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A Model of Aircraft Retirement and Acquisition Decisions Based On Net Present Value Calculations

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This paper discusses a model of airlines' fleet planning decisions. In this model, aircraft retirement decisions are based on the net present value of potential new versus existing aircraft, and new aircraft acquisition decisions are based on the expected market demand to be satisfied in the future years. The model runs through three scenarios of passenger demand and aircraft technology evolution, and the results obtained show a comparison of effects of airline decision-making on their fleet composition and the environmental impact.

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Nomenclature

ac_order_i	=	Number of class i aircraft demanded (ordered)
$avail_i$	=	Number of available class i aircraft
avg_trips_i	=	Average number of trips made by class i aircraft
dem_cap_i	=	Class i aircraft passenger demand capacity
$num\_delivered\_ac_i$	=	Number of class i aircraft delivered by manufacturer
$num\_new\_ac_i$	=	Number of new class i aircraft required to satisfy passenger demand
$num\_retire\_ac_i$	=	Number of class i aircraft retired
$prod_i$	=	Number of existing class i aircraft produced
$require_i$	=	Number of existing class i aircraft required to satisfy passenger demand
$seat\_cap_i$	=	Class i aircraft seat capacity

I. Introduction

Airlines' decisions on which aircraft to acquire, how many, and when, are long-term strategic decisions which have an effect on all aspects of the airlines' operations from their profits to the operating network. At the same time, these decisions are interdependent on numerous factors such as the airlines' own network, available fleet, forecasts of demand growth, the performance characteristics of available aircraft, as well as environmental impact, and even political influences.[1] Complicating these decisions is the time scale involved, as the airlines forecast their need for a given time, and the effects of these decisions are felt for several years afterwards. Not surprisingly, fleet planning are some of the most important decisions airlines make.

A tool useful for airline fleet planning, therefore, will have to take into account the many factors that play a role in fleet planning decisions. This paper presents an aircraft retirement and acquisition model which serves this purpose. This model is part of the Fleet-Level Environmental Evaluation Tool (FLEET), a simulation tool which helps answer the question of how new aircraft might get used by a profit-seeking airline under given conditions of market demand and environmental policy. A resource allocation problem is a big part of FLEET as it mimics the airlines' decisions on fleet allocation on different routes to serve available demand. This resource allocation problem is setup within a system dynamics-type framework of model-based prediction on future demand, fleet turnover, and environmental impact.

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It is within the system dynamics framework of FLEET that the model of aircraft retirement and acquisition is formulated. This model calculates the number of existing aircraft to be retired from the current fleet and new aircraft to be acquired on the basis of net present value calculations for these aircraft. It does these calculations for each class of aircraft to account for aircraft aging and increase in seat capacity required to meet increasing demand. Ultimately a tool that facilitates decision-making for airline fleet planning is useful for a number of different stakeholders including the airlines themselves, as well as the manufacturers who can use it to forecast aircraft requirement and adjust their production.

The next section describes the platform and approach used to develop the retirement and acquisition model, followed by a section discussing sample results and insights gleaned from the modeling approach. We conclude with a section highlighting areas for further research.

II. Description of the Model

This section first introduces FLEET, and then discusses its aircraft retirement and acquisition model in further detail. The discussion of FLEET in this section is brief, Refs.[2–7] give a more detailed description of the tool.

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A. The Fleet-Level Environmental Evaluation Tool (FLEET)

FLEET is a MATLAB-based simulation tool that models the fleet utilization decisions of a profit-seeking airline. It can simulate a variety of scenarios of economic growth, fuel price variation, and environmental policy. Its model of airline decision-making takes form of a resource allocation problem set within a system dynamics-type framework of models of aircraft technology evolution, economic and policy changes. Each of these models interact with one another, see Fig. 1. Due to the complexity of modeling the air transportation system, FLEET makes a number of simplifying assumptions including aggregating all airlines into a single large airline that operates all routes in the US domestic network, and taking a set of 24 aircraft, divided into six size-classes of four technology ages, as a representative set of all aircraft operating in the network.

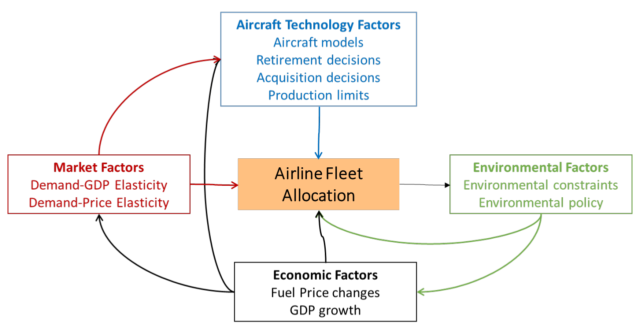

Figure 1. Schematic of the FLEET system dynamics model. Full version of the system dynamics model can be found in Ref.[7]

The resource allocation problem, which forms the backbone of FLEET, is setup as a mixed integer programming problem with the objective of maximizing airline profit. This problem is solved under the constraints of available fleet, market demand, and aircraft seat capacities. For the sake of completeness, the form of the resource allocation problem is given below, albeit without a detailed discussion, which can be

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found in Ref.[7]

$$\text{maximize} \quad \sum_{k=1}^{K}\sum_{j=1}^{N}(pax_{k,j} \cdot P_{k,j}) - \sum_{k=1}^{K}\sum_{j=1}^{N}(C_{k,j} \cdot x_{k,j}) \tag{1}$$

$$\text{subject to} \quad \sum_{k=1}^{K} pax_{k,j} \leq dem_j, \quad \forall j \tag{2}$$

$$\sum_{k=1}^{K} pax_{k,j} \geq 0.2 \cdot dem_j \tag{3}$$

$$2[x_{k,j} \cdot BH_{k,j}(1 + (EMH/BH)_k) + t] \leq 72 \cdot fleet_{k,j=1} \tag{4}$$

$$pax_{k,j} - x_{k,j} \cdot cap_k \leq 0 \tag{5}$$

In the above set of equations, the integer decision variable $x_{k,j}$ is the number of trips that aircraft type k flies on route j. The variable $pax_{k,j}$ is the number of passengers that fly on aircraft type k on route j. Eq. 1 is the objective function; this is the profit of the airline, defined as the difference between revenue and cost. Constraint Eq. (2) ensures that the airline does not transport more passengers than the market demand on each route, while the constraint Eq. (3) ensures that the airline meets at least 20% of the demand on each route. Constraint Eq. (4) counts the number of aircraft necessary to satisfy segment demand and limit the number of hours available for aircraft "use" over a three-day period. Finally, constraint Eq. (5) ensures that the airline flies a sufficient number of trips to meet passenger demand while considering the seat capacity of each aircraft type, cap_k.

Figure 1 shows four blocks surrounding the airline fleet allocation block. The block on the left in this figure shows the modeling of market factors, particularly the two models of demand growth as a result of GDP growth and ticket price changes. Both of these models are set up as elasticities, and are referred to as Inherent Demand and Elastic Demand. The bottom block shows economic factors including changes in GDP growth rate as well as fuel price which has a direct effect on ticket prices. Note that, in FLEET, the airline passes along all its costs to the passengers in form of increased or decreased ticket prices, and hence the economic factors have a direct impact on passenger demand via the two elasticities defined above. The block on the right shows the environmental factors including policy implementation, sometimes modeled in form of constraints on the airline's operations.

B. The Aircraft Retirement and Acquisition Model

The top block in Figure 1 represents the aircraft technology factors and it includes the aircraft retirement and acquisition model which is the focus of this paper. This retirement and acquisition model makes decisions based on predicted future demand and the net present values (NPV) of both existing and potential new aircraft. The model consists of five sections as shown in Figure 2. The section labeled "Initial Calculation" assesses performance of each class of aircraft in the airline's fleet. The performance metrics include number of deployed and available aircraft in airline's fleet, average number of trips for each class (seat capacity) of aircraft, and the fraction of total market demand served by each class of aircraft.

Using the value of the predicted demand for next year, the "New Capacity" section assesses the required increase in seat capacities to satisfy increasing demand, which can be translated into number of required aircraft in each seat capacity. Following this, the "Aircraft Retirement" section estimates the number of aircraft to be retired in each technology generation and each seat capacity class. The calculation in this section is in two parts; the NPV comparisons and the aircraft frame age checks. For the NPV comparison, the maximum number of aircraft which are available to replace the existing aircraft, $avail_i$, is equal to the total number of aircraft produced in each seat class, $prod_i$, minus the required number of aircraft required to satisfy the increasing demand, $require_i$; see Eq. (6). Subsequently, the model compares NPV of two strategies, which are, first, keeping the existing aircraft and, second, replacing the existing aircraft with new and similar class aircraft. The airline in FLEET follows whichever strategy that provides higher NPV.

$$avail_i = prod_i - require_i \tag{6}$$

If there are no available aircraft to replace the existing ones, the model starts to compare the strategy of keeping existing aircraft against that of replacing it with an aircraft one class higher in seat capacity. At this

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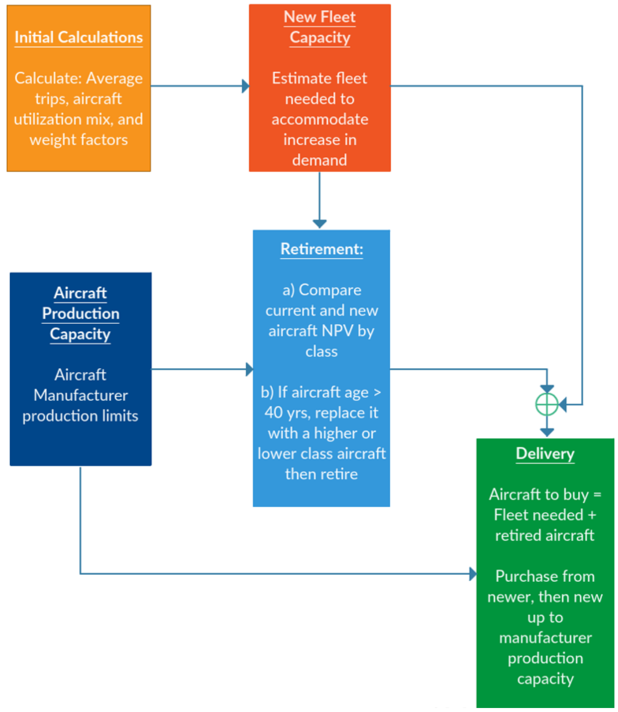

Figure 2. Flowchart of the aircraft retirement and acquisition model

stage, the airline will replace the existing aircraft with a number of new aircraft which can provide the same demand capacity as shown in Eq. (7). In this section, since the aircraft with different class might satisfy different routes, the demand capacity is the seat capacity times the average number of trips per aircraft in each seat class as shown in Eq. (8). Similarly, the airline shall follow the strategy with higher NPV. Finally, the smaller aircraft in FLEET always has higher profitability due to relatively higher ticket fare margin on shorter routes in the FLEET network, so aircraft acquisition and retirement model neglects the strategy of replacing existing aircraft with lesser seat capacity aircraft.

$$num\_new\_ac_{(i+1)} = \frac{dem\_cap_i}{dem\_cap_{(i+1)}} \times num\_retire\_ac_i \tag{7}$$

$$dem\_cap_i = seat\_cap_i \times avg\_trips_i \tag{8}$$

In the second part of "AC Retirement" section, based on assumptions on the maximum aircraft frame age, the model checks the aircraft frame age to retire the aircraft which are more than 40 years old. If there is any available aircraft to replace the existing one, the model replaces the existing one with the same seat class aircraft. Subsequently, it replaces the existing one with, first, a larger class aircraft and, second, a smaller class aircraft. Similarly, the number of new (replacement) aircraft should be used such that the same demand capacity of the existing aircraft is satisfied, and this is shown in Eq. (9). Finally, if there is no available aircraft to replace an existing aircraft, the model retires the old aircraft without replacement. The total number of acquired aircraft equals the sum of the number of new aircraft from the "AC Retirement" section and the number of required aircraft from the "New Capacity" section, as shown in Eq. (10).

$$num\_new\_ac_{(i\pm1)} = \frac{dem\_cap_i}{dem\_cap_{(i\pm1)}} \times num\_retire\_ac_i \tag{9}$$

$$ac\_order_{(i\pm1)} = num\_new\_ac_i + require_i \tag{10}$$

In the "Delivery" section, the aircraft manufacturer tries to satisfy the airline's demand for aircraft -while accounting for limited maximum production capacity for each aircraft technology generation and demand capacity. The manufacturer delivers the highest technology aircraft with the same demand capacity for newly ordered aircraft by the airline. For a scenario where there is unsatisfied number of aircraft orders, the manufacturer will deliver, first, a larger class aircraft and, second, a smaller class aircraft to the FLEET airline to satisfy the need for increased demand capacity as represented by Eq. (11).

$$num\_delivered\_ac_{(i\pm1)} = \frac{dem\_cap_i}{dem\_cap_{(i\pm1)}} \times num\_retire\_ac_i \tag{11}$$

III. Results and Discussion

Table 1 shows the 24 representative aircraft utilized in the FLEET simulation, based on the labels for seat capacity and technology ages of representative-in-class, best-in-class, new-in-class, and future-in-class. Each aircraft model was sized using the Flight Optimization Systems (FLOPS) tool,[8] where several mission profiles were simulated to generate look-up tables for direct operating costs (DOC), fuel burn and LTO NOx over all ranges and load factors for the aircraft models. Representative-in-class aircraft are those that had the highest number of aircraft operations in 2005 within each seat class and are typically older aircraft. The best-in-class aircraft are those that had the most recent service-entry date within each seat class and are generally equipped with the latest technologies. The new-in-class aircraft are aircraft currently in development that will enter service in the future or conceptual aircraft that incorporate future technology improvements. Likewise, the future-in-class aircraft are those aircraft expected to include another generation of technology improvements and therefore expected to enter service at a later date in the future. The aircraft models are further divided into six classes based on seat capacity, such that classes 1, 2, 3, 4, 5, and 6 are equivalent to small regional jet, regional jet, single aisle, small twin aisle, large twin aisle, and large quad aircraft respectively.

Table 1. Aircraft Models used in FLEET[7]

Class (Seats)	Representative-in-Class	Best-in-Class	New-in-Class	Future-in-Class
1 (20 – 50)	Canadair RJ200/RJ440	Embraer ERJ145	Small Regional Jet	
2 (51 – 99)	Canadair RJ700	Embraer 170	CS100	
3 (100 – 149)	Boeing 737-300	Boeing 737-700	Boeing 737-700 Re-engined	Purdue Small ASAT with N+1 / N+2-level tech
4 (150 – 199)	Boeing 757-200	Boeing 737-800	Boeing 737-800 Re-engined	D-8 "Double Bubble"
5 (200 – 299)	Boeing 767-300	Airbus A330-200	Boeing 787	
6 (300+)	Boeing 747-400	Boeing 777-200ER	Large Twin Aisle	

FLEET can handle several different scenarios of economy, demand growth, and policy implementation. While the primary objective of FLEET is to assess the environmental impact of aviation as a result of the airline's decisions, this section presents results of three plausible future scenarios with emphasis on airline decisions for aircraft retirement and acquisition. The three scenarios discussed in this section are the *Baseline*, *Late EIS*, and *Low GDP* scenarios. These scenarios stem from those investigated in an ongoing effort within the FAA ASCENT Center of Excellence Project 10. The variation amongst the scenarios is primarily based on demand for air travel and expected date of new aircraft technology introduction as a result of research and development (R&D) expenditure. FLEET uses historical data for demand estimation from 2005 to 2008. After 2008, a 1% GDP growth rate leads to an annual inherent demand growth rate of 1.4%.

Table 2 shows the entry into service dates for next generation (next-gen) aircraft throughout the FLEET simulation period for the *Baseline* scenario. Latest small regional jet (class 1) production forecasts reveal that aircraft manufacturers are rapidly reducing small regional jet aircraft production (due to reduced airline utilization), and increasing the production of larger next-gen regional jets (Class 2).[9] Hence, next-gen class 1 aircraft are unavailable to the FLEET airline during the simulation period.

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Table 2. **Entry-into-Service (EIS) Dates for Next-Gen FLEET Aircraft - *Baseline* scenario**

Generation	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
New-in-Class	-	2016	2016	2018	2018	2020
Future-in-Class	-	2028	2025	2024	2030	2027

1. ***Baseline***: New-in-class and future-in-class aircraft are first introduced in 2016 and 2024 respectively. This scenario represents the "best guess" expected date of new aircraft technology with respect to current trends and events. Also, a GDP growth rate of 2.8%, starting in 2009, is used to estimate inherent demand on all FLEET routes except routes to and from Asia where a GDP growth rate of 4.3% is used.

2. ***Late EIS***: Here, future aircraft with technological advancements are introduced much later than expected. As compared to the Baseline scenario, new-in-class aircraft are introduced 5 years later, while future-in-class aircraft are introduced 10 years later. However, the GDP growth rate remains the same as the Baseline scenario. This scenario portrays an instance where less expenditure is allocated to R&D as compared to the Baseline scenario, thus delaying the availability of next-gen aircraft.

3. ***Low GDP***: In this scenario, next-gen aircraft (i.e. new-in-class and future-in-class aircraft) are introduced at the same time as in the Baseline scenario, but the inherent demand for air travel is much lower when compared to the Baseline scenario (GDP growth rate of 2% for all routes except routes to and from Asia where a GDP growth rate of 3.07% is applied).

Except the aforementioned differences in entry-into-service dates of new technology aircraft and passenger demand, all three scenarios are identical in all respects:

1. FLEET simulations start in the year 2005 and run to 2050.

2. A network of 169 airports including U.S. domestic routes and international routes that either originate or terminate in the U.S.

3. Jet fuel prices increase according to the U.S. Energy Information Administration (EIA) reference fuel price projections (increases slightly above predicted inflation).[10]

4. No airport capacity constraints are imposed.

5. No biofuel option is introduced.

Figure 3 shows the retirement and acquisition behavior for the class 1 aircraft during the simulation period. In the *Baseline* and *Late EIS* scenarios, the number of class 1 aircraft delivered to the airline after the mid 2020s is limited to the number of aircraft produced by the manufacturer. However, the *Low GDP* scenario reveals that the number of class 1 aircraft delivered to the airline towards the later part of the simulation is exactly equal to the number of aircraft demanded (or required) by the airline, which never exceeds the number of class 1 aircraft produced during the simulation. Also, the airline retires more class 1 aircraft, between early 2020s and early 2030s, in the *Low GDP* scenario when compared to the other scenarios. Notably, in the *Baseline* and *Late EIS* scenarios, the rate at which the airline requires class 1 aircraft for its operation (after the late 2020s) consistently supersedes the rate at which the aircraft manufacturer produces new class 1 aircraft, thus allowing the number of class 1 aircraft demanded to exceed the amount produced after the early 2040s. This behavior reveals that the aircraft manufacturer is unable to keep up with the airline's need for more class 1 aircraft to serve increasing passenger demand on short routes in the FLEET network.

Figure 4 shows the retirement and acquisition behavior for the class 3 aircraft throughout the simulation. While the general retirement and acquisition behavior (in all three scenarios) for the class 3 aircraft are somewhat similar to those observed for the class 1 aircraft, it is important to note the significant increase and fluctuation in total number of aircraft delivered and retired for class 3 as compared to class 1. This increase is due to a wider variation in operational range of the class 3 aircraft, which makes them more susceptible to fleet turnover because the airline acquires next-gen variants (and retires older versions) as they become available.

