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AIRCRAFT FLEET MODELS USING A BOTTOM-UP APPROACH FOR SIMULATING AVIATION TECHNOLOGICAL PROSPECTIVE SCENARIOS

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Abstract

Modeling prospective scenarios for aviation in the context of climate issues is a scientific topic of major interest. For this purpose, the development of models to integrate technological improvements in these scenarios is necessary. This paper focuses on the use of a bottom-up approach to establish aircraft fleet models, in order to integrate them into CAST, an open-source tool for simulating and evaluating prospective scenarios for air transport. These models are based on logistic functions which allow representing the gradual replacement of current aircraft by future aircraft architectures obtained from overall aircraft design. The efficiency improvement of the aircraft fleet can then be assessed. To illustrate the use of the models, some case studies, considering for example turboprop and hydrogen aircraft, are performed for analyzing efficiency scenarios for air transport. Also, the effect of accelerated fleet renewal and earlier introduction of new aircraft architectures is studied.

Keywords: Aircraft fleet modeling, Logistic function, Bottom-up approach, Prospective scenarios, Sustainable Aviation

Nomenclature

ASK	Available Seat Kilometers
ATAG	Air Transport Action Group
CAST	Climate and Aviation - Sustainable Trajectories
EIS	Entry-Into-Service
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
RPK	Revenue Passenger Kilometers
w.r.t	with respect to

1. Introduction

Due to climate change, the states that have ratified the Paris Agreement have committed to limit global warming well below +2°C above pre-industrial levels and to pursue efforts to limit the increase to +1.5°C [1]. As a consequence, these states have to mitigate their climate impact, in particular decreasing their CO_2 emissions in order to reach carbon neutrality.

Commercial aviation has a hybrid placement in this framework. Indeed, domestic flights are under the jurisdiction of states, while international flights are not. Aviation currently represents between 2 and 3% of CO_2 emissions, to which must be added non-CO_2 climate impacts such as condensation trails [2]. Various actors have committed to reducing CO_2 emissions. For instance, the International Civil Aviation Organization (ICAO) has committed itself to stabilizing the sector's CO_2 emissions by 2020 [3] when Air Transport Action Group (ATAG) aims at net-zero CO_2 emissions by 2050 [4].

Aviation is a hard-to-abate sector, which means it is difficult to decarbonize. Recent studies have focused on prospective scenarios specific to aviation concerning its CO_2 emissions [5] or more generally its climate impact [6, 7, 8]. These studies are performed using more or less open-source tools which make it possible to simulate and assess climate scenarios in terms of CO_2 and non-CO_2 effects, with regards to various levers of action such as the evolution of the air traffic level or technological improvements.

Technological levers of action to reduce CO_2 emissions are particularly studied in the scientific literature. First, the use of low-carbon alternative fuels, like hydrogen [9], biofuel [10, 11] or electrofuel [12], is considered to replace fossil kerosene. Secondly, improving the energy efficiency of the aircraft, through for instance propulsion or aerodynamics, reduce CO_2 emissions by minimizing energy consumption [13].

The integration of technological improvements in prospective scenarios is based on more or less complex models. On the one hand, top-down approaches make it possible to simply model the global trends of technological improvements. For instance, with this approach, the efficiency improvement of the aircraft fleet can be modeled with an annual gain, which can be estimated via historical trends or projections [6]. On the other hand, bottom-up approaches allows modeling more accurately technological improvements through its future characteristics. For example, with this approach, the efficiency improvement of the aircraft fleet can be modeled using estimated gains of the future aircraft architectures coupled with fleet renewal models [7]. Although more complex, this approach makes it possible to directly link prospective technological scenarios to detailed models of future aircraft architectures.

Some limitations can be noted on these different studies. Indeed, works based on simplified top-down approaches do not allow to easily make the link with aircraft design and overall aircraft design frameworks such as FAST-OAD [14]. Then, for bottom-up approaches, the categorization of the fleet is not always possible, which induces some limitations. For instance, some technological solutions will only be available for certain categories of aircraft, such as hydrogen which is initially planned for short and medium-haul aircraft. Moreover, the parameters used in the different approaches can be complex to manipulate for a user because they are not directly correlated to physical parameters such as aircraft entry dates or gains in fuel consumption compared to the previous generation. Also, the frameworks for simulating aviation prospective scenarios are often not accessible or partially, which makes it difficult to homogenize methods and models. Finally, the parameters used in the models can be complex to manipulate for a user because they are not directly correlated to real parameters such as aircraft entry dates or fleet renewal rates.

