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MHyTech – An aircraft retrofitting simulation tool for hydrogen-based technologies

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Abstract

Nowadays, the air transport contributes around 2-3% of global greenhouse gases (GHG) emissions. Despite the fact that strong efforts in engineering have led to more efficient engines, this cannot reduce GHG emissions enough to achieve European Commission targets. Besides, the pandemic crisis has greatly affected the aeronautic sector in a way that a massive effort is oriented towards the use of hydrogen as an energy carrier. Indeed, hydrogen is a promising alternative to kerosene to the aeronautic sector, capable of reducing carbon emissions by 50% to 90%. In this work, MHyTech project is presented which main goal consists in the study of aircraft retrofitting by means of mathematical modelling and simulation, enabling the pre-sizing of hydrogen technologies for aviation, including combustion and electric engines, fuel cell, batteries and hybrid systems.

1. Introduction

The aviation sector is responsible for 2-3% of all anthropogenic carbon emissions and 12% of transport-related emissions. In this context, the European Commission devised the "Flight Path 2050" reduction targets: 75% reduction of CO_2 emissions per passenger kilometer, 90% reduction of NOx emissions, and 65% reduction of the perceived noise.[3, 11–13] Although the Covid19 pandemic has changed the flight model, increases in air travel activities are still expected meaning that these goals are unlikely to be reached by simply evolutionary improvements to existing aviation technology.[6,9]

As an alternative to hydrocarbon fuels (directly correlated with CO_2 emissions), hydrogen-powered aircraft appears as one solution.[3, 12] Compared to kerosene, hydrogen has three times higher gravimetric energy density.[7] Nevertheless, its volumetric energy density is four times lower, leading to some difficulties regarding the tanks' integration into the aircraft.[1, 3, 8, 10, 12, 14] Despite the large volume requirement related to hydrogen, the fact that no carbon emissions are related to it still atracts scientists and engineers making an effort to use it in aviation.[9] Moreover, once hydrogen is considered as fuel, it can be exerted for producing propulsive thrust from a gas-turbine engine or for generating electricity using fuel cells (e.g., PEMFC).[2]

Although the uses of hydrogen are regarded as well established in the automotive and stationary sectors (mainly due to the remarkable achievements made by Toyota in the recent past years), it remains at a demonstrator level in the air mobility sector. For the past ten years, some projects of hydrogen aircraft demonstrators such as HY4 (2015), HES Element One (2018), Apus i-2 (2019), ZeroAvia (2019), ZEROe (2020), etc., have been announced and are still under the development step.[3, 12] They are mainly focused on a propulsive system powered by hydrogen fuel cells even if a few examples of hydrogen combustion exist (Airbus cryoplane in 2003) and mainly corresponds to small aircrafts (2-5 seats).[3, 12, 13] For larger aircrafts (until 75 seats), other strategies like retrofit are under development for hydrogen-powered flight. Indeed, Universal Hydrogen is developing conversion kits to retrofit the existing fleet or regional aircraft with a hydrogen fuel cell powertrain.[4] With this solution, the modular capsules tanks could be loaded directly into the aircraft. Despite this strategy to power larger aircrafts with hydrogen, a question remains in the case of aircrafts with more than 150 seats: a retrofit could be possible with an aircraft such as A320?

Shifting aviation to hydrogen-based propulsion is very challenging. In this study, we discuss the implications of hydrogen technologies for the engines design and fuel storage solutions in the case of a retrofit. At the first steps, the consideration of the system details are not involved, but only the major consideration of weights and volumes resulting to the integration of the hydrogen systems (storage tanks, engines, fuel cells, batteries, etc.) are considered in this pre-sizing study. Afterwards, a mathematical optimization approach is employed to evaluate the compromise between

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carbon emissions and the different technologies used. In this context, the propulsion systems include hydrogen-fuelled gas turbine propulsion, hydrogen fuel cell electric propulsion (which can be coupled with lithium-ion batteries), as well as the current technology used, i.e., kerosene-fuelled gas turbine propulsion.

