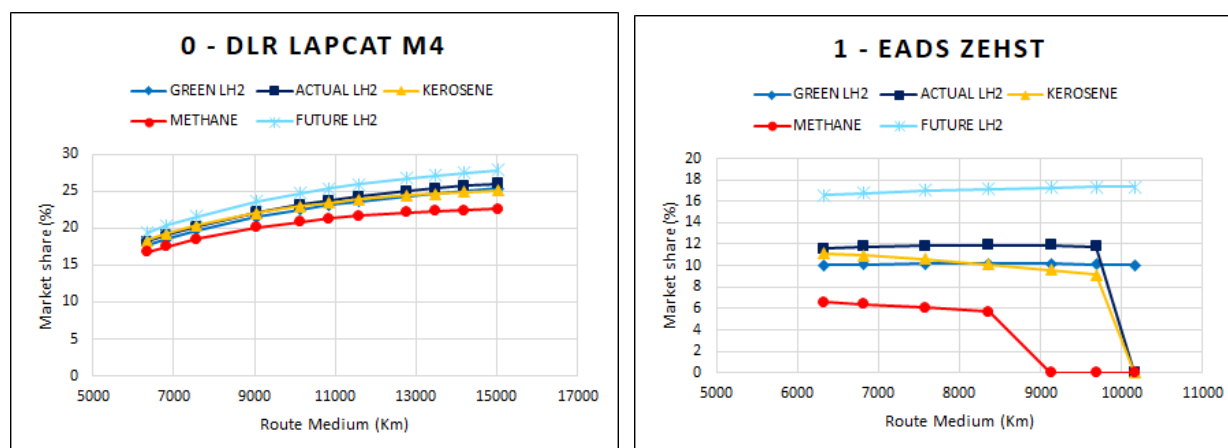


Figure 5.9
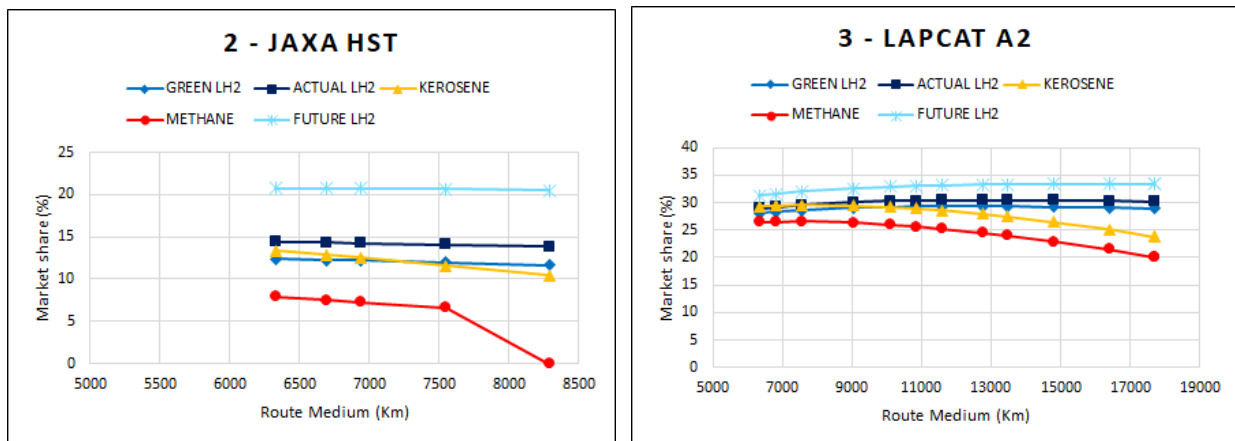
Figure 5.10
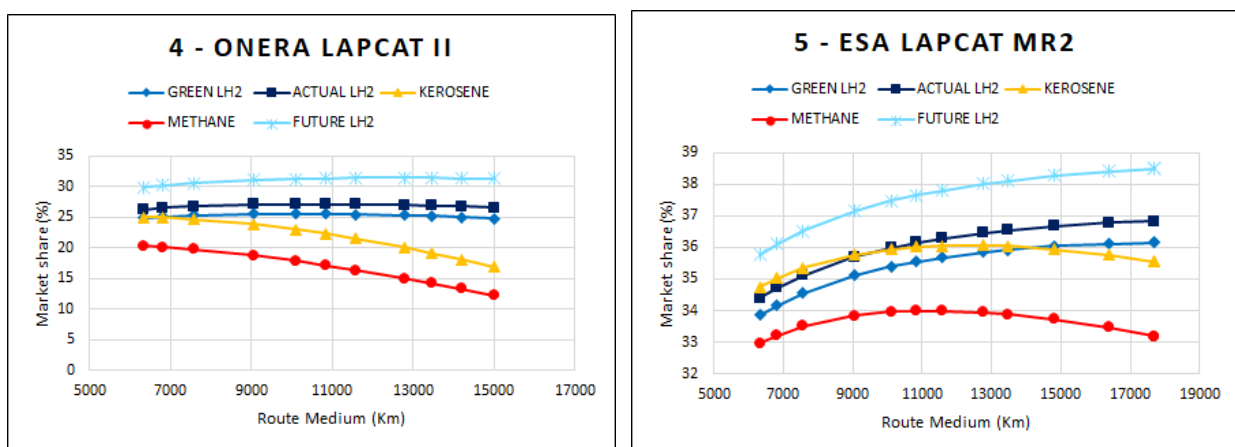


Figure 5.11: Market share comparison for each fuel, with each concept

It can easily be seen that the future LH$_2$ fuel is the best options in any situation in terms of market share, which, it should not be forgotten, combines two important goals of our process: ticket price and flight time.

A first observation that can be made is that in certain cases the market share goes to zero, in particular with the concepts that seem to have the worst results, and that is due to the fact that the model, usually when the market share goes under 5%, tends to diverge. That is because with a lower MS one has lower number of passengers flying with HST, and even if like this the costs diminish, the people on who the costs are to be divided lower even more, increasing the ticket price and making it so that the number of people wanting to fly with HST will be even lower, and so on.

A second observation is that not all graphs have the same maximum range values, that is because every concept as a different maximum range and here are not reported the higher ranges if one cannot fly as long, as it would be useless.

Finally it is interesting to see that for some concepts and fuels, the MS grows with range, because the time bought outweighs the higher costs caused by the fuel increase. This phenomenon is much more likely to occur for LH$_2$ than for kerosene or methane, as it easily seen from the 3 - LAPCAT A2 and 4 - ONERA LAPCAT II graphs, because of the much higher heating value of the first. The difference between market share and ticket price variation with range can be observed in the following

graphs about the 5 - ESA LAPCAT MR2 analysis:
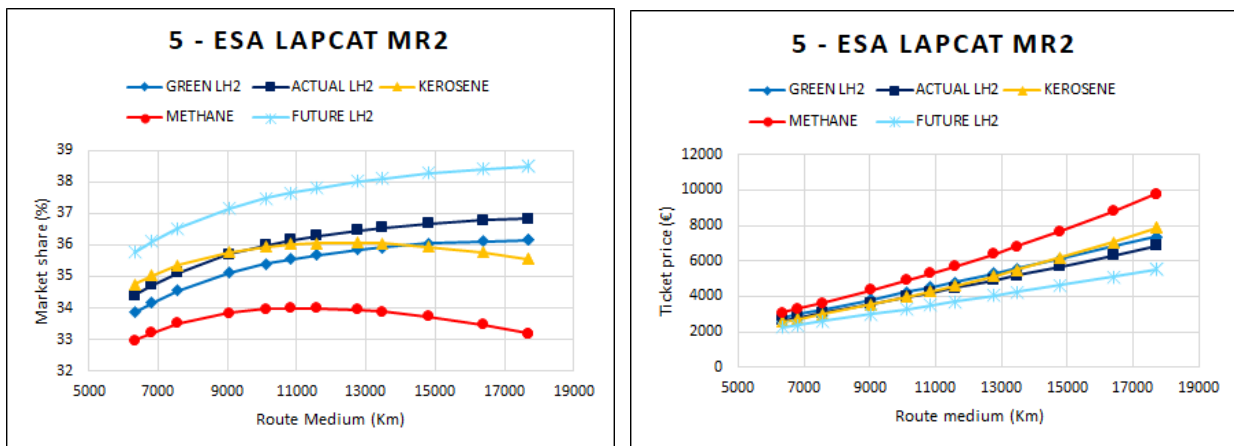


Figure 5.12: Market share and ticket price comparison for each fuel

The graphs clearly show the previous observations, as the ticket price growth is countered by the time gained only for different types of liquid hydrogen fuels. It will be discussed more precisely in the General Concept model's results.

## 5.2.2 Varying range and aircraft

The fixed values of design variables for this analysis are:

- Percentual profit = 15%.

- Maximum yearly workload = 5000 h.

- GHG tax coefficient = 0.1.

- Load factor = 0.75.

In this subsection the goal is to analyze which concept would be more suitable for the different ranges and fuels, in the same way as the fuel comparison.
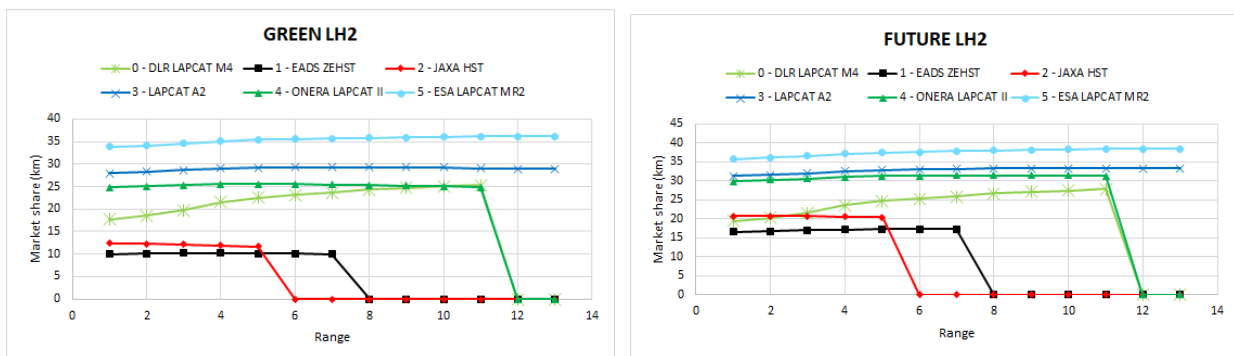


Figure 5.13
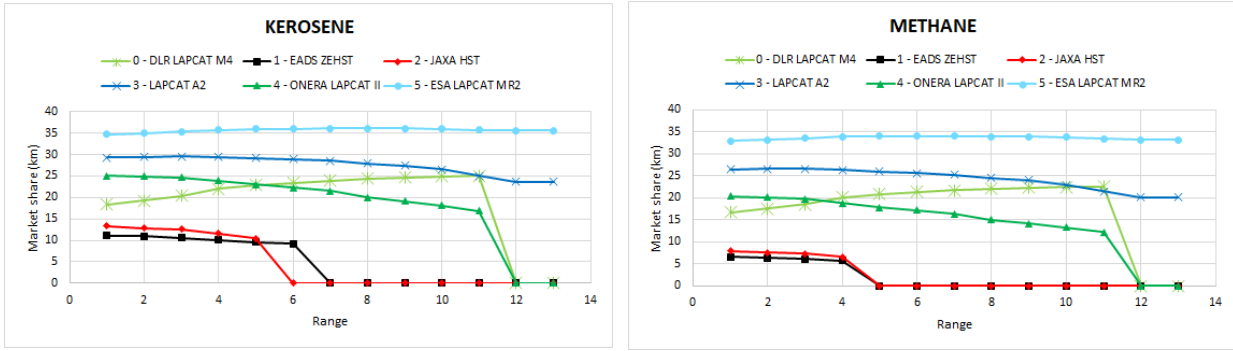
Figure 5.14: Market share comparison for each concept, with each fuel
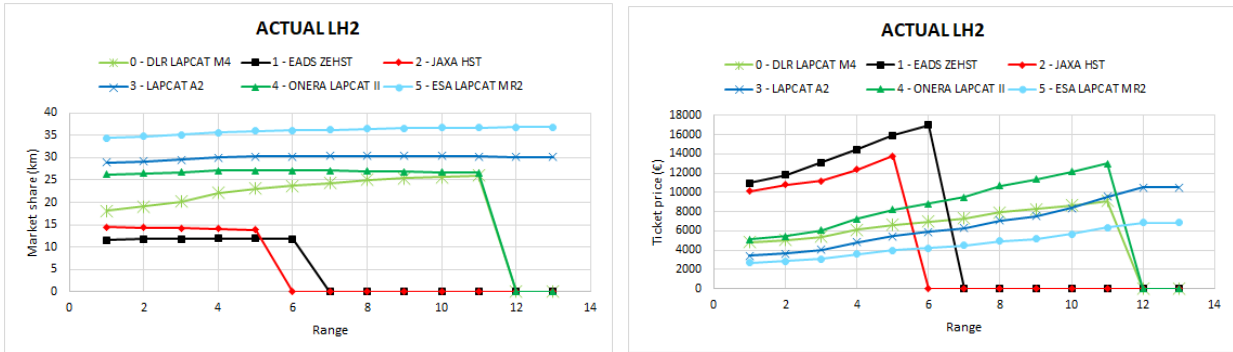


Figure 5.15: Market share and ticket price comparison for each concept

As expected and mentioned in the simple analysis section, the MR2 concept has the overall best results, while the ZEHST has the worst. It is important to specify that for all these analysis the same load factor of 0.75 is used, which is not totally realistic. In fact a 60 passengers aircraft like the ZEHST should be much easier to fill than a 300 passengers aircraft like the MR2, and that's without mentioning that with a small aircraft that does more flights, many different time slots can be covered, optimizing the market demand. Not taking into consideration all these factors puts smaller concepts at a disadvantage, and thus does not totally represent what their actual market share would be. In conclusion for higher ranges the higher passengers and L/D ratio concepts are obviously the best options, but for shorter ranges a more precise market and performance analysis will be necessary to assess which concept would be better suited.

## 5.3   Optimizations

As previously said, a multiobjective optimization tool was not available during this thesis, therefore all the optimizations presented will only have the objective of minimizing or maximizing one (1) design variable.

As the model is still far from perfect, all optimizations have important limitations, that will be discussed one by one. It was decided to show them nonetheless, as they are part of the work done. The optimizer used is COBYLA [8], as it seemed to have the best results among the different methods implemented in WhatsOpt. It uses Future hypothetic $LH_2$ for the ONERA LAPCAT II configuration.

In particular, relatively to the fixed concepts, only one optimization was carried out, as the design variables are not that interesting to study. It was mainly made as an exercise, to test the model.

Details:

- **Goal:** minimization of greenhouse gasses mass emitted per passenger flown and per km traveled (kg/(pax*km)).

- **Constraints:** at least 20% of market share wanted. It was set because while the objective is to minimize emissions, it's also important to have sufficient market coverage to make the whole project worth investing in. Besides, without this constraint the model will find that the easiest way to minimize emissions is to have the smallest market share possible, which is a consequence of setting design variables in a way that maximize costs and minimize time gains, going against the thesis goals.

- **Design variables:**

  1. **load_factor**: varying between 0.6 and 1.
  2. **profit_perc**: varying between 10% and 20%.
  3. **tax_GHG**: varying between 0.06 €/kg to 0.14 €/kg.
  4. **time_work_annual**: varying between 3150 h to 5000 h.
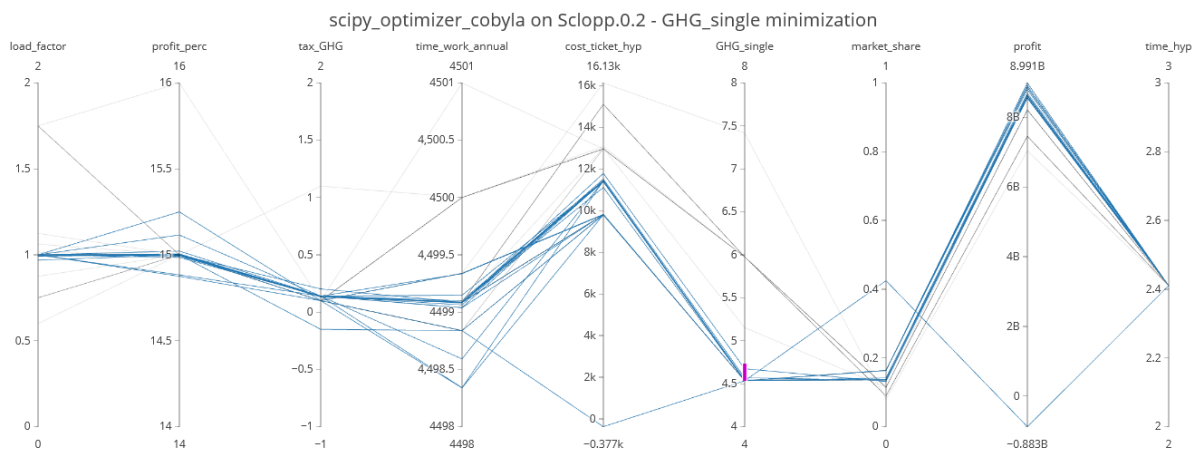


Figure 5.16: Fixed concepts optimization

The optimization results are:

- **load_factor** = 1.