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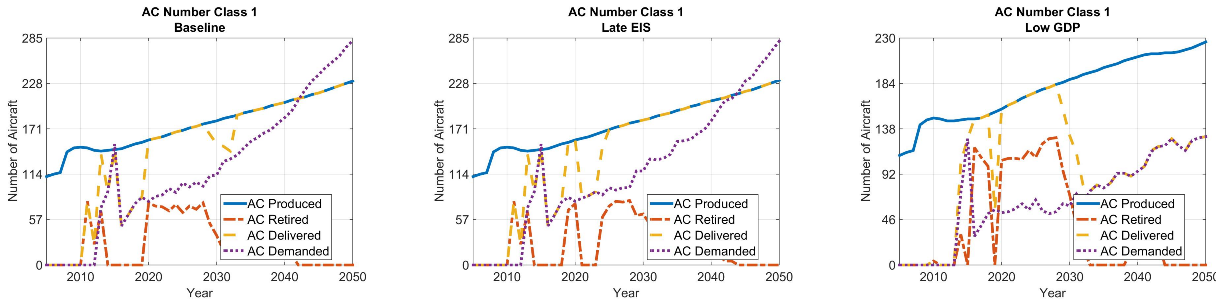
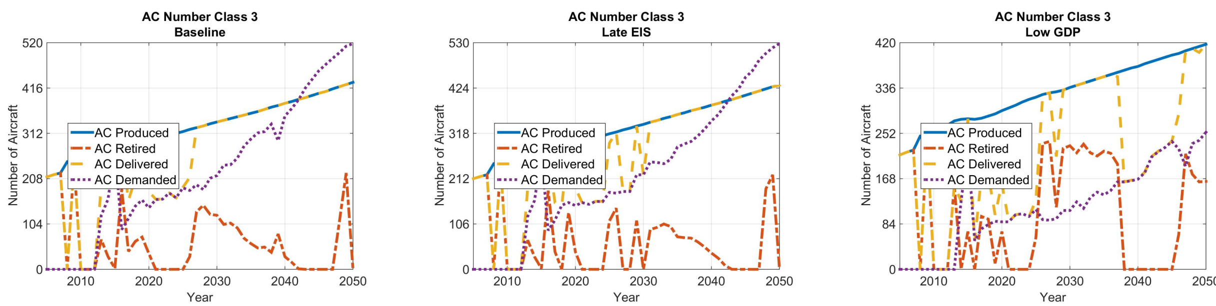