As a consequence, this paper proposes aircraft fleet models through a bottom-up approach adapted for simulating technological transition scenario for aviation, which allow modeling the integration of multiple aircraft architectures for different aircraft categories. An existing open-source framework for simulating prospective scenarios for aviation is updated with the bottom-up approach.

To this end, the paper is organized as follows. In section 2. the open-source platform used in this paper for simulating aviation prospective scenarios is detailed. Then, section 3. presents the developed bottom-up approach for modeling technological improvements taking into account aircraft fleet renewal. Different case studies are detailed in section 4. in order to apply the previous models through illustrative scenarios which are analyzed in terms of efficiency. Lastly, section 5. offers concluding remarks.

2. Methods and tools

This section introduces the open source platform used for simulating and evaluating prospective scenarios for aviation. The limits of this tool and the improvements targeted by this paper are detailed hereafter.

CAST (Climate and Aviation - Sustainable Trajectories) is an open-source platform developed in order to simulate and evaluate sustainable scenarios for aviation [15]. The architecture of the tool is briefly given in Figure 1. Thanks to input data and parameters, models from CAST allow drawing trajectories until 2050 for CO_2 emissions or effective radiative forcing for aviation. It also allows achieving an environmental analysis in terms of climate or energy issues. The different initial models used in CAST, briefly explained in the following, are detailed in [6].

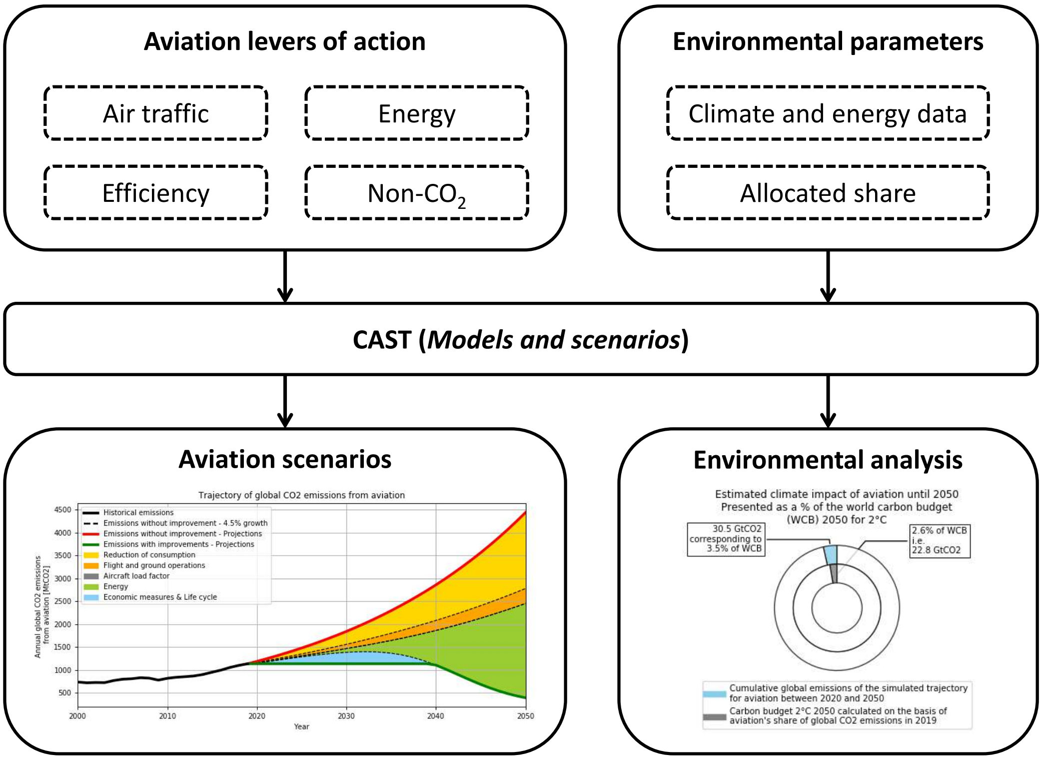

Figure 1 – CAST schematic diagram.

To model aviation scenarios, levers of action such as air traffic growth, fuel consumption efficiency or alternative fuels must be described. The evolution of air traffic is modeled using exponential functions whose parameters are adjustable by decade to take into account, for instance, the attenuation of the growth rate over time. The evolution of energy efficiency is determined using a top-down approach and is based on annual gains integrated in exponential functions. Finally, the integration of alternative fuels to replace fossil kerosene and strategies to mitigate contrails are modeled using logistics functions. This last type of functions is detailed in the next section.

Concerning environmental constraints, two major issues are considered. On the one hand, the availability of energy resources (electricity and biomass) are taken into account. Availability, obtained using scenarios from Intergovernmental Panel on Climate Change (IPCC) or International Energy Agency (IEA), is compared to the needs in biofuel, electrofuel and hydrogen estimated by CAST when analyzing aviation scenarios. On the other hand, climate constraints based on the concept of carbon budget are considered. This concept allows linking the remaining cumulative CO_2 emissions with the increase in average temperature [16]. The sustainability of a scenario can be analyzed by comparing an allocated carbon budget for aviation with the cumulative emissions due to a specific scenario for aviation. Moreover, specific methods for including non-CO_2 effects are also proposed.

One of the main limitations to these models concerns the top-down approach used to estimate the evolution of the fuel efficiency of the aircraft fleet. Indeed, this method does not allow to simply link CAST with aircraft design platforms. The effect of the integration of a new aircraft architecture cannot then be properly studied and assessed. Moreover, this approach makes it difficult for aircraft design specialists to use the tool, as they must estimate fleet renewal models by themselves. Finally, the categorization of the aircraft fleet is also made more difficult in this approach which standardizes the fleet and thus offers less freedom to build the future aircraft market. As a consequence, a bottom-up approach has been developed in order to solve this problem and is detailed in the following section.

3. Aircraft fleet models with a bottom-up approach

The objective of this section is to present the bottom-up approach developed for establishing aircraft fleet models which can be integrated into CAST. After defining the aircraft categories considered, the models used for the fleet renewal as well as their calibration thanks to aircraft data are detailed. Some examples are given to illustrate the use of this approach.

3.1 Categorization of the aircraft fleet

In order to accurately model the aircraft fleet, it is first necessary to define some representative aircraft categories. Indeed, some future aircraft architectures, like hydrogen or all-electric aircraft, may only be available on specific missions with a limited range.

Aircraft categories can be defined taking into account the range (short, medium, long-haul) or the type of aircraft (regional, narrow-body, wide-body). Here, the following categories have been considered:

- Short range: passenger aircraft that fly less than 1500 km;
- Medium range: passenger aircraft that fly between 1500 km and 4000 km;
- Long range: passenger aircraft that fly more than 4000 km;
- Freight: belly cargo on passenger aircraft and dedicated freighter aircraft.

Aircraft categories are heterogeneous because they include many types of aircraft for a given range. For estimating future efficiency improvements, representative aircraft types have to be selected. Here, it is assumed that the short-range category is composed of regional aircraft (with turbofan or turboprop) and narrow-body aircraft. It is assumed that medium-range category and long-range category only include narrow-body and wide-body aircraft respectively. Lastly, for freight category, no representative aircraft is selected and it is considered that the efficiency gains specific to this category are equal to the average gains of passenger aircraft categories.

3.2 Calibration method

The definition of these representative categories and aircraft types is useful for defining the average characteristics of the aircraft fleet. Before defining fleet renewal models, it is necessary to perform a calibration with the current aircraft fleet.

Firstly, the energy consumption needs to be estimated by category. These data are obtained using emissions factors from 2019 ICCT data [17] and presented on Table 1. Data are expressed per Revenue Passenger Kilometers (RPK) or per Available Seat Kilometers (ASK). It allows focusing on the characteristics of the fleet, leaving aside the influence of the air traffic. The conversion between emission factor and energy consumption is achieved considering a direct emission factor of $73.2\ gCO_2/MJ$ for the kerosene [18] and a mean aircraft load factor of 82.4% according to ICAO 2019 data [19].

Table 1 – Fleet characteristics in 2019.

Category	Emission factor [gCO_2/RPK]	Energy consumption [MJ/ASK]
Short range - Regional	172.8	1.95
Short range - Narrow-body	98.8	1.11
Medium range	76.9	0.87
Long range	89.9	1.01

Secondly, for each category, two aircraft representative of the fleet are considered: one for the old generation and another for the recent one. The representative aircraft characteristics are estimated using a mix of existing aircraft. Current figures about the number of aircraft in service and the average performance of these aircraft are extracted from ICAO databases, averaged over the range considered [20]. For instance, for the medium-range category, the old representative aircraft is a weighted mix between Airbus and Boeing aircraft (A319, A320, A321, B737-700, B737-800, B737-900) and the recent one is the Airbus A320neo. Results are given in Table 2.

Table 2 – Representative aircraft characteristics for medium-range category.

Aircraft	**Energy consumption [MJ/ASK]**	**Representative distribution in the fleet**
Mean aircraft	0.87	100%
Old aircraft	0.92	77%
Recent aircraft	0.70	23%

Lastly, for a category, the representative distribution of old and recent aircraft in the fleet, given in Table 2, are determined thanks to equation (1).

$$E_{mean} = xE_{old} + (1-x)E_{recent} \tag{1}$$

with E_{mean} the mean aircraft fleet efficiency per ASK, E_{old} the one for old aircraft, E_{recent} the one for recent aircraft and x the representative share of old aircraft in the fleet.