- **profit_perc** = 15%.

- **tax_GHG** = 0.14 €/kg.

- **time_work_annual** = 4450 h.

First, it can be seen that to minimize the emissions and costs, the load factor is maximized, meaning that all the flights are completely full of passengers. As it is the parameter that impact the most, with it the market share is already higher than 20%. Therefore, to diminish even more the emissions, the model increases profit, taxes and lowers the working time, so that the costs will rise with a consequently lower market share, just enough to respect the constraint. This way less clients will fly with

HST and therefore less emissions will be released into the atmosphere.

However, a load factor equal to one is an unrealistic prevision, as it's linked to the passengers choice and not to the design process, therefore the observations from this particular optimization are not to be intended as indication for a future design, just as a demonstration that with this process and relative model an optimization can be done.

# Chapter 6

# General concept

### 6.0.1   Model's limitation reminder

## 6.1   Simple analysis

The most basic thing that can be done with this model is a simple analysis of a fixed scenario, without any design variable varying.

Two examples are reported here, using the fixed concepts ZEHST and MR2 data as input. Therefore, in addition to verifying the analysis results, it will also be possible to compare them with the fixed concepts analysis results:

### 6.1.1   ZEHST like general concept

Initial values:

- Mach number = 4.

- Maximum seats = 60.

- Küchemann's tau = 0.2, for all analysis it was chosen to set it like this as it is almost in the middle of the physically possible configurations.

- Percentual profit = 15%.

- Maximum yearly workload = 5000 h.

- Range interval = 3000 - 9050 km, therefore containing all the routes shorter than ZEHST's maximum range in the entire HIKARI network. This will result in a medium route of 7252 km, same as ZEHST's fixed concept analysis.

- GHG tax coefficient = 0.1.

- Load factor = 0.75.

The following results will be obtained:
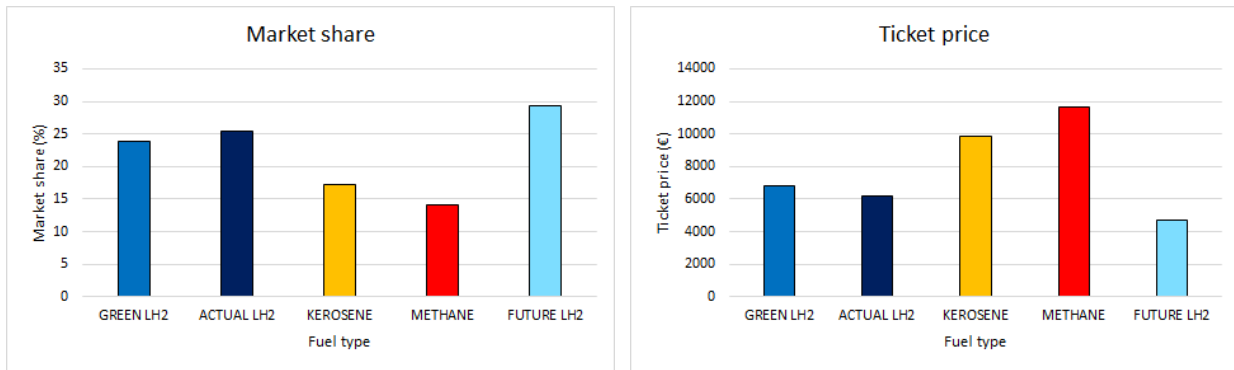
Figure 6.1: Market share and ticket price

As it can be seen, compared to the ZEHST's fixed concept analysis, the ticket price is much lower, and therefore the highest market share is much higher. That is mainly due to two substantial differences:

1. MTOW: for the fixed configurations the MTOW was fixed as well, being 340000 kg for the ZEHST. In this case, however, the MTOW is returned from the design cycle and is significantly lower for the LH$_2$ based fuels and for methane, while a bit higher for kerosene. All MTOWs are shown in the graph down below.

2. L/D ratio: the lift to drag ratio was fixed at 5 for the actual concept, but here is calculated through an empirical law and has a value of 5.28. It might not seem like much, but a slight change in lift to dag ratio has a big impact on the results, and that is why this small increase is enough to counterbalance the higher MTOW of the kerosene configuration, making it so that the final ticket price is lower.
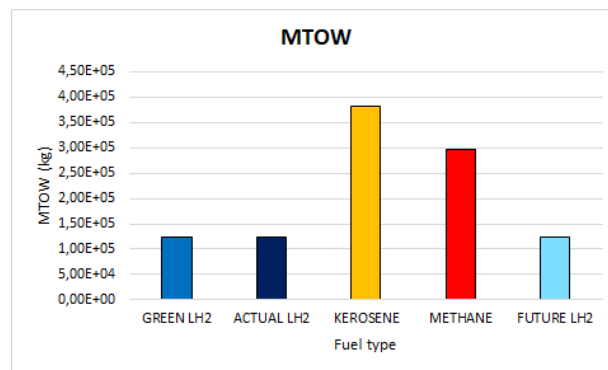


Figure 6.2: MTOW converged
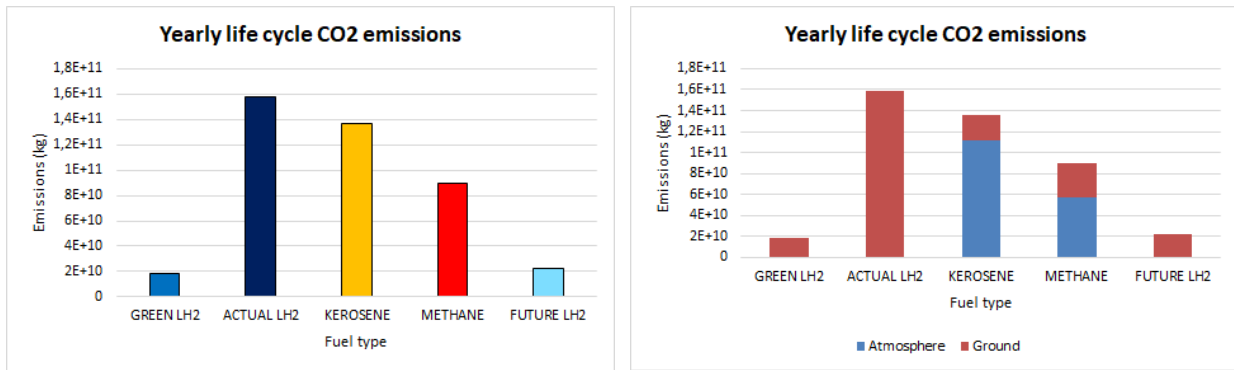
Figure 6.3: Fixed MS $CO_2$ emissions
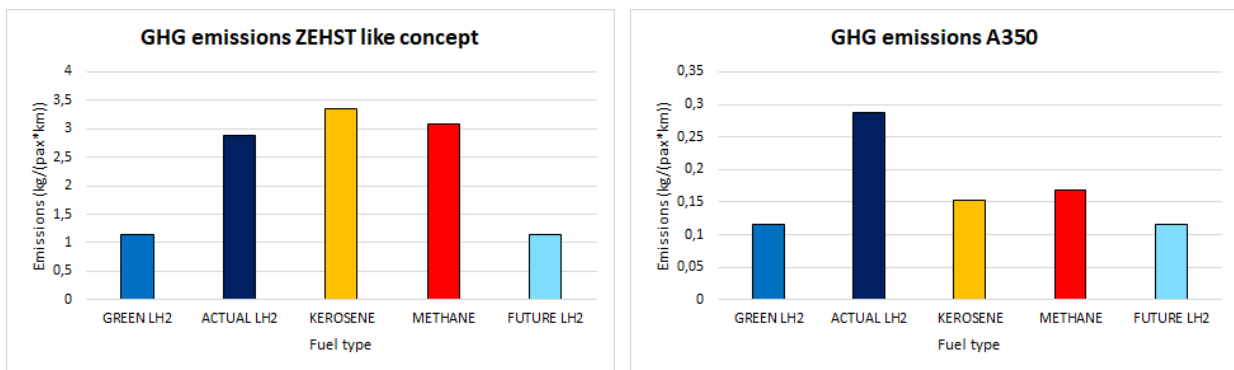


Figure 6.4: Life cycle GHG per pax per km emissions

Even though the lift to drag ratio is so important, the impact of MTOW is still high, as now the highest $CO_2$ life cycle emissions mass is not relative to the actual $LH_2$ anymore, but to the kerosene, and the same goes for the total life cycle emission per passenger per km, and that is despite the kerosene scenario having a lower market share than the $LH_2$ based fuels.

The ZEHST like general concept emissions are still higher than the A350, but lower than the actual ZEHST. Still, it has a much higher pollution than the worst fuel type subsonic configuration, raising the question as to whether hypersonic civil transport will really be worth it.

## 6.1.2 ESA LAPCAT MR2 like general concept

In the same way a MR2 like general concept was analyzed with the following initial values:

- Mach number = 8.

- Maximum seats = 300.

- Küchemann's tau = 0.2, for all analysis it was chosen to set it like this as it is almost in the middle of the physically possible configurations.

- Percentual profit = 15%.

- Maximum yearly workload = 5000 h.

- Range interval = 3000 - 16170 km, therefore containing all the routes shorter than MR2's maximum range in the entire HIKARI network. This will result in a medium route of 8788 km, same as MR2's fixed concept analysis.

- GHG tax coefficient = 0.1.

- Load factor = 0.75.
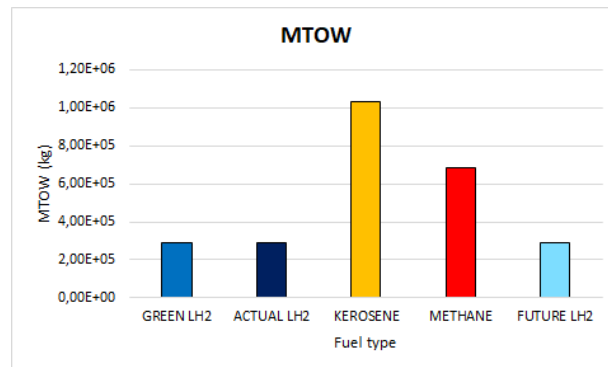


Figure 6.5: MTOW converged
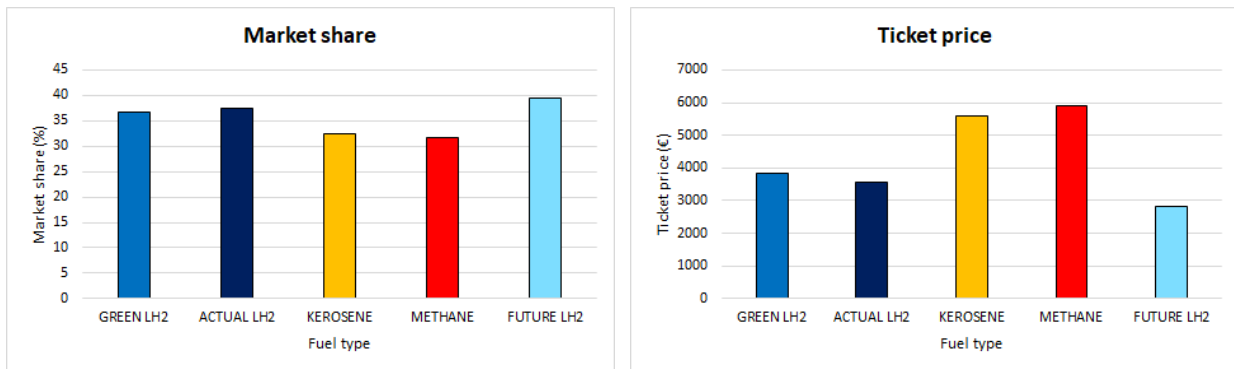


Figure 6.6: Market share and ticket price

It's interesting to see that, because of the huge increase in MTOW, the highest $CO_2$ life cycle emissions mass is not relative to the actual $LH_2$ anymore, but to the kerosene, and the same goes for the total life cycle emission per passenger per km, and that is despite the kerosene scenario having a lower market share than the $LH_2$ based fuels.
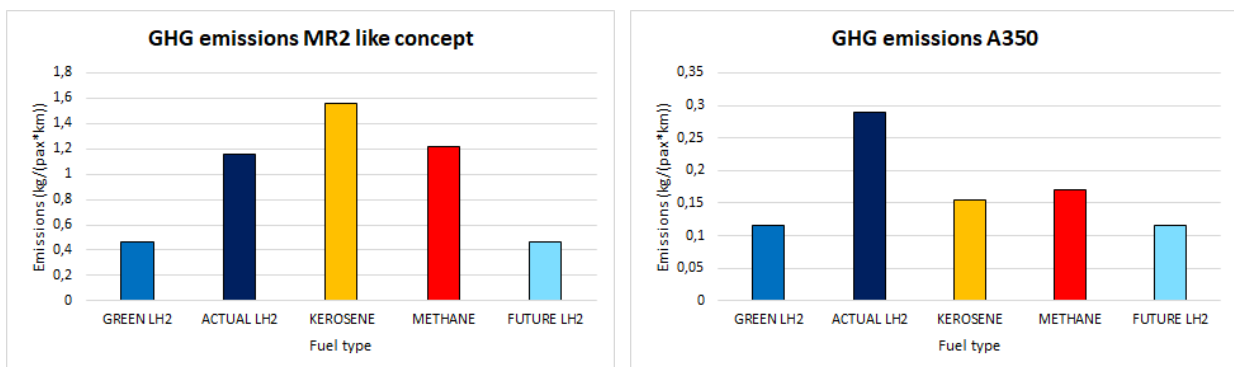


Figure 6.7: Life cycle GHG per pax per km emissions

It can also be observed that while the ZEHST like general concept has better results than the actual ZEHST, that is arguably the opposite for the MR2 like general concept. That can be explained by the fact that some of the empirical or statistical equations used in this model are created using the fixed concepts as a database, which means that the is is reasonable for it to have results between the worst and best fixed concepts. That is also valid in the case of the empirical equation regarding the lift to drag ratio, that here is lower than the actual MR2.

## 6.2 Parametric studies

By varying some of the design variables it is possible to analyze the impact on the results and help choose the best configuration for a specific combination of parameters.

### 6.2.1 Impact on MTOW of range and fuels

The fixed values of design variables for this analysis are:

- Maximum seats = 300.

- Küchemann's tau = 0.2.

- Percentual profit = 15%.

- Maximum yearly workload = 5000 h.

- GHG tax coefficient = 0.1.

- Load factor = 0.75.

In this subsection the goal is to analyze the impact of the range and fuel on the maximum take off weight, with Mach number fixed:
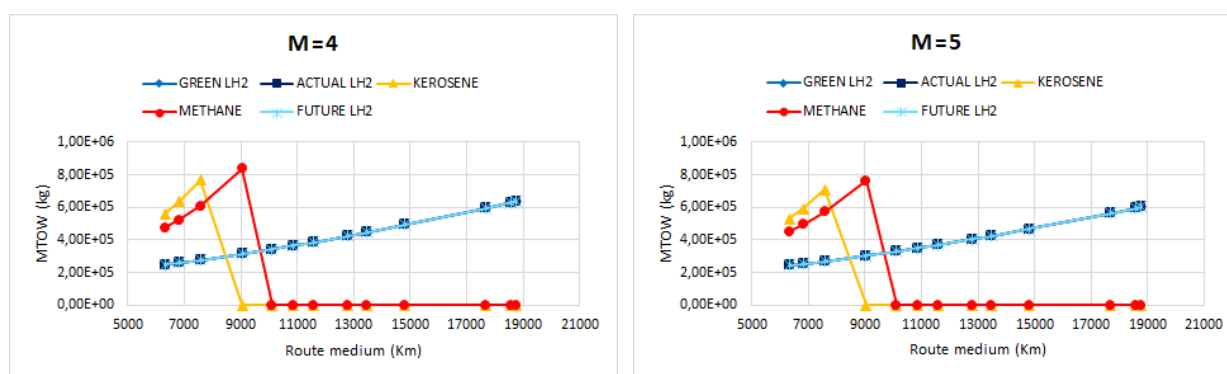


Figure 6.8

As it can be observed in the various graphs, while not having problems with the design cycle convergence for $LH_2$ related fuels, the same does not apply for kerosene and methane. Instead, for those scenarios, the MTOW grows esponentially with range until it diverges, and would grow infinitely but is therefore brought to zero.

