DEVELOPING OPTIMAL AIRLINE FLEETS UNDER ENVIRONMENTAL AND CAPACITY CONSTRAINTS

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Abstract

Fleet-level Environmental Evaluation Tool (FLEET) is a NASA sponsored simulation tool to assess environmental impact of aviation (emissions and noise) impact under scenarios of market demand and aircraft technology availability. By modeling airline operations as a resource allocation problem, various scenarios of market and economic conditions, aircraft technology availability and policy implementation can be studied using FLEET.

The current work focuses on evaluation of the decisions airlines make in order to stay competitive and the consequent impact on air travel in the face of imposed environmental policy and airport capacity constraints. Also, the fraction of market demand served under various emissions reduction targets is computed. Results indicate that imposing very strict carbon emissions constraints could be counterproductive in the sense that a significant portion of demand will go unmet.

1 Introduction and Motivation

The environmental impact of aviation has come under increasing focus over the past few years. In response to the attention, agencies such as NASA and ICAO, among others, have set forth goals for reduced CO_2 and NO_x emissions from aviation. NASA, for example, aims to reduce fuel burn by 33% with respect to current aircraft, cumulative certification noise by 32 dB from Stage 4 levels, and landing and takeoff nitrogen oxide (LTO NOx) emissions by 60% from CAEP/6 levels for N+1 generation aircraft that use technology with predicted availability by 2015. With technology available by 2020, NASA's N+2 generation aircraft will reduce fuel burn by 50% from current aircraft, cumulative noise by 42 dB from Stage 4 levels and LTO NO_x by 75% from CAEP/6 levels. The goals for N+3 generation aircraft, with technology available by 2025, aim to reduce fuel burn by more than 70%, cumulative noise by 71 dB, and LTO NO_x by more than 75%.[1]

The impact of aviation, however, depends not just on the availability of technology, but also on its utilization by the airlines. Furthermore, even with improving aircraft technology, future emission and noise levels can exceed current levels if the demand for air transportation continues to grow. Hence, the motivation for the development of Fleet-Level Environmental Evaluation Tool (FLEET) was to provide a tool to enable a simultaneous assessment of market demand, airline economics, aircraft technology introduction into airline fleet and the emissions resulting from their operation.

The engine behind FLEET is an aircraft allocation model that represents airlines operations and decision-making. This allocation model is surrounded by a system dynamics approach that mimics the economics of airline operations, models the airlines' decisions regarding retirement and acquisition of aircraft as well as market demand growth in response to economic conditions. Since eventually each of these factors would affect the airline fleet, a unifying study to integrate these and thereby suggest an optimal fleet composition is required. This unified study provides a goalpost for an optimal fleet composition and may aid decision-making about future policies and investment in technologies.

2 Scope and Methods of Approach

The flight operations in FLEET are based on a benevolent monopoly airline model wherein all US airlines are aggregated into one airline that operates all aircraft. The interactions between various components of the air transportation network are modeled as a systems dynamics stock-and-flow model. This section provides an overview of various components of FLEET; details of their development can be found in [2-6].

2.1 Route Network, Demand and Fleet Composition

A number of abstractions are used to account for the large number of actual routes and aircraft in operation while still keeping the size of the problem manageable. The air transportation network modeled consists of only those routes that connect the WWLMINET 257 airports [7] including international routes with either the origin or destination in the US. In 2005, approximately 65% of all passenger air traffic – 80% of international passengers traveling to and from the US and domestic passengers – had as origin or destination one of these airports. The 2005 passenger demand between these 257 airports is obtained from data provided by the Bureau of Transportation Statistics DB1B database.[8]

The aircraft in operation are represented by a set of 18 aircraft divided into 6 classes based on seat capacity. To represent technology groups (or technology "ages") within the aircraft classes, each class is further segregated into a representative-in-class, a best-in-class, and a new-in-class aircraft. Representative-in-class aircraft are those that had the highest number of 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 thus equipped with the more recent technological advances. The new-in-class aircraft are either aircraft currently under development that will enter service in the future or concept aircraft that incorporate technology improvements expected in the future. Table 1 presents the representative-, best- and new-in-class aircraft used in FLEET.

Each of these aircraft were sized using the Flight Optimization System (FLOPS).[9] FLOPS was used to simulate various missions to generate tables for direct operating costs (DOC), fuel burn and LTO NO_x over all ranges and load factors for the aircraft.

2.2 Solution Methodology

The backbone of FLEET is an aircraft allocation problem, which is formulated and solved as a mixed integer programming problem. As mentioned, this problem is based on the modeling of a single benevolent monopoly airline that operates all aircraft. This Mixed Integer Programming problem is solved using the GAMS software package.[10] The problem uses the performance characteristics of the aircraft in table 1 to maximize profit while meeting demand and operational constraints as a model of airline operations and decision-making. The mathematical form of the resource allocation problem is given by equations (1) – (4):

Table 1: Aircraft types modeled in study

Class	Seats	Representative-in-Class	Best-in-Class	New-in-Class
Class 1	20 – 50	Canadair RJ200/RJ440	Embraer ERJ145	Aircraft X1
Class 2	51 – 99	Canadair RJ700	Embraer 170	Aircraft X2
Class 3	100 – 149	Boeing 737-300	Boeing 737-700	CS100
Class 4	150 – 199	Boeing 757-200	Boeing 737-800	Purdue ASAT
Class 5	200 – 299	Boeing 767-300	Airbus A330-200	Boeing 787
Class 6	300+	Boeing 747-400	Boeing 777-200ER	Aircraft X6

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

$$\sum_{k=1}^{K} pax_{k,j} = dem_j \quad (2)$$

$$pax_{k,j} \le x_{k,j}\cdot\left(cap_k \cdot LF_k\right) \quad (3)$$

$$\sum_{k=1}^{K}\left(x_{k,j}\cdot\left(BH_{k,j}+MH\right)+x_{k,j}\cdot t\right) \le \left(24/2\right)\cdot fleet_k \quad (4)$$

where $x_{k,j}$ *and* $pax_{k,j}$ are integer variables.

The integer decision variable $x_{k,j}$ is the number of trips that aircraft type k flies on route j while the integer variable $pax_{k,j}$ is the number of passengers that fly on aircraft type k on route j. Routes use a single subscript, because of a round trip assumption described below. Eq. (1) is the objective funtion to be maximized by the optimization program. It gives the operating profit margin of the airline, defined as the difference between revenue and cost. Revenue is a function of ticket price, $P_{k,j}$, and the number of passengers on each aircraft type and route, $pax_{k,j}$. Ticket price is a function of the aircraft type and route on which a passenger flies. Profit is, therefore, the sum of profit from each of the routes and for each of the aircraft types.

Constraints in Eq. (2) ensure that the airline meets all passenger demand while constraints in Eq. (3) ensure that the airline flies a sufficient number of trips to meet passenger demand while considering the seat capacity of each aircraft type, cap_k, and its load factor, LF_k. The constraints in Eq. (4) count the number of aircraft necessary to satisfy demand and limit the number of hours available for aircraft "use" in a given day. The problem assumes that passenger demand is symmetric and the aircraft can fly round-trips; therefore, the number of available hours is limited to 12 hours (24/2). This is a reasonable assumption because the fleet allocation problem estimates the cost and profit of average daily operations, and the BTS data [8] shows that average daily demand is nearly symmetric although a given passenger may not fly a return trip on the same day. Bounds on the decision variable $x_{k,j}$ ensure that an aircraft type does not operate in and out of an airport that does not have a long enough runway and that an aircraft does not operate on routes that exceed its design range. The round-trip simplification removes the need for flow-balance constraints in the allocation problem.