It is important to note that the representative distribution obtained is just a modeling because the aircraft market is more complex and includes a significant number of different aircraft.

With these data, it is possible to calibrate the aircraft fleet renewal models that are detailed hereafter.

3.3 Fleet renewal models and estimation of the aircraft fleet efficiency

For modeling aircraft fleet renewal into a category, logistic functions are used and presented in equation (2). These functions, also called “S-shaped” curves, are particularly relevant to model the integration of a product in a market [21]. As a consequence, they are used in economic, technological, medical or sociological fields [22, 23, 24]. Logistic functions have already been used in the scientific literature to study the renewal of aircraft fleets [25, 26, 7].

Logistic functions are expressed as:

$$f(x) = \frac{A}{1+e^{-k(x-x_0)}} \tag{2}$$

where A, k and x_0 are parameters which allow the model to be adjusted.

In order to use this function, a calibration of the different coefficients needs to be performed. The coefficient A represents the final value of the function. Its value is set to 100% to model the fact that, in the long term, a new aircraft architecture will constitute the entire fleet. Then, the coefficient k allows estimating the renewal speed or turnover rate of the fleet. It can be linked to the duration D for the replacement of $(100-l)\%$ of the fleet using equation (3). Lastly, the coefficient x_0 allows defining the timing of the aircraft's appearance. It can be calculated with equation (4) thanks to the apparition year x_a, which represents the Entry-Into-Service (EIS) year of the aircraft.

$$k = \frac{\ln\left(\frac{100}{l}-1\right)}{D/2} \tag{3}$$

$$x_0 = x_a + D/2 \tag{4}$$

An example is given in Figure 2 (left). The fleet renewal for a category is represented using the distribution of the aircraft fleet and the corresponding models. The previous calibration method is used considering for instance the medium-range category. It is assumed that a new aircraft appears each 15 years with a period of 20 years for a replacement of 98% of the fleet, which means $l = 2$.

A limitation of these basic models is that they can only be used for a single homogeneous category. Indeed, it is not possible to model a market that splits into two main aircraft architectures. However, this aspect is important for integrating specific competing aircraft, such as hydrogen-powered aircraft on short and medium-range category or narrow-body aircraft like the Airbus A321XLR on long-range category. As a consequence, models are adapted to create subcategories as needed. Logistic functions are also used and the coefficient A is adjusted to vary the different market shares within the whole category.
Another example is given in Figure 2 (right). The previous example with a simple renewal is considered. This time, a new aircraft, representing a specific new subcategory, appears in 2035 with the same renewal characteristics and will eventually represent 50% of the market in this category.

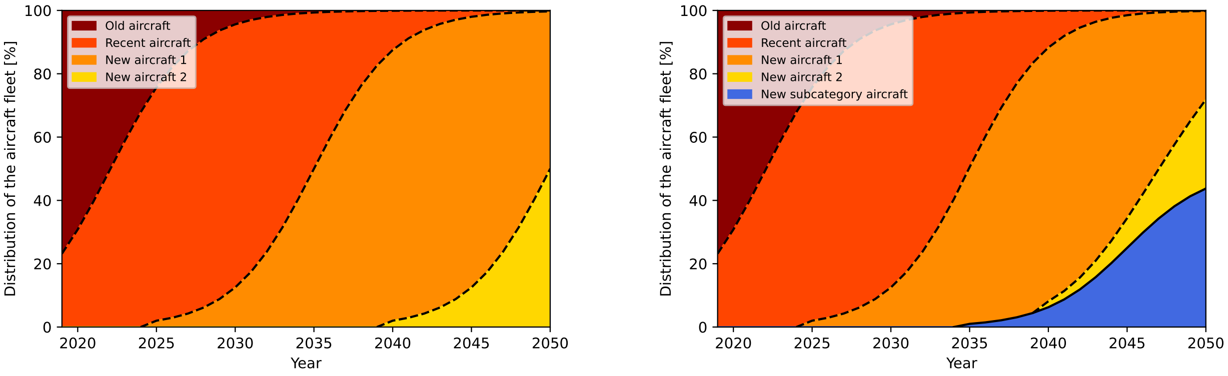

Figure 2 – Examples of aircraft fleet renewal models. Left: basic renewal every 15 years. Right: basic renewal every 15 years including the appearance of a subcategory.