That is because of the Breguet range equation, and how it is structured:
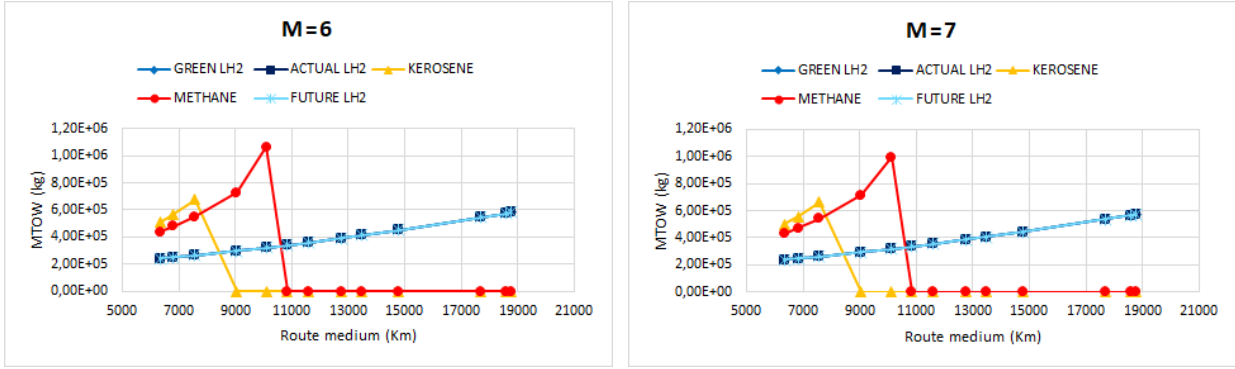
Figure 6.9
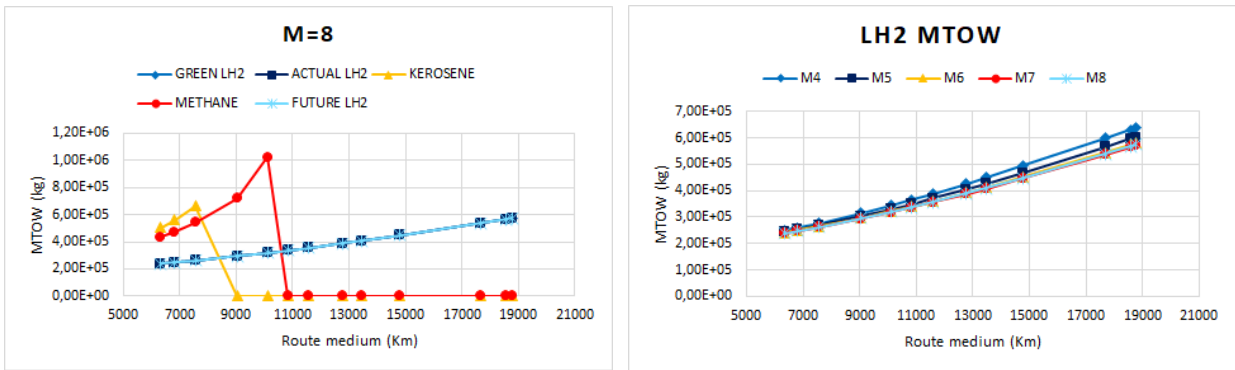


Figure 6.10: MTOW convergence as function of range and fuel

$$mass\_fuel\_burnt\_medium = mass\_dry * \left(e^{\overline{(ld\_ratio * \frac{route\_medium * 1000}{\frac{speed\_cruise\_hyp}{3.6} * isp\_cruise}})} - 1\right) \quad (6.1)$$

As you can see the exponent in the equation is, among other things, composed by the route length and the specific impulse. The latter is of course related to the heating value of the fuel, and is significantly lower for kerosene and methane. Therefore what happens is that, when the route length goes higher than a certain value, the exponent becomes > 1, as the specific impulse is not high enough. Thus in the design cycle when this situation occurs, the cycle will calculate a huge fuel mass, and then a huge MTOW in function of it, that will need a even bigger fuel mass to fly the chosen range, and so on, growing more with each iteration.

This phenomenon seems to indicate that to create hypersonic concepts meant to fly longer ranges, only fuels with high heating value as $LH_2$ can be used.

Finally, the last graph shows how the Mach affects the MTOW convergence, suggesting an optimal cruise Mach that would minimize the maximum takeoff weight between M = 7 and M = 8.

## 6.2.2 Impact of range and tau

The fixed values of design variables for this analysis are:

- Mach number = 8.

- Maximum seats = 300.

- Percentual profit = 15%.

- Maximum yearly workload = 5000 h.

- GHG tax coefficient = 0.1.

- Load factor = 0.75.

The purpose is to analyze the impact of the range and Küchemann's tau on the maximum take off weight, market share (that contains ticket price and flight time) and greenhouse gasses emissions:
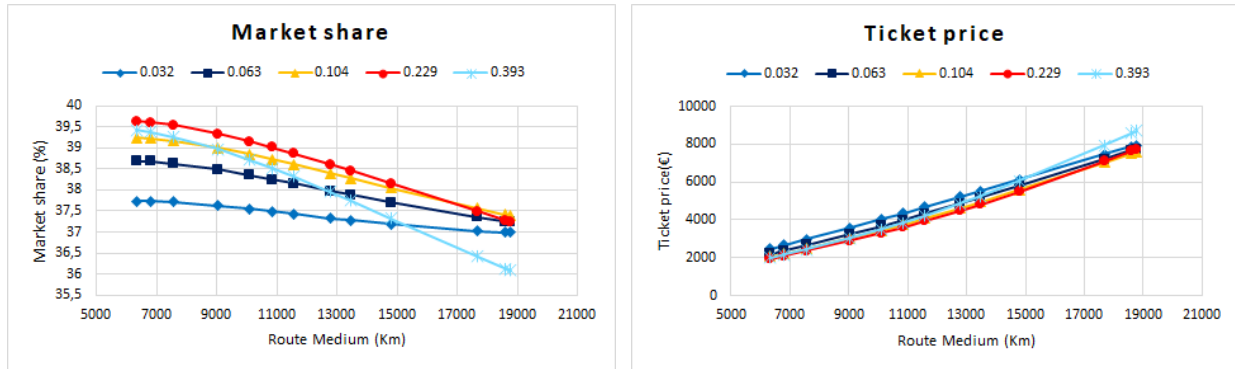


Figure 6.11: Market share and ticket price varying range and $\tau$
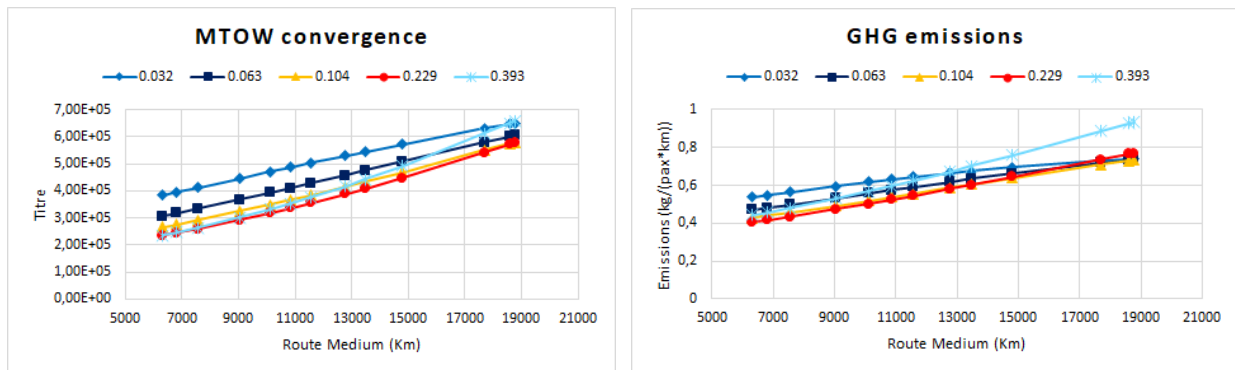


Figure 6.12: MTOW and GHG emissions varying range and $\tau$

It is interesting to observe that the results for this scenario suggest an overall optimal $\tau$ parameter that would minimize the maximum takeoff weight, ticket price and emissions, and would maximise market share, between $\tau = 0.104$ and $\tau = 0.229$. However, for really low ranges a $\tau$ parameter of 0.393, which corresponds to a conical form, seems to actually be better than the 0.104 option, while for higher ranges it obviously becomes worse than every other configurations as the cone is not a really aerodynamic shape.

### 6.2.3 Varying cruise Mach and altitude

The goal is to analyze how cruise Mach and altitude impact on the different output variables. It was therefore decided to set the cruise altitude as a design variable for this analysis, by untying it from the cruise Mach.

It is important to mention that in this analysis a hypothesis is used: the altitude is varied not counting if the aircraft could actually fly this high, as the engines design is not part of the process. It is

simply to analyze the effect of the altitude.

The fixed values of design variables for this analysis are:

- Medium range = 8788 km.

- $\tau = 0.2$.

- Maximum seats = 300.

- Percentual profit = 15%.

- Maximum yearly workload = 5000 h.

- GHG tax coefficient = 0.1.

- Load factor = 0.75.
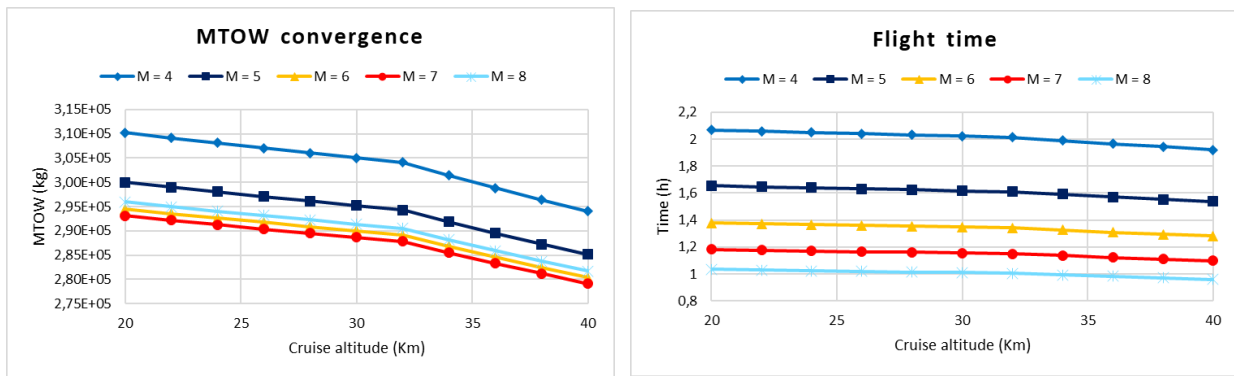


Figure 6.13: MTOW converged and flight time
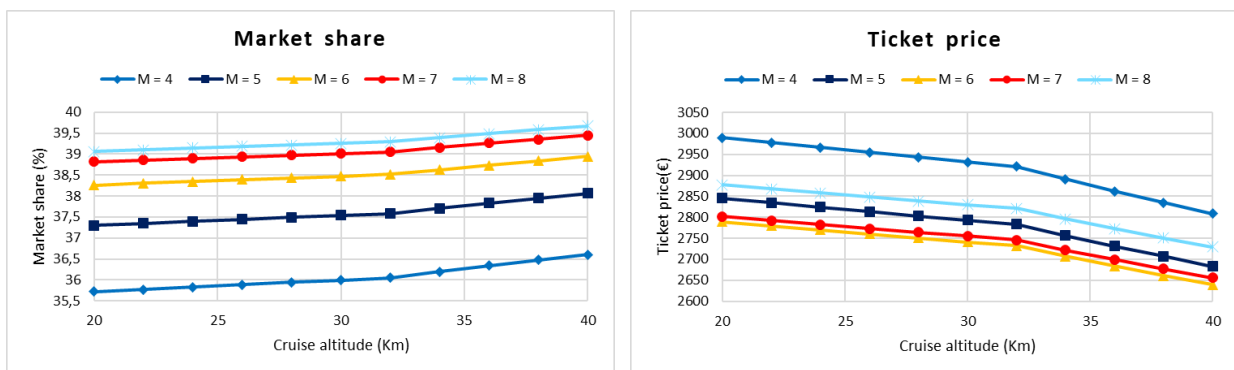


Figure 6.14: Market share equilibrium and relative ticket price

It's interesting to see that from 32 km of altitude all graphs change, that is because using a simplified ISA atmosphere method, the temperature gradient is 1 K/km before and 2.8 K/km after. Therefore it changes the speed of sound in the atmosphere, consequently modifying every result.

The optimal Mach for emissions and ticket price seems to be round 7, in agreement with the results found before, even if the difference between M = 6,7,8 is minimal.
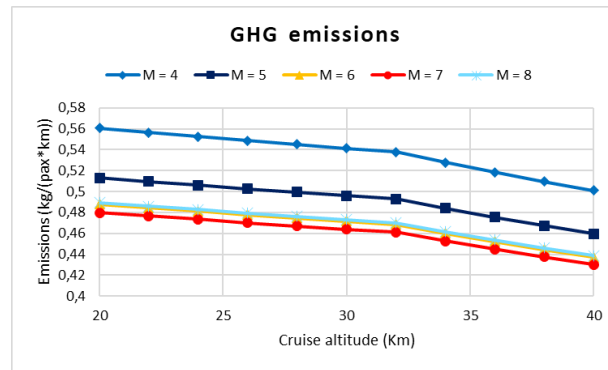
Figure 6.15: GHG emissions

Looking at market share however the optimal point is at M = 8, as this parameter takes into consideration time gain in addition to ticket price, which will obviously be more important with a higher speed.

There doesn't seem however to be an optimal altitude, as the output variables all improve with it. That can be explained by the fact that with a higher cruise altitude a higher air temperature is present, therefore increasing the actual flying speed,

# 6.3 Optimizations

As previously said, a multiobjective optimization tool was not available during this thesis, therefore all the optimizations presented will only have the objective of minimizing or maximizing one (1) design variable.

As the model is still far from perfect, all optimizations have important limitations, that will be discussed one by one. It was decided to show them nonetheless, as they are part of the work done. The optimizer used is still COBYLA [8], using Future hypothetic $LH_2$ fuel.

Details:

- **Goal:** minimization of greenhouse gasses mass emitted per passenger flown and per km traveled (kg/(pax*km)).

- **Constraints:** at least 20% of market share wanted.

- **Design variables:**

  1. **mach**: varying between 4 and 8.
  2. **profit_perc**: varying between 10% and 20%.
  3. **tau**: varying between 0.032 to 0.393.
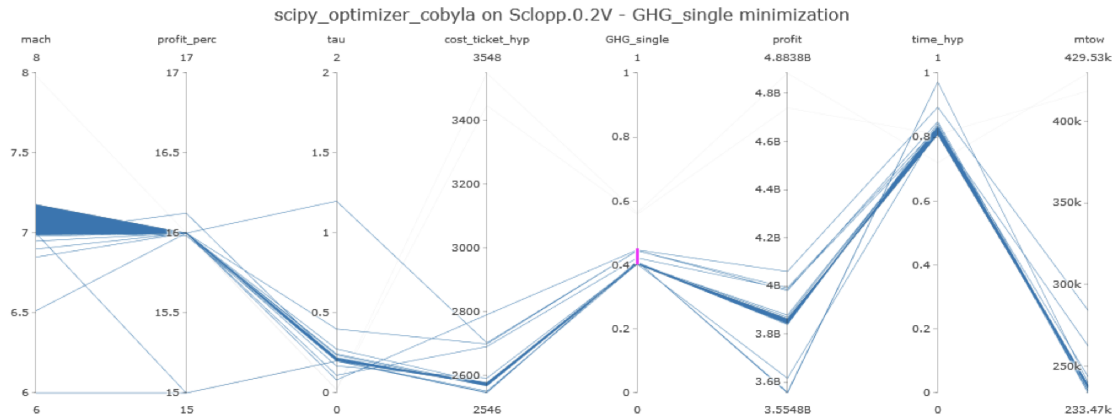
Figure 6.16: General concept optimization

The optimization results are:

- **mach** = 7.178.

- **profit_perc** = 16%.

- **tau** = 0.209.

The first thing observed is that what seems to be the optimal Mach is in line with the parametric study on Mach and altitude presented in the last section, as it is around Mach = 7. Therefore, even if it's a preliminary analysis and should be taken as such, the coherence between results is still a positive indicator of the validity of the process.

Secondly it is interesting that the seemingly best shape of the aircraft is relatively bulky, as a tau form parameter of 0.209 is closer to a cone than a flat surface, as seen from the next figure:



$\tau = 0.032$     $\tau = 0.063$     $\tau = 0.104$     $\tau = 0.229$     $\tau = 0.393$
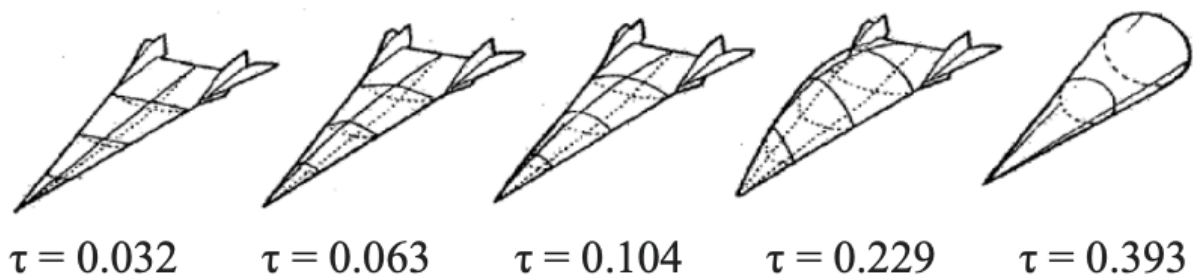
Figure 6.17: Tau parameter effect on shape

This probably stems from the fact that the fuel chosen need a large volume to be stored, as its density is extremely low.

Finally, the resulting percentual profit probably comes from the fact that to minimize the emissions the model wants to increase the costs to lower the share of the market covered by HST, therefore lowering the total number of flights and pollution.

# Part IV

# Conclusions and recommendations

# Chapter 7

# Conclusions

Finally, a few things can be said:

First, the process with its models can be used for different purposes:

- Help the fuel and specification choice before a detailed design process.

- Compare and evaluate different concepts.

- Optimize an existing concept in function of an existing or future market.

Relatively to the first use it has been observed that while $LH_2$ is usually thought of as the best alternative to fossil fuel for the future of aviation, if produced with methane combustion like the majority of liquid hydrogen is right now, it would have an even bigger impact on climate than kerosene and methane. On the other hand, while allegedly being better than actual $LH_2$, both fossil fuel analyzed are still highly impacting fuels, with the additional problem of not having a heating value high enough to be used for higher ranges, that are the most convenient ranges for HST.

Therefore the only option that seems to be worth developing is electrolysis produced liquid hydrogen, that as of now has still a price too high and a quantity too low to be employed as a fuel for a satisfactory part of the market. Of course, by dropping the price and augmenting the quantity produced, the need of electricity for this kind of process will be immense, therefore a sufficiently big source of energy must be available. But as of now, the only option that could give that much energy without polluting even more the atmosphere would be atomic energy, which would be highly difficult to politically and socially promote.

Relatively to performances instead, the best performances seems to be given of course by aircraft with higher maximum seats numbers, but that is without taking into consideration that maybe an aircraft this big would be much more difficult to fill, especially as the clients targeted would be only the minority that travels with first or business class, or private jets. About private jets, emission and pollution made by them is still a problem, and maybe the hypersonic travel would alleviate it, but it must be taken into consideration the fact that even if HST is much faster, it would only cover a single time slot in the day, while private jets would be able to depart whenever chosen, meaning that it is not obvious if traveling by HST would be actually saving time for the intended clients.

It is also interesting to point out that both parametric studies and optimizations show that the best performances seem to be relative to aircraft flying at around M = 7, which means that if hypersonic travel will go in that direction, the technology level required for it would still not be ready for a long

time.

In conclusion it is important to note that every result obtained underlines the huge difference in climate impact between high speed travel and its subsonic counterpart, not only in terms of emissions, but also in terms of chemical species life, that is much higher for water vapour at altitudes of 25 - 35 km. Therefore, even with a high consequential productivity increase, it's not obvious whether it is actually a path that should be taken.

# Chapter 8

# Recommendations

The most important limitation of this process are of course the lack of data and models for the phenomenon observed. Therefore, the author's suggestions for a future development are the following:

- Develop or obtain a simplified climate impact model returning the Radiative Forcing or even the global warming caused by the fleet in a year, so that a real feedback on the climate impact can be implemented instead of only a greenhouse gasses tax.

- Integrate the other phases, in particular climb and descent, for the fuel consumption and emissions calculation.

- If a climate impact model is available, divide each part of each route into finite elements, so that each slot (identified by a specific altitude and latitude) will have the emissions that are released in it. This way the climate impact model will be able to evaluate with a sufficient degree of precision the total temperature rise.

- Implement a way to do multiobjective optimization, so that it will effectively be possible to find the optimal design variable's values taking into consideration flight time, ticket price and climate impact, and not only one of those.

- Integrate the existing process with equations that will take into consideration the necessary changes to the structure in function of the fuel type chosen. As a result also develop equations estimating the costs of those structure changes to be added in the costs modules.

- Test the process with different kind of concepts, also subsonic, by changing the relative equations, and see if it can also help the design process in those scenarios.

# Part V

# Sclopp 0.1 version

**In this part all the essential component of the first full-working version of the Sclopp model will be described in detail.**
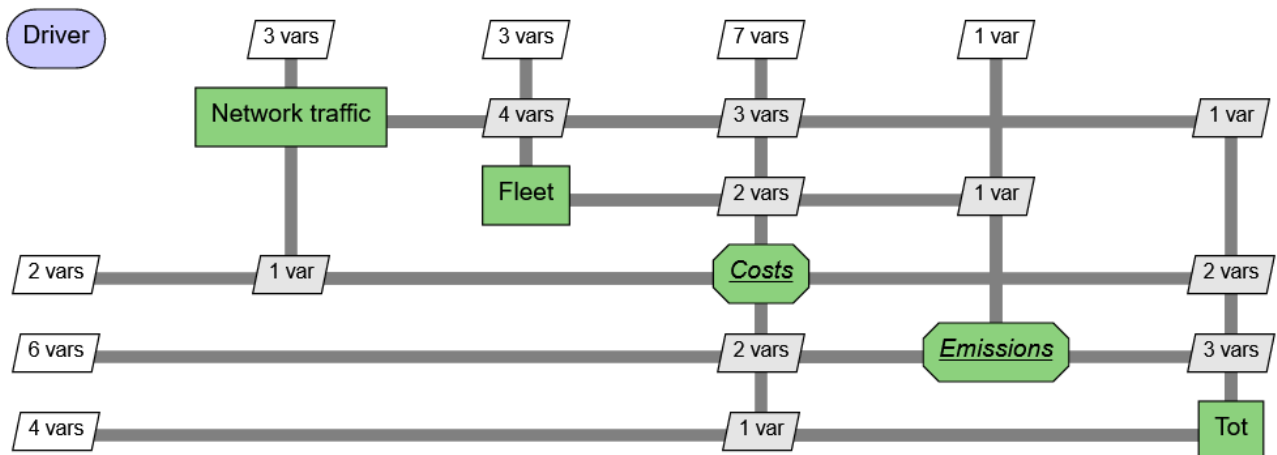
# Chapter 9

# External files

In this chapter are presented the libraries that are used for the correct compilation of the code.

## 9.1 Utility.py

It contains some simple functions that were defined to make coding easier, in particular functions like **linspace** and **ones** were created to help the author's transition from MATLAB to Python language.

## 9.2 ZLibAtmosphereISA.py

As the name implies, it contains different functions relatives to the atmosphere:

- **atmosphere(h)** is the principal function, and given the altitude in meters (m), it returns a float vector (Python list) containing:

    1. Air density ($kg/m^3$).
    2. Air pressure ($Pa$).
    3. Air temperature ($K$).
    4. Speed of sound ($m/s$).
    5. Temperature gradient dT/dZ ($K/m$).

- **visco_air(T)**: returns the air dynamic viscosity for a given temperature in kelvin (K), using Sutherland's law.

- **pvs(T)**: returns the pressure of saturated water vapour for a given temperature in kelvin (K), choosing between two methods: first the empirical law calculated by [9] and second a simplified but still precise equation developed in [10].

## 9.3 ZLibAeroProp.py

This library contains functions that, with empirical or statistical equations, return parameters used in the main code. In the 0.1 version, only one function is implemented:

- **ISP(fuel_type, engine_type, M)**: returns the specific impulse (s) for a given engine, fuel and Mach, using an empirical law calculated with linear interpolation [11].

$$ISP = (a * M + b) * (1 + tf_{prop}) * \frac{combustion\_heat\_fuel}{combustion\_heat\_LH2} \tag{9.1}$$

With tf$_{prop}$ a correction factor to take into consideration two possible engine types:

- Combined cycles engines.
- Precooled turbojets.

To have better results with the interpolations, the coefficient are different for Mach lower and higher than 3.12:

1. M < 3.12:
   - a = $\frac{3660-7000}{3.12}$
   - b = 7000
2. M > 3.12:
   - a = $\frac{1010-3660}{11.4-3.12}$
   - b = 1010-a*11.4

As it is originally calculated for liquid hydrogen engines, to adapt it to other fuels it is multiplied for the fuel's combustion heat and divided for hydrogen's combustion heat.

As it is not extremely accurate, it would be interesting to improve in a later version of the model.

## 9.4   Zdata.py

In this library were created a series of functions to access fixed data, useful in different parts of the code.

It was made so that when one particular value needs to be changed, like the cruise speed of a subsonic reference aircraft, it suffice to change it in this library and not in every part of the model.

It is particularly useful to choose which type of aircraft or fuel the model will analyze, varying values in a discrete way (for example between 0/1/2/3/4).

It will not describe every small function here, as it is not in the interest of the study, except for the function **fuel_data**.

### 9.4.1   fuel_data(fuel_type)

- Inputs: the fuel type, choosing between actual green liquid hydrogen, actual produced LH$_2$, kerosene, methane and hypothetical future LH$_2$).

- Outputs: it returns a vector with respectively:

1. The cost of the fuel ($\$/kg$).
2. The emission index of water from the combustion of said fuel ($kg$ of H$_2$O / $kg$ of burned fuel).

3. The emission index of $CO_2$ from the combustion of said fuel ($kg$ of $CO_2$ / $kg$ of burned fuel).

4. The ground specific emission ($kg$ of equivalent $CO_2$ / $MJ$ of fuel produced). This data was taken from the estimation made by the HIKARI project in [7].

5. The combustion heat ($MJ/kg$).

For the emission in the atmosphere it was hypothesized $LH_2$ composed only by $H_2$ molecules, kerosene composed only by $C_{11}H_{21}$ [12] molecules and liquid methane only by $CH_4$ molecules, then made the reaction:

$$X + O_2 \longrightarrow H_2O + CO_2$$
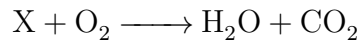
With as X the molecules mentioned before.

Then by balancing the reaction the coefficients from the atomic weight are returned.
For example the emission index for $H_2O$ comes from the reaction:

$$2 * H_2 + O_2 \longrightarrow 2 * H_2O + 0 * CO_2$$
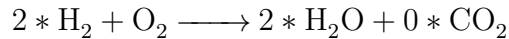
As 36 is the atomic weight of $2 * H_2O$, and 4 is the atomic weight of $2 * H_2$, the water emission index will be 36/4, while the $CO_2$ emission index will be 0.

This way, for a kg of $LH_2$ burned, 9 kg of water vapour and zero kg of carbon dioxide will be emitted in the atmosphere.

# Chapter 10

# Common modules

In this chapter are presented the various WhatsOpt [4] modules that are necessary to calculate the inputs for the Costs and Emissions modules.

## 10.1 Driver

In this module are defined several variables:

- **load_factor**: IEP, design variable.

- **profit_perc**: IEP. It is set to be a design variable, varying from 5% to 15%, with an initial value of 8%.

- **time_work_annual**: IEP.

- **tax_CO2**: It sets a coefficient necessary for the implementation of a carbon dioxide tax. It is set to be a design variable, varying from 0.05 €/kg to 0.12 €/kg of CO2 produced, with an initial value of 0.08 €/kg, set by choice to increase costs of a LAPCAT fleet with kerosene fuel choice.

- **tax_GHG**: It sets a coefficient necessary for the implementation of a greenhouse gasses tax. It is set to be a design variable, varying from 0.02 €/kg to 0.1 €/kg of GHG produced, with an initial value of 0.05 €/kg, set by choice to increase costs of a LAPCAT fleet with kerosene fuel choice.

- **combustion_efficiency**: the combustion efficiency is a value that indicates the degree completion of the combustion reaction happening in the engine. With this value it is possible to take into consideration the fact that not all fuel will be successfully burned by the engine, therefore giving energy and thrust, which is more realistic. It is set to be a parameter with an initial value of 0.9, which means that the reaction will be, on average, with a 90% combustion rate.

- **cost_ticket_sub_14**: medium cost of first and business class tickets in 2014 as per market study documented in [5]. It is set to be a parameter with an initial value of 4300 €.

- **dol_to_eur**: factor of conversion from dollars to euros as of 2022, set to be a parameter with initial value of 1.03.

- **inflation_14to22**: inflation multiplicative parameter calculated since 2014, HIKARI project year of release, to adjust values taken from there. It is set to be a parameter with an initial value of 1.129.

- **learning_factor**: the learning factor is a value that shows how the production cost of a product falls depending on the number of units manufactured. It allows that, if the first product made has a cost, the next ones will cost less to make, as there will be optimizations on the process, and both materials and transport of pieces cost less in bulk. It is set to be a parameter with an initial value of 97.145358%, and more of how it works will be explained in the section about the Aircraft cost module.

- **pax_tot**: it's the total number of first and business class passengers in 2032 hypotetized by Airbus in [5]. As they estimate there will be roughly 5579528 monthly FC+B passengers, the total yearly passengers is set to be a parameter with initial value of 66954528.

- **speed_cruise_sub**: cruise speed of a reference subsonic aircraft (A350), set to be a parameter with initial value of 1049.58 km/h.

Each one of those variables were scaled to be not lower than 1 and not higher than 20, because it was seen that doing so decreased numerical cancellation problems. Therefore they need to be adjusted in every other module before being used in an equation. The outputs of this module are therefore all the variables previously mentioned.

## 10.2 Network traffic

Network traffic is the module in which the data about the trajectory, that will be essential to obtain costs and emissions, is calculated.

The module takes as input:

- **load_factor** from Driver.

- **pax_tot** from Driver.

- **speed_cruise_sub** from Driver.

- **market_share** from Market share: as there is a feedback loop.

And gives as an output:

- **mass_fuel_burnt_medium**, fuel burned in a medium range flight.

- **seats**, aircraft maximum number of seats.

- **pax** total year fleet effective passengers.

- **time_sub**, medium subsonic reference flight time.

- **time_hyp**, medium hypersonic flight time.

There are actually three other inputs that this module needs, however it was decided not to put them in the Driver, and instead place them in a different file as function to be called. They are contained in the library Zdata.py, as explained in the previous chapter.

Those inputs are:

- **a_type**: it's a discrete variable that allows you to choose between two different configuration implemented:

  1. LAPCAT: giving the a_type variable the value 0, it is possible to use the model to evaluate flight time, ticket cost and emissions of an aircraft fleet made by ONERA LAPCAT II M=8 concepts.

  2. ZEHST: giving the a_type variable the value 1, it is possible to use the model to evaluate flight time, ticket cost and emissions of an aircraft fleet made by EADS ZEHST concepts.

