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FLEET DEVELOPMENT PLANNING OF AIRLINES: INCORPORATING THE AIRCRAFT OPERATING ECONOMICS FACTOR

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Abstract

This study evaluates the effect of implementing a minimization of trip direct operating cost in aircraft allocation. The problem focus was the impact of fuel price projections on fleet development and fleet level metrics. Using the same user-defined aircraft production capacities, seat and freight load factors, and traffic growth rates projection as used in a previous study, uniform route group distances were defined and a comparison was made between the fuel burn minimization and DOC minimization methods. DOC minimization was estimated to result in a higher global fleet-wide fuel burn and CO_2 emissions. Also, at a high fuel price, the cost-optimized fleet allocated more narrow-body aircraft, whereas more wide-body aircraft were allocated at a lower fuel price.

1 Introduction

In order to properly evaluate the future effects of aviation activity on the atmosphere, say, for compliance with goals identified by the International Air Transport Association (IATA) [1], there is need to properly model fleet development changes in the longer term (usually twenty to fifty years and longer). The goals identified by IATA can be measured at the fleet level and are:

i. an average improvement in fuel efficiency of 1.5% per year from 2009 to 2020
ii. a cap on net aviation carbon dioxide (CO_2) emissions from 2020 (carbon neutral growth)
iii. a reduction in net aviation CO_2 emissions of 50% by 2050, relative to 2005 levels.

Current works model the longer term fleet development process either using an extrapolation of historic development of fleet purchase and retirement [2], or by associating the demand growth rate expressed in Revenue Passenger kilometers (RPK) and Revenue Tonne kilometers (RTK) to industry response in terms of available seat kilometers (ASK) and available tonne kilometers (ATK) needed to meet this demand; with growth in ASK and ATK accompanied by increases in aircraft productivity in terms of seating capacity and flight frequency [3].

However, a review of literature [4–6] reveals a system-level approach to fleet development planning. This considers other factors such as the aircraft operating economics which, in addition to air travel demand, affect the planning process.

It is therefore necessary for aircraft fleet development models to be able to model airline operations, taking into account the operating economics of aircraft and airlines. This will enable a better evaluation of the effect of various market and economic conditions on longer term fleet development modeling.

Some studies exist that investigate the effect of some economic conditions on longer term aviation activity. For example, the impact of oil prices on air transportation has been investigated [7], showing that fuel price increase leads to a decrease in traffic. Also, there are other studies conducted on assessing the impact of new technologies and aircraft concepts on fleet-level metrics, by allocating the aircraft to the network with the objective function of minimizing Direct Operating Costs (DOC) [8]. In the work of [8], the allocation problem uses DOC as a surrogate for profit and revenue, assuming that the lowest DOC will provide the largest profit.

However, none of the works have investigated the impact of fuel price changes on the fleet-level metrics. Since a third to half of operating costs of airlines are spent on fuel [9], this study therefore aims at investigating the impact of longer term fuel price projections on longer term global fleet development and fleet level metrics.

1.1 Fleet Planning Theory

The macro-evaluation method of fleet planning usually implemented by airlines within the long-term planning horizon of 10-15 years basically involves the determination of aircraft retirements from a scenario-estimated capacity gap. Through scenario planning, a certain yearly traffic growth rate is used to define the expected traffic RPK_2 in a following year *2* from the base year so that the market growth gap, the additional capacity an airline is required to supply above the current capacity ASK_1 of the base year. Next, a retirement gap exists after the retirement of old inefficient aircraft. Therefore, the capacity gap is calculated as the sum of the retirement gap and the market growth gap.

This method is based on the assumption that the aircraft assignment method, and the schedule-evaluation method have been implemented, leading to an optimized aircraft assignment and utilization [4,10,11].

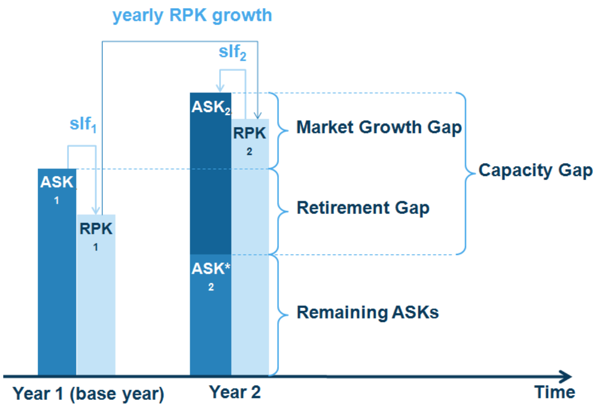

Fig. 1. Macro-evaluation Fleet Planning Method [4,10,11]

1.2 Fleet Development Modelling Approach

The "Fleet System Dynamics Model" (FSDM) [12], a global fleet development model developed at the Institute of Aircraft Design, Technical University of Munich, which is based on the macro-evaluation method described, was used and extended in this study.

1.2.1 Fleet Representation

In the model, every aircraft type which produced at least 0.1% of the global ASK in the year 2008 (base year) belong to one of nine aircraft categories (called clusters) of the initial fleet, based on multiple aircraft type-specific criteria, including transport performance-related, operational, and technical metrics. The nine clusters and their representative aircraft are shown in Table 1.

1.2.2 Representation of the global route network

Since the FSDM simulates the development of the global fleet, six geographical regions were considered in the model representing the global air traffic markets: North America (NA), South America (SA), Europe (EU), Middle East (ME), Africa (AF), and Asia (AS). The model thus simulates inter- and intra-regional flights of the representative aircraft along twenty-one route-groups, as shown in Figure 2.

Table 1. Representative Aircraft of the Initial-fleet Clusters [12]

Cluster ID	Cluster Name	Representative Aircraft Type
1	Long-range combi	Boeing MD 11
2	Long-range heavy	Boeing 747-400
3	Mid-range freