AN EMPIRICAL AND CUSTOMISABLE FLEET RENEWAL MODEL FOR PROSPECTIVE SCENARIOS USING OPEN-ACCESS DATA

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Abstract

Rapid and radical action is needed to decarbonise air transport. Developing new, more efficient aircraft architectures is part of the solution to this challenge. However, maximising the efficiency gains associated to these new aircraft requires focusing on fleet renewal strategies. The strategies depend on technical, operational, and economic logics, and are uncertain at the global scale. Modelling fleet renewal and its impact on global efficiency is therefore crucial. Current fleet renewal models face several limitations such as the isolation of renewal efficiency levers, or the representation of retirement heterogeneity. This paper proposes a new model for studying different fleet renewal scenarios on a segment (e.g. narrow-bodies). It combines a push fleet model with a statistical module to handle the empirical heterogeneity of retirements. This approach is then applied to an open-access fleet database, on narrow-bodies. Based on this new model, we estimate the combined environmental benefits of a higher renewal rate and a lower production delay for new aircraft generations. We also estimate the fuel savings that could be achieved with better prioritisation of aircraft retirements (2.5%) and deliveries (1.5%).

Keywords: Air transport system; Prospective decarbonisation scenarios; Fleet renewal models; Production ramp-up; Renewal prioritisation

1. Introduction

Despite continued improvements in aircraft efficiency over the last decades, air transport greenhouse gases emissions have continued to trend upwards. For instance, before COVID-19, CO_2 emissions were 34.7% higher than in 2013 [1, 2]. Overall, the contribution of aviation in total anthropogenic CO_2 emissions is estimated at 2.4% in 2018 [3]. Besides, non-CO_2 effects are also responsible for an overall warming effect despite more uncertainties on its exact value [3]. The total contribution of aviation on effective radiative forcing is thus estimated at 5.1% [4] for the period 2000–2018.
Air traffic is expected to grow in the next few decades in most global prospective scenarios. For instance, Airbus Global Market Forecast forecasts a 3.6 % Compound Annual Growth Rate (CAGR) for the next two decades [5]. Such a sustained increase in traffic would offset the improvement in fleet efficiency due to renewal, and raise aviation's contribution to global warming to even higher levels [4]. To reverse this trend, several actors such as airlines aimed at net-zeros targets, through the voice of IATA [6]. This level of ambition requires the use of all available levers of action, including further improving energy efficiency, up-taking low-carbon fuels as well as improving operations. Yet, offsetting, carbon capture or demand management would still be necessary.
While setting a long-term target is an important policy-driving tool, the pathways to achieve the target are more meaningful from a climate change perspective. The total cumulative CO_2 emissions along the pathway can be compared to carbon budgets, which are total cumulative emissions allowed to respect given climate targets in terms of temperature. The remaining carbon budget to stay below 1.5℃ of warming with a 67% likelihood of success is estimated at 400 Gt [7], starting in 2020. Depending on the transformation path taken, international air transport would use between 4.1% and 11.3% of this budget until 2070 [8].

In this context, various stakeholders are elaborating prospective scenarios to assess the climate relevance of different decarbonisation strategies. It includes both academics [9, 10, 11, 12, 13, 14] and industrial stakeholders [15, 16]. This work itself is part of the ongoing development of AeroMAPS, an open-access prospective scenarios simulator [17].

Further improvements in aircraft fuel efficiency are one of the most sought-after levers for decarbonising aviation. For example, higher bypass ratio engines, laminar wings, weight savings or the electrification of several systems are expected to preserve the established trend of efficiency improvements [4]. Breakthrough concepts such as the blended wing body or the hydrogen-powered aircraft are also being explored by both academia and industry [18, 19, 20]. However, as aircraft generally have a life span of 20-30 years, innovations slowly make their way into the fleet. What's more, fleet renewal represents a high investment cost, making it a key strategic issue for airlines. Various strategies can be envisaged, so it is essential to explore the dynamics of fleet evolution and its environmental impact in a prospective scenario simulator such as AeroMAPS.

For now, AeroMAPS captures the impact of new architectures for a given scenario using a simplified top-down approach based on annual efficiency gains, or a bottom-up approach based on fleet renewal models using logistic functions [21]. This approach was also used in [9]. The AeroMAPS fleet model uses main aircraft characteristics (e.g. entry-into-service year) and penetration rates but does not rely on a tangible description of aircraft flows (production and retirements). For this reason, it is not adapted to easily perform validity checks in terms of deliveries and retirements, or simulate unconventional scenarios.

In order to improve the fleet modelling in AeroMAPS, three main requirements guided its design:

- to be economically realistic,
- to be adapted to capture the global determinants of fleet renewal efficiency,
- to be calibrated on data, but versatile enough to explore disruptive scenarios.

Based on these criteria, possibilities for setting up a relevant theoretical approach were explored. Founding the fleet model on tangible variables (delivery rates, retirement laws) is valuable because it provides a direct interpretation of the results and allows easy coherence checks. More importantly, it can encode an economic/physical logic that makes the model more versatile to represent new situations (see Section 2.4 for an example). This approach is used in the work of Dray *et al.* [22, 23], and Kuhlen *et al.* [24]. The proposals made by Dray *et al.* are implemented in AIM2015, an aviation integrated assessment model. This project incorporates an open-access fleet model that predicts the evolution of the fleet based on assumptions on the retirement of individual aircraft. More specifically, it uses the distribution of age at retirement adjusted on historical data. Kuhlen *et al.* [24] also uses a tangible description to deduce retirements from deliveries. A key distinction between these models is that AIM2015 derives deliveries from retirement hypotheses, whereas Kuhlen *et al.* deduce retirements from delivery assumptions. For this reason, Kuhlen *et al.* qualify their methodology as *push*. In contrast, the AIM2015 model could be qualified as *pull*. These two logics are schematised in Figure 1. Here, and throughout this paper, productivity is defined as the number of ASKs an aircraft produces per year. The variable can be seen as exogenous to the aircraft (correlated to the airline practices regarding the optimisation fleet's utilisation, or with the average flight leg), or endogenous to the aircraft types (related to the technical features of the aircraft such as speed and maintenance).

Retirements are not industrially constrained so are more flexible in the short term than deliveries. Also, traffic levels can be considered exogenous as stored aircraft can be operated to respond to an unexpected surge in demand. For these reasons, in the short term, the operation of old aircraft should be determined by the traffic and delivery rates [25]. This observed economic logic is represented by the *push* model but not by the *pull* one. Furthermore, the *pull* model is not well suited to isolate the efficiency determinants of fleet renewal. *Pull* models use the age at retirement as a decarbonisation lever. If early retirements lead indeed to improved fleet efficiency on average, there are exceptions. To illustrate this point, let's consider an aircraft that is scheduled to be withdrawn in 2034 while a new generation of aircraft will appear in 2035. In the long run, it is more efficient not to retire the aircraft for one additional year as it allows the renewal to be done with the efficiency gain brought

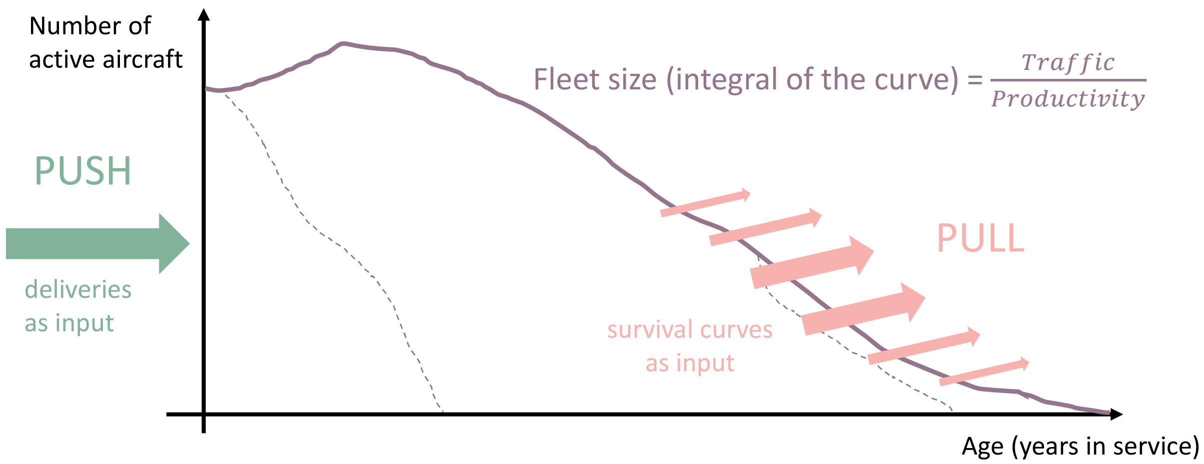

Figure 1 – Illustration of *push* and *pull* paradigms. Different aircraft generations are distinguished with the dotted grey lines.

by the new generation. This would result in the underestimation of the efficiency of fleet renewal by *pull* models. To test aggressive renewal strategies, the *pull* models decrease the age of retirement. Nevertheless, doing so raises questions about the realism of the transition. Instantly switching from 25-year-old retirements to 20-year-old retirements implies a steep transition period which would require an unrealistic ramp-up in delivery numbers. This leads to non-feasible fleet trajectories.

To improve *pull* models and for more general purposes, there are contributions to renewal criteria that are based on an economic aircraft-valuation approach, using estimated net present values [26, 27, 28]. Generalised with a dynamic component, these additional model components would capture the inefficiency of retiring an aircraft one year before the issue of a new generation (as in the above example). It would also enable the identification of cost-optimisation strategies for various airlines. However, generalizing this individual logic without industrial constraints would also lead to unrealistic results. This would mean that most aircraft would have to be produced in the year they became available.

For these different reasons, the *push* method, which relies on macro-level delivery assumptions, seems to be the most relevant approach to account for industrial constraints. However, *push* models may struggle to capture retirement heterogeneity. Kuhlen *et al.* highlight that their modelling approach group the retirements of similar aircraft. However, the heterogeneity of retirement is real and has implications for fleet economics, environmental performance, and Original Equipment Manufacturers (OEMs) aftermarket strategies.

This paper presents a new hybrid approach, combining a straightforward *push* model with a statistical module capable of representing heterogeneous retirements. These two blocks are employed to construct prospective scenarios for the narrow-body (NB) segment, which includes common aircraft such as the A320 or the B737. This work aims at overcoming the previous limitations of AeroMAPS by calibrating the models on individual aircraft renewal data and by using a renewal model making delivery and heterogeneity of retirements hypotheses rather than hypotheses directly on the shares of each generation.

The paper is organised as follows. Section 2. describes the methods, resources and models used. Section 3. presents the results of a case study that employs the *push* model to demonstrate the impact of temporality in aircraft production. In Section 4. it is then combined with the retirements heterogeneity module to characterise the environmental efficiency limit of fleet renewal and to study the environmental contribution of prioritising retirements and production towards respectively less and more efficient aircraft. Concluding remarks and prospects for future works are given in Section 5.

2. Methods and tools

This section details the main methods and models developed in this paper. First, the Planespotters database is presented. Then, the *push* model is described. A focus on a statistical model for aircraft retirements is also proposed. Finally, simulations with the heterogeneous *push* model are exposed and put in perspective with the AeroMAPS current model.

2.1 Planespotters open-access fleet dataset

The models proposed in this paper are calibrated with an open-access fleet database: Planespotters [29]. The version used in this paper was made available by the website on the 17th of January 2023. As this section will show, the Planespotters dataset has some limitations, so this paper uses a commercial database for some analyses when specified.

2.1.1 Description of the dataset

Planespotters dataset includes more than 60 aircraft types and describes with accuracy the current fleet. An extract of the database is given in Table 1.

Aircraft Type	Engine Type	Operator	Status	Delivery	Age
Airbus A319-100	CFM56-5	Jet Midwest Group	Scrapped	2001-12-01	14
Airbus A319-100	CFM56-5	AerCap	Stored	2001-12-01	21.2
Airbus A319-100	V2500	American Airlines	Active	2001-12-01	21.1
Airbus A319-100	CFM56-5	Air France	Active	2001-12-01	21.1
Airbus A319-100	V2500	United Airlines	Active	2002-01-01	21

Table 1 – Extract of the fleet database. More columns are available but not used for this project.

Planespotters constitutes a historical list of production dates and retirement dates for each aircraft recorded. This database can be used to reconstruct the history of the fleet, as shown in Figure 2 for the NB fleet. Here, NB aircraft are distinguished by engine type, as there are fewer engine types than aircraft types in the database, and because the engine is a correct indicator of the aircraft's technology. This dataset is reliable for new aircraft but is insufficient for old aircraft. To illustrate this, in Table 2, a comparison was made between the total NB aircraft from the Planespotters database, and the total number of NB aircraft extracted from Figure 11 in Morell and Dray [30], using Webplotdigitizer [31]. It was observed that part of the lack of completeness of the data comes from the absence of some aircraft types. For instance, they are lacking the Boeing 707 aircraft, SE Caravelle aircraft, and some freighters. The aircraft delivery data is of great quality starting from 1985 (see for instance Table 3). The production dates seem trustworthy, but for around 20% of the remaining aircraft, there are inaccuracies in the retirement dates. This is because Planespotters writes as "stored" aircraft that have not been active in decades. It is hard to discriminate these and temporally stored aircraft especially because we received the dataset at the end of COVID. This is why, in the heterogeneity of retirements analysis, "parked" and "stored" aircraft are not considered. Also for this reason, the number of old aircraft may be overestimated in the historical evolution of the fleet.

Date	1960	1970	1980	1990	2000	2007
Aircraft quantity from PP	124	890	1 397	3 318	7 004	10 508
Approximate aircraft quantity from [30]	340	3 930	7 150	9 880	12 650	14 110

Table 2 – Comparison between Planespotters (PP) dataset and the one used in Morell *et al.*

Planespotters sometimes lacks completeness. To address these limitations, it is possible to duplicate the analysis with a database with a similar structure to Planespotters (CIRIUM, OAG, The Airline Analyst, Airfleets...). Nevertheless, interesting analysis can already be performed with Planespotters.

2.1.2 Delays of production

The earlier an aircraft is delivered to the market, the greater the fuel savings that can be achieved. Quantifying the potential fuel savings behind this intuitive phenomenon requires two steps:

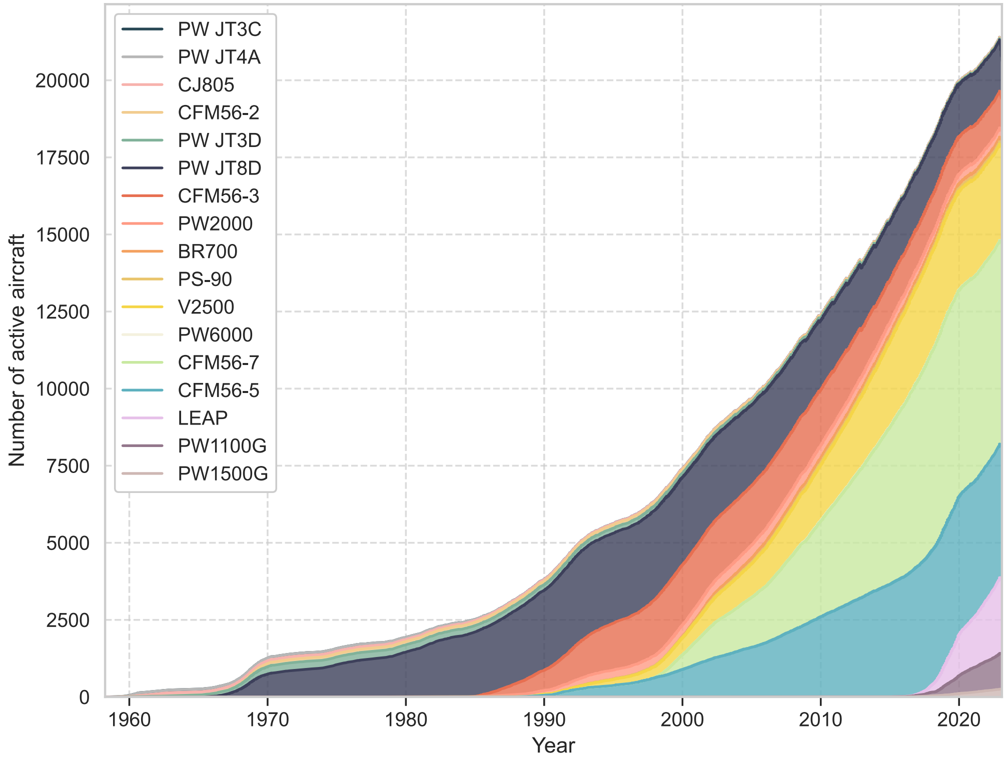

Figure 2 – Evolution of the NB fleet per engine type, according to Planespotters. The precision is best for aircraft produced after 1985.

- measuring the historical delays,
- linking these delays to the long-term environmental performance of the fleet.

Planespotters allows a correct estimation of the mean interval between the advent of technology and the manufacturing of aircraft models. Figure 3 illustrates the phenomenon for the top 5 NBs ever produced, no longer produced, and present in the Planespotters database. It is striking that most aircraft tended to be built more than a decade after the technology was developed. To temper this analysis, it is important to highlight that aircraft at the start of production differed from those at the end, as there were incremental efficiency improvements throughout the production period.
Now that the typical production delays of the past have been quantified, it is necessary to connect the delay of production rates to the intertemporal environmental efficiency of the NB segment. The timing of deliveries is not a controllable variable in *pull* models, so it is required to use a *push* model.

2.2 Fleet renewal model based on a *push* approach

2.2.1 Theoretical model

A simple *push* model is presented here. The logic is similar to the one presented by Kuhlen *et al.* [24, 32], but on a segmented market. As explained before, a *push* model supposes that the global amount of retirements results from the volume of deliveries and the fleet size (related to traffic and productivity evolution), rather than from direct ageing mechanisms.
The main inputs of the model are D_t the deliveries, and F_t the number of aircraft needed to serve the traffic for each period t. This variable depends on the level of traffic at date t and the average productivity of the fleet. R_t the number of retirements are deduced from these variables.
To mathematically express the relationships between these variables, two assumptions are required:

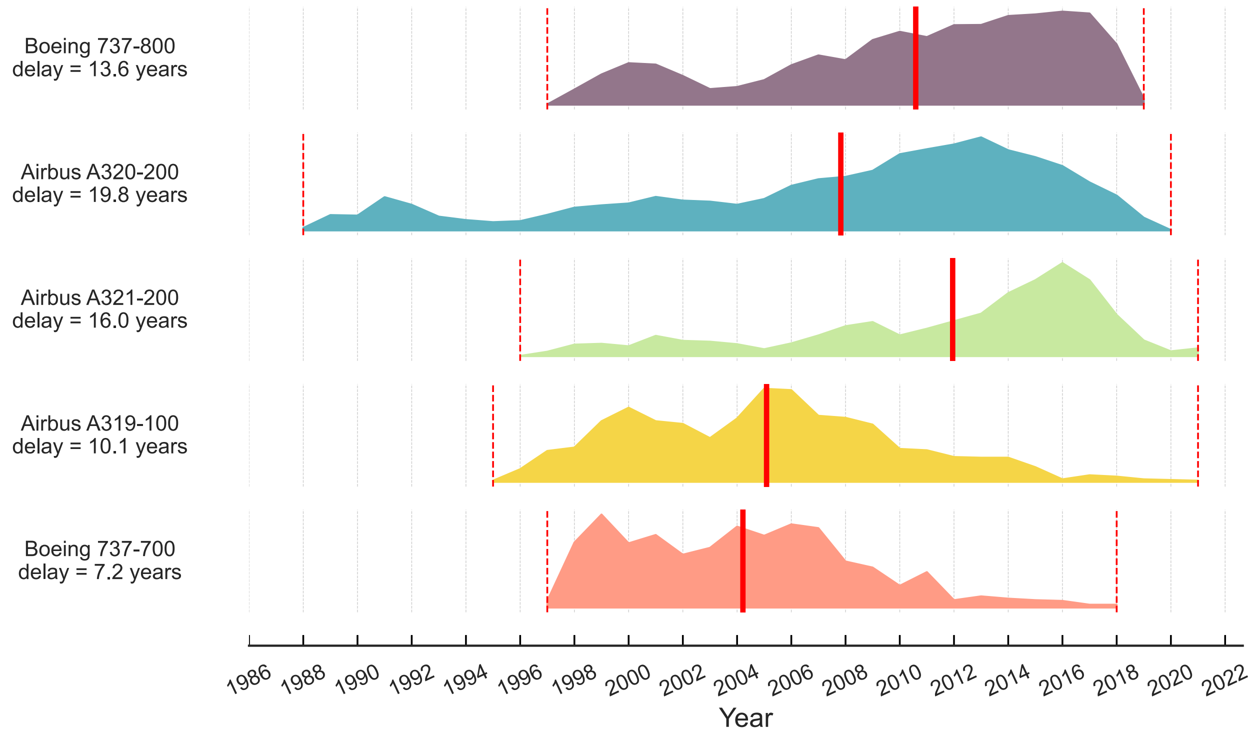

Figure 3 – Relative production profile of top 5 produced NB, mean delay of production (continuous red lines), Planespotters data.

- This version of the model assumes that the planes have homogeneous productivity. Without this hypothesis, the model can be adapted by counting ASKs needed for the production year and converting this number to production volumes depending on the aircraft characteristics. Even then, the relative productivity of different aircraft must be independent of time.
- It is assumed that there is only one aircraft type (with different generations) per segment. If one wants to introduce several aircraft types simultaneously, more segments must be created.

Hence, on the considered segment, the number of aggregated retirements can be simply expressed, as shown in Eq. (1).

$$F_t = F_{t-1} + D_t - R_t \;\Leftrightarrow\; R_t = F_{t-1} - F_t + D_t \tag{1}$$

This formula can lead to negative retirements in the case of very high growth after an event like COVID-19. The issue can be fixed by cancelling retirements in the case where an aircraft is needed in the future (because the recovery would be faster than the deliveries). A general formula, given in Eq. (2), allows taking into account this anticipation phenomenon. More details are provided in Appendix A.1. In this situation, the number of aircraft stored at date t can also be theoretically expressed.

$$\overline{R}_t = \min_{u \geq t} \left(F_{t_0-1} - F_u + \sum_{i=t_0}^{u} D_i \right) - \min_{u \geq t-1} \left(F_{t_0-1} - F_u + \sum_{i=t_0}^{u} D_i \right) \tag{2}$$

2.2.2 Choice of deliveries and retirements

The *push* model calculates a macro-equilibrium between the exogenous number of deliveries and level of traffic, and the endogenous number of retirements. For a given set of inputs, it remains necessary to choose the ventilation of deliveries between aircraft generation, and the ventilation of the deduced retirements between aircraft generations and years of production.
To investigate this point, Planespotters was used to extract the historical ventilation of deliveries and retirements between aircraft generations and production years (Figures 4 and 5). Here the different

NB engines were separated into three generations (Table 6 in Appendix B). This classification is derived from the date of entry into service of the engines. It could be improved, especially concerning "old" and "medium" engines. Also, Planespotters data is not exhaustive, particularly concerning aircraft produced before 1985. This means that the absolute values of these series (especially the retirements because they are older aircraft and can be omitted when the aircraft is categorised "stored" in the database) should be taken with caution.

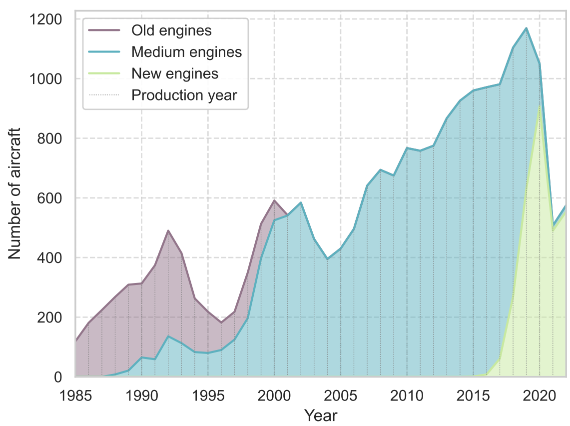

Figure 4 – Distribution of introductions per engine group and production year, Planespotters data.

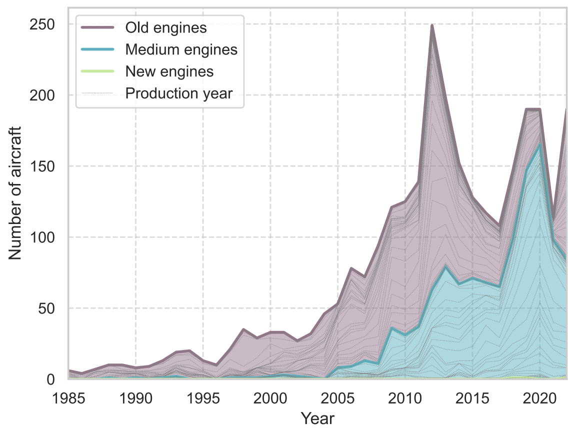

Figure 5 – Distribution of retirements per engine group and production year, Planespotters data.

The distribution of deliveries (Figure 4) is a relatively straightforward process because, by definition, there is only one production year per year. Thus, only assumptions about the share of aircraft generations are required. For instance, one can use a parameter for a linear transition from 100% of the old generation produced to 100% of the new generation produced.
It is more challenging to distribute the retirements between generations and manufacturing years. Indeed, there are plenty of manufacturing years and generations that are simultaneously retired (Figure 5). Furthermore, there are population effects which make aircraft produced in greater quantities more likely to be retired. To solve this issue, Kuhlen *et al.* [24] equally distribute the retirements on the leftover aircraft obtained after an endogenous allocation method based on an optimisation problem. Because it derives from an optimisation, this approach provides little heterogeneity: it would be equivalent to retiring only the oldest generation or the oldest aircraft. An alternative method, based on a statistical measure of the heterogeneity of retirements, is suggested in the following.

2.3 Statistical model to include and measure retirements heterogeneity

According to Planespotters, it took 15 years to completely shift production from "old" engines to "medium" engines, while it took more than 20 years to shift retirements from "old" engines to "medium" engines. More heterogeneity was observed in retirements than in production. Nevertheless, the heterogeneity of production is expected to have a greater environmental impact as it concerns aircraft that will be operated for more than 20 years in most cases, compared to old aircraft that will be operated for a few years.
Although the Planespotters dataset is incomplete and occasionally inaccurate, it is sufficient to demonstrate the following environmental inefficiency: the aircraft produced (retired respectively) is not always the most (least respectively) efficient.
What global efficiency gains can be expected from improved prioritisation at retirement? To explore this, a statistical module was built. This module can be calibrated on historical fleet data and used in prospective models, regardless of the volume of deliveries.

2.3.1 Theoretical model

Here we introduce a measure of the heterogeneity of retirements, to address this issue independently of the issue of the volume of retirements. The idea is to create a relative propensity to retirement. This

characteristic can then be used to allocate the retirements to aircraft according to their historical or expected relative propensities to be retired.
The issue of the volume of retirements can be reformulated as the question of the temporality of retirements. This means that for the heterogeneity to be independent of the volume, every aircraft's relative propensity of retirement must be independent of the time. This hypothesis has its limits, but is necessary for the topics to be tackled independently.
The relative propensity function was constructed to be compliant with this rule: if A is twice more likely to be retired than B, and if B is twice more likely to be retired than C, then A is four times more likely to be retired than C. We wanted our variable to have an impact in terms of the relative probability of being retired. Therefore, an exponential form for the relative propensity was chosen.
Aircraft are classified through their model i and their year of production j. The relative propensity of retirement for this aircraft type, noted $rp_{i,j}$, can be written with Eq. (3), with $\alpha_{i,j}$ a coefficient for this aircraft type.

$$rp_{i,j} = e^{-\alpha_{i,j}} \tag{3}$$

The relative propensity of retirement characterises the relative probability of retirement for individual aircraft. If $F_{i,j,t}$ represents the number of active aircraft of type (i,j) at date t, Eq. (4) allows to calculate the probability $P_{i,j,t}$ that an aircraft type (i,j) is retired given that an aircraft is retired in the fleet at date t.

$$P_{i,j,t} = \frac{F_{i,j,t} \times \; rp_{i,j}}{\sum_{m,n} F_{m,n,t} \times \; rp_{m,n}} \tag{4}$$

Let's write $s_{i,j,t} = F_{i,j,t}/F_{i,j,t_0}$ the share of active aircraft for one aircraft type (i,j). In this case, $s_{i,j,t}$ for one aircraft type (i,j) can be connected to another one (k,l) through Eq. 5. The calculation details are provided in Appendix A.2.

$$s_{i,j,t} = s_{k,l,t}^{exp(\alpha_{k,l} - \alpha_{i,j})} \tag{5}$$

The polynomial form shown above is applied to the construction of flexible or calibrated scenarios. Figure 6 presents historical and hypothetical shares of active B737 aircraft. Depending on the values of α_i , projections were made about the evolution of the share of active aircraft in the future. The hypothesis of a constant α_i gives a linear relationship between the survival rates. Conversely, the hypothesis $\alpha_{B737-700} \gg \alpha_{B737-300} \gg \alpha_{B737-200}$ creates an escalated graph with a high prioritisation of old aircraft. The last scenario uses coefficients calibrated with a statistical model. This allows the creation of an intermediate projection based on the past heterogeneity of retirements.
Once the heterogeneity plots have been extended, these extensions can be used to respect the total number of retirements in the *push* model, but also respect the empirical heterogeneity of retirements. To do so, the aircraft $(0,0)$ is used (usually the one with the highest relative propensity of retirement). The composition of the fleet is then calculated for many values of $s_{0,0}$, this heterogeneous pictures of the fleet than can be associated to each total number of retirement.
The following subsection explains how the statistical adaptation of the model was built and used to calibrate the heterogeneity of retirements.

2.3.2 Statistical calibration

The probabilistic retirement model can be adapted to measure relative propensities on past data. Let N be the total number of retirements in the past data. The fleet data in Planespotters is interpreted as a list $(X_t)_{t\in[1,N]}$ of retired aircraft types. Here t represents the rank of the retirement considered. For instance for X_1 is the first retirement in the data, in 1960, and X_N is the last retirement, in 2023. For each retirement, at date t, the fleet context is expressed : $(F_{k,l,t})_{k\in[1,N_{modele}],l\in[1960,2023]}$. It allows to know the fleet that was operated when the retirement occured. Using these variables, the likelihood function for each retirement X_t is expressed in Eq. (6).

$$V_{X_t=(i,j)}\left(\left(\alpha_{i,j}\right)_{i,j}\right) = \frac{e^{-\alpha_{i,j}} \times F_{i,j,t}}{\sum_{m,n} e^{-\alpha_{m,n}} \times F_{m,n,t}} \tag{6}$$

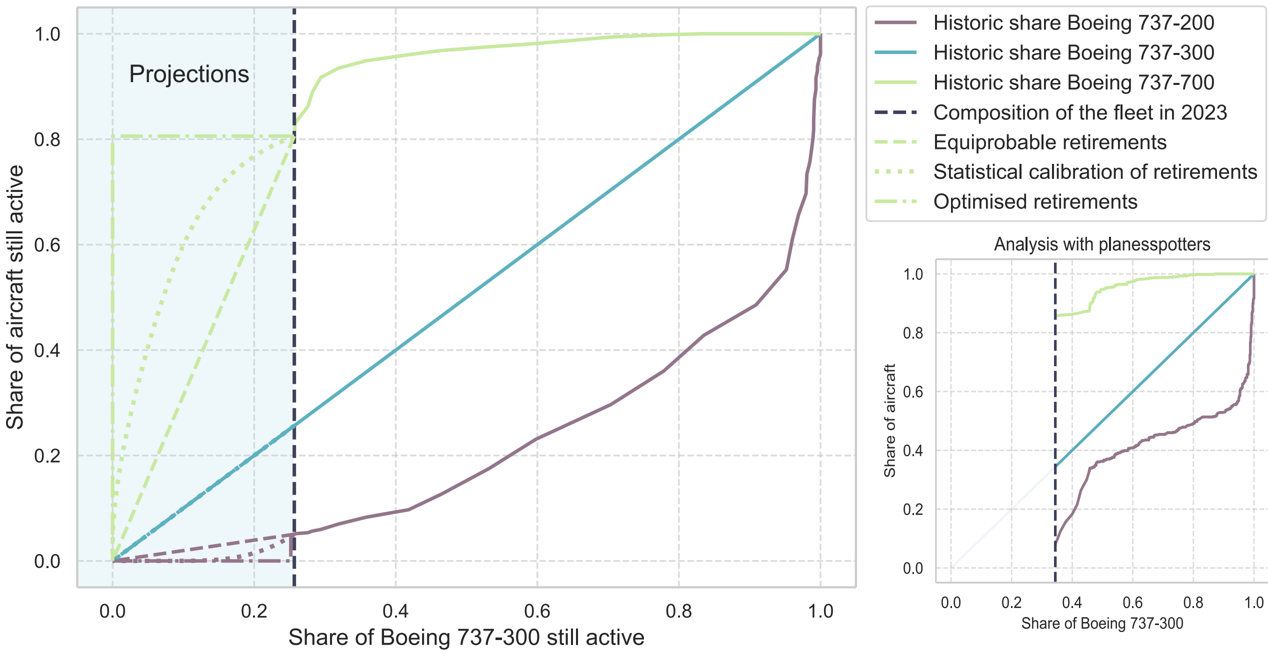

Figure 6 – Historical evolution of the shares of active aircraft for three Boeing 737 models. A commercial dataset was used, because Planespotters was not precise enough.

The likelihood of all combined observations can then be maximised, by applying the log and using a gradient descent algorithm (see Appendix A.3 for more details). Figure 7 shows the results obtained. This figure only shows the 20 most frequently occurring aircraft types of the dataset. For these aircraft, only the years where the number of aircraft produced was superior to 4 and the current number of aircraft retired was superior to 2 were selected. Notably, Planespotters is not very accurate for old aircraft. The trend is more consistent when the methodology is applied to commercial databases.
An expression of $\alpha_{i,j}$ without any constraints was chosen. This gives a lot of freedom in the parameters, but also potentially leads to some overfitting. The linear trend of the relative propensities per aircraft model suggests that it may be relevant to reduce the number of parameters. For instance, $\alpha_{i,j}$ could be constrained to the form: $\alpha_{i,j} = \alpha_i + \beta_i \times j$. This requires a slight change in the expression of the log-likelihood gradient but is even faster in terms of computation. For an aircraft in production for 15 years, the number of parameters drops from 15 to 2, significantly reducing the measurement uncertainties.
More generally, the model can be adapted to measure the impact of variables other than the year of production and the aircraft model. For instance, one could measure the impact of the number of hours/cycles flown, the type of the owner, or the engine type.
Here, the general ideas behind measuring the relative propensities of retirements were presented. However, there is still some work to be done to refine the approach. First, Planespotters often provides multiple simultaneous retirements, and for now, this is handled using weighted random draws. While it can be shown that this is a satisfying approximation, it could be improved to a rigorously unbiased method. Also, it would be valuable to calculate metrics to qualify the relevance of the modelling hypothesis and to quantify the uncertainties in the estimates.

2.4 Comparison with the current AeroMAPS fleet renewal model

In this subsection, the new fleet models are compared to the current AeroMAPS fleet renewal model using prospective scenarios on the NB segment. An illustrative growth scenario (2% annual ASK growth, constant aircraft productivity) was simulated in Figures 8 and 9. The AeroMAPS model, based on logistic functions, is calibrated assuming that 98 % of the fleet is replaced after 26 years. The new model, including the *push* approach and heterogeneity in retirements, assumes delivery volumes such that, each year, 1/20$^{\text{th}}$ of the fleet is retired. The retirement heterogeneity is calibrated using a simple form for the relative propensity of retirement of aircraft produced at date j: $\alpha_j = \beta \times j$. The best

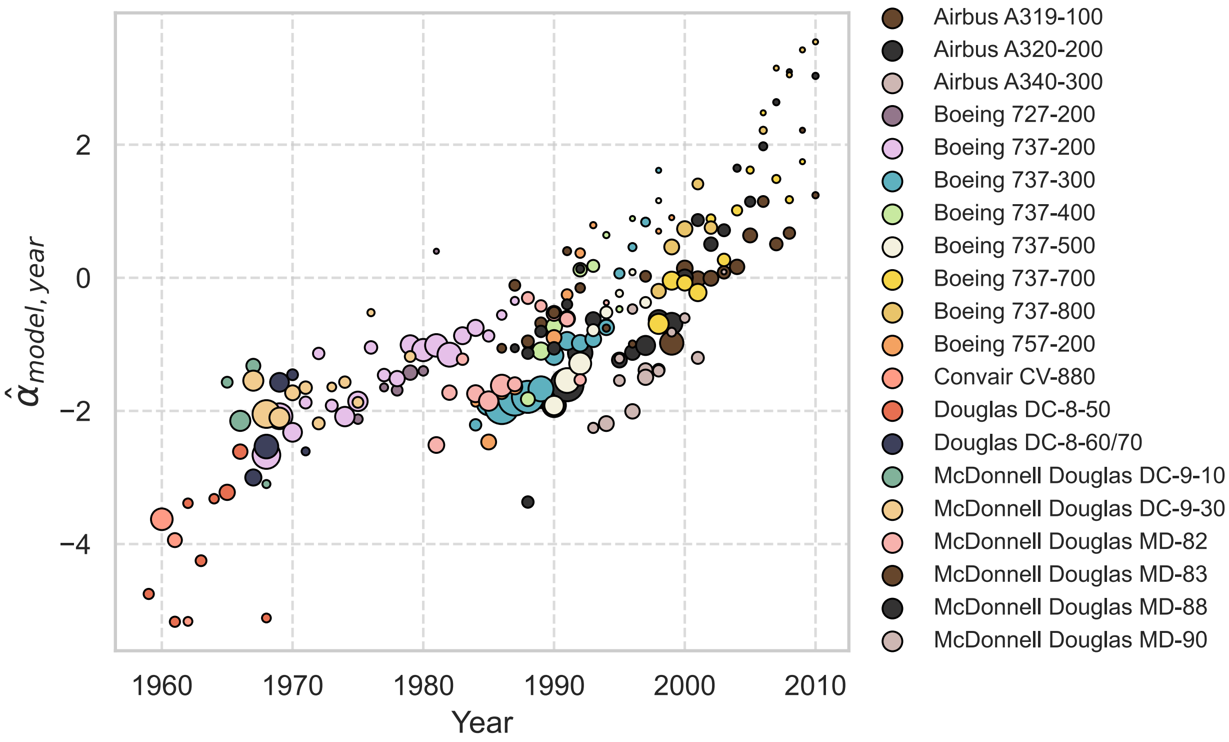

Figure 7 – Best estimates $\hat{\alpha}_{\text{model, year}} = -ln(\hat{rp}_{\text{model, year}})$, Planespotters data. The size of the markers is proportional to the number of retirements.

estimate obtained is $\hat{\beta} = 0.107$, i.e. being produced one year before brings $e^{0.107} - 1 = 11.3\%$ more chance to be retired.

A first difference can be observed: the new approach allows a representation of the different production years. The new model offers a direct interpretation in terms of which aircraft are retired. The two models provide similar behaviour (S-shaped curve). In the AeroMAPS fleet model, this shape comes from the logistic expression of the shares of aircraft. For the new heterogeneous *push* model, it comes from the delay of the production transition between generations, from the heterogeneity of retirements, from the assumptions about the number of deliveries, and is influenced by the evolution of traffic. Note that, in the new model, with the current calibration of the retirement heterogeneity, the total withdrawal of an aircraft generation is slower than expected before.

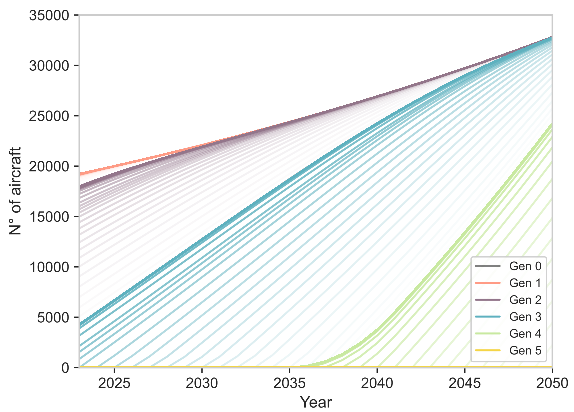

Figure 8 – Fleet evolution using the new model (*push* approach with retirement heterogeneity).

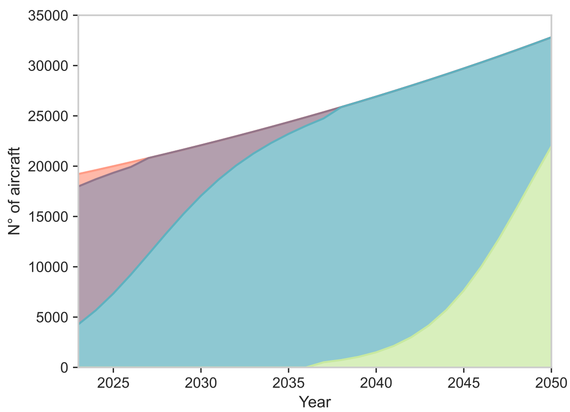

Figure 9 – Fleet evolution using the AeroMAPS model relying on logistic functions.

The supplementary degrees of freedom in the new model enable the creation of scenarios where the share of aircraft will not follow this S-shaped curve. The *push* model can easily be adapted to test several production/retirement scenarios, integrate constraints on aircraft production, and simulate original scenarios. In the shares model, these features are a consequence of the chosen function and not the input. For instance, it is possible to study the impact of a 5-year traffic depression, depending on the impact it has (or not) on aircraft deliveries. The previous growth scenario is modified: +2% until 2035 then -1% until 2040 and +2% until 2050. Running these simulations with the AeroMAPS model has no interest as the shares of each generation would remain similar to the previous simulation. The results with the heterogeneous *push* model are shown in Figures 10 and 11.

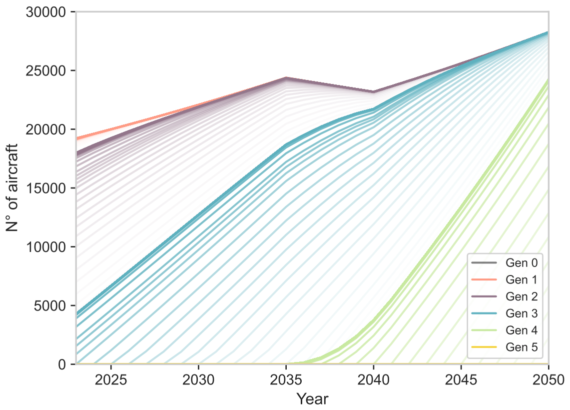

Figure 10 – Fleet evolution with a traffic crisis (no impact on deliveries).

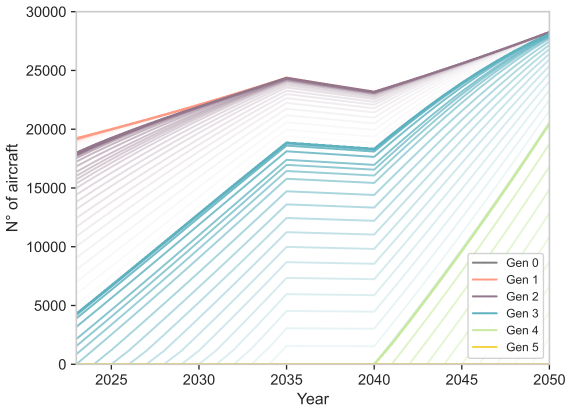

Figure 11 – Fleet evolution with a traffic crisis (5 years stop in deliveries).

To summarise, the AeroMAPS initial model constituted a good approximation of fleet renewal trends but did not investigate the phenomena at the source of these curves. It lacked a customisable description of aircraft production volumes and retirement heterogeneity. The new model provides greater flexibility and an easier realistic tuning, and allows more in-depth analysis of fleet renewal.

3. Case study n°1: impact of cyclicity and volume of production

This section provides answers to the following question: how do the production volume and timing of an aircraft renewal relate to the long-term environmental efficiency of the fleet?

3.1 Scenarios definition

For a given segment (e.g. NBs), we suppose a new generation of aircraft (Gen 4) produced between 2035 and 2049, thus generating environmental impacts until the 2070s. To study the different delivery scenarios for Gen 4 aircraft "all things equal", assumptions must be made for the composition of the fleet at the beginning of the scenario (Gen 2 and Gen 3 aircraft, corresponding respectively for A320 and A320neo for instance), and for Gen 5 aircraft delivery rates after 2050.
Nevertheless, this methodological necessity has an unavoidable flaw: the results of the study are sensitive to the composition of the fleet in 2035 and to the delivery hypothesis of Gen 5 (in this case post 2050). For example, if very little renewal was performed with Gen 3, it means that Gen 4 will be able to replace Gen 2 aircraft, bringing a lot of efficiency. Similarly, if rapid renewal is expected for Gen 5, there will be less incentive to renew with Gen 4 aircraft because they are expected to be used less. For performing this case study, the following illustrative assumptions are chosen. As will be emphasised later, the growth rate of the fleet may not change the relevance of the renewal levers, but it has a major impact on the relative size of the levers. Therefore, a stagnant fleet was chosen to simplify the interpretation.

- Composition of the fleet at the beginning of the simulation: 100 % Gen 3
- Rate of production for Gen 5: 20 years full replacement of the fleet
- Growth rate of the fleet: 0 %

3.2 Environmental efficiency indicators

This paper focuses on aircraft using conventional fuels (i.e. fossil kerosene and drop-in alternative fuels). We are interested in cumulative CO_2 emissions due to the lifetime of CO_2 in the atmosphere. If we consider a fixed alternative fuel supply in quantity, cumulative CO_2 emissions are directly correlated with the cumulative fuel consumption of the fleet.
The environmental indicator chosen for the rest of the paper is the cumulative fuel consumption of the entire fleet. It is written $F_{\text{Time span, Scenario}}$ for a given production scenario over a given time span. It can be used to calculate the emission reduction associated with a renewal scenario. Eq. (7) provides the definition of an absolute fuel consumption reduction metric M_1. This metric is useful because it allows for comparing different scenarios and ranking them.

$$M_1 = F_{2035-2070,\text{No renewal}} - F_{2035-2070,\text{Scenario}} \tag{7}$$

This metric is then normalised to provide information about the percentage of gains obtained. The difficulty is that an aircraft is produced for 15 years, but might have an impact on emissions for 30 years, for instance. To avoid double counting, it was chosen to normalise the impact on emissions (30 years in the example) over the production period (15 years in the example). Eq. (8) provides the definition of a relative fuel consumption reduction metric M_2. This metric encapsulates the absolute metric because it is a linear function of it. It has an intuitive meaning: using this metric, with an average renewal cycle, an aircraft with 15% improvement in fuel burn yields a 15% reduction in the cumulative fuel consumption.

$$M_2 = 1 - \frac{F_{2035-2070,\text{No renewal}} - F_{2035-2070,\text{Scenario}}}{F_{2035-2050,\text{No renewal}}} \tag{8}$$

3.3 Key determinants of environmental efficiency

Now that an environmental indicator and a scenario context have been defined, one can look at the key features that may determine the impact of fleet renewal. If n production years are considered, all the fleet production possibilities are in a n dimensional space. The objective is to identify relevant features of fleet renewal that reduce the size of the optimisation space and provide a better understanding of the challenges of fleet renewal. To characterise fleet dynamics with a minimum number of indicators, the key is to have linear effects of fleet renewal. This requires two assumptions (the first one should be questioned in further work, the second one is investigated in the second case study):

- each aircraft in the fleet has the same productivity,
- the priority is given to the production of the newest aircraft and the retirement of the oldest.

If g is the number of aircraft generations still in service when renewal starts, it can be shown mathematically that $g+1$ parameters are sufficient to describe the efficiency of fleet renewal. Hence, to have only two key parameters determining the environmental efficiency of fleet renewal, the assumption that the fleet is only composed of Gen 3 aircraft in 2035 is required. Then, the calculations of the environmental efficiency of fleet renewal can be reduced to only these two parameters:

- The share of aircraft replaced: $\tau_{renewal} = \frac{\sum_{t=2035}^{2049} Delivery_t - N_{fleet,2034} \times \tau_{growth,2035-2050}}{N_{fleet,2034}}$
- The average delay in aircraft production: $\frac{\sum_{t=2035}^{2049}(t-2035)\times Delivery_t}{\sum_{t=2035}^{2049} Delivery_t} = \frac{\sum_{t=2035}^{2049}(t-2035)\times Delivery_t}{N_{fleet,2034}\times(\tau_{renewal}+\tau_{growth,2035-2050})}$

3.4 Results

Let's first remember the key assumptions from the previous discussions:

- homogeneous productivity (ASK/aircraft/year),
- illustrative reference fuel performance per ASK, specified in Table 7 in Appendix B,
- instantaneous production switch from Gen i to $i+1$,

- prioritisation of retirements

All the assumptions and parameters mentioned previously allow the creation of a counterfactual scenario where the renewal rate is 0% for Gen 4 (Figure 12). It is then possible to evaluate scenarios based on delivery hypotheses. Figures 13 and 14 illustrate two contrasted delivery scenarios leading to the same environmental output. The environmental output is calculated by summing the total operating time of each aircraft generation. It is equivalent to the weighted sum (weighted by aircraft performance) of the areas belonging to each generation on the graph. This provides a geometric interpretation of why the environmental performance of the fleet depends directly on the renewal rate of Gen 3 and the average production delay of Gen 4.

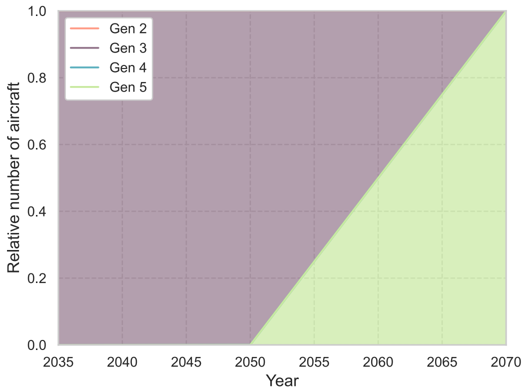

Figure 12 – Counterfactual scenario for comparison.

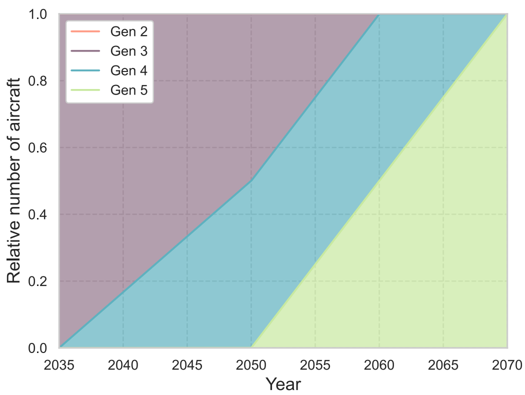

Figure 13 – Scenario 1: average delay of 7.5 years, renewal rate of 50%

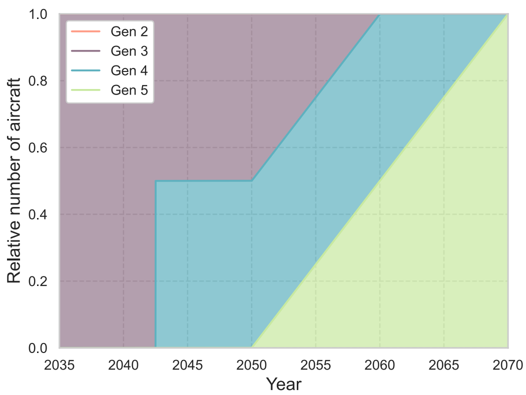

Figure 14 – Scenario 2: average delay of 7.5 years, renewal rate of 50%

More generally, Figure 15 is obtained by calculating the relative metric for each possible combination of renewal rate and production delay. It is clear that the impact of reducing the production delay depends on the volume of deliveries and vice versa. Let's look at two contrasting cases: it is striking to see that a 37% instantaneous renewal is equivalent to a full but late renewal with an average delay of 14 years (staying on the 89% isoquant line). Taking less extreme cases, for a 60% renewal rate, moving from a 12-year renewal delay to an 8-year renewal delay would yield efficiency gains of about 2.8% of the cumulative fuel consumption of the fleet.
It is worth stressing that these results overestimate the benefits of increasing the renewal rate and underestimate the benefits of reducing the production delay for the following reasons:

- The heterogeneity of the fleet in 2035: there might be some Gen 2 aircraft still in service. Taking into account these aircraft would mean there could be a two-generation gap for the first

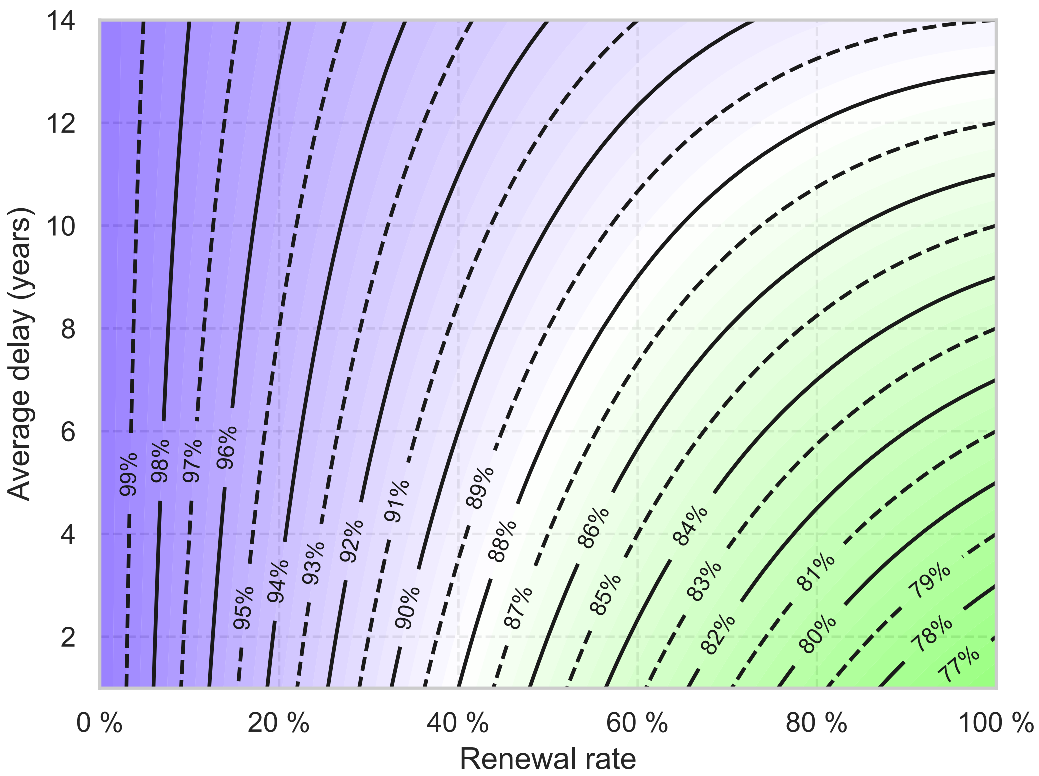

Figure 15 – Heatmap of the cumulative relative fuel consumption metric, depending on renewal rate and average aircraft production delay.

replacements which would lead to more fuel savings. This would increase the impact of cyclicity as the first replacements would be the most impacting.

- The distribution of productivity: Taking into account that the most productive aircraft are the most efficient leads to decreasing marginal returns of the replacement rates. This means higher efficiency of rapid and partial renewal.
- The emissions at the production of aircraft. Using EcoInvent 3.10 database for production [33], and assuming an average fuel consumption of 3000L/hour per aircraft, flying 10 hours per day for 20 years, it was roughly estimated that 0.5% of lifetime emissions of aircraft are during the production process. This is a cause of slight underestimation of CO_2 emissions in scenarios with massive aircraft replacement.
- The cumulative fuel consumption indicator: This indicator gives equal weight to short-term and long-term fuel use. It may be relevant to consider carbon intensity to be higher in the short term due to the possible deployment of low-carbon fuels in the future. In this case, it would mean that the current metric is biased in favour of late decarbonisation scenarios.

3.5 Discussion

To put the results in perspective with the historical values, one can have a look at the historical aircraft production delays in Table 3. These are extracted from Figure 3. It would also be interesting to calculate a market-wide replacement rate. Currently, the data is not accurate enough to calculate one for past generations.

As aircraft acquisition is often motivated by traffic growth, the delay in past deliveries could be explained by the temporality of past traffic growth. Therefore, the delay in aircraft production would not be a degree of freedom. It is worth noting, however, that in high-growth scenarios more efficiency could be achieved if deliveries were decoupled from traffic growth. In practice, this would correspond to

Aircraft series	B737-800	A320-200	A321-200	A319-100	B737-700
Aircraft produced (OEM data)	4 813	4 728	1 684	1 413	1 128
Aircraft produced (PP data)	5 000	4 700	1 704	1 463	1 219
Mean production delay (PP data)	13.6	19.8	16.0	10.1	7.2

Table 3 – Historically most sold NBs, and delay of production in years between the first and the average aircraft, Planespotters (PP) and OEMs (Airbus [34], Boeing [35]) data.

delivering most new aircraft as soon as possible and storing old aircraft in anticipation of future growth. There may be obvious economic reasons why this is not the case, but it means that aircraft delivery delay can still be considered as an efficiency parameter, even in growth periods.
When there is a high growth rate, most new aircraft would be produced anyway to serve growth. It means that the environmental impact of renewal is low in relative terms (see Morell and Dray [30]). If the no-growth scenario has significant implications on the relative value of the environmental impact of renewal, it does not affect the environmental comparison between high renewal and high cyclicity (of the aircraft production dedicated to renewal, not the aircraft production).
The results are sensitive to the composition of the fleet at the start of the simulation, post-simulation delivery scenarios, traffic assumptions and assumptions concerning the heterogeneity of aircraft retirements/deliveries. All these sensitivities could be taken into account and evaluated later in an integrated fleet model, providing refinements to the analysis. In particular, it was assumed that the aircraft produced (retired respectively) were always the most (least respectively) efficient technology. The next section focuses on the impact of prioritising the production of new-generation aircraft and prioritising the retirement of older-generation aircraft.

4. Case study n°2: impact of prioritisation of production and retirements on the cumulative emissions

This section quantifies the fuel consumption reduction that could be achieved by an environmental prioritisation of fleet renewal. The statistical heterogeneity module for aircraft retirements is used in combination with the *push* model. The cumulative fuel consumption remains the key indicator and the assumption of homogeneous productivity within the fleet is maintained.

4.1 Calibration and scenarios definition

To calibrate today's fleet, simplistic NB classification and performance assumptions are used (Tables 7 and 8 in Appendix B). The classification is based on engine type, assuming a 15 % performance difference between each generation. For simplicity, each aircraft type of the same aircraft generation is aggregated.
In line with the previous case study, a 0 % growth rate is chosen. A predetermined number of deliveries is also chosen, keeping in mind that a retirement age of 25 years seems to be a relevant trend in the long run. This translates into a fixed renewal rate of 1/25$^{\text{th}}$ (i.e. 4 %) of the fleet each year.
Using the *push* model, these assumptions provide an aggregated view of the fleet, meaning a quantity of aircraft, a quantity of deliveries and a quantity of retirements (constant series in this case).
The retirement heterogeneity is again calibrated using a simple form for the relative propensity of retirement of aircraft produced at date j: $\alpha_j = \beta \times j$. The estimate used is still $\hat{\beta} = 0.107$. It is assumed for the next generations the time it took from fully producing Gen 2 aircraft (Ceos) to fully producing Gen 3 aircraft (Neos): $T = 6$ years.
Four scenarios are built for studying the different fleet renewal strategies mentioned. Table 4 summarises the corresponding parameters. To prioritise retirements a parameter $\beta = 5$ was chosen to do heavy prioritisation with a reasonable calculation cost. It is sufficient for prioritisation as it means that being produced one year before brings $e^5 - 1 = 150$ times more chance to be retired.

4.2 Results

Based on the calibration and using the prospective assumptions, the evolution of the fleets is simulated. The trend scenario is illustrated in Figure 16, the optimised retirement scenario in Figure 17, the

N°	Name	β	T	Annual fleet renewed
1	Trend (Reference)	0.107	6	4%
2	Optimised retirements	5	6	4%
3	Optimised retirements and deliveries	5	0	4%
4	Instantaneous optimised renewal	5	0	100%

Table 4 – Key parameters of the scenarios for the second case study.

optimised scenario (for retirements and deliveries) in Figure 18, and the optimised scenario with instantaneous renewal in Figure 19.

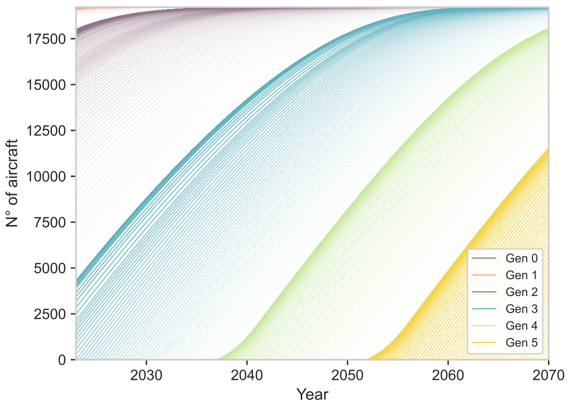

Figure 16 – NBs fleet for Scenario 1 (trend on deliveries and retirements).

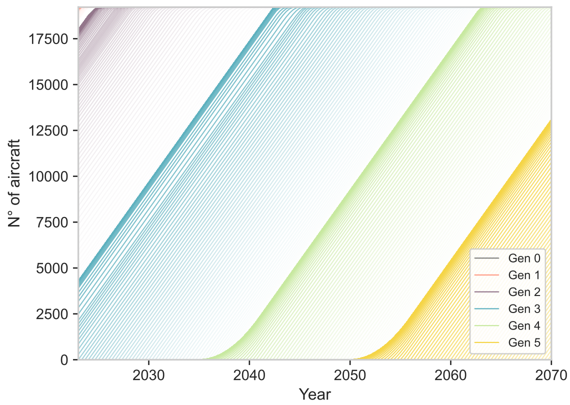

Figure 17 – NBs fleet for Scenario 2 (trend on deliveries, prioritisation for retirements).

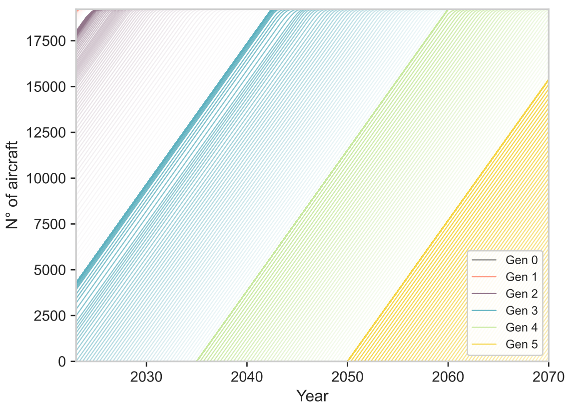

Figure 18 – NBs fleet for Scenario 3 (prioritisation for deliveries and retirements).

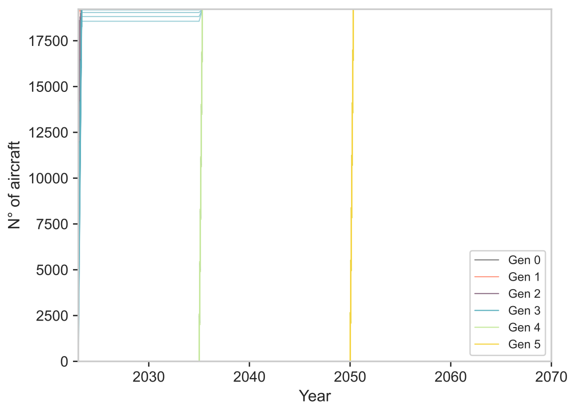

Figure 19 – NBs fleet for Scenario 4 (instantaneous optimised fleet renewal).

In scenario 1, S-shaped curves are observed first because of slow ramp-up, then because of retirement heterogeneity : old generation tend persist in low volumes. Scenario 4 with instantaneous and full fleet renewal is the most environmental friendly scenario for given technological hypotheses.
Figure 20 shows how each scenario compares with Scenario 1 in terms of fuel consumption. For each scenario, the cumulative fuel consumption for the period 2023-2070 (relative to the reference one) is shown in Table 5. With the current assumptions, at 2070 horizon, prioritising retirements could bring up to 2.3% of fuel savings at the fleet level. Switching the aircraft produced in one year instead of six could bring up to 1.5% fuel savings. Scenario 4 allows to estimate the maximum gains that can be achieved until 2070 through more environmentally optimised fleet renewal. This technological limit is estimated at 14.2%.

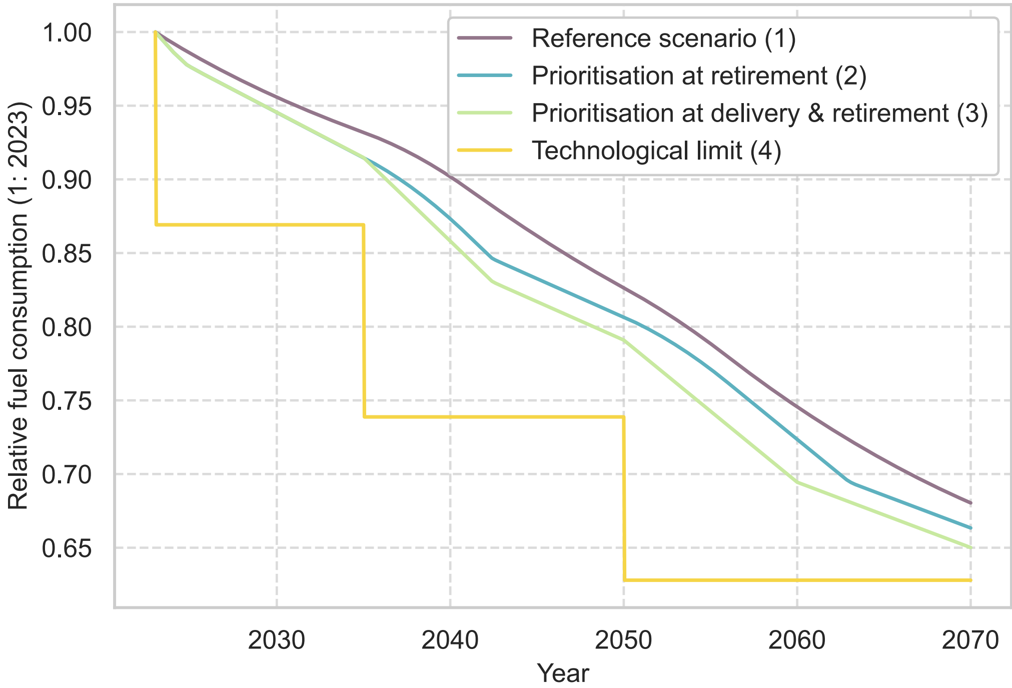

Figure 20 – Evolution of relative fuel consumption for each scenario.

Scenario	Reference	Prioritisation of retirements	Prioritisation of retirements and deliveries	Technological limit
Cumulative fuel consumption (2023-2070)	100%	97.7%	96.1%	85.8%

Table 5 – Relative cumulative fuel consumption for each scenario.

4.3 Discussion

This case study investigated the impact of the time it takes to switch from one generation produced to another. In a way, it can be linked to the precedent study about aircraft production delays because both may stem from industrial constraints.

It is important to remember that the estimates are highly sensitive to delivery and traffic assumptions. A growth scenario could mask the positive impact of prioritised fleet renewal and increase the importance of prioritising new aircraft deliveries.

It was explained before that a growth trend masked the efficiency effect of aircraft renewal because deliveries for new traffic become preponderant compared to deliveries for replacing old aircraft. An additional persistent effect is observed in Figure 20: the gains from prioritizing retirements tend to be small at the beginning of the simulation and larger around the 2040s. It can be explained by the fact that the growth trend in the past has caused the age structure of the fleet to follow an exponential rather than a constant trend. Even if the growth stops now, old aircraft will remain a minority, for at least 10 years, and it reduces the potential gains from prioritizing retirements.

A limit of the estimations provided here is that it was based on a simplification of the fleet (only one aircraft type per generation) and simple fuel burn assumptions (-15 % per generation). Keeping the same model, these estimations could be improved by specifying the different efficiencies of aircraft and incorporating the relative propensities of retirement to each aircraft type (using the results presented in Section 2.3.2).

Also, the 2.3% fuel savings from prioritising retirements may be an optimistic estimation. Indeed, productivity heterogeneity was not taken into account. As a consequence, the impact of replacing old aircraft, which in reality tend to fly less than new aircraft, may have been overestimated.

5. Conclusions

5.1 Key findings

In this paper, a new approach to fleet renewal modelling was proposed to enable detailed analyses of renewal levers. The main module is a generic *push* model and was motivated by the need for a flexible and realistic approach. It is based on models that already exist in the literature. A second module provides an original statistical model for measuring past heterogeneity in aircraft retirement and projecting it into the future.

The first module was used alone to illustrate the impact of the timing of renewal on the environmental performance of the fleet. This original lever is not mentioned in the literature but is a key factor for long-term environmental performance. As the impact of the temporality of the renewal is directly correlated to the renewal rate, the fuel savings estimates are highly context-dependent. For a 60% renewal rate, it was estimated that moving from a classical 12-year renewal delay to an 8-year renewal delay could yield an approximate gain of 2.8% in cumulative fuel consumption.

The two modules were then combined to evaluate the cumulative fuel consumption in various scenarios. In a zero-growth future, it has been estimated that the technological limit would enable a maximum of 14.2% fuel consumption reduction for the period 2023-2070, compared to the trend scenario. The choice of positive growth assumptions tends to reduce this figure. This 14.2% is a worldwide limit. To tend towards this limit, the following factors have been studied:

- increasing the renewal rate,
- decreasing the delivery delay,
- prioritising the deliveries by rapidly switching between two generations,
- prioritising the retirements of older aircraft.

Estimating the potential of each factor is complicated by the interdependence of the effects of each of them. Nevertheless, it was shown that prioritising deliveries (retirements respectively) of new (old respectively) technologies could lead to efficiency gains of around 1.5% (2.3% respectively) for the period 2023-2070. Notably, these gains would be achieved without producing more aircraft.

5.2 Next steps

This work offers many perspectives. Some of these are detailed in the following.

First, the presented modules could be combined with other existing AeroMAPS modules. It would allow integrated analyses, for instance including the impact of the alternative fuel supply.

In parallel, it is important to keep developing relevant models to tackle current limitations. In particular, this work suffers from two major blind spots that should be investigated: the geographical allocation of aircraft and the impact of productivity heterogeneity.

For now, it was chosen to develop the renewal models on segmented markets (e.g. NBs). Nevertheless, merging these segments using an endogenous allocation model would be important for two main reasons. First, it would provide a methodology to distribute traffic growth to the different segments. Without a clear understanding of where aircraft are operated, it is complicated to make relevant growth assumptions. Second, and more importantly, the segmented representation of the fleet is incorrect. In reality, different aircraft segments are not managed independently and there are substitution patterns between these. The substitution patterns should be key in the environmental assessment of the new aircraft, as we are interested by the relative gains brought by an aircraft. For instance, the A321 XLR architectures could replace NBs or wide-bodies.

The first point could be addressed alone in the same way as Dray *et al.*, keeping a segmented model, and using a traffic share model to endogenously predict the growth of each segment. Nevertheless, it would still imply simulating independently the renewal of each aircraft segment. A second and more insightful approach would be to abolish segmentation and build a competition framework between all aircraft. This approach would be akin to the one in Kuhlen *et al.*. Again, the challenge would then be to find a way to respect the empirical heterogeneity of the data.

Taking into account the geographical allocation of aircraft would also be valuable as it impacts fuel consumption. Different aircraft have different designs and are specialised for different missions.

Depending on where aircraft are allocated, the fuel consumption will change. It would be important to estimate the potential of fuel savings if the comparative advantages of aircraft at different ranges were activated. Moreover, the geographical allocation impacts not only flight efficiency but also the number of flights performed. Indeed, long routes tend to be the most productive ones [36], so long-haul aircraft tend to serve more ASKs than short-haul ones.

Concerning the topic of aircraft productivity, it is not tackled in this work, is not deeply investigated in the literature and may have a great impact. Productivity is critical because an aircraft's fuel consumption is roughly proportional to its number of flight hours. This paper assumed constant productivity, which declines discontinuously to 0 when the aircraft is retired. In reality, aircraft productivity varies not only with the stage length but also with the route, the operator and the age of the aircraft. It is expected that productivity heterogeneity brings non-linearities and counter-intuitive results on the decarbonisation levers mentioned in this paper (renewal rate, reducing production delays, production/retirement prioritisation).

More broadly, the previous models exposed global decarbonisation levers which relied on key variables (renewal rate, reducing production delays, production/retirement prioritisation). Therefore, it would be valuable to understand the practical actions that could impact these indicators:

- What stops from decreasing delivery delays?
- What determines the share of aircraft replaced?
- What causes the retirement of one aircraft to be more likely than the other?

Answering these questions could help in understanding how companies, OEMs or governments can influence the environmental efficiency of the fleet.

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7. Copyright Statement

Appendix

A Mathematical details

A.1 Taking into account rebound expectations for an adequate level of retirement, and aircraft storage

To account for future growth, let's first consider the cumulative number of retirements according to the naive version. It is rearranged using a telescopic sum.

$$\sum_{i=t_0}^{t} R_i = \sum_{i=t_0}^{t} (F_{i-1} - F_i + D_i) = F_{t_0-1} - F_t + \sum_{i=t_0}^{t} D_i$$

The period of high growth may imply that too many aircraft have been retired. The anticipation process amounts to setting cumulative retirements at the minimum of all the future number of unused aircraft. This allows an aircraft not to be retired if it may be used in the future. If the anticipated number of retirements is written $\overline{R}_t$, then:

$$\sum_{i=t_0}^{t} \overline{R}_i = \min_{u \geq t} \left(\sum_{i=t_0}^{u} R_i \right)$$

By subtracting this relationship from itself, the following expression is obtained:

$$\overline{R}_t = \min_{u \geq t} \left(F_{t_0-1} - F_u + \sum_{i=t_0}^{u} D_i \right) - \min_{u \geq t-1} \left(F_{t_0-1} - F_u + \sum_{i=t_0}^{u} D_i \right)$$

In this approach, the stored aircraft can be interpreted as unused aircraft that would have been retired without anticipation. Therefore, S_t is the number of stored aircraft can be written:

$$S_t = \sum_{i=t_0}^{t} R_i - \sum_{i=t_0}^{t} \overline{R}_i = \min_{u \geq t} \left(F_{t_0-1} - F_u + \sum_{i=t_0}^{u} D_i \right) - F_{t_0-1} - F_t + \sum_{i=t_0}^{t} D_i$$

A.2 Deriving active aircraft shares from a relative propensity model

For an aircraft type (i, j), the relative propensity $rp_{i,j}$ allows the estimation of the probability that an aircraft of this type is retired in a fleet context $(F_{k,l})_t$.

$$P_{i,j,t} = \frac{F_{i,j,t} \times rp_{i,j}}{\sum_{m,n} F_{m,n,t} \times rp_{m,n}}$$

On average, this probability of retirement approximates the share of aircraft retired around date t. Under this approximation, if the number of retirements during period dt is written $dR(t)$, we have:

$$\forall (i, j), t, dF_{i,j,t} = -P_{i,j,t} \times dR(t) = -\frac{F_{i,j,t} \times rp_{i,j}}{\sum_{m,n} F_{m,n,t} \times rp_{m,n}} \times dR(t)$$

It can also be written as:

$$\forall (i, j), t, \frac{dF_{i,j,t}}{F_{i,j,t} \times rp_{i,j}} = -\frac{1}{\sum_{m,n} F_{m,n,t} \times rp_{m,n}} \times dR(t)$$

The right side of the expression is independent of (i, j) which means it is the same for any aircraft model. Then, for all t, during dt:

$$\forall ((i, j), (k,l)), \frac{dF_{i,j,t}}{F_{i,j,t} \times rp_{i,j}} = \frac{dF_{k,l,t}}{F_{k,l,t} \times rp_{k,l}}$$

Integrating these expressions on $[t_0,t]$, we get the following expression:

$$\frac{ln\left(\frac{F_{i,j,t}}{F_{i,j,t_0}}\right)}{rp_{i,j}} = \frac{ln\left(\frac{F_{k,l,t}}{F_{k,l,t_0}}\right)}{rp_{k,l}}$$

This can be rewritten:

$$ln(s_{i,j,t}) = \frac{rp_{i,j}}{rp_{k,l}} \times ln(s_{k,l,t})$$

Applying the exponential function to this expression provides this relation:

$$s_{i,j,t} = s_{k,l,t}^{\frac{rp_{i,j}}{rp_{k,l}}} = s_{k,l,t}^{exp(\alpha_{k,l} - \alpha_{i,j})}$$

Note that this approach implicitly assumes that all aircraft have been produced in t_0. While it is qualitatively false it remains quantitatively satisfying because when applied with empirical measures, it generates near zero retirements before delivery.

A.3 Maximum likelihood calculations and gradients

As expressed before, here is the expression of the likelihood function for one observation:

$$V_{X_t=(i,j)}\left((\alpha_{i,j})_{i,j}\right) = \frac{e^{-\alpha_{i,j}} \times F_{i,j,t}}{\sum_{m,n} e^{-\alpha_{m,n}} \times F_{m,n,t}}$$

To within one constant, the log-likelihood expression is the following:

$$v_{X_t=(i,j)}\left((\alpha_{i,j})_{i,j}\right) = log\left(V_{X_t=(i,j)}\left((\alpha_{i,j})_{i,j}\right)\right) = -\alpha_{i,j} - log\left(\sum_{m,n} e^{-\alpha_{k,l}} \times F_{m,n,t}\right)$$

The gradient of the expression can be explicitly calculated:

$$\vec{\nabla}(v(\ldots)) = -\frac{\sum\limits_{(m,n)\neq(i,j)} e^{-\alpha_{m,n}} \times F_{m,n,t}}{\sum\limits_{m,n} e^{-\alpha_{m,n}} \times F_{m,n,t}} \times \vec{e}_{\alpha_{i,j}} + \sum_{(k,l)\neq(i,j)} \left(\frac{e^{-\alpha_{k,l}} \times F_{k,l,t}}{\sum\limits_{m,n} e^{-\alpha_{m,n}} \times F_{m,n,t}} \times \vec{e}_{\alpha_{k,l}} \right)$$

For M (either for a mini-batch learning method or for all observations) a subset of R the retirement observations, a gradient can be associated:

$$\vec{\nabla}(v_{tot}(\ldots)) = \sum_{t\in M} \left(-\frac{\sum\limits_{(m,n)\neq(i,j)} e^{-\alpha_{m,n}} \times F_{m,n,t}}{\sum\limits_{m,n} e^{-\alpha_{m,n}} \times F_{m,n,t}} \times \vec{e}_{\alpha_{i,j}} + \sum_{(k,l)\neq(i,j)} \left(\frac{e^{-\alpha_{k,l}} \times F_{k,l,t}}{\sum\limits_{m,n} e^{-\alpha_{m,n}} \times F_{m,n,t}} \times \vec{e}_{\alpha_{k,l}} \right) \right)$$

This expression is then used in the gradient descent algorithm to find the best estimates $(\hat{\alpha}_{i,j})_{i,j}$.

B Complementary tables

Engine	JT8D	CFM56-3	CFM56-5	CFM56-7	V2500	PW6000	LEAP	PW1100G
Entry in service	1965	1984	1987	1997	1988	2007	2015	2015
Classification	old	old	medium	medium	medium	medium	new	new

Table 6 – Engines classification used to illustrate heterogeneity of deliveries and retirements.

Aircraft generation	1	2	3	4	5
Entry in service				2035	2050
Gains compared to last generation		-15%	-15%	-15%	-15%
Relative performance	100%	85%	72.2%	61.4%	52.2%

Table 7 – Aircraft and performance assumptions in the fleet models.

Aircraft generation	1	2	3
Engine types	CFM56-2, CFM56-3, PW JT3D, PW JT8D PW2000	BR700, PS-90, V2500 CFM56-5, CFM56-7 PW6000	LEAP, PW1100G, PW1500G
Aircraft types	B727-2, B737-2, B737-3 B737-4, B737-5, B757-2 B757-3, MD-81, MD-82 MD-83, MD-87, MD-88, DC-9-30, DC-8-60/70 DC-9-10, DC-9-20	A318-1, A319-1, A320-2 A321-1, A321-2, A340-2 A340-3, B717-2, B737-6 B737-7, B737-8, B737-9 B737-9 ER, MD-90 Il-96, Tu-204,Tu-214	A320neo, A319neo A321neo B737 MAX7, B737 MAX8 B737 MAX9, B737 MAX10 A220-100,A220-300 C919
Aircraft number (2023)	1 213	13 025	3 815

Table 8 – Aircraft/engine classification for NB fleet construction.

References

[1] IATA„ "Airline Industry Economic Performance Mid 2015," tech. rep., IATA, 2015. https://www.iata.org/en/iata-repository/publications/economic-reports/airline-industry-economic-performance---2015-mid-year---report/.

[2] IATA„ "Airline Industry Economic Performance - June 2020," tech. rep., IATA, 2020. https://www.iata.org/en/iata-repository/publications/economic-reports/airline-industry-economic-performance-june-2020-report/.

[3] Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., Doherty, S. J., Freeman, S., Forster, P. M., Fuglestvedt, J., and others„ "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018," *Atmospheric Environment*, vol. 244, p. 117834, 2021. https://doi.org/10.1016/j.atmosenv.2020.117834.

[4] Delbecq, S., Fontane, J., Gourdain, N., Planès, T., and Simatos, F., "Sustainable aviation in the context of the paris agreement: a review of prospective scenarios and their technological mitigation levers," *Progress in Aerospace Sciences*, vol. 141, p. 100920, 2023. https://doi.org/10.1016/j.paerosci.2023.100920.

[5] Airbus„ "Global Market Forecast," tech. rep., Airbus, 2022. https://www.airbus.com/en/products-services/commercial-aircraft/market/global-market-forecast.

[6] Mikosz, S., "IATA- Airline commitment to Net Zero 2050," 2021. https://www.iata.org/en/iata-repository/pressroom/presentations/environment-net-zero-carbon-at-iata-agm-2021/.

[7] Arias, P. A., Bellouin, N., Jones, R. G., Naik, V., Plattner, G.-K., Rogelj, J., Sillmann, J., Storelvmo, T., Thorne, P. W., Trewin, B., Rao, K. A., Adhikary, B., Allan, R. P., Armour, K., Barimalala, R., Canadell, J. G., Cassou, C., Cherchi, A., Collins, W., Corti, S., Cruz, F., Dentener, F. J., Dereczynski, C., Luca, A. D., Diongue, A., Doblas-Reyes, F. J., Dosio, A., Douville, H., Engelbrecht, F., Fyfe, J. C., Gillett, N. P., and Goldfarb, L., "Ipcc ar6 wg1 technical summary," tech. rep., IPCC, 2021.

[8] ICAO„ "Report on the feasibility of a long-term aspirational goal (LTAG) for international civil aviation CO2 emission reductions," tech. rep., International Civil Aviation Organisation, 2022. https://www.icao.int/environmental-protection/Pages/LTAG.aspx.

[9] Grewe, V., Gangoli Rao, A., Grönstedt, T., Xisto, C., Linke, F., Melkert, J., Middel, J., Ohlenforst, B., Blakey, S., Christie, S., Matthes, S., and Dahlmann, K., "Evaluating the climate impact of aviation emission scenarios towards the Paris agreement including COVID-19 effects," *Nature Communications*, vol. 12, p. 3841, June 2021. https://doi.org/10.1038/s41467-021-24091-y.

[10] Planès, T., Delbecq, S., Pommier-Budinger, V., and Bénard, E., "Simulation and evaluation of sustainable climate trajectories for aviation," *Journal of Environmental Management*, vol. 295, p. 113079, 2021. https://doi.org/10.59490/joas.2023.7201.

[11] Klöwer, M., Allen, M., Lee, D., Proud, S., Gallagher, L., and Skowron, A., "Quantifying aviation's contribution to global warming," *Environmental Research Letters*, vol. 16, p. 104027, Oct. 2021. https://doi.org/10.1088/1748-9326/ac286e.

[12] Dray, L., Schäfer, A. W., Grobler, C., Falter, C., Allroggen, F., Stettler, M. E., and Barrett, S. R., "Cost and emissions pathways towards net-zero climate impacts in aviation," *Nature Climate Change*, vol. 12, no. 10, pp. 956–962, 2022. https://doi.org/10.1038/s41558-022-01485-4.

[13] Bergero, C., Gosnell, G., Gielen, D., Kang, S., Bazilian, M., and Davis, S. J., "Pathways to net-zero emissions from aviation," *Nature Sustainability*, vol. 6, no. 4, pp. 404–414, 2023. https://doi.org/10.1038/s41893-022-01046-9.

[14] Sacchi, R., Becattini, V., Gabrielli, P., Cox, B., Dirnaichner, A., Bauer, C., and Mazzotti, M., "How to make climate-neutral aviation fly," *Nature Communications*, vol. 14, no. 1, p. 3989, 2023. https://doi.org/10.1038/s41467-023-39749-y.

[15] Group, A. T. A., "Waypoint 2050," tech. rep., Air Transport Action Group, 2021. https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf.

[16] NLR„ Economics, S. A., A4E„ ACI-Europe„ ASD„ CANSO„ and ERA„ "Destination 2050, A route to net zero european aviation," tech. rep., A4E, ACI, ASD, CANSO, ERA, 2021. https://www.destination2050.eu/wp-content/uploads/2021/03/Destination2050_Report.pdf.

[17] Planès, T., Delbecq, S., and Salgas, A., "Aeromaps: a framework for performing multidisciplinary assessment of prospective scenarios for air transport," *Journal of Open Aviation Science*, vol. 1, no. 1, 2023. https://doi.org/10.59490/joas.2023.7147.

[18] Liebeck, R. H., "Design of the Blended Wing Body Subsonic Transport," *Journal of Aircraft*, vol. 41, pp. 10–25, Jan. 2004. https://doi.org/10.2514/1.9084.

[19] Verstraete, D., “On the energy efficiency of hydrogen-fuelled transport aircraft,” *International Journal of Hydrogen Energy*, vol. 40, pp. 7388–7394, June 2015. https://doi.org/10.1016/j.ijhydene.2015.04.055.

[20] Airbus„ “ZEROe - Zero emission aircraft homepage,” 2022 [Online]. https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe.

[21] Delbecq, S., Planès, T., Delavenne, M., Pommier-Budinger, V., and Joksimović, A., “Aircraft fleet models using a bottom-up approach for simulating aviation technological prospective scenarios,” in *33rd Congress of the International Council of the Aeronautical Sciences*, 9 2022. https://oatao.univ-toulouse.fr/29578/1/Delbecq_29578.pdf.

[22] Dray, L., Evans, A., Reynolds, T., Schäfer, A. W., Vera-Morales, M., and Bosbach, W., “Airline fleet replacement funded by a carbon tax: An integrated assessment,” *Transport Policy*, vol. 34, pp. 75–84, 2014. https://doi.org/10.1016/j.tranpol.2014.02.021.

[23] Dray, L., Krammer, P., Doyme, K., Wang, B., Al Zayat, K., O’Sullivan, A., and Schäfer, A. W., “AIM2015: Validation and initial results from an open-source aviation systems model,” *Transport policy*, vol. 79, pp. 93–102, 2019. https://doi.org/10.1016/j.tranpol.2019.04.013.

[24] Kühlen, M., Lütjens, K., Linke, F., and Gollnick, V., “An explanatory approach to modelling the fleet assignment in the global air transportation system,” *CEAS Aeronautical Journal*, vol. 14, pp. 255–269, Jan. 2023. https://doi.org/10.1007/s13272-022-00622-1.

[25] Lampert, A., Humphries, C., and Hepher, T., “Boeing 737 MAX crisis adds to high demand for older planes,” *Reuters*, Feb. 2024. accessed 2024-04-23 https://www.reuters.com/business/aerospace-defense/boeing-737-max-crisis-adds-high-demand-older-planes-2024-02-01/.

[26] Justin, C. Y. and Mavris, D. N., “Aircraft and engine economic evaluation for fleet renewal decision-making and maintenance contract valuation,” *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, vol. 229, pp. 2051–2065, Sept. 2015. https://doi.org/10.1177/0954410014564403.

[27] Dray, L., “Aim2015: Documentation,” [Accessed May 2024].

[28] Oguntona, O. T., *Aircraft Fleet Renewal: Assessing Measures for Reducing CO2 Emissions*. PhD thesis, TUM, 2019.

[29] Planespotters.net„ “Production lists database.” https://www.planespotters.net/aircraft/index, 2023. Accessed : 17/01/2023.

[30] Morrell, P. and Dray, L., “Environmental aspects of fleet turnover, retirement and life cycle,” 2009. https://dokumen.tips/documents/environmental-aspects-of-fleet-turnover-retirement-and-life-cycle.html.

[31] “Webplotdigitizer: Version 4,” 2024. https://apps.automeris.io/wpd4/.

[32] Kühlen, M., Kölker, K., Linke, F., Dahlmann, K., Gollnick, V., and Lütjens, K., “From passenger itineraries to climate impact: Analyzing the implications of a new mid-range aircraft on the global air transportation system,” *Journal of Air Transport Management*, Oct. 2023. https://doi.org/10.1016/j.jairtraman.2023.102474.

[33] Notten, P., “Aircraft production, passenger aircraft, medium-haul, glo, allocation, cut-off by classification, ecoinvent database version 3.1.”

[34] Airbus„ “Orders and deliveries | airbus.” https://www.airbus.com/en/products-services/commercial-aircraft/market/orders-and-deliveries, 2024. Accessed : 28/05/2024.

[35] Boeing„ “Orders and deliveries | boeing.” https://www.boeing.com/company/about-bca#orders-deliveries, 2024. Accessed : 28/05/2024.

[36] Swan, W. M. and Adler, N., “Aircraft trip cost parameters: A function of stage length and seat capacity,” *Transportation Research Part E: Logistics and Transportation Review*, vol. 42, pp. 105–115, Mar. 2006. https://doi.org/10.1016/j.tre.2005.09.004.