In the next section, the methodology is described, this comprises the simulation approach adopted, along with the main assumptions taken into account in this study. Then, Section 2.2.1 is devoted to the optimization framework, and thus the model describing the system is presented with some details focusing on the design variables such as the engine choice and storage system selection. Section 3 presents some representative results obtained for two well-known aircrafts: A320-200 and ATR 72-600. Finally, Section 4 draws some conclusions and perspectives of this work.

2. Methodology

2.1 Simulation environment

With the aim of analyzing the technical feasibility of retrofit for commercial aircrafts, and in particular for hydrogen-based technologies considering primarily mass and volume constraints, we adapted a numerical approach which consists in a simulation environment. In this context, the modelling incorporates aerodynamic equations which describe a given flight mission, aircraft attributes such as wing surface, available volume for energy containers, rate of climb, maximum take-off weight, etc., physical characteristics associated to the chosen technology such as the efficiency of fuel cell systems, gravimetric index for hydrogen storage tanks, etc. In Figures 1 and 2, some representative screenshots of MHyTech simulation tool are displayed. Moreover, the tool enables the user to make some modifications to the baseline aircraft.

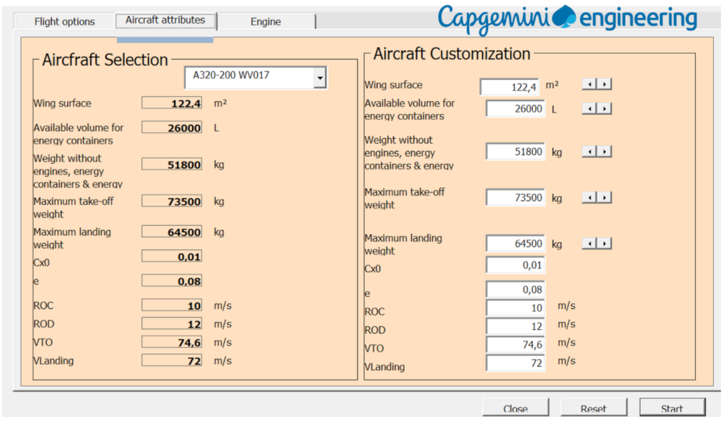

Figure 1: Representative screenshot of MHyTech simulation tool: Aircraft attributes selection.

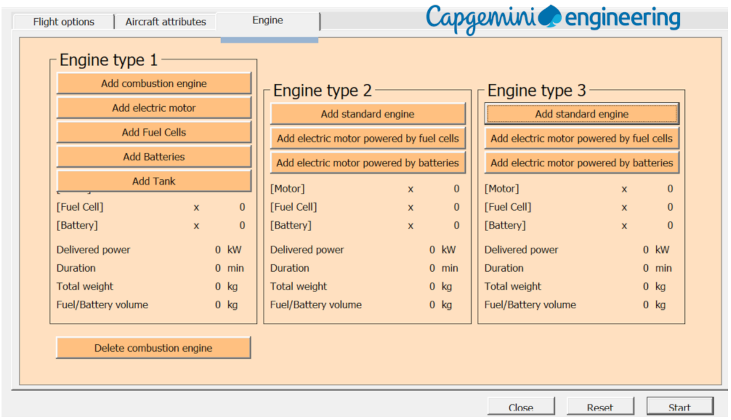

Figure 2: Representative screenshot of MHyTech simulation tool: Engine options selection.

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In the first step, the user enters some information relative to the flight mission, namely, the flight distance, the flight altitude and the cruise speed. Then, the baseline aircraft is selected in addition to some characteristics for retrofitting like the engine type, fuel type, storage system, and auxiliary systems in the case of fuel cells and batteries use, among other alternatives. According to flight physics models[5] and emissions models,[11] the energy requirements and the GHG emissions are estimated for the entire mission.