- **fuel_type**: it's a discrete variable that allows you to choose between five different fuels used by the aircraft chosen previously:

  1. Green LH2: giving the fuel_type variable the value 0 means that the previously mentioned function **fuel_data(fuel_type)** will return values pertaining to liquid hydrogen fuel, produced by electrolysis and therefore considered green.

  2. Methane produced LH2: giving the fuel_type variable the value 1 means that the previously mentioned function fuel_data will return values pertaining to liquid hydrogen fuel, produced by burning methane.

  3. Kerosene: giving the fuel_type variable the value 2 means that the previously mentioned function fuel_data will return values pertaining to kerosene fuel.

  4. Methane: giving the fuel_type variable the value 3 means that the previously mentioned function fuel_data will return values pertaining to liquid methane fuel.

  5. Future green LH2: giving the fuel_type variable the value 4 means that the previously mentioned function fuel_data will return values pertaining to liquid hydrogen fuel, produced by electrolysis with the target price of 1.5 €/kg.

- **engine_type**: it's a discrete variable that allows you to choose between two engine groups:

  1. Combined cycles engine: giving the engine_type variable the value 0 means that the model will use parameters and ISP curves pertaining to ramjets/scramjets.

  2. Precooled turbojet: giving the engine_type variable the value 1 means that the model will use parameters and ISP curves pertaining to precooled turbojets, analyzed in [13].

This module is structured so that, receiving the inputs aforementioned, it can calculate the outputs with two steps:

Fist step is using the **a_type** variable to choose between the two aircraft configuration, and define all the necessary data relative to it.

More specifically, different values are taken from [2]:

- Cruise Mach.

- Cruise L/D ratio.

- Cruise altitude , that in the future could be made into a design variable to study how costs and emission change.

- Maximum seats.

- MTOW.

- Maximum payload weight.

while others are taken from [11] or calculated from equations explained in the same document:

- Airframe weight.

- Systems weight, as 10% of the MTOW.

- Fixed weight, as 5000 kg for both configurations.

- Overall engine thrust to weight ratio.

The speed of sound is returned using the Atmosphere() function mentioned before in the external files chapter, with cruise altitude in input, and with it it's possible to calculate the cruise speed.

Finally, instead of using every single trajectory and flight from the year, a passenger weighted medium is calculated from the excel file containing all flights suggested in the HIKARI project. With this medium range of flight it is possible to calculate the medium time of flight by dividing the range for the speed, as, like we said, we are approximating by considering only the cruise phase. The same process is used for the subsonic time.

The second step needs all the data collected in the previous one, and consists of a series of equations to calculate all the outputs remaining.

First calculate the engine mass using the formula

$$mass\_engines = \frac{MTOW/(L/D\_ratio)}{T/W\_ratio} \tag{10.1}$$

because of the fact that the thrust to weight ratio (T/W_ratio) is defined as the cruise thrust at mass equal to the maximum takeoff weight, divided by the mass of the engines, so by isolating the engines mass we obtain the previous formula.

The effective medium payload mass is calculated by multiplying the maximum payload mass for the load factor taken into consideration.

Finally, the medium fuel mass consumed in a flight is computed using the Breguet equation as:

$$mass\_fuel\_burnt\_medium = mass\_dry * \left(e^{\overline{\left(ld\_ratio * \frac{speed\_cruise\_hyp}{3.6} * isp\_cruise\right)}} - 1\right) \tag{10.2}$$

With the dry weight calculated as the sum of engines weight, airframe weight, systems weight payload weight and fixed weight, and the specific impulse is found using the dedicated function implemented in the ZLibAeroProp.py library. The medium range (route_medium) and hypersonic cruise speed are adjusted to have the correct units of measure.

Finally the effective passengers that are evaluated using HST are calculated multiplying the market share (from the feedback) and the total passengers on the network.

## 10.3   Fleet

Fleet is the module in which both the total necessary number of aircraft and the total fuel mass consumed are calculated.

The module takes as input:

- **load_factor** from Driver.

- **combustion_efficiency** from Driver.

- **time_work_annual** from Driver.

- **mass_fuel_burnt_medium** from Network traffic.

- **pax** from Network traffic.

- **seats** from Network traffic.

- **time_hyp** from Network traffic.

And gives as an output:

- **a_num**, total necessary number of aircraft.

- **mass_fuel_used**, total fuel mass consumed.

It's a simple module with a few equations:
the yearly flights are found by using:

$$yearly\_flights = \frac{pax}{seats * load\_factor} \tag{10.3}$$

and then multiplied for the medium hypersonic time of flight to find the total work time of the fleet. This last value is then divided by the maximum workload (time_work_annual) and will be rounded up to find the necessary number of aircraft to withstand the annual traffic flow of the entire fleet.

Finally, the total fuel weight consumed is computed by multiplying the medium fuel mass burnt in a flight for the yearly number of flight, and divided by the combustion efficiency, so that the amount of energy produced by the engines won't diminish even if the degree of combustion goes below one.

# Chapter 11

# Costs modules

In this chapter are presented the different WhatsOpt Costs modules.

## 11.1 Aircraft cost

It is the main module of the three, and its goal is to estimate the total life cycle cost of the entire fleet of aircraft. It was determined that the latter could be approximated with the sum of three different costs:

1. RDTE costs.

2. Production costs.

3. Operational costs.

It should be noted that it is still an approximate, and not at all precise, measure, as the author didn't have neither the experience nor the data to create an high fidelity cost model. It just serve as a first assessment.

The module takes as input:

- **inflation_14to22** from Driver.

- **learning_factor** from Driver.

- **dol_to_eur** from Driver.

- **a_num** from Fleet.

- **mass_fuel_used** from Fleet.

- **mass_atm_CO2** from Atmosphere.

- **mass_ground_CO2** from Ground.

- **mass_tot_GHG** from Tot.

And gives as an output:

- **cost_tot_hyp**, total hypersonic fleet cost.

The values of **a_type** and **fuel_type** are also recalled here.

### 11.1.1 RDTE costs

RDTE stands for Research, Development, Tests and Evaluations, and its costs are usually a small percentage of the total, but since in this report the aircraft evaluated are hypersonic, and therefore need technology not yet invented to be implemented, they cannot be ignored.

Because of the fact that there is not much data available on civil supersonic aircraft, and zero data for hypersonic ones, it is difficult to make a prevision on how much RDTE for this type of vehicle would cost, or to elaborate a statistical analysis to interpolate. Therefore it was decided once more to rely on the HIKARI project, in particular on [14], in which it is evaluated by Oxford Economics that to research all necessary parts and technology to create an aircraft with the characteristics of the ONERA LAPCAT II M = 8 concept, about €24 B would be required.

For a ZEHST like aircraft sadly there was not an evaluation of the RDTE costs, so it was decided by the author of this paper to estimate a third of the LAPCAT cost: €8 B, as the ZEHST has both a much lower maximum speed (M = 8 vs M = 4 respectively), and a much lower maximum seats capacity (300 vs 60 respectively), thus making it much easier to develop.

It was therefore decided to set them in function of the configuration chosen (**a_type**), and to adjust them to 2022 prices.

### 11.1.2 Production costs

The production costs consist of every process necessary in the construction of the aircraft. Therefore it is normal that when a product is built for the first time it costs more, while if it is produced in bulk, the price will fall. This effect is due to different factors:

- The building team experience, that will increase with more pieces produced.

- The optimization of building processes, that could not be perfect at the beginning.

- The fact that buying materials and pieces for one product cost more than buying them in bulk for many products.

- The transportation fees are less if the materials are in bulk and not single pieces.

That is why the production cost of a single product can be approximated by an exponential equation like this one:

$$y = C_0 * LF^n \tag{11.1}$$

With:

- $C_0$ = cost of production of the fist product.

- n = number of the aircraft produced before the one evaluated, so for example n = 0 for the first aircraft produced, and n = 9 for the tenth.

- LF = learning factor, it's a fraction or a percentage, usually between 70% and 90%, that indicated the degree of diminution of the cost with the increase in number of products built. For example, an aircraft without big innovations will have a learning factor more towards the 90% mark, as it has small space for improvement in the production processes. Instead, a really innovative product will start at a really high price but will fall by a lot if produced in bulk, so it could have a learning factor closer to the 70% mark.

The same problems that are described for the estimation of RDTE costs are applied for the production costs, so it was decided to do the same thing and follow [14], where it is evaluated that the first LAPCAT vehicle would cost around €1 B, but by the 15th it would fall by a third.

By interpolating this two points with an equation like this (eq 11.1), a learning factor of 97.145358 was obtained. It is much higher than the 90% mark, that was already suggested for conservative measures, and in this case it's about a really innovative product, so it should be much lower. Nevertheless it was decided to use this value as a learning factor for both LAPCAT and ZEHST configurations, because of the fact that it is usually better to overestimate costs than to underestimate them. It was decided to give the ZEHST configuration a first product cost of €500 M (evaluated by the author as a reasonable but conservative value). Moreover, the production costs are not the biggest factor on the total costs, as it will be obvious after the following sections.

Thus the equations that calculate the production costs of the two configurations are:

$$LAPCAT\_prod\_cost = \sum_{i=0}^{n} 1 * 10^9 * learning\_factor^i \qquad (11.2)$$

$$ZEHST\_prod\_cost = \sum_{i=0}^{n} 5 * 10^8 * learning\_factor^i \qquad (11.3)$$

With learning_factor = 97.145358.

### 11.1.3 Operational costs

The operational costs are usually divided into direct operational costs, that are linked with the single aircraft, like:

- Fuel, usually the biggest factor not only in term of operational costs but also in terms of total life cycle costs, especially for civil aircraft.

- Crew.

- Maintenance, especially regarding the engines.

- Insurance.

- Depreciacion, that is the loss in value of a product over the years.

And indirect, that are relative to the full fleet, and are more difficult to calculate as they change depending on the airline company, like:

- General administrative.

- Reservation sales.

- Ground station.

- Airport navigation charges.

- Passenger service.

- Aircraft rentals.

- Traffic service

- Aircraft servicing

In this module they were evaluated estimating the fuel costs as 68.83% of the total operational costs, as indicated for the hypersonic cruiser category in [15]

### 11.1.4 Final aircraft cost

It was decided to implement both a CO2 tax and a GHG tax, to help include the optimization process also emissions and climate impact.

The way this was implemented is that two activating values (act_CO2 and act_GHG) are imported from the ZData.py library, that can have value equal to 0 or 1. Those activating values are then multiplied for the tax coefficient that is given as an input from the Driver, so that only the tax with the activating value will be taken into consideration.

Finally the total hypersonic cost is calculated by adding all the costs explained previously to the tax costs, that come from the product of the tax coefficient and the relative total mass of emission in kg, given as an input by the modules Atmosphere, Ground and Tot (feedback).

## 11.2 Ticket cost

This module's goal is to calculate the ticket cost for a medium hypersonic flight. In the beginning, the author tried to implement the same process as [5] and [16], that consisted in calculating the ticket cost from a top line estimate. This estimate can be defined as the total "value" in a year considered to be given to the total time saved by the HST passengers. It was calculated multiplying the medium number of hours saved by each passenger, the total number of said passengers and the Value of Time.

Unfortunately in no HIKARI paper was described the precise steps to go from the top line estimate to the ticket price, so in the end it was decided to change it to a more intuitive approach:

The module takes as input:

- **profit_perc** from Driver.

- **pax** from Network traffic.

- **cost_tot_hyp** from Aircraft cost.

And gives as an output:

- **cost_ticket_hyp**, medium hypersonic flight ticket cost.

In this module it was decided to use a simple but efficient approach to determine the ticket price from the total life cycle cost of the hypersonic fleet, by applying a profit with a percentage decided in the Driver, adding it to the total cost and dividing the outcome by all the passenger using HST travel.

This way it could be also interesting to see how every variable changes the total profit, and not only the ticket price.

## 11.3  Market share

This is the final Costs module, that has the objective of linking the ticket price to the total passengers flying with the hypersonic fleet studied, via a variable called the market share, that will then go as a feedback to the Network traffic module.

The module takes as input:

- **inflation_14to22** from Driver.

- **cost_ticket_sub_14** from Driver.

- **time_sub** from Network traffic.

- **time_hyp** from Network traffic.

- **cost_ticket_hyp** from Ticket cost.

And gives as an output:

- **market_share**, slice of the total First class + Business class passengers taken over by the hypersonic fleet.

This module uses an empirical equation created by Oxford Economics and Airbus in [5] in 2014:

$$market\_share = \frac{1}{1 + \exp b0 + b1 * time\_ratio + b2 * fare\_ratio} \tag{11.4}$$

With b0, b1 and b2 empirically derived coefficients with value:

- b0 = 0

- b1 = 0.939

- b2 = 0.692

While the time ratio and fare ratio are given by the equations:

$$time\_ratio = \frac{time\_hyp}{time\_sub} \tag{11.5}$$

$$fare\_ratio = \frac{cost\_ticket\_hyp}{cost\_ticket\_sub} \tag{11.6}$$

Of course before calculating the fare ratio the subsonic reference first + business ticket cost was adapted to 2022 prices with the inflation coefficient.

Nevertheless, given that this equation was relative to 2014 VoT and prices, it is reasonable to think that it underestimates the market share, because of the continuous growing of the inflation and the resulting actual higher VoT. However the author of this paper does not have the means to obtain a new empirical equation with relative coefficients, therefore it was decided to use the same equation and overlook this detail.

# Chapter 12

# Emissions

In this chapter are presented to present the different WhatsOpt Emissions modules.

## 12.1 Atmosphere

Goal of this module is to calculate the total yearly emissions of the fleet in the phase of cruise, that is considered as the only phase for the flight. Therefore those emissions will be considered released at the cruise altitude.

The module takes as input:

- **combustion_efficiency** from Driver.

- **mass_fuel_used** from Fleet.

And gives as an output:

- **mass_atm_CO2**, mass of carbon dioxide released into the atmosphere by burning fuel.

- **mass_atm_H2O**, mass of water vapour released into the atmosphere by burning fuel.

- **mass_atm_NOX**, mass of NO and $NO_2$ released into the atmosphere by burning fuel.

- **mass_fuel_unburned**, mass of unburned fuel released into the atmosphere due to the combustion efficiency not being 100%.

- **mass_atm_GHG**, total mass of greenhouse gasses released into the atmosphere by burning fuel, sum of all the previous inputs.

In this module is also called as an input the variable **fuel_type** and the vector given by the function fuel_data(fuel_type), in particular the values in position 1 and 2 of said vector, that are the emission indexes respectfully for water vapour and carbon dioxide. The principles behind those emission indexes are better explained in the section about the relative function (9.4.1).

Unlike for water vapour and carbon dioxide, there was not a simple but accurate chemical reaction that could provide an emission index for the $NO_x$ molecules, and for ramjets/scramjets there is no standard data available. Therefore it was decided to use the data from [17], which states that:

- With no specific injection strategy, the $NO_x$ emission index would be in the order of magnitude of 20 g/kg of fuel burned (similar to turbofans).

- With a simple adjustment of the injection strategy (distributed injection) it would be possible to reduce it to $3*10^{-2}$ g/kg, without notable performance penalties.

- With a more complex injection strategy (and potentially a performance penalty) it would be possible to drive it to $3*10^{-5}$ g/kg

It was decided to implement the first emission index, as a worst case scenario, knowing that even with it the $NO_x$ emission would not be the main contributor to climate change next to the water vapour.

Finally, for every fuel type a series of equation were set to obtain the emission mass in kg, using both the general emission indexes calculated from the chemical reactions and the combustion efficiency taken into consideration.

It is interesting to note that even if all types of liquid hydrogen considered have the same emission indexes (As the reaction is the same), the final emissions will come out different, as the market equilibrium for each one will be different.

## 12.2   Ground

Goal of this module is to calculate the total yearly emissions of the fleet in kg of equivalent $CO_2$ due to the production of the fuel used.

It was decided not to include ground emission of equivalent $CO_2$ due to the production of materials for the airframe, engines, etc because of the incapacity to find the necessary data to complete this task.

The module takes as input:

- **mass_fuel_used** from Fleet.

And gives as an output:

- **mass_ground_CO2**, mass of equivalent carbon dioxide released into the atmosphere by producing, transporting and storing fuel.

In this module is also called as an input the variable **fuel_type** and the vector given by the function fuel_data(fuel_type), in particular the values in position 3 and 4 of said vector, that are the ground specific emission and the combustion heat for said fuel. The process to find those values is better explained in the section about the relative function.