Time contributors to the aircraft utilization are block time ($BH_{k,j}$), which accounts for the taxi-out time, flight time on route j, and taxi-in time. The turnaround time, t, is assumed to be one hour per trip for all aircraft. In this constraint, an aggregate approach accounts for the unavailability of aircraft due to maintenance. By accounting for maintenance hours for each flight hour for all the aircraft, MH, the total number of aircraft the airline needs to serve the daily demand cannot exceed the available number of aircraft in the fleet, including those available for flight and those in maintenance. By analyzing the aircraft utilization and traffic data of the BTS database, the Airline Data Project [11] presents a breakdown of the average daily departures and daily block hour utilization of the aircraft utilized by main and regional domestic carriers. Using this data and assuming a turnaround time of one hour per departure it is possible to account for the aircraft activity during an average day by computing the sum of the time the aircraft spent in flight, in maintenance, and preparing for departures:

$$BH_a\left(1+\frac{EMH_a}{BH_a}\right)+t.departures_a = 24 \quad (5)$$

where BH_a is the average daily block hour utilization for each aircraft type a ([11] classifies aircraft into three types: small narrow-body, large narrow-body, and wide-body), EMH_a is the Elapsed Maintenance Hours, which captures the clock time that the aircraft is unavailable and $departures_a$ is the average daily departures of aircraft type a.

Solving Eq. (5) for the ratio of Elapsed Maintenance Hours per block hour, EMH/BH, estimates the unavailability of aircraft due to maintenance as a function of the aircraft utilization. Because FLEET uses six classes of aircraft based on their seating capacity, we

Table 2: Equivalent Maintenance hours per block hour (*EMH/BH*) of modeled aircraft

Aircraft Type	EMH/BH
Class 1	0.936
Class 2	0.936
Class 3	0.936
Class 4	0.948
Class 5	0.866
Class 6	0.866

apply the EMH/BH ratio of the small narrow-body aircraft to the class-1, class-2 aircraft, and class-3 aircraft, the ratio of the large narrow-body aircraft to class-4 aircraft, and the ratio of the wide-body aircraft to class-5 and class-6 aircraft. Table 2 presents EMH/BH for the aircraft modeled in the study. With finer data resolution, each of the aircraft types modeled here – representative-, best-, and new-in-class – and each aircraft class could have a different ratio of maintenance hours per block hour because newer designs explicitly address maintainability and an aircraft's physical size impacts the inspection and repair time.

Integer Programming methods can solve the allocation problem presented in Eqs. (1)-(4). The software package GAMS (General Algebraic Modeling System) facilitates formulation and solution of this IP problem. GAMS provides an algebraically-based, high-level language for the compact representation of large and complex models and uses the CPLEX solver to solve the IP problem. [12]

Finally, total noise area is not a commonly used metric; generally, aviation noise deals with noise associated with a local airport. However, to provide a single metric to describe the broad fleet impact, "total noise area" is the sum of the predicted area inside the 65 dB DNL contour at all 102 domestic airports in the LMINET. This metric does not include international airports, because the airline model does not attempt to represent all operations at those airports; the current airline model more nearly represents all operations at US airports. The daily cost, CO_2 production, total NO_X and total noise area values reflect the allocated fleet to optimize profit while meeting demand, with the aircraft class abstractions and round trip assumptions described above.

3 Aircraft Retirement and Acquisition

The primary focus of this paper is on the outcome of airlines' decision making concerning retirement of old aircraft and acquisition of new ones in presence of environmental constraints. The aircraft retirement and delivery model that was developed makes possible the consideration of several aircraft delivery approaches that can lead to the analysis and identification of technology penetration schemes that can help to achieve the NASA SFW goals.

3.1 Aircraft Retirement

To model aircraft retirement, the BTS Schedule B-43 Aircraft Inventory database [13] is used to determine entry-in-service date of the aircraft modeled here. The Schedule B-43 database contains detailed information regarding the entry in operation of passenger transport aircraft by tail number. Keeping track of the entry in service dates and availability of the new aircraft in the market, the model seeks to find an optimal retirement age of the aircraft in the fleet.

The new retirement model evaluates, annually, economic feasibility of retaining an aircraft for an additional year versus its immediate retirement. It works by comparing the net present values of the following two options:

Option 1: Operate the existing aircraft for one more year and the replacement aircraft enters service in the following year.

Option 2: The replacement aircraft enters in service in the current year.

In calculation of the NPV, all future cash flows are discounted with respect to the base year 2005 using a discount factor as prescribed by the Office of Management and Budget. [14]

The retirement function requires a detailed cost and revenue structure for both the existing and replacement aircraft. The components of cash flows for an aircraft include the fuel costs, initial acquisition cost, maintenance costs, other direct operating costs such as insurance, crew salaries and servicing and its indirect operating costs. All these values are obtained from FLOPS. The revenues in form of ticket prices are obtained from the ticket price function in FLEET as described above. To simulate the increase in maintenance cost as the aircraft ages, the model uses the RAND maturity curve.[15, 16] Finally, since the number of deliveries are limited, a cap is set on the number of aircraft that can be retired and this cap equals the total number of possible deliveries per class.

The retirement function makes some assumptions in its calculations, including:

1. The aircraft maximum airframe life is assumed to be 40 years. This means once an aircraft is over 40 years old, it is automatically retired from service.
2. The acquisition cost is paid off over a period of 15 years with an annual interest rate of 5%. Early retirement of an aircraft leads to a penalty being applied.
3. The resale value of an aircraft depreciates according to a bi-linear curve wherein its value falls to 10% of original in the first 15 years and then reduces to 1% of original by the end of 40 years.

3.2 Aircraft Acquisition

The aircraft acquisition process has two main steps:

1. The calculation of maximum number of deliveries possible based on aircraft production capacity, and
2. The calculation of number of aircraft to be acquired to meet projected demand for the following year.

3.2.1 Aircraft Production Capacity

The total number of deliveries possible each year is constrained by the production capacity of the various airframe manufacturers as approximated by eq. (6).

$$production = 1309 + 30.83 \times time \qquad (6)$$

This equation is based on regression of the historical data of actual deliveries of the six classes aircraft used in FLEET. Here, *production* gives the total number aircraft that are produced in the current year and *time* indicates the number of years since start of simulation. This production capacity is then split amongst the six classes based on the market share of each of these classes. A detailed description of this function can be found in [5, 6].

3.2.2 Aircraft Delivery

The aircraft delivery model calculates the number of aircraft to be acquired in the following year as a function of estimated future demand growth and current capacity. Demand for next year is estimated based on inherent demand growth rate and demand price elasticity. The inherent demand growth rate reflects the continuing trend of growing demand for air travel as the economy grows. Thus inherent demand is setup to be proportional to GDP growth with a proportionality constant of 1.4, which results in demand growth of 1.4% for 1% economic growth. Demand-price elasticity reflects passengers' sensitivity to ticket price changes. This is because an increase in ticket prices is expected to lead to lower demand and vice versa. Passenger sensitivity is also a takes into account the distance of travel and availability of alternate modes of transport.

Once the additional capacity required to handle demand growth is calculated, the number of aircraft to be acquired is computed based on available capacity, the number of retirements, and unused capacity. Eq. (7) gives this number for each class in each year.

$$acquisitions_i = fleet\_need_i + retirements_i \qquad (7)$$

Here, *fleet_need* reflects the increased capacity required due to an increase in demand while *retirements* accounts for the number of aircraft retired this year and the subscript *i* indicates that these values are calculated for each class. The calculation of *fleet_need* and *retirements* is done as shown in eqs. (8) to (11).

$$fleet\_need_i = \frac{cap\_needed_i}{average\_trips_i \times seat\_cap_i} \quad (8)$$

$$cap\_needed_i = (\Delta demand \times acquisition\_factor_i) - (unused\_ac_i \times average\_trips_i \times seat\_cap_i) \quad (9)$$

$$acquisition\_factor_i = \frac{\sum_j weighted\_factor_{i,j}}{\sum_i \sum_j weighted\_factor_{i,j}} \quad (10)$$

$$weighted\_factor_{i,j} = \alpha \frac{pax_{i,j}}{\sum_j pax_{i,j}} + \beta \frac{1/unitDOC_{i,j}}{\sum_j 1/unitDOC_{i,j}} \quad (11)$$

First the additional capacity required in number of seats is calculated as the increase in demand from previous year. This capacity is distributed to the six classes of aircraft based on a calculated *weighted_factor* for each class which is calculated as explained below. Also, from the calculated capacity, excess capacity in form of unused aircraft is subtracted. This reflects the extra aircraft available to the airline in the previous year that were not required to solve the allocation problem.

The *weighted_factor* determines the distribution of new capacity between the six classes of aircraft on each route. This factor assigns weights to aircraft based on their market share as measured by the fraction of passengers carried by that class on each route, and their predicted operating cost per seat mile. The rationale for this is that a higher utilization would mean that the airline would seek to buy more of similar aircraft while a lower operating DOC would mean that aircraft would be more economically efficient and thus desirable for inclusion into the fleet. In the calculation of *weighted_factor*, the parameters α and β can be used to assigned different importance to each of the two contributing factors. Here, both were given a value of 0.5 to indicate the airline giving equal importance to both factors. Finally, the *acquisition_factor*, calculated as in eq. (10), assigns weights to acquisition of a particular class of aircraft based its *weighted_factor*.

4 Studies and Results

Studies selected for this paper aim to analyze and suggest an optimal aircraft fleet to the airline under constraints of environmental policy and airport capacity. An optimal aircraft fleet composition would be one that meets market demand, is economically attractive to the airline and is efficient with regards to operations and emissions. An understanding of the optimal aircraft fleet implies understanding the distribution of the fleet with respect to the size of aircraft as well as the technology level. Such an understanding would assist the airlines in their decisions as they balance their economic objectives with environmental constraints.

4.1 Environmental Objectives

Two notable organizations have specified emissions reductions targets. These targets provide the motivation for studies conducted in this paper and are described in the following subsections.

4.1.1 ATA Goals

Airlines for America, formerly known as Air Transport Association of America, Inc. (ATA), has set up goals for CO_2 emissions reduction by 2050.[17] Their goals can be summarized as follows:

1. Improve fuel efficiency by an average of 1.5% annually to 2020
2. Achieve carbon neutral growth by 2020
3. Reduce emissions by 50% by 2050 from 2005 value

They aim to achieve these goals by means such as modernization of air traffic control systems, and investments in research and development and sustainable alternative aviation fuels. [17]

4.1.2 ACES Goals

The American Clean Energy and Security Act of 2009 (ACES) also called the Waxman-Markey Bill, sets provisions regarding transitioning to using clean and efficient sources of energy and reducing carbon emissions. [18] Under this bill, the government establishes carbon emissions caps limiting the maximum emissions to be emitted in United States. Companies that emit carbon can buy or sell emissions permits as per their need. Also, the cap is gradually tightened as per the schedule given in table 3.

Table 3: ACES carbon reduction targets

Year	% Reduction in CO_2
2012	3.0
2020	17.0
2030	42.0
2050	83.0

These goals apply to entire economic sector, but the studies conducted here assume that aviation gets equivalent targets.

4.2 Studies Setup

4.2.1 Studies on Environmental Policies

Both the ATA and ACES scenarios were simulated in FLEET to assess their impact on demand for air travel and airline response to the constraints. The allocation problem described earlier is solved with the addition of fuel burn limit constraint as given by eq. (12).

$$\sum_{k=1}^{K}\sum_{j=1}^{N} fuelburn_{k,j} \leq fuelburn_{\mathrm{limit}} \qquad (12)$$

This constraint imposes a limit on CO_2 emissions by setting the maximum amount of fuel that the airline can burn throughout its network (1 kg of fuel burn is equivalent to 3.16 kg of CO_2). For both scenarios, the total fuel burn limits in consequent years changed linearly such that the specified objectives would be met. In the ATA scenario, the airline was allowed unrestricted amount of fuel burn until 2020. Any improvements to efficiency were assumed to result from shift to new technology aircraft, two of which were introduced before this date. Thereafter, the maximum fuel burn limit was held constant until 2035 to suggest carbon neutral performance. Between these years, the remaining four N+2 generation aircraft came into service. Also, the year 2035 is close to the introduction date of N+3 generation aircraft. Thereafter, the fuel burn limit fell linearly to 50% of the 2005 level by 2050. In the ACES scenario, fuel burn limits varied linearly between the various targets suggested by the bill.

4.2.2 Studies on Airport Capacity

With the growth in air travel, some large airports are now reaching their maximum capacity leading to congestion. Since these large airports also handle the flights, congestion at these airports leads to delays system-wide and inconvenience to passengers.

Studies were setup to analyze airline response to congestion at large airports. For all 257 airports used in the simulation, data for their maximum operating capacity and daily number of operations in 15 min periods was gathered from BTS database. Then using the peak operations as the effective capacity, constraints on number of operations were set up as shown by eq. (13).

$$P\sum_{i}\sum_{j} x_{ij} \leq x_{\max} \qquad (13)$$

Here, $x_{i,j}$ specifies the number of operations of aircraft type *i* on route *j* at that airport and x_{max} specifies the maximum level of operations possible. *P* is the fraction of operations that take place at the airport when it is operating at its peak capacity over the total number of daily operations.

4.3 Results and Analysis

Studies conducted under the ATA and the ACES emissions reduction targets showed that as a result of these objectives, the market demand served by the airlines dropped drastically as the cap limits become stricter. Figure 1 shows the total market demand served by the airline in a given year normalized by its

2005 value. The line labeled 'No Carbon Constraints' is the market demand, assuming a GDP growth of 2% per annum, had the fuel burn constraint not been imposed. The total market demand served, which due to the profit making nature of the airline, tends to equal the actual market demand for air travel, grows to about 3.6 times its 2005 value if no emissions constraint is imposed. On the other hand, the demand served under the ATA and ACES scenarios is significantly lower. Demand served in 2050 is only 1.21 times its 2005 value in the former scenario, while in the latter scenario, this value is 0.55 times.

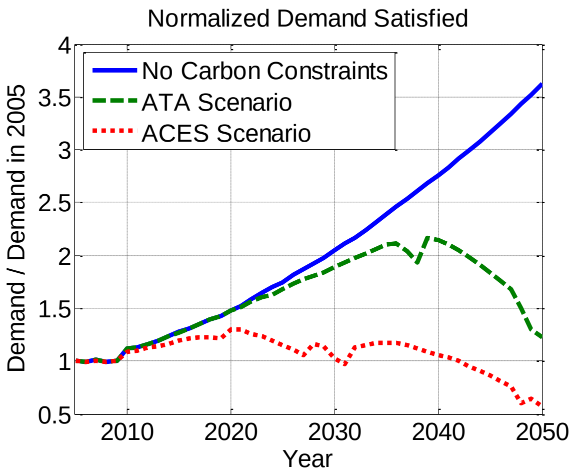

Fig. 1: Normalized demand served values for simulated cases

Demand in the ATA scenario follows a trend similar to the baseline for 10 years after introduction of the constraints. However, the demand served begins to fall rapidly after 2037 as can be seen by the downward slope of the curve. By 2037, all N+2 technology aircraft have already been introduced in the fleet, and though the entire fleet has not been upgraded, the airline stops buying any more aircraft due to the tightening constraints and its inability to meet demand. The ACES scenario, on the other hand, shows strong divergence almost right from the beginning.