The environmental impact is quantified as the emissions relative to a given fight mission, contrary to a life cycle assessment (LCA) approach. Indeed, in LCA approach emissions regarding the source, production, transportation, use and end-of-life phases of each technology are taken into consideration. Further, in order to establish a basis of comparison for carbon emissions for the different propulsion technologies, the global warming potential (GWP) is employed to estimate the GHG emissions in the basis of kg CO_2-eq, per seat per 100 km, and are also given relative to the emissions corresponding to the baseline aircraft, that is, using Jet A-1 fuel in a thermic engine. Then, different scores are attributed to each technology, being "A" the best solution from and environmental perspective, and "E" the worst solution. This is illustrated in Figure 3. Note that different ranges for each note are assigned arbitrarily.

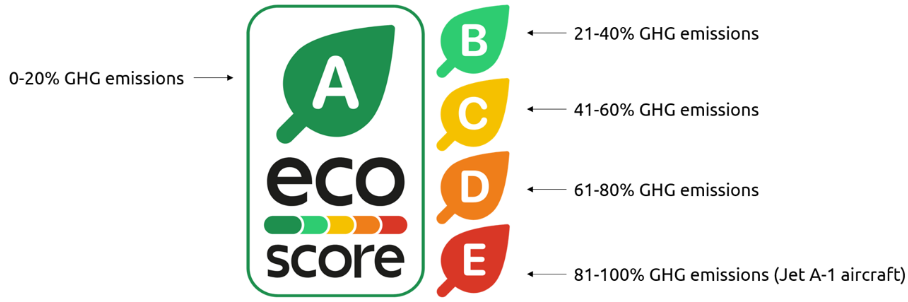

Figure 3: Environmental score.

Regarding the modelling of flight physics, as a first approximation a classic aerodynamic model has been considered for validation purposes.[5] We consider a quasi-steady flight comprising only three phases, namely, climb, cruise and descent. Besides, the continuous climb and descent operation assumption is considered, that is, the climb and descent rates (ROC and ROD, respectively) over time are constant and therefore the evolution of altitude and speed are linear over time. In this respect, the aviation authorities in the framework of CleanSky look for implementing this principle to reduce GHG emissions.

2.2 Optimization framework

Besides, once the model has been implemented in MHyTech environment, an optimization approach is investigated to find the configurations of aircraft retrofitting that enable the largest range and that entail the least GHG emissions. Since conflict between these two objectives seems to arise (that is, the improvement in range results in an increase in GHG emissions), multi-objective optimization theory is used to find the best compromising solutions. The problem is written as a constrained optimization problem and tackled by an evolutionary algorithm. In Figure 4, the optimization methodology is described in more details.

2.2.1 Mathematical model

The mathematical model representing the aircraft retrofitting considers different types of constraints, namely, mass and volume constraints as well as thrust requirements contraints. The aircraft architecture must ensure the feasibility of the flight for each flight leg. In the following, the model is presented with focus on the decision variables regarding the choice of different propulsion and storage technologies.

Model constraints

The total mass of the aircraft at take-off must be below a certain limit denoted as $MTOM$. This is written as:

$$m_0 + m_P + m_{fS} \leq MTOM \tag{1}$$

where m_0 is the aircraft mass with neither the propulsion system nor the fuel storage system, m_P is the mass of the propulsion system and m_{fS} is the mass of the fuel storage system, that is, the fuel and the storage tank.