Knowing aircraft fleet renewal, it is possible to estimate the mean aircraft fleet efficiency per ASK thanks to the characteristics of the different aircraft. Equation (5) gives E_{mean} the aircraft fleet efficiency per ASK for a given year thanks to the efficiency per ASK of the different aircraft E_i and the corresponding available seat-kilometer ASK_i depending on the given year. Here, the efficiency in terms of fuel consumption is considered. However, other parameters such as NO_x or particulate matter emissions can be used.

$$E_{mean} = \frac{\sum_i E_i \cdot ASK_i}{\sum_i ASK_i} \tag{5}$$

Also, these models can be coupled with other parameters to estimate for instance the CO_2 emissions of the fleet. It can involve the evolution of the air traffic via RPK, the load factor to calculate ASK or the carbon intensity of the energy used. Finally, it is possible to estimate the aircraft production and retirement knowing ASK and the coefficient which gives the number of ASK per aircraft.

3.4 A comprehensive example for the medium-range category

Thanks to the previous models, an example with medium-range category including subcategories is analyzed, using illustrative values. It is assumed that a new aircraft appears each 15 years inside a subcategory with a period of 20 years for a replacement of 98% of the fleet. The three subcategories considered, whose the distribution over year is given in Figure 3, are:

- basic narrow-body architectures with turbofan (named "Turbofan"), which represent all the market in 2020;
- regional architectures with turboprop (named "Turboprop"), available for medium range in 2030, which will represent 30% of the market;
- hydrogen-powered architectures (named "Hydrogen"), available for medium range in 2035, which will represent 20% of the market.

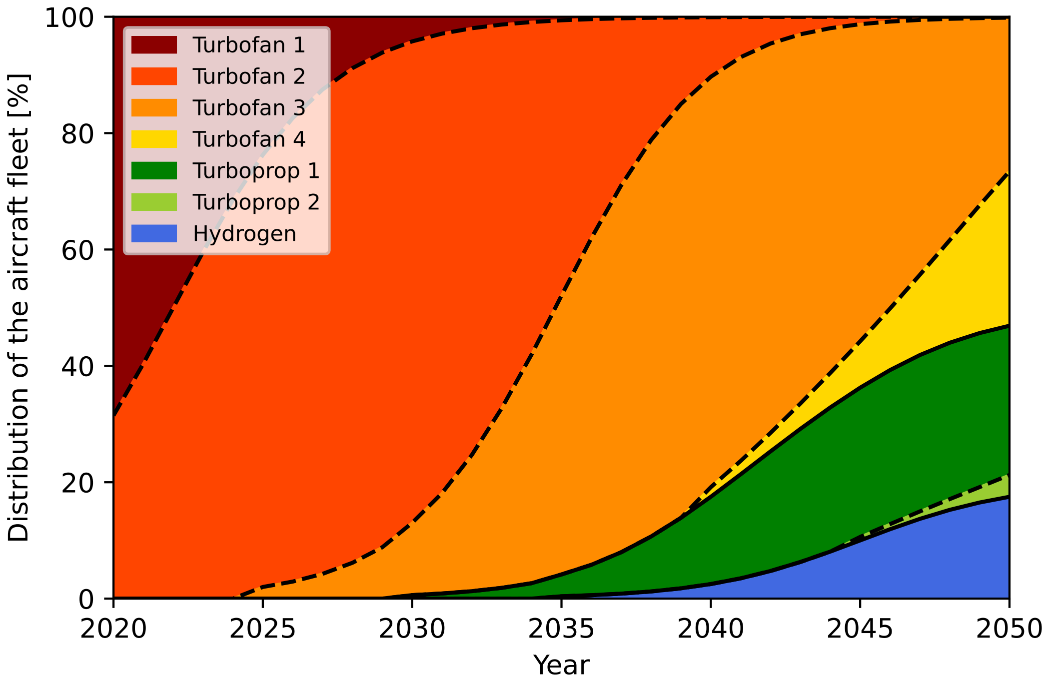

Figure 3 – Aircraft fleet renewal illustration for the medium-range category application.

The illustrative characteristics considered for the future aircraft are given in Table 3. It is assumed that turboprop architectures allow reducing energy consumption (at the cost of a lower speed and lower payload) but that hydrogen aircraft yield an increase of energy consumption due to constraints like tanks volume and mass.

Table 3 – Future aircraft characteristics of the comprehensive example.