Likewise, Figure 2 gives the progression in CO_2 emissions under these scenarios. Since CO_2 emissions are directly proportional to fuel burn, they follow a trajectory similar to the network-level fuel burn of the airline.

However, in both cases, results indicated that to meet these constraints, airlines had to

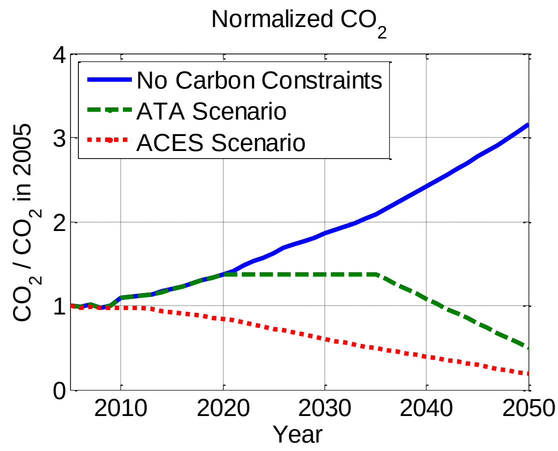

Fig. 2: Normalized CO_2 emission values for simulated cases

drop several long distance routes which led to an unrealistically large proportion of market demand not being satisfied. This indicated that these objectives may be highly ambitious especially if attainment of these goals is dependent solely on introduction of new technology. Thus to understand how quickly and to what extent do carbon reduction goals affect the aviation industry, a parametric study was setup which varied this reduction target.

Figure 3 shows the setup of the parametric study. In this study, as in ATA scenario, fuel burn was allowed to grow unrestricted until 2020. Thereafter, this limit varied linearly to some fraction of 2005 value by 2050. Here, the fractions ranged from 20% to 200% of the 2005 level.

As demonstrated in the case of ATA and ACES scenarios, emissions reduction targets induce the airline to drop some service in order to meet these targets. Figure 4 shows the effect on demand served as a fraction of total market demand across a range of carbon constraints simulated. As can be seen from the figure, the percentage of market demand served drops to very low values as the constraint is tightened. In the case where the 2050 value for total emissions is limited to 20% of 2005 value, the demand served drops to close to 20% of total market demand in the years after 2047. Thus more stringent carbon constraints severely reduce air travel demand, an insight that should be taken into consideration while formulating policies to meet emissions targets.