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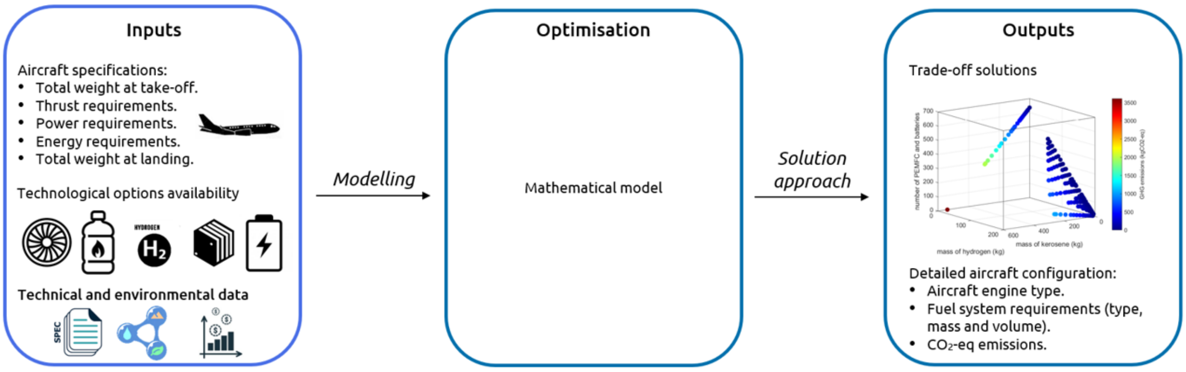

Figure 4: Methodological optimization framework.

The propulsion system mass, m_P, comprises the type and number of engines as follows:

$$m_P = mE_{th_{ker}} nE_{th_{ker}} + mE_{th_{H2}} nE_{th_{H2}} + mE_{el} nE_{el} \tag{2}$$

where $mE_{th_{ker}}$ and $mE_{th_{H2}}$ are the unit mass of internal combustion engines powered by kerosene and hydrogen, respectively, and $nE_{th_{ker}}$ and $nE_{th_{H2}}$ are the respective number of combustion engines. The mE_{el} and nE_{el} are the corresponding unit mass and quantity of electric engines. Therefore, the variables $nE_{th_{ker}}$, $nE_{th_{H2}}$ and nE_{el} can take only nonnegative integer values ($nE_{th_{ker}}, nE_{th_{H2}}, nE_{el} \in \mathbb{N}_0$).

Besides, the number of engines (whether thermic engines powered by kerosene or hydrogen, or electric ones) is bounded within some upper and lower limits as follows:

$$nE^{\min}_{th_{ker}} X_{th_{ker}} \le nE_{th_{ker}} \le nE^{\max}_{th_{ker}} X_{th_{ker}} \tag{3}$$
$$nE^{\min}_{th_{H2}} X_{th_{H2}} \le nE_{th_{H2}} \le nE^{\max}_{th_{H2}} X_{th_{H2}} \tag{4}$$
$$nE^{\min}_{el} X_{el} \le nE_{el} \le nE^{\max}_{el} X_{el} \tag{5}$$

where $nE^{\min}_{th_{ker}}$, $nE^{\min}_{th_{H2}}$, $nE^{\min}_{el}$, $nE^{\max}_{th_{ker}}$ and $nE^{\max}_{th_{H2}}$, $nE^{\max}_{el}$ are input parameters that depend on the aircraft, and $X_{th_{ker}}$, $X_{th_{H2}}$ and X_{el} are binary variables related to the use of each type of engine.

In the context of aircraft retrofitting, the number of thermic and electric engines must be an even number, and the number of thermic engines cannot be greater than the number of engines of the baseline aircraft. This can be represented as:

$$nE_{th_{ker}} + nE_{th_{H2}}, nE_{el} \in 2\mathbb{Z}_{\ge 0} \tag{6}$$

The following constraint establishes that the system must use at least one technology type:

$$1 \le X_{th_{ker}} + X_{th_{H2}} + X_{el} \tag{7}$$

Besides, if an electric engine is used, then fuel cells and batteries need to be employed as electricity source. This is written mathematically as:

$$X_{FC} \le X_{el} \tag{8}$$
$$X_{bat} \le X_{el} \tag{9}$$
$$X_{el} \le X_{FC} + X_{bat} \tag{10}$$

where X_{FC} and X_{bat} are binary variables representing respectively the use of fuel cells and batteries for providing electricity to the electric engine.