Aircraft	EIS year	Compared energy consumption
Turbofan 1	-	+31%
Turbofan 2	-	Reference
Turbofan 3	2025	-15%
Turbofan 4	2040	-30%
Turboprop 1	2030	-25%
Turboprop 2	2045	-40%
Hydrogen	2035	+10%

Equation (5) is used to plot Figure 4. Historical data have been obtained using CAST data and assuming a proportionality between the energy consumption of medium-range category and that of all aviation. The red line provides the evolution of the energy consumption per ASK with the bottom-up approach. In comparison, two trajectories using a top-down approach are presented. The first approach is based on an exponential model considering a regular rate in order to equal the value obtained with the bottom-up approach in 2050, whereas the second one uses an exponential model considering this time the characteristics of the more efficient aircraft available in 2050. It is interesting to note the difference between the bottom-up and top-down approaches. The bottom-up approach allows a more accurate modeling based on aircraft design and fleet renewal. Particularly, the acceleration of fleet renewal or penalizing architectures such as hydrogen-powered aircraft make it more difficult to use top-down approaches. As an example, if a stagnation of ASK between 2020 and 2050 is considered, these approaches would lead to a difference in energy consumption of +6% for the first method and of -8% for the second one, compared to the bottom-up approach.

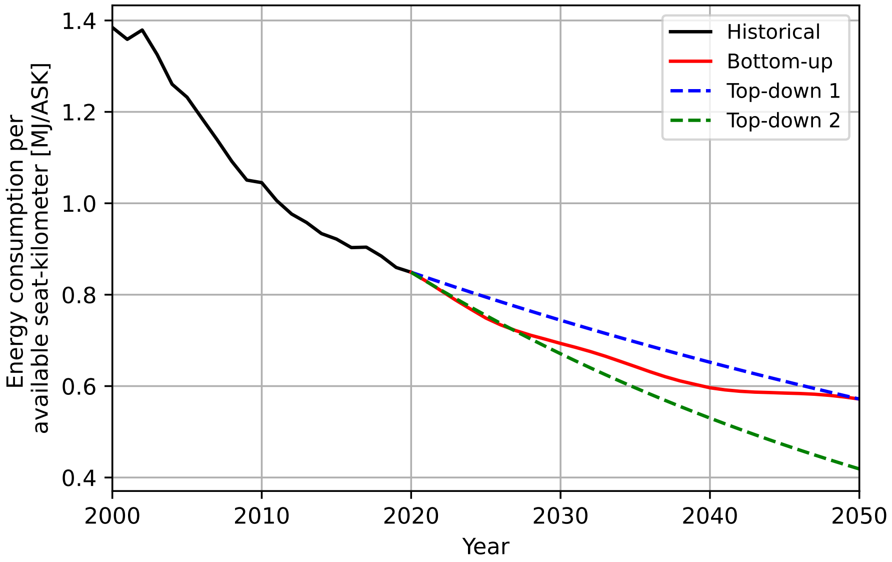

Figure 4 – Aircraft fleet efficiency for different approaches.

4. Applications and results

In this section, the models developed in this paper are used on medium-range category and results are discussed. After defining representative technological scenarios, the objectives are to assess the impact of different fleet renewal parameters and to estimate the impact of aircraft subcategories. Possible energy efficiency gains are provided between 2020 and 2035 and between 2020 and 2050. The method and models presented in this paper are used for all the results.

4.1 Representative technological scenarios

For defining representative technological scenarios, it is first necessary to detail the parameters required for setting a pathway.

Considering fleet renewal, the chosen parameters are based on the previous models developed in this paper. The following parameters are studied in this paper:

- EIS year of the aircraft: earlier commercialization or shorter time between aircraft development;
- Efficiency gains due to new aircraft: incremental technological gains or breakthroughs leading to significant improvements;
- Fleet renewal duration (for a replacement of 98% of the fleet): current (around 25 years) or improved renewal rate, requiring more aircraft produced.

In terms of aircraft subcategories, in addition to basic narrow-body architectures with turbofan, two additional subcategories are studied in this paper: hydrogen-powered aircraft and regional aircraft with turboprop extended to medium-range. A market share for each subcategory is then assumed.

Once the parameters have been defined, illustrative scenarios have been proposed based on academic, industrial and institutional data [27, 28, 29, 30] in order to study the sensitivity of the energy efficiency to the defined parameters. The values and the corresponding results are given in the next section.

4.2 Impact of fleet renewal characteristics

The results of the sensitivity analysis on fleet renewal parameters are provided in this section. In this section, only the initial narrow-body subcategory is studied.

Representative scenarios are given in Table 4. Each scenario includes two types of aircraft, defined by an EIS year and a value for the efficiency gain given with respect to the recent representative aircraft (A320neo). A reference scenario is proposed and other scenarios are defined with respect to (w.r.t) this one by improving the efficiency gain, or by bringing forward the EIS, or by a combination of the different improved parameters. For each scenario, two fleet renewal duration are considered in order to study the impact of this parameter.