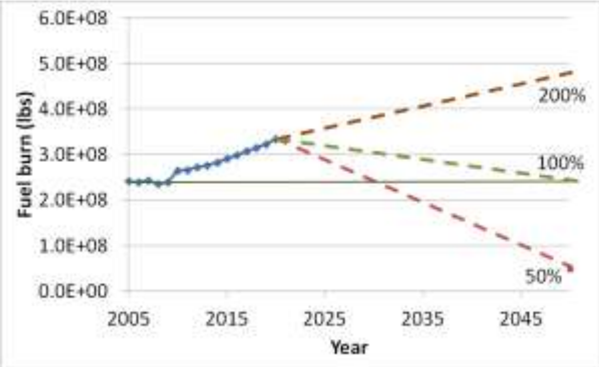

Fig. 3: Emissions reduction targets for parametric studies

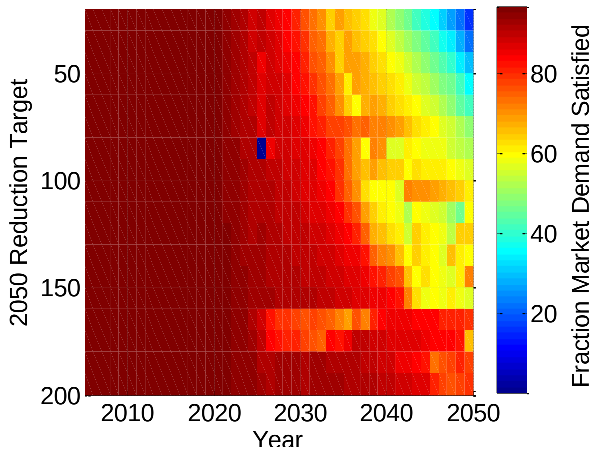

Fig. 4: Fraction of market demand served (color bar) under various emissions reduction targets

Since the airline is setup to be profit seeking, it achieved the goals by dropping demand on long-distance low profit generating routes that required high amounts of fuel. Thus, many long-haul markets would not be served by the airlines due to such constraints. Furthermore, since airlines could not meet demand due to stringent constraints, they did not have a necessity to acquire more aircraft, leading to a reduction in fleet size. This would lead to a decrease in demand for new aircraft, severely affecting the aircraft manufacturing industry.

While constraints on emissions lead the airline to stop serving some routes, capacity constraints at the airports lead them to use large aircraft to meet demand. Table 4 gives a comparison of the fleet utilized in two scenarios, one of which had airport capacity constraints imposed and the other which did not.

As seen from the table, the airline increases the use of class 6 in order to meet demand at congested airports. However, as can be seen in Figure 5, despite this increase in use of larger aircraft, the airline is still not able to meet all demand.

Table 4: Comparison of distribution of classes in fleet used in 2050

	Number of aircraft deployed in 2050	
Aircraft Class	**No Capacity Constraints**	**Airport Capacity Constraints**
Class 1	4901	5036
Class 2	1706	1729
Class 3	12012	11950
Class 4	546	295
Class 5	1965	1964
Class 6	269	405

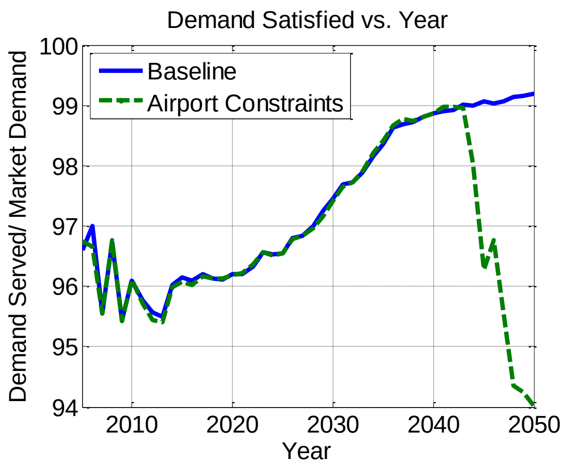

Fig. 5: Fraction of market demand satisfied

That only a few large airports can have a significant impact on the airline network can be seen from the fact that nearly 5% of market demand is dropped despite the fact that only 18 out of a total of 257 airports reach their capacity limits by 2050.

5 Conclusions and Future Work

This paper demonstrated an approach to quantify and analyze the impact of environmental constraints on demand served and decisions regarding aircraft use by the airline. The results obtained indicate that some of the proposed constraints may be too strict and that a significant reduction in demand served would result from a profit seeking airline. In the study to simulate impact of airport capacity constraints, the airline chose to use a larger number of large aircraft in order to meet demand. Despite this however, the total demand served dropped as compared to the case with no constraints.

All improvements to aviation efficiency in this work were solely due to technology introduction. However, without introducing improvements in other areas of air travel such as air traffic management, the environmental goals can either not be met or only be achieved at significant cost to passengers. Future work using FLEET would take into account improvements in airline operations in addition to technological advancements. Additionally, implementation of aircraft scheduling would help assess the propagation of capacity constraints to the rest of the network.

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