The mass of the fuel system, m_{fS}, considers the mass associated to the storage tank, that to the fuel, as well as the mass of hydrogen fuel cells and batteries. This can be written as follows:

$$mfS = mSys_{ker} + mSys_{H_2} + mSys_{FC} + mSys_{bat} \tag{11}$$

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where $mSys_{ker}$ is the mass of the kerosene fuel system, which comprises the mass of the fuel itself as well as the mass of the storage tank:

$$mSys_{ker} = mSt_{ker} + m_{ker} \tag{12}$$

Since the base aircraft contains already the storage tanks for kerosene, mSt_{ker} is considered as zero. The mass of kerosene, m_{ker}, is bounded by the maximum mass that the aircraft can store (volume constraints) as follows:

$$0 \leq m_{ker} \leq m_{ker}^{\max} X_{th_{ker}} \tag{13}$$

where

$$m_{ker}^{\max} = V_0^{\max} \rho_{ker} \tag{14}$$

where $V_0^{\max}$ is the fuel volume storage of the aircraft in m^3 and ρ_{ker} is the mass density of kerosene in kg/m^3. From equation (13), it can be noted that the mass of kerosene is zero if no thermic engine is used.

Regarding the mass of the hydrogen system ($mSys_{H_2}$), it considers the mass of the storage tank (mSt_{H_2}) plus the mass of hydrogen (m_{H_2}). This is expressed as:

$$mSys_{H_2} = mSt_{H_2} + m_{H_2} \tag{15}$$

The storage tank mass is estimated as a function of the total mass of hydrogen, according to the following relationship:

$$mSt_{H_2} = K_{H_2} m_{H_2} \tag{16}$$

where K_{H_2} is a parameter related to the gravimetric index, itself depending on the storage technology type. Also, the maximum mass of hydrogen is bounded by the maximum hydrogen mass that the aircraft can store (volume constraints), taken into consideration the type of engine as follows:

$$0 \leq m_{H_2} < m_{H_2}^{\max} X_{H_2} \tag{17}$$

where

$$m_{H_2}^{\max} = V_{H_2}^{\max} \rho_{H_2} \tag{18}$$

and

$$X_{el} \leq X_{H_2} \tag{19}$$

$$X_{th_{H2}} \leq X_{H_2} \tag{20}$$

$$X_{H_2} \leq X_{el} + X_{th_{H2}} \tag{21}$$

where $V_{H_2}^{\max}$ is the maximum hydrogen system volume that the aircraft allows in m^3 and ρ_{H_2} is the mass density of hydrogen in kg/m^3. It can be noted that the weight of the hydrogen fuel system, mSt_{H_2}, is zero if neither an electric engine nor a hydrogen combustion engine are used.

Then, the weight of the fuel cell system is computed as following:

$$mSys_{FC} = n_{FC} m_{FC} \tag{22}$$

where n_{FC} is the number of fuel cells and m_{FC} is the unit mass of fuel cells. The number of fuel cells must take only nonnegative integer values and can only be positive if electric engines are used. This can be mathematically stated as:

$$n_{FC} \in \mathbb{N}_0 \tag{23}$$

$$n_{FC} \leq n_{FC}^{\max} X_{el} \tag{24}$$

where $n_{FC}^{\max}$ is the maximum number of fuel cells that can be used (a parameter).

Similarly, the battery system mass is calculated as:

$$mSys_{bat} = n_{bat} m_{bat} \tag{25}$$

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where n_{bat} is the number of batteries used and m_{bat} is the battery unit mass. The number of batteries must take only nonnegative integer values, and can only be positive if electric engines are used. This is expressed as:

$$n_{bat} \in \mathbb{N}_0 \tag{26}$$

$$n_{bat} \leq n_{bat}^{\max} X_{el} \tag{27}$$

The aircraft needs to fulfill minimal thrust requirements for each flight leg. In the cruise phase and in an ideal situation, the forces acting on an aircraft in the cruise phase flight produce no net external force. In this situation the lift is equal to the weight, and the thrust is equal to the drag. While the weight decreases due to fuel burned, the change might not be significant with respect to the total aircraft weight. In this situation, the following equation is stated:

$$T_{cr} = \frac{mg}{f} \tag{28}$$

where T_{cr} is the thrust, m is the total aircraft mass in kg, g is the gravitational acceleration in m/s^2 and f is the "finesse", also known as the lift and drag coefficients ratio (C_L/C_D). The total mass of the aircraft is computed as:

$$m = m_0 + m_P + m_{fS} \tag{29}$$

The lift coefficient (dimensionless) in the cruise phase is calculated as:

$$C_L = \frac{2L}{\rho S v^2} \tag{30}$$

where ρ is the air density (kg/m^3), S is the wing surface (m^2) and v is the airspeed (m/s). Note that the drag, L, is equal to the airplane weight (w) in the cruise phase.

Similarly, the drag coefficient (dimensionless) is calculated as a function of the lift coefficient as follows:

$$C_D = C_{D_0} + kC_L^2 \tag{31}$$

where C_{D_0} and k are aircraft parameters.

In the climbing phase, the aircraft bears the effects of lifting force, gravity, drag, and thrust in the flight, which directly affect its flight speed. On the basis of aerodynamic performance data in this phase, drag and thrust models can be obtained as follows:

$$T_{cl} = D + mg\sin\gamma + m\frac{dv}{dt} \tag{32}$$

$$D = \frac{1}{2}\rho S v^2 C_D \tag{33}$$

$$L = \frac{1}{2}\rho S v^2 C_L = mg\cos\gamma \tag{34}$$

where C_D is computed as:

$$C_D = \frac{C_D^*}{\sqrt{1 - M^2}} \tag{35}$$

$$C_D^* = C_{D_0} + kC_L^2 \tag{36}$$

Finally, for the descent phase, the required thrust is computed as:

$$T_{dsc} = D - mg\sin\gamma + m\frac{dv}{dt} \tag{37}$$

These equations act as constraints from an optimization point of view. The flight mission is discretized in a several time intervals Δt (we consider $\Delta t = 10$ s). Then, the thrust provided at each time interval must be at least that of the required thrust at each flight phase, T_{cr}, T_{cl} and T_{dsc}.

Objective functions

As a first study, the resulting problem is formulated as a four-objective problem, consisting in the minimization of 1) the mass of kerosene, 2) the mass of hydrogen storage system, 3) the number of PEMFC and batteries, and 4) the amount of CO2-eq emissions.

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3. Results and discussions

The simulation environment is developed in VBA language in Microsoft Excel. The simulation tool allows to study multiple commercial aircrafts; in this study the results are oriented only to ATR 72-600 and A320. The A320-200 is a short-range aircraft, one of the most used aircraft class in the world and therefore responsible of an important amount of CO_2 emissions. The ATR 72-600 is a regional aircraft, which seems to be the most promising class of aircraft for the implementation of hydrogen technologies in the short and medium-term.

The results obtained for the commercial aircraft ATR 72-600 and A320 are presented in Figures 5 and 6, respectively. The graphs show the maximum range (in km) as a function of the percentage of seats removed for different propulsion technologies with current performances and those expected for 2030. Indeed, it is necessary to remove seats or passengers for two reasons: either to save weight (and put more kerosene since the tanks can only be filled completely if the aircraft is not full because of the MTOM), or to gain volume in the cabin to put the hydrogen tanks (the one alternative considered here). Besides, we also have a vision on CO_2 emissions, with the CO_2-equivalent graph, which presents the emissions per passenger per 100 km.