Similarly to the Atmosphere module, for every fuel type a series of equation were set to obtain the ground equivalent $CO_2$ emission mass in kg:

$$energy\_equivalent = mass\_fuel\_used * combustion\_heat \tag{12.1}$$

$$mass\_ground\_CO2 = ground\_specific\_emission * energy\_equivalent \tag{12.2}$$

# Chapter 13

# Final modules

## 13.1   Tot

Tot is a simple module, used mainly to obtain the final values of total $CO_2$ mass and total GHG mass to return them as a feedback to the Aircraft cost module, for the tax implementation. It could also be used to implement some indexes to better evaluate and optimize different outputs of the model.

The module takes as input:

- **mass_atm_CO2** from Atmosphere.

- **mass_atm_GHG** from Atmosphere.

- **mass_ground_CO2** from Ground.

And gives as an output:

- **mass_tot_CO2**, total mass of carbon dioxide released into the atmosphere in a year.

- **mass_tot_GHG**, total mass of greenhouse gasses released into the atmosphere in a year.

# Part VI

# Sclopp 0.2 version - Fixed concepts

**In this part it was decided not to describe again in detail every single component of the model, but only the changes from the previous versions, not to make this report unnecessarily long.**
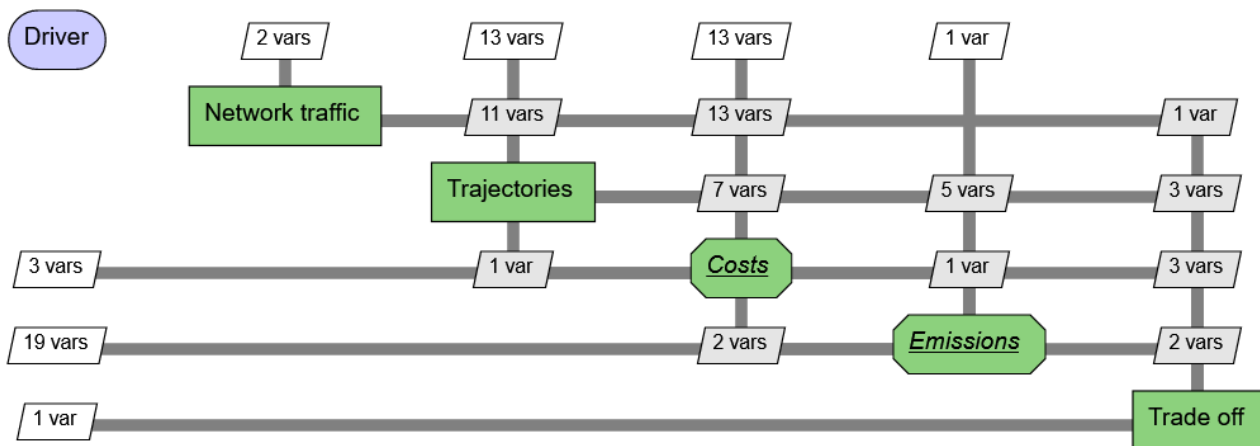
# Chapter 14

# External files

The biggest changes from the previous version are the two excel files created specifically to support the first modules of the model:

## 14.1  Aircraft_data.xlsx

As the name implies, it is a file with different civil hypersonic concepts with all the necessary specifics taken from [2].

It was created to add more configurations to the original two implemented in annex 1 (V), that were limiting the analysis to only two specific scenarios.

More precisely here are all the concepts taken into consideration, that can also be seen in the table in figure 1.4:

### 0 - DLR LAPCAT M4

It's a civil supersonic airplane with cruise Mach = 4.5, 202 passengers and an ambitious range of 16000 km achieved thanks to a really high cruise L/D of 7.7.
Its data is called to the model by setting **a_type** = 0.

### 1 - EADS ZEHST

Created to fly Tokyo to Los Angeles in less than three hours, the ZEHST is a M = 4, 60 passenger aircraft with three different engines to optimize consumption in the different phases of the flight.
It is identified by the number 1.

### 2 - JAXA HST

Optimized to be the minimum weight possible for a 100 passenger, M = 5 aircraft flying from Tokyo to Los Angeles, with the objective to test the hypersonic turbojet engine.
It is identified by the number 2.

### 3 - LAPCAT A2

It has the longest maximum range of the concepts taken into consideration, with 18700 km, and its goal is to fly it in 4.6 hours thanks to a M = 5 cruise with 300 passengers maximum. It uses a

precooled turbojet engine, conceptualized by Reaction Engines LTD, that makes it possible to use a single engine from take off to landing, compromising of course the cruise performances.

It is identified by the number 3.

### 4 - ONERA LAPCAT II

It's a 300 passenger, M = 8 aircraft with a range of 16200 km inspired by previous analysis led by ONERA. Its propulsion system is composed by a turbofan for the first phases and a dual-mode ramjet for the cruise.

It is identified by the number 4.

### 5 - ESA LAPCAT MR2

It's a 300 passenger, M = 8 aircraft with a range of 18200 km based upon a waverider with a dorsal mounted engine.

It is identified by the number 5.

In this file, for every concept aforementioned, are indicated:

- Essential data: M, maximum range, seats, etc.

- Weight data: MTOW, OEW, airframe weight [11], etc.

- Propulsion data.

- Trajectory data.

Other concepts were also available but were discarded for various reasons:

1. It was an outlier and therefore too complicated to include in the model: DLR SpaceLiner 7, a M = 25 cruiser.

2. Some of the necessary data was not available: GDL ATLLAS M3T, IHI ZEHST-like Aircraft, MBDA Axisymetric concepts.

## 14.2   HST_traffic.xlsx

It is a file with all the necessary traffic information, based on the HIKARI project [1] study and using as horizon the year 2031. in particular it takes into consideration 490 (counting NYC-LON different than LON-NYC) direct routes between 42 airports:

For each city pair the file contains:

- IATA identifications of both airports.

- Longitude and latitude of both airports.

- Distance in km.

- FC+B yearly pax estimated, approximated from the total FC+B network yearly pax, and the monthly first class pax estimated by HIKARI.

It was used to implement an evaluation of specific shares of the network, containing only ranges between a lower limit and an upper limit, as explained here: 3.2.1.

## 14.3  Libraries

### 14.3.1  Zdata.py

A couple of small changes were made to this function:

- The function that generates **a_type** in Zdata.py changed from giving as output 0-1 to 0-5, as a consequence of the increase of concepts implemented.

- A function was added to implement two different types of fuel injection: 0 for normal injection, 1 for distributed injection. As studied in [17], this slight change of injection strategy would give a much lower mass of $NO_x$ emissions, while not worsening the performance enough to notice.

All the remaining libraries described in annex 1 (V) stayed the same.

# Chapter 15

# Common modules

In this chapter are presented the various WhatsOpt [4] modules that are necessary to calculate the inputs for the Costs and Emissions modules.

## 15.1 Driver

In this module are defined several variables:

- **load_factor**: IEP.

- **profit_perc**: IEP.

- **range_limit_down**: IEP.

- **range_limit_up**: IEP.

- **time_work_annual**: IEP.

- **tax_CO2**: it is set to be a design variable, varying from 0.1 €/kg to 0.18 €/kg of CO2 produced, with an initial value of 0.14 €/kg, set by choice to increase costs of a LAPCAT fleet by 50% with kerosene as a fuel choice.

- **tax_GHG**: it is set to be a design variable, varying from 0.06 €/kg to 0.14 €/kg of CO2 produced, with an initial value of 0.1 €/kg, set by choice to increase costs of a LAPCAT fleet by 50% with kerosene as a fuel choice.

- **combustion_efficiency**: IEP.

- **cost_ticket_sub_14**: IEP.

- **dol_to_eur**: IEP.

- **ERF**: extended Range Factor, it's a multiplicative parameter that indicates how much longer it is wise to consider the range of an high speed flight in medium. Its goal is to take into consideration the detours necessary to minimize the effects of sonic boom on the population. Set at 1.127 as estimated in [1].

- **g0**: constant of gravity, fixed parameter with the value of 9.81.

- **inflation_72to22**: inflation multiplicative parameter calculated since 1972, [1] year of release. It is set to be a parameter with an initial value of 7.13.

- **inflation_12to22**: inflation multiplicative parameter calculated since 2012, year of the data from [18], from where some of the values used to calculate the IOC are taken. It is set to be a parameter with an initial value of 1.297.

- **inflation_14to22**: inflation multiplicative parameter calculated since 2014, HIKARI project year of release, to adjust values taken from there. It is set to be a parameter with an initial value of 1.258.

- **inflation_17to22**: inflation multiplicative parameter calculated since 2017, year of the data from [19]. It is set to be a parameter with an initial value of 1.215.

- **inflation_22to31**: inflation multiplicative parameter estimated by setting a trend on the inflation variation since 1970,, to adjust values to the horizon chosen for the traffic data. It is estimated to be equal to 1.06193047.

- **ld_ratio_sub**: subsonic reference cruise lift to drag ratio, set at 19.

- **mass_dry_sub**: subsonic reference dry mass, set at 223000 kg.

- **seats_sub**: subsonic reference seats, set at 240. its number is much lower than the maximum seats on a normal A350, because if for HST only FC+B passengers are taken into consideration, the same must be done for the subsonic reference. Consequentially the seats would take more space than the economy ones, diminishing the maximum number of passengers that can be on a single flight.

- **speed_cruise_sub**: IEP.

- **tsfc_sub**: thrust specific fuel consumption, set at 0.49 lb/(lbf*h).

- **distance_climb_sub**: Parameter, average distance of climb of an A350 international flight: 240 km.

- **distance_descent_sub**: parameter, average distance of descent of an A350 international flight: 240 km.

- **time_climb_sub**: parameter, average time of climb of an A350 international flight: 0.33 h (20 min).

- **time_descent_sub**: parameter, average time of descent of an A350 international flight: 0.33 h.

The outputs of this module are therefore all the variables previously mentioned. All the subsonic reference variables are relative to the A350 1000 aircraft.

## 15.2 Network traffic

It was decided that the market share feedback would be shifted to the next module, that will be explained in detail later. The goal of this module is to define all the necessary data about the aircraft and the total network traffic, that is different from the actual passengers who would travel on HST.

It takes as input:

- **load_factor** from Driver.

- **tsfc_sub** from Driver.

And gives as an output:

- **distance_climb_hyp**: IEP.

- **distance_descent_hyp**: IEP.

- **isp_cruise**: IEP.

- **isp_cruise_sub**: IEP.

- **ld_ratio**: IEP.

- **mach**: IEP.

- **mass_airframe**: Airframe weight, (kg).

- **mass_dry**: dry weight, (kg).

- **mass_payload**: maximum payload weight, (kg).

- **mass_systems**: IEP.

- **mtow**: IEP.

- **n_rj**: number of ramjet/scramjet engines of the aircraft considered.

- **n_tj**: number of turbojet/turbofan engines of the aircraft considered.

- **pax_tot_HST**: Total number of yearly passengers considered, meaning all the FC+B pax estimated to be traveling on the network.

- **range_max**: maximum aircraft range, , (km).

- **route_medium_general**: medium weighted route considering all network, (km).

- **seats**: IEP.

- **speed_cruise_hyp**: IEP.

- **T0_single**: sea level static thrust of each turbojet/turbofan engine, (N).

- **thrust_takeoff**: takeoff thrust, assumed to be maximum sea level static thrust, calculate multiplying the number of turbojets/turbofans for the thrust of each turbojet/turbofan engine, (N).

- **time_climb_hyp**: time of climb, (h).

- **time_descent_hyp**: time of descent, (h).

All the variables ending with _sub are relative to subsonic reference.

Here as well are other inputs that this module needs, that were decided not to be put in the Driver but instead in different files:

Those inputs are:

- **a_type**: it's a discrete variable that allows you to choose between six different configuration implemented, as explained before. It is contained in the library Zdata.py.

- **fuel_type**: IEP.

- All aircraft chosen data, from the excel file Aircraft_data.xlsx, as explained before.

- All traffic data from the excel file HST_traffic.xlsx, as explained before.

This module is structured so that, receiving the inputs aforementioned, it can calculate the outputs with two steps:

Fist step is using the **a_type** variable to choose between the six aircraft configuration, and define all the necessary data relative to it by reading the excel file, converting it into a DataFrame and taking the necessary values.

Other values are calculated as explained in annex 1 (V):

- Systems weight.

- Fixed weight.

- Overall engine thrust to weight ratio, in function of engine and fuel type.

- Engines weight.

- Dry weight.

- Specific impulse.

Then, by importing the file HST_traffic.xlsx, **route_medium_general** and **pax_tot_HST** are calculated.

Finally, the subsonic reference ISP is returned from the TSFC, as the thrust specific fuel consumption used is relative to kerosene and needs therefore to be adapted to other fuels. Of course, in this case all fuels are considered as drop-in fuels and do not take into consideration the modifications that would really have to be made on the aircraft.

## 15.3   Trajectories

In this module the goal is to define all necessary data for the mission trajectory to be defined. The module takes as input:

- **load_factor** from Driver.

- **range_limit_down** from Driver.

- **range_limit_up** from Driver.

- **combustion_efficiency** from Driver.

- **distance_climb_sub** from Driver.

- **distance_descent_sub** from Driver.

- **time_climb_sub** from Driver.

- **time_descent_sub** from Driver.

- **ERF** from Driver.

- **speed_cruise_sub** from Driver.

- **distance_climb_hyp** from Network traffic.

- **distance_descent_hyp** from Network traffic.

- **isp_cruise** from Network traffic.

- **isp_cruise_sub** from Network traffic.

- **ld_ratio** from Network traffic.

- **ld_ratio_sub** from Network traffic.

- **mass_dry** from Network traffic.

- **mass_dry_sub** from Network traffic.

- **range_max** from Network traffic.

- **seats** from Network traffic.

- **seats_sub** from Network traffic.

- **speed_cruise_hyp** from Network traffic.

- **time_climb_hyp** from Network traffic.

- **time_descent_hyp** from Network traffic.

- **market_share** from Market share.

And gives as an output:

- **mass_fuel_used**, total fuel mass consumed.

- **mass_fuel_used_sub**, subsonic reference total fuel mass consumed, that will be used to calculate its total emissions.

- **mass_fuel_used_medium**, medium flight fuel mass consumed, taking only in consideration the flights between city pairs with distance in the range limits decided by the driver.

- **pax**: IEP.

- **route_medium**: medium flight distance, taking only in consideration the flights between city pairs with distance in the range limits decided by the driver.

- **time_hyp**: IEP.

- **time_sub**: IEP.

- **yearly_flights**: IEP.

- **module_act_T**: variable used in case the ranges taken into consideration didn't have any routes on the network, or in case the user selected a lower range limit higher than his higher range limit. If one of these two conditions takes place, the model would diverge, therefore this value was set so that every module after this will give every output equal to zero, avoiding errors and printing a communication to advise the user on what was the problem.

There are two differences between the **route_medium_general** and the **route_medium**: The first difference is that **route_medium** takes only into consideration the routes within the range limits, and the second is that **route_medium** is obtained by multiplying the effective weighted medium route by the ERF, because hypersonic vehicles need to have a detour to optimize the flight and sonic boom effects.

For this reason it is important to specify that while for the calculation of the hypersonic flight time uses the **route_medium**, the subsonic flight time uses the effective medium route, as subsonic vehicles don't need to do that detour.

Aside from that, the time calculation formula has been improved from annex 1 (V), as it additionally takes into consideration the phases of climb and descent.

It is also important to note that while for the time calculation phases of climb and descent were taken into consideration, the same thing was not done for the fuel used calculation, that is still retrieved with a simple Breguet equation.

That is because even if there were data about fuel burned in those phases, it was only with one type of fuel, and therefore if the goal is also to confront the different fuels, a value like this cannot be used. In conclusion the fuel mass is still calculated approximating the flight as only cruise.

Finally, the passengers effectively traveling with HST are calculated using the market share from the feedback line and the FC+B pax considered, similarly to annex 1 (V), if not only for the exclusion of passengers that don't fly within the range limits.

# Chapter 16

# Costs modules

In this chapter are presented the different WhatsOpt Costs modules. They have been reduced to two, as it was decided to unify the Aircraft cost module with the Ticket cost module.

## 16.1  Ticket cost

Its goal is to estimate the total life cycle cost of the entire fleet of aircraft, and with it the medium HST ticket price for the ranges taken into consideration. As this was most likely the weakest link in the model, it was decided to research methods to improve it and make it more precise.