Table 4 – Fleet renewal scenarios for medium-range category and resulting energy efficiency gains in 2035 and 2050.

	First aircraft		Second aircraft		Results for 25-year fleet renewal		Results for 15-year fleet renewal	
Scenarios	EIS year	Efficiency gains (w.r.t representative recent aircraft)	EIS year	Efficiency gains (w.r.t representative recent aircraft)	Gains in 2035 (w.r.t 2020 mean fleet)	Gains in 2050 (w.r.t 2020 mean fleet)	Gains in 2035 (w.r.t 2020 mean fleet)	Gains in 2050 (w.r.t 2020 mean fleet)
Reference	2030	15 %	2045	30 %	18,7%	30,4 %	19,8 %	32,3 %
Increased gains	2030	20 %	2045	40 %	19 %	34,5 %	20,7 %	37,3 %
Earlier EIS	2028	15 %	2040	30 %	19,5 %	33,7 %	22,6 %	39,4 %
Breakthrough	2030	15 %	2045	50 %	18,7 %	31,9 %	19,8 %	35,8 %
Combination	2028	20 %	2040	50 %	20,1 %	41,4 %	24,4 %	53,3 %

The study of the scenarios with the models of this paper gives the mean efficiency gains for the fleet in 2035 and 2050 compared to 2020 (Table 4). The efficiency gains of the fleet renewal with the first and second aircraft are given with respect to the representative recent aircraft whose characteristics are stated in Table 2. It is interesting to note that the combination of all the improved parameters leads to important efficiency gains both in 2035 and in 2050 in comparison to the reference scenario. Moreover, the introduction of a breakthrough aircraft has only a delayed effect due to its late appearance, which does not allow a rapid change in the aircraft fleet energy intensity in the short term. Lastly, even if all the levers have significant impacts, selecting which ones to focus on is complex. For instance, while improving the efficiency of new aircraft and advancing the EIS year are limited by technology, accelerating the deployment of new aircraft in the fleet depends on production constraints.

4.3 Impact of aircraft subcategories

The results for the impact of aircraft subcategories are given in this section.

4.3.1 Introduction of turboprop aircraft

On the one hand, the introduction of turboprop aircraft is studied. In this case, a study is achieved concerning the effect of the market share dedicated to these aircraft. Indeed, turboprop is limited in terms of speed and power. As a consequence, illustrative market share considered in this paper are 0%, 20% and 50%, the rest being provided by conventional narrow-body architectures. For narrow-body subcategory, the reference scenario presented in the previous section is considered. Concerning turboprop aircraft, a first aircraft is forecast in 2028 allowing efficiency gains of 15% in comparison to the recent representative aircraft. Moreover, a second one is forecast for 2040 considering an efficiency gain of 40%. Lastly, a 20-year fleet renewal is assumed.

Results are given in Figure 5. Increasing the market share for turboprop marginally improves the mean fleet efficiency. For instance, the scenario without turboprop allows a reduction of fuel consumption of 31.4% in 2050 compared to 2020 whereas the scenario with half of turboprop allows a reduction of 35.9%. By studying the potential gains for the short-range category, the gains would be greater because of better comparative performance, particularly in comparison with regional turbofan.

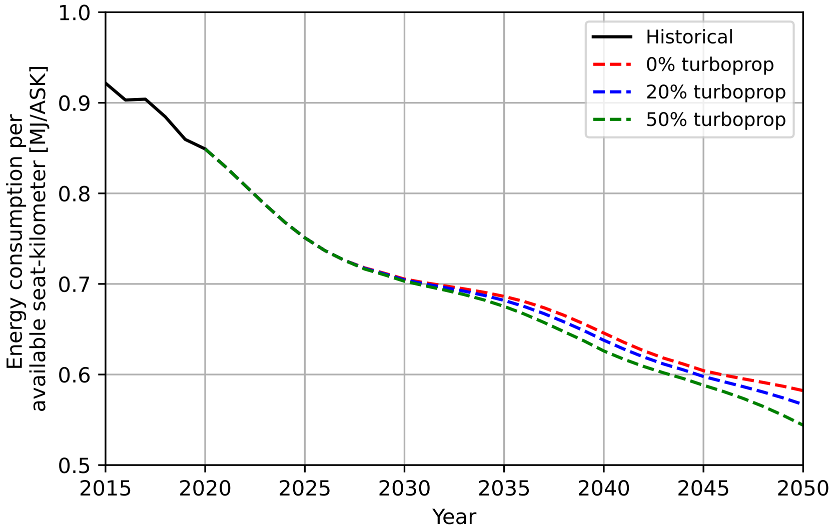

Figure 5 – Aircraft fleet energy efficiency depending on turboprop introduction in the market.