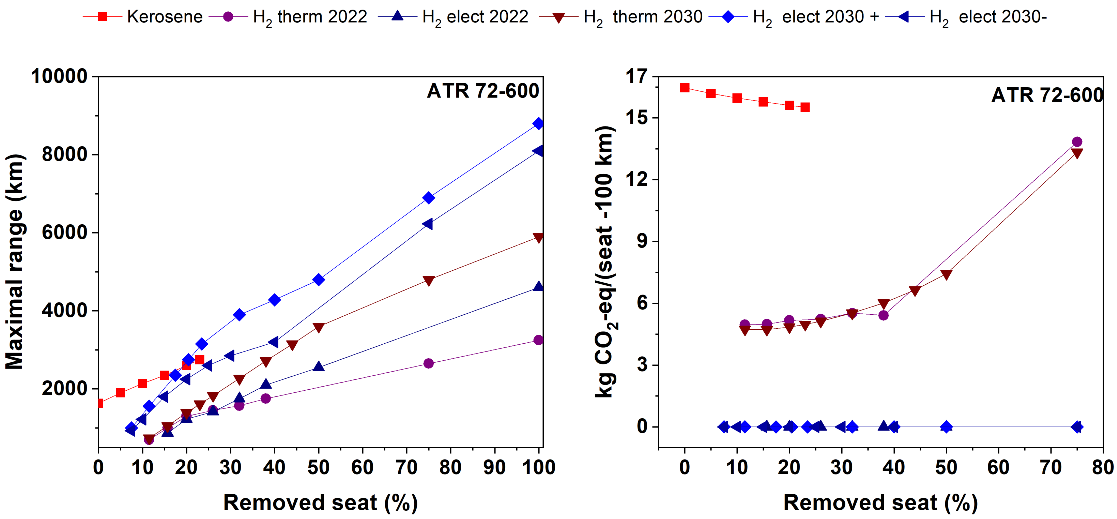

Figure 5: Simulation results on ATR 72-600.

For the ATR 72-600, the current case (kerosene) is depicted in the red color curve. With the maximum number of passengers, it is only possible to travel 1 600 kilometers. If there are 25% fewer passengers, the weight saved allows the tanks to be filled to 100% and to travel 2 700 kilometers. According to our carbon emission model, the ATR 72-600 is responsible of ≈16.5 kg CO_2-eq/seat-100km in the base case, and ≈15.5 kg if reduction of passengers is carried out.

Regarding the use of hydrogen technologies, PEM fuel cells and the hydrogen tanks add a significant additional weight, which is especially crucial at landing, because of the “dead weight” that is not consumed during the flight unlike kerosene. So with current performances, some capacity has to be removed (about 30%) to gain weight and reach the same performances as kerosene. However, for most of the missions currently performed by an ATR 72-600, these performances seem to be acceptable. Besides, once unrestrained from weight constraints with fuel cells and tank performances foreseen for 2030, electric motors being more efficient than thermic ones, especially for climb and descent legs (indeed thermic motors performs poorly at low speeds and altitudes), allow to have promising results close to those with current kerosene. Concerning carbon emissions, electric motors and fuel cells do not emit anything except water, so the radiative impact with contrails remains to be evaluated. In summary, from Figure 5, the ATR 72-600 seems to be able to be retrofitted with fuel cells for limited distances, with technological advances allowing for rather good performances.

Regarding, the A320-200 aircraft, it is relatively much heavier that the ATR 72-600 and thus it needs more propulsive power, which implies therefore more fuel cells in the case of the electric architecture. PEM fuel cell systems have relatively high mass density at present, and therefore their performance might not be acceptable for this kind of aircrafts. Besides, according to the obtained results, the same is true for other hydrogen architectures: thermic or hybrid hydrogen/kerosene solutions have poor performances displaying short ranges, even though the environmental score aspect seems to be acceptable. Only with the improvement of technology performances in the near future, fuel cell architecture could be considered as an alternative solution. Besides, if volume appears to be the major limitation,