To do so, and to avoid fixed cost ( Development) to be too impactful for a fleet that, with a small range interval, would have much less passengers, it was decided to use only the Operational costs dividing them in:

- DOC: Direct Operational Costs, all measured in $ per ton-mile.

- IOC: Indirect Operational Costs.

as explained in [20].

This way not only the model is less likely to diverge because of a too high ticket cost, but the costs estimation becomes much more precise and elaborate.

It is still important to clarify that the equations used in this module are exclusively valid for hypersonic civil aircraft, as they are empirical equations estimated for this exact purpose.

The module takes as input:

- **dol_to_eur** from Driver.

- **g0** from Driver.

- **inflation_12to22** from Driver.

- **inflation_17to22** from Driver.

- **inflation_22to31** from Driver.

- **inflation_72to22** from Driver.

- **load_factor** from Driver.

- **profit_perc** from Driver.

- **tax_CO2** from Driver.

- **tax_GHG** from Driver.

- **time_work_annual** from Driver.

- **ld_ratio** from Network traffic.

- **mach** from Network traffic.

- **mass_airframe** from Network traffic.

- **mass_payload** from Network traffic.

- **mass_systems** from Network traffic.

- **mtow** from Network traffic.

- **n_rj** from Network traffic.

- **n_tj** from Network traffic.

- **seats** from Network traffic.

- **speed_cruis_hyp** from Network traffic.

- **T0_single** from Network traffic.

- **thrust_takeoff** from Network traffic.

- **pax** from Trajectories.

- **route_medium** from Trajectories.

- **mass_fuel_used_medium** from Trajectories.

- **time_hyp** from Trajectories.

- **yearly_flights** from Trajectories.

- **module_act_T** from Trajectories.

- **mass_tot_CO2** from Total, feedback.

- **mass_tot_GHG** from Total, feedback.

And gives as an output:

- **cost_ticket_hyp**, medium hypersonic fleet ticket price for the routes within the range interval chosen (€).

- **profit**, total hypersonic fleet profit (€).

The values of **fuel_type** are also recalled here.

## 16.1.1 Operational costs

This part of the module consists in a series of equations and parameters used to calculate all Direct Operational Costs and Indirect Operational Costs relative to the hypersonic fleet.

Most of the equations are taken from [20], made in 1973 with the specific objective to evaluate high speed civil transport. Some of them have been revisited in a more recent time in [15], therefore the adjusted equations were used when possible.

First thing necessary is to define some essentials parameters, all taken from [20]:

- **labor_rate**: it is defined as the average labor rate per hour for all personnel involved in maintenance activities. It is suggested to be set at 5.30 $, and adjusted with inflation.

- **time_operations_ratio_TJ**: time of operation of the turbojet engines as a ratio of flight time recommended.

- **time_operations_ratio_RJ**: time of operation of the ramjet engines as a ratio of flight time recommended.

- **KLTJ**: turbojet maintenance labor ratio (HST turbojets to present subsonic turbojets).

- **kmTJ**: turbojet maintenance material ratio (HST turbojets to present subsonics turbojets).

- **KLRJ**: ramjet maintenance labor ratio (HST ramjets to present subsonic turbojets).

- **kmRJ**: ramjet maintenance material ratio (HST ramjets to present subsonic turbojets).

- **area_inlet**: inlet area assumed for ramjets, ($m^2$).

Following the definition of all those parameters, there is the estimation of the cost of different parts of the aircraft.

**Aircraft parts cost**

If the aircraft is provided with turbojets engines, the cost ($) of each of them is estimated with the equation:

$$cost\_TJ = tj\_act * 6300 * (n\_tj^{-0.15}) * (T0\_single^{-0.33}) * \frac{thrust\_takeoff}{(g0 * mtow)} \quad (16.1)$$

If the aircraft is provided with ramjets engines, the cost ($) of each of them is estimated with the equation:

$$cost\_RJ = 33900 * area\_inlet^{0.9} * mach^2 \quad (16.2)$$

While the other necessary cost to estimate are the cost ($) of the airframe:

$$cost\_airframe = 855 * (mass\_airframe)^{0.68} * mach^2 \quad (16.3)$$

and the cost ($) of the avionics

$$cost\_avionics = 2760 * mass\_systems \quad (16.4)$$

While the total acquisition cost of the aircraft (cost_HST) is the sum of the previous variables.

**Fuel DOC**

$$DOC\_fuel = \frac{1677.78 * cost\_fuel * \frac{mass\_fuel\_used\_medium}{mtow} * (1 - reserve\_fuel\_fraction)}{load\_factor * \frac{mass\_payload}{mtow} * route\_medium}$$

(16.5)

With

- reserve_fuel_fraction set = 0.08 as suggested, meaning that the 8% of the fuel is used as reserve.

- speed_block = $\frac{route\_medium}{time\_block}$ (km/h).

- time_block: it consists of the flight time with the addition of ATA hypothesized preflight and postflight taxi time.

**Crew DOC**

$$DOC\_crew = \frac{cost\_crew}{0.63 * load\_factor * mass\_payload * mach * \frac{speed\_block}{speed\_cruise\_hyp}}$$

(16.6)

With cost of the crew estimated around 320 \$/h and adjusted with inflation.

**Insurance DOC**

$$DOC\_insurance = \frac{insurance\_rate * \frac{cost\_HST}{mtow}}{0.63 * load\_factor * \frac{mass\_payload}{mtow} * mach * \frac{speed\_block}{speed\_cruise\_hyp} * time\_work\_annual}$$

(16.7)

Assuming insurance rate of 2%.

**Depreciation DOC**

$$DOC\_depreciation =$$
$$\frac{1.1 * \frac{cost\_HST}{mtow} + 0.3 * \left(\frac{cost\_TJ}{mtow} + \frac{cost\_RJ}{mtow}\right)}{0.63 * load\_factor * \frac{mass\_payload}{mtow} * mach * \frac{speed\_block}{speed\_cruise\_hyp} * time\_work\_annual * depreciation\_life}$$

(16.8)

Taking into consideration a depreciacion life of 10 years, that is less than what the medium aircraft life, but it was the value recommended and it means it is a conservative value.

**Maintenance DOC**

The maintenance DOC is divided in 6 parts:

DOC for maintenance labor effort required for the airframe:

$$DOC\_MAFL =$$
$$\frac{(3.70 + 2.18 * time\_hyp) * (\frac{0.05}{1000} * (\frac{m\_af}{mtow} + \frac{m\_sys}{mtow}) + (\frac{3}{mtow} - \frac{315}{mtow*(2*\frac{m\_af+m\_sys}{1000}+120)})) * mach^{0.5} * lr}{load\_factor * \frac{mass\_payload}{mtow} * \frac{route\_medium}{1000}}$$

$$(16.9)$$

With m_af = mass_airframe, and m_sys = mass_systems, lr = labor_rate.

DOC for maintenance material cost for the airframe:

$$DOC\_MAFM =$$
$$\frac{(5.22 * time\_hyp + 10.57) * (\frac{cost\_HST}{mtow} - \frac{cost\_TJ}{mtow} - \frac{cost\_RJ}{mtow})}{load\_factor * \frac{mass\_payload}{mtow} * route\_medium * 1000}$$

$$(16.10)$$

DOC for maintenance labor effort required for the turbojet engines:

$$DOC\_MTJL =$$
$$tj\_act * \frac{\frac{thrust\_takeoff}{g0*mtow} * (1 + tr\_TJ * time\_hyp) * (0.1 + \frac{9.91}{\frac{T0\_single}{1000}}) * labor\_rate * KLTJ}{load\_factor * route\_medium * \frac{mass\_payload}{mtow}}$$

$$(16.11)$$

With tr_TJ = time_operations_ratio_TJ.

DOC for maintenance material required for the turbojet engines:

$$DOC\_MTJM =$$
$$tj\_act * \frac{\frac{cost\_TJ}{mtow} * (0.034 * tr\_TJ * time\_hyp + 0.042) * kmTJ}{load\_factor * route\_medium * \frac{mass\_payload}{mtow}}$$

$$(16.12)$$

DOC for maintenance labor required for the ramjet engines:

$$DOC\_MRJL =$$
$$rj\_act * \frac{(1 + tr\_RJ * time\_hyp) * (0.1 + (1.01 * ld\_ratio * \frac{n\_rj}{\frac{mtow}{1000}})) * lr * KLRJ}{ld\_ratio * load\_factor * route\_medium * \frac{mass\_payload}{mtow}}$$

$$(16.13)$$

With tr_RJ = time_operations_ratio_RJ, lr = labor_rate.

DOC for maintenance material cost for ramjet engines:

$$DOC\_MRJM =$$
$$rj\_act * \frac{\frac{cost\_RJ}{mtow} * (0.034 * tr\_RJ * time\_hyp + 0.042) * kmRJ}{load\_factor * route\_medium * \frac{mass\_payload}{mtow}}$$

$$(16.14)$$

And the final maintenance DOC is the sum of all six.

## Total DOC

Finally the total DOC can be found of course with the sym of fuel, crew, insurance, depreciacion and maintenance DOCs, and with the following formula:

$$DOC\_TOTPerFlight = DOC\_tot * (load\_factor * \frac{mass\_payload}{907.185} * \frac{route\_medium}{0.621371}) \quad (16.15)$$

The effective DOC for a single flight in the considered range interval is calculated ($).

## IOC

The calculation of Indirect Operative Costs is based on coefficient estimated both by IATA and ICAO in 2012 and 2017, that quantify the different costs. The coefficient are the following:

- **IOC_GeneralAdministrative**: quantifying the general administration costs. It's estimated to be $7.2 * 10^{-3}$ ($/ASK) by [18].

- **IOC_ReservationSales** quantifying the sales reservation costs. It's estimated to be $7.6 * 10^{-3}$ ($/ASK) by [18].

- **IOC_StationGround** quantifying the ground stations costs. It's estimated to be $9.2 * 10^{-3}$ ($/ASK) by [18].

- **IOC_AirportNavigationCharges** quantifying the charges for airport navigation. It's estimated to be $8.3 * 10^{-3}$ ($/ASK) by [18].

- **IOC_PassengerService** quantifying the passenger service costs. It's estimated to be $7.9 * 10^{-3}$ ($/ASK) by [18].

- **IOC_AircraftRentals** quantifying the aircraft rentals costs. It's estimated to be $5.2 * 10^{-3}$ ($/ASK) by [18].

- **IOC_TrafficService** quantifying the traffic services costs. It's estimated to be 15 ($/ES) by [19].

- **IOC_AircraftServicing** quantifying the aircraft servicing costs. It's estimated to be 800 ($/flight) by [19].

All of them are finally combined using the equation:

$$IOC\_TOTPerFlight = (IOC\_GeneralAdministrative + IOC\_ReservationSales$$
$$+IOC\_StationGround + IOC\_AirportNavigationCharges + IOC\_PassengerService$$
$$+IOC\_AircraftRentals) * seats * route\_medium * inflation\_12to22$$
$$+(IOC\_TrafficService * seats + IOC\_AircraftServicing) * inflation\_17to22$$
$$(16.16)$$

## Total operational costs

Finally, the total yearly operational costs in (€) are found:

$$cost\_op = (DOC\_TOTPerFlight + IOC\_TOTPerFlight) * dol\_to\_eur * yearly\_flights$$
$$(16.17)$$

### 16.1.2   Emission tax

It was decided to implement both a CO2 tax and a GHG tax, to help implement the optimization process considering also emissions and climate impact.

The way this was implemented is that two activating values (act_CO2 and act_GHG) are imported from the ZData.py library, that can have value equal to 0 or 1. Those activating values are then multiplied for the tax coefficient that is given as an input from the Driver, so that only the tax with the activating value is taken into consideration.

Finally the total hypersonic cost is calculated by adding the operational cost to the tax costs, that come from the product of the tax coefficient and the relative total mass of emission in kg, given as an input by a feedback from the Climate impact module in Emissions.

### 16.1.3   Ticket price

Using all the data gathered in the previous sections and subsections the total hypersonic fleet cost can be found by summing the operational costs and the taxes due to pollution masses.

Of course, until now those costs are only adjusted with inflation to year 2022, so they also need to be adjusted to year 2031, as it is the horizon set for this project to be coherent with traffic estimations.

And last but not least, a profit has still to be made, or else it would not make fiscal sense to even start an hypersonic civil fleet, as there are still the RDTE, production and disposal costs to cover, with all sorts of additional costs that can come with a huge project like this.

Therefore it was decided to use a slightly higher percentual profit than annex 1 (V), in which RDTE and Production were already accounted for.

Finally, dividing the total cost plus the profit for the number of passengers taken into consideration, the medium ticket price (€) for the given range interval is calculated.

## 16.2   Market share

This is the final Costs module, that has the objective of linking the ticket price to the total passengers flying with the hypersonic fleet studied, via a variable called the market share, that will then go as a feedback to the Trajectories module.

The module takes as input:

- **inflation_14to22** from Driver.

- **inflation_22to31** from Driver.

- **cost_ticket_sub_14** from Driver.

- **route_medium_general** from Network traffic.

- **route_medium** from Trajectories.

- **time_sub** from Trajectories.

- **time_hyp** from Trajectories.

- **module_act_T** from Trajectories.

- **cost_ticket_hyp** from Ticket cost.

And gives as an output:

- **market_share**: IEP.

- **module_act_P**: same as the module_act_T, it is needed to avoid zero division errors in this module to propagate and create problems in the following ones. When equal to zero, the outputs of all following modules will also defined as zero and it will print how to avoid the problem.

The method and the considerations are the same as in annex 1 (V), but the subsonic price, that was taken as a medium in 2014, has to be adjusted to the range taken into consideration to have a more effective response in the Market share.

Additionally, every price is adapted to the year 2031, but that doesn't change anything in terms of market share output as the inflation coefficient simplifies divides by itself in the fare ratio formula.

# Chapter 17

# Emissions

In this chapter are presented to present the different WhatsOpt Emissions modules.

## 17.1 Atmosphere

This module essentially stayed the same as annex 1 (V), except for the fact that all subsonic reference emission are also calculated.

Additionally, as already mentioned in the the section about external files, a different choice of fuel injection was implemented.

Giving as an input the variable **ei_nox_type** generated in Zdata.py, there is a choice of two injection strategies:

- O - Normal injection: using this type of injection gives an average emission index for the $NO_x$ = 20 g every kg of fuel burnt [17].

- 1 - Distributed injection: using this type of injection gives an average emission index for the $NO_x = 3 * 10^{-2}$ g every kg of fuel burnt, therefore significantly diminishing the $NO_x$ emissions, without almost any performance penalty [17].

## 17.2 Ground

This module stayed exactly the same as annex 1 (V), with of course the subsonic reference emission calculation added.

## 17.3 Climate impact

A simple module was added after the two main Emission modules, for the purpose of calculating the climate impact of the fleet, and use it as a feedback to the Ticket price module. Unfortunately that was not possible for lack of data or a climate impact model for the altitudes and latitudes needed. Therefore this module is used to to calculate the total emissions masses (that are given as a feedback to the ticket price module) and the emissions per passenger per km, enabling better comparison between concepts and fuels.

The module takes as input:

- **pax** from Trajectories.

- **route_medium** from Trajectories.

- **mass_atm_CO2** from Atmosphere.

- **mass_atm_GHG** from Atmosphere.

- **mass_ground_CO2** from Ground.

And gives as an output:

- **mass_tot_CO2**, total mass of carbon dioxide and $eqCO_2$ produced by fuel production and transportation, and released into the atmosphere by burning said fuel.

- **mass_tot_GHG**, total mass of greenhouse gasses produced.

- **CO2_single**, mass of carbon dioxide and $CO_2$eq produced for every passenger that has traveled one (1) km, in ($\frac{kg}{Pax*km}$).

- **GHG_single**, mass of greenhouse gasses produced for every passenger that has traveled one (1) km, in ($\frac{kg}{Pax*km}$).

Even if the effective climate impact is not calculated, the name of the module was not changed as the main goal of this stage is not to make a perfectly working machine, but to create a structure that can be taken over and continued to implement further even after the author of this thesis stopped working on it.

Therefore it leaves place for a future in which, with the necessary data available, this climate impact module can be implemented and inserted in the structure.

# Chapter 18

# Final modules

## 18.1 Trade off

Trade off is the final module, meant to implement some indexes to better evaluate and optimize the different outputs of the model, as the final goal should be to optimize simultaneously flight time, ticket price and climate impact of the hypersonic fleet. It is also used to find the effective market share taken into consideration with the chosen range interval.