4.3.2 Introduction of hydrogen aircraft

On the other hand, the introduction of hydrogen aircraft is studied. In this case, the study is achieved for different efficiency performance of hydrogen aircraft. Indeed, uncertainties remain on the performance of a future hydrogen aircraft, the fuel occupying a larger volume but being less heavy. As a consequence, based on extreme values from literature [31], three levels of performance in comparison with aircraft of the same generation are considered: an efficiency improved by 10%, a similar efficiency and an efficiency degraded by 22%. It is assumed that the EIS year of this aircraft is 2035 and that it will represent 80% of the market. The rest of the market is conventional narrow-body aircraft and the reference scenario presented in the previous section is considered for this subcategory. Lastly, a 20-year fleet renewal is assumed.

Results are given in Figure 6. In the pessimistic scenario, the energy performance of the fleet could decrease. However, despite this aspect, the performance in terms of CO_2 emissions could still be improved if the hydrogen used is low-carbon.

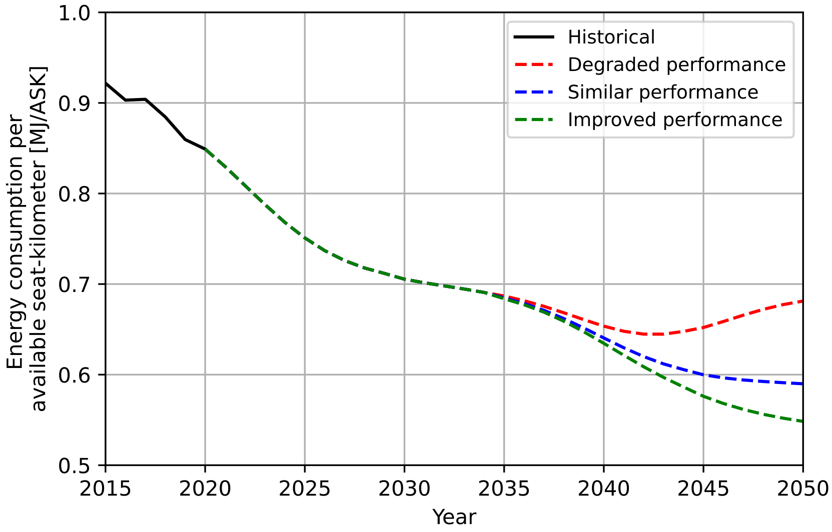

Figure 6 – Aircraft fleet energy efficiency depending on hydrogen aircraft efficiency.

5. Conclusions

In this paper, aircraft fleet models based on a bottom-up approach are developed and integrated into CAST, an open-source tool for simulating sustainable prospective scenarios for air transport. The specific models are used on technological prospective scenarios for aviation in terms of efficiency. Some examples and applications are given considering the aircraft medium-range category.

After introducing CAST and the need to develop aircraft fleet renewal models for estimating the fleet energy consumption evolution, the specific method is detailed. The fleet is divided into categories and data calibrations using representative aircraft are performed. Logistic functions are used for aircraft fleet renewal models and allows estimating the future energy consumption of the fleet. A comparison with the initial method used in CAST, a top-down approach based on constant annual gains, is achieved. The bottom-up approach allows an accurate simulation of the fleet efficiency evolution.

In terms of results, the models enable to assess the benefits on the fleet efficiency evolution of different levers of action: earlier EIS year, development of more optimistic efficient aircraft, and shorter fleet renewal periods. Also, the effect of increased market share of relatively more efficient architectures like turboprop aircraft is evaluated. Finally, in the case of new hydrogen aircraft architectures for which fuel consumption is uncertain, the fleet efficiency evolution is estimated for different efficiencies. Even with increasing fleet energy consumption, a reduction of CO_2 emissions is possible if the hydrogen is produced in a "clean" way.

This work could be complemented by additional studies. First, these models could be improved by calibrating correction factors with historical fleet efficiency values, despite the difficulty in obtaining complete data on the fleet and the many aircraft that are used. Then, other technological scenarios could be studied. On the one hand, the efficiency scenarios could be completed and extended to other aircraft categories and a regionalization could be studied. On the other hand, analyses could also be carried out on the scenarios of introduction of low-carbon alternative fuels, with specific models used in CAST. Last, but not least, an assessment of the sustainability of these scenarios, coupled with assumptions on other levers of action (low-carbon fuels, mitigation strategies of contrails, evolution of air traffic...), could be conducted from a climate (CO_2 and non-CO_2) and energy point of view using the CAST tool.

6. Supplementary materials

CAST is available online at `https://cast.isae-supaero.fr/`.

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8. Copyright Statement

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