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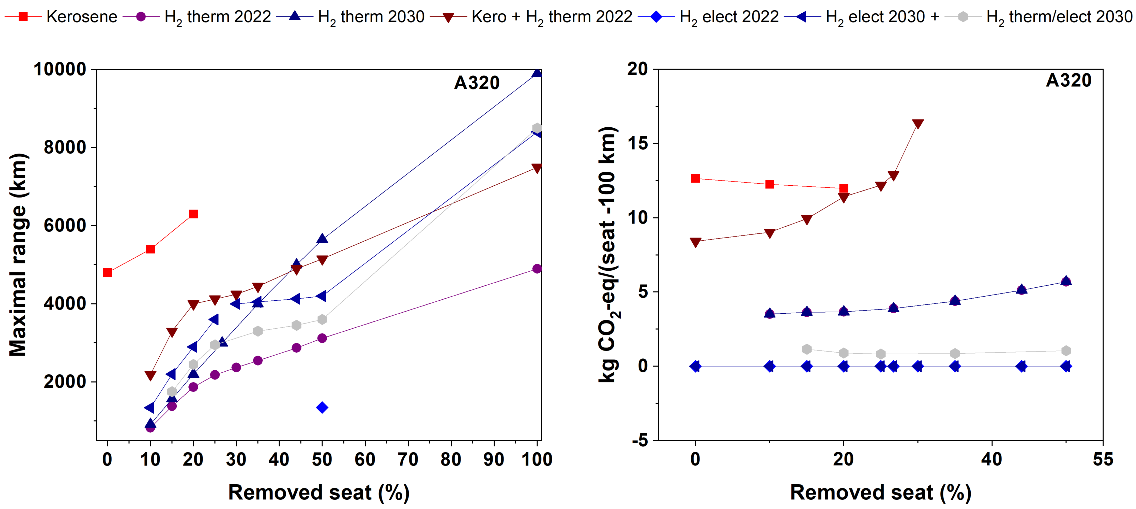

Figure 6: Simulation results on A320-200.

weight is also really crucial and it would be necessary to increase the maximum weight at take-off and landing (MTOW and MLM). This can be done by modifying the structure and landing gear.

Finally, preliminary results regarding the optimization study has been obtained, in order to better analize the compromise between CO_2 emissions and the technology type. The solution of the problem has been addressed through an evolutionary algorithm based on the decomposition paradigm (MOEA/D) using the augmented achievement scalarizing function (AASF), with a population of 300 individuals and a maximum number of generations of 10 000. In this work, a 1 000 km flight mission is considered for A320-200 aircraft. The obtained approximation of the Pareto front is shown in Figure 7. It is observed that solutions that promotes the use of hydrogen correspond to those that entail the lowest carbon emissions. Please note that total carbon emissions for the given flight mission are indicated.

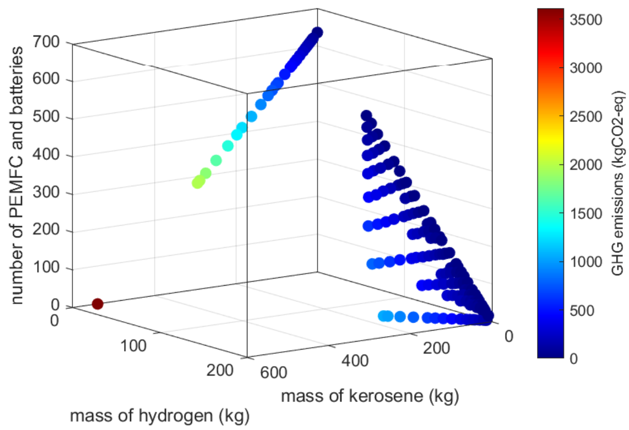

Figure 7: Preliminary results: Obtained approximation of the Pareto front for a given flight mission for A320-200 aircraft.

4. Conclusions and perspectives

In this work, MHyTech simulation environment has been presented with the aim to evaluate the feasibility of aircraft retrofitting for hydrogen-based technologies, with focus on weight and volume constraints, and this through the mathematical modelling of the system. The results obtained for commercial aircrafts show that compromise needs to be done namely in terms of amount of seats to be removed and/or reduction in aircraft range if implementation of hydrogen

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technologies is carried out. Moreover, the reduction of CO_2 emissions for each architecture can be easily quantified and compared to the current kerosene-based solution.

Regarding the perspective of this work, we envisage to further develop the model to estimate the carbon emissions integrating a life cycle assessment approach, as well as to integrate the take-off and landing phases.

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