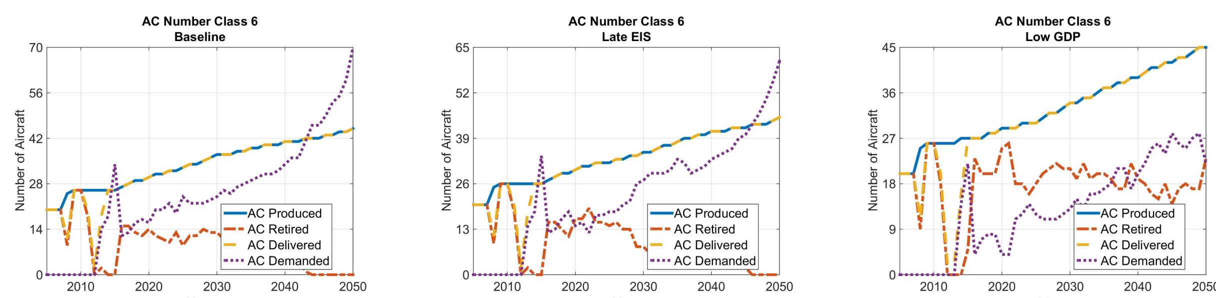
(a) Baseline (b) Late EIS (c) Low GDP

Figure 3. Retirement and Acquisition for Class 1 Aircraft



(a) Baseline (b) Late EIS (c) Low GDP

Figure 4. Retirement and Acquisition for Class 3 Aircraft



(a) Baseline (b) Late EIS (c) Low GDP

Figure 5. Retirement and Acquisition for Class 6 Aircraft

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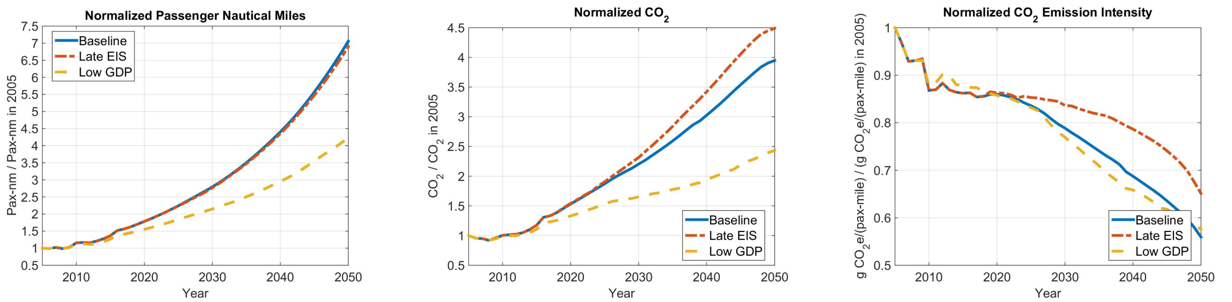
Figure 5 shows the retirement and acquisition behavior for the class 6 aircraft. The total number of class 6 aircraft produced by the aircraft manufacturer and delivered to the airline is considerably less compared to classes 1 and 3. Unlike the trends observed for classes 1 and 3, the number of class 6 aircraft delivered to the airline for most of the simulation period, in all three scenarios, is equal to the amount produced by the manufacturer. This behavior reveals that the airline's need to serve the demand on very long routes, which can only be achieved by this class of aircraft. The reduced number of retirements in the *Baseline* and *Late EIS* scenarios towards the later part of the simulation is a strategy the airline employs while operating on very long routes as passenger demand increases.



(a) Normalized passenger nautical miles (b) Normalized CO_2 emissions (c) Normalized CO_2 emission intensity

Figure 6. Fleet-wide Economic and Environmental Results

The fleet-wide economic and environmental results - comprised of passenger nautical miles, total CO_2 emissions, and CO_2 emission intensity - are shown in Figure 6, such that the yearly results in each scenario are normalized by their corresponding values in 2005. While the *Baseline* and *Late EIS* scenarios have very similar trends in passenger nautical miles throughout the simulation, the *Late EIS* scenario has higher CO_2 emissions and emission intensity starting from the mid 2020s until 2050. The increased total CO_2 emission in the *Late EIS* scenario is due to the delay in availability of next-gen aircraft, such that the FLEET airline is unable to acquire next-gen aircraft fast enough to reduce emissions. Relatively low total CO_2 emissions from the *Low GDP* scenario is due to low demand for air travel, which consequently reduces aircraft utilization.

IV. Conclusion and Ongoing Work

Many factors contribute to airlines' decisions on fleet planning. FLEET models aircraft retirement decisions on the basis of NPV of potential new versus existing aircraft, and new aircraft acquisition decisions on the basis of expected market demand to be satisfied in the future years. The model presented in this paper has performed satisfactorily on a range of different scenarios.

As part of ongoing work, we are exploring a number of improvements and changes that can be made on the model. One such change is on the aircraft production capacity model. Currently the aircraft production limits are not responsive to market demand. However, given that the aircraft manufacturers also forecast demand, it is reasonable to expect them to increase or decrease production capacity based on their estimates of number aircraft required in the future. We are working towards implementation of this capability, viz., that the production limits change as expected future demand growth changes.

Yet another improvement that we are currently exploring is how future requirement of number of aircraft by seat capacity is calculated. Currently, FLEET looks at previous years' average utilization of aircraft by class to estimate future requirement of each class of aircraft. Our current exploration centers around using aircraft performance data in addition to their utilization to calculate future requirement of aircraft.

FLEET uses several abstractions to model the complex social, economic and technological interactions within the air transportation system. For example, the aircraft acquisition module in FLEET assumes that the airline properly ordered aircraft so they are available exactly when needed. Future work can consider the effect of time delay between aircraft orders and deliveries. Further, some scenarios explored using FLEET have demonstrated the effect of entry-in-service dates of new technology aircraft, which can vary depending on the level of investment on research and development that aircraft manufacturers make.

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