The module takes as input:

- **pax_tot_HST** from Network Traffic.

- **pax** from Trajectories.

- **time_hyp** from Trajectories.

- **cost_ticket_hyp** from Ticket cost.

- **market_share** from Market share.

- **mass_tot_CO2** from Total.

- **mass_tot_GHG** from Total.

And gives as an output:

- **market_share_eff**: the effective market share:

The difference between market share and effective market share is that the first is found in relation to the total FC+B passengers flying on the routes within the range interval chosen while the effective market share is calculated in relation to the total FC+B passengers flying on the entire network.

It means that the smaller the range interval taken into consideration, the bigger the difference between market share and effective market share.

The other inputs taken are still not used, as it is yet to find a way to do multiple objective optimization.

Nonetheless it was decided to leave the model like this, as one of the main goals is to create a structure that can be taken over and continued to implement further even after the author of this thesis stopped working on it.

# Part VII

# Sclopp 0.2 version - General concept

**Created by integrating into the 0.2 model a design cycle, to evaluate a general concept given specific parameters as input.**
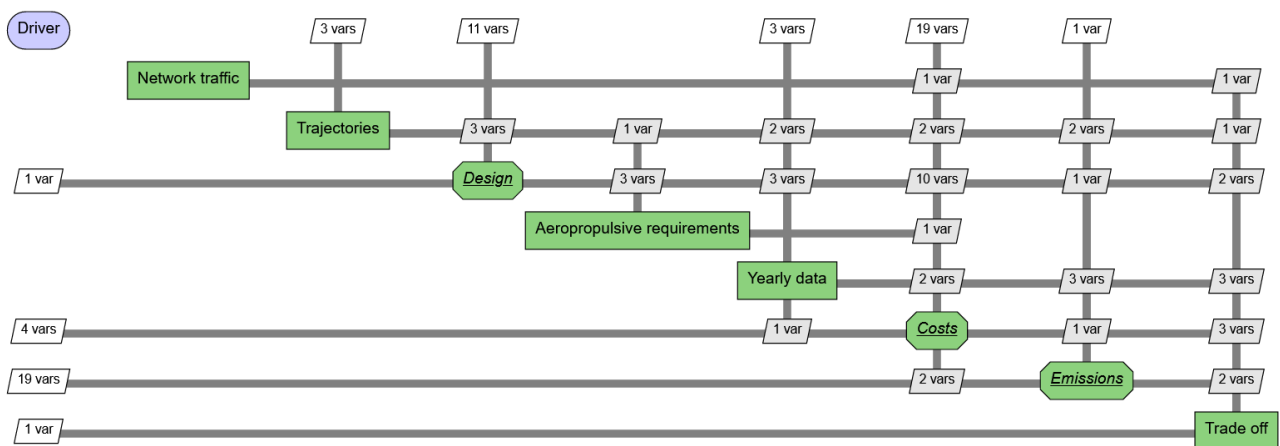
# Chapter 19

# External files

As it is obvious from the structure, the biggest change is the fact that fixed concepts are not given as an input anymore, but a general configuration is created from convergence of the design equations and feedbacks.

Therefore the Aircraft_data.xlsx file is no longer necessary, while the HST_traffic.xlsx file is exactly the same.

## 19.1  ZLibAeroProp.py

This library contains functions that, with empirical or statistical equations, return parameters used in the main code. Most of the equations are taken from the annex 1 of [11]:

- **ISP(fuel_type, engine_type, M)**: IEP.

- **CruiseAltitude(M)**: returns the cruise altitude (m) of the aircraft given its cruise Mach number.

- **LD_Ratio(M, tau)**: returns the cruise lift to drag ratio of the concept given its cruise Mach number and Küchemann parameter.

$$\frac{L}{D} = \frac{A*(M+B)}{M} * \frac{1.0128 - 0.2797 * ln(\frac{\tau}{0.03})}{1 - \frac{M^2}{673}} * (1 + tf\_aero) \tag{19.1}$$

With

- M = Mach number.
- $\tau$ = Küchemann parameter.
- A = 6.
- B = 2.
- tf_$aero$ is a statistical adjustment parameter developed by HIKARI to make it better represent the hypersonic concepts used in their studies.

The first part of the equation is an empirical law for waveriders, taken from [21], while the second part is a correction made using wind tunnel tests, as reported in [11].

- **Sea_Level_Thrust_Max(mtow (kg), ld_ratio)**: returns the sea level maximum thrust (N) following a statistical law developed using different hypersonic civil aircraft concepts.

$$T0\_max = 1437191.79 * ln(\frac{mtow}{ld\_ratio}) - 14544245.43 \tag{19.2}$$
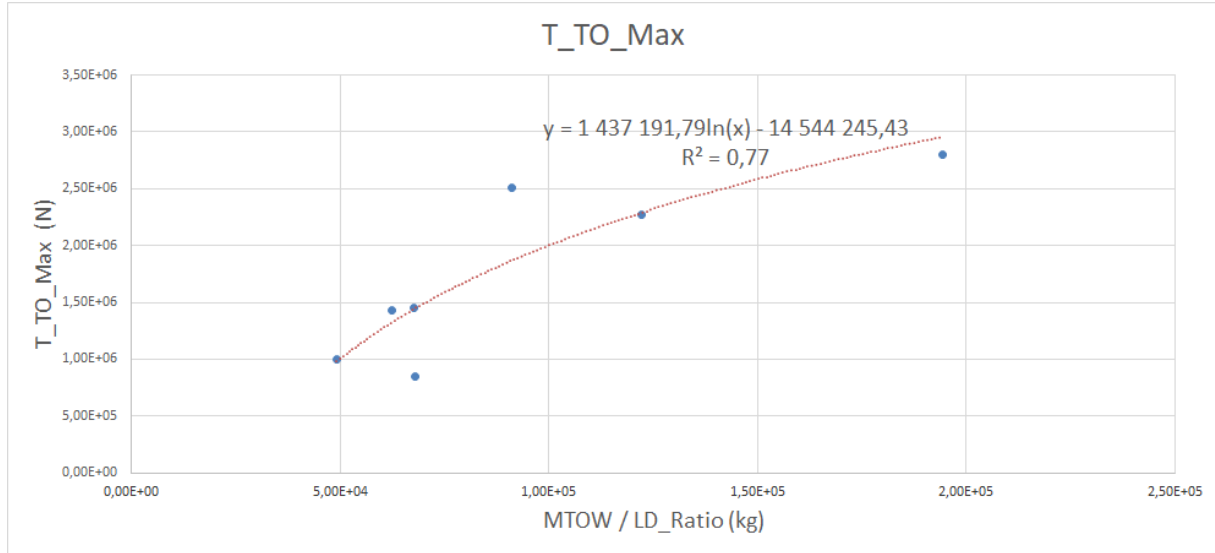


Figure 19.1: Sea level maximum thrust statistical law

it is also set not be lower than 50000 N.

## 19.2 Zdata.py

A couple of small changes were made to this function:

- The function that generates **a_type** in Zdata.py is removed, as the concepts taken into consideration are not fixed anymore.

- The function fuel_data(fuel_type) now additionally returns a sixth value with the fuel density (kg/m$^3$)

.

All the remaining libraries stayed the same.

# Chapter 20

# Common modules before Design cycle

In this chapter are presented the various WhatsOpt [4] modules that are necessary to calculate the inputs for the Design, Costs and Emissions modules.

## 20.1 Driver

In this module are defined several variables:

- **mach**: Mach number, design variable of this model as not fixed anymore with the concept of choice.

- **profit_perc**: IEP, design variable.

- **seats**: maximum aircraft passengers seats, design variable of this model as not fixed anymore with the concept of choice.

- **tau**: Küchemann form parameter.

- **combustion_efficiency**: IEP.

- **cost_ticket_sub_14**: IEP.

- **dol_to_eur**: IEP.

- **ERF**: IEP.

- **filling_coefficient**:

$$filling\_coefficient = \frac{fuel\_volume + payload\_volume}{aircraft\_total\_volume} \quad (20.1)$$

- **g0**: IEP.

- **inflation_72to22**: IEP.

- **inflation_12to22**: IEP.

- **inflation_14to22**: IEP.

- **inflation_17to22**: IEP.

- **inflation_22to31**: IEP.

- **ld_ratio_sub**: IEP.

- **load_factor**: IEP.

- **mass_dry_sub**: IEP.

- **n_rj**: IEP.

- **n_tj**: IEP.

- **range_limit_down**: IEP.

- **range_limit_up**: IEP.

- **reserve_fuel_fraction**: IEP.

- **seats_sub**: IEP.

- **speed_cruise_sub**: IEP.

- **tax_CO2**: IEP.

- **tax_GHG**: IEP.

- **time_work_annual**: IEP.

- **tsfc_sub**: IEP.

The outputs of this module are therefore all the variables previously mentioned.

## 20.2   Network traffic

As this version of the model hasn't got fixed concepts, all the aircraft data is to be defined in the following Design modules. Therefore the goal of this module only is to define the total network traffic data.
The only input taken is the HST_traffic.xlsx file.
Outputs:

- **pax_tot_HST**: IEP.

- **route_medium_general**: IEP.

The two outputs are calculated in the same way as for annex 2 (VI), by weighting in function of the passenger for each route.

## 20.3   Trajectories

In this module the goal is to define all necessary data for the design cycle to take place.
The module takes as input:

- **range_limit_down** from Driver.

- **range_limit_up** from Driver.

- **ERF** from Driver.

And gives as an output:

- **pax_tot_considered**, total FC+B passengers on the routes selected, meaning only the routes between the range limits.

- **route_medium**: IEP.

- **route_medium_sub**: subsonic reference's medium route taking into consideration only the city pairs between the range limits. It is different than his hypersonic counterpart for the fact that the ERF is not counted.

- **module_act_T**: IEP.

The routes are calculated in the same way as the fixed concept versions.

# Chapter 21

# Design

In this chapter are presented the various WhatsOpt [4] modules pertaining to the Design cycle, that after convergence will return all the necessary information about the aircraft and its mission.

## 21.1 Mission

Here are defined all the necessary mission data, for both hypersonic and subsonic reference fleets. The module takes as input:

- **mach** from Driver.

- **tau** from Driver.

- **speed_cruise_sub** from Driver.

- **tsfc_sub** from Driver.

- **route_medium** from Trajectories.

- **route_medium_sub** from Trajectories.

- **module_act_T**: from Trajectories.

And gives as an output:

- **isp_cruise**, IEP.

- **isp_cruise_sub**, IEP.

- **ld_ratio**: IEP.

- **speed_cruise_hyp**: IEP.

- **time_hyp**: IEP.

- **time_sub**: IEP.

- **z_cruise**: IEP.

As for the previous versions, the cruise speed is found using the speed of sound and Mach retrieved thanks to the ISA atmosphere library in function of the cruise altitude.

At the same time, to find the cruise altitude, the specific impulse and the lift to drag ratio, the respective function implemented in the aeropropulsive library is called.

The cruise altitude could also be given as a model design variable instead, to vary it and evaluate its effects.

Finally, the subsonic reference ISP is returned from the TSFC. As the thrust specific fuel consumption used is relative to kerosene and needs therefore to be adapted to other fuels. Of course, in this case all fuels are considered as drop-in fuels and do not take into consideration the modifications that would really have to be made on the aircraft.

## 21.2 Geometry

The objective of this module is to define the different geometric parameters needed to calculate the different masses.

The module takes as input:

- **filling_coefficient** from Driver.

- **tau** from Driver.

- **reserve_fuel_fraction** from Driver.

- **seats** from Driver.

- **module_act_T**: from Trajectories.

- **mass_fuel_used_medium** from Driver.

And gives as an output:

- **s_wet**, wetted surface of the aircraft (m$^2$).

First the payload volume (m$^3$) is calculated, using the simplified equation contained in annex 1 of [11]:

$$volume\_payload = seats * \frac{1400}{300} \tag{21.1}$$

Then the fuel volume is computed counting the fuel reserve needed, and the the total volume of the aircraft is found by using the definition of filling coefficient.

Subsequently the planform area is retrieved using the definition of Küchemann tau parameter, and the wetted coefficient is calculated using an empirical law, also from annex 1 of [11].

Finally, the wetted area is returned by multiplying the wetted coefficient and the planform area.

## 21.3 Dry mass

As the name implies, the goal of this module is to return the aircraft dry weight so that the Breguet equation can be used. Additionally, other masses needed for the cost computations are estimated.

The module takes as input:

- **load_factor** from Driver.

- **mtow** from Driver.

- **seats** from Driver.

- **module_act_T**: from Trajectories.

- **ld_ratio** from Mission.

- **s_wet** from Geometry.

And gives as an output:

- **mass_airframe**, airframe mass of the aircraft (kg).

- **mass_dry**, dry mass of the aircraft (kg).

- **mass_payload**, payload mass of the aircraft (kg).

- **mass_systems**, systems and avionics mass of the aircraft (kg).

In particular, the payload mass is returned in function of the passenger number, with the mass hypothesized for a single passenger, his luggage and the dedicated equipment in the aircraft chosen to be 200 kg, as conservative value, from the fact that dividing all maximum payload masses of the hypersonic civil concepts studied for the seats of said concepts, the maximum single seat relative mass was exactly 200 kg.

The propulsion mass is derived from the definition of overall engine thrust to weith ratio, as explained before.

Finally the airframe weight is returned by using the definition of the ISTR, a structural weight per area parameter. The ISTR is retrieved from a correlation developed in [11] that makes it function of MTOW.

## 21.4   Fuel mass

The module takes as input:

- **combustion_efficiency** from Driver.

- **mass_dry_sub** from Driver.

- **speed_cruise_sub** from Driver.

- **route_medium** from Trajectories.

- **module_act_T**: from Trajectories.

- **route_medium_sub** from Trajectories.

- **isp_cruise** from Mission.

- **isp_cruise_sub** from Mission.

- **ld_ratio** from Mission.

- **ld_ratio_sub** from Mission.

- **speed_cruise_hyp** from Mission.

- **mass_dry** from Dry mass.

And gives as an output:

- **mass_fuel_used_medium**: IEP.

- **mass_fuel_used_medium_sub**: IEP.

Both the outputs are returned using Breguet's equation and taking into consideration the combustion efficiency chosen.

## 21.5    Mass breakdown

Final module of the design cycle, returns the mtow adding the mass of fuel used on a medium flight for the range interval chosen to the dry mass.

The module takes as input:

- **mass_dry** from Dry mass.

- **mass_fuel_used_medium** from Fuel mass.

- **module_act_T**: from Trajectories.

And gives as an output:

- **mtow**, maximum takeoff weight of the aircraft (kg).

- **module_act_M**: IEP.

# Chapter 22

# Common modules after Design cycle

## 22.1   Aeropropulsive requirements

The goal of this module is to calculate the necessary propulsion data for costs and emissions modules. As the emissions are already calculated with the Breguet equation, assuming all the range as cruise, the actual goal of this module is just to estimate the single engine maximum thrust at sea level, that will be used in the DOC equations to evaluate operational costs.

- **module_act_T**: from Trajectories.

- **ld_ratio** from Mission.

- **mtow** from Mass breakdown.

- **module_act_M**: from Mass breakdown.

And gives as an output:

- **T0_max**, single engine maximum thrust at sea level (N).

The output of the model is calculated by recalling the Sea_Level_Thrust_max function from the ZLibAeroProp.py library, that uses a statistical law function of MTOW and L/D ratio to find said thrust.

## 22.2   Yearly data

In this module, all the remaining data that was returned by the Trajectories module in annex 2 (VI), and that has not been calculated yet, is estimated.

- **load_factor** from Driver.

- **seats** from Driver.

- **seats_sub** from Driver.

- **pax_tot_considered** from Trajectories.

- **module_act_T**: from Trajectories.

- **mass_fuel_used_medium** from Fuel mass.

- **mass_fuel_used_medium_sub** from Fuel mass.

- **module_act_M**: from Mass breakdown.

- **market_share** from Market share feedback.

And gives as an output:

- **pax**: IEP.

- **mass_fuel_used**: IEP.

- **mass_fuel_used_sub**: IEP.

- **yearly_flights**: IEP.

## 22.3   Costs, Emissions and Trade off

Finally, all the other modules after remain the same as annex 2 (VI), with some small differences on the modules where their inputs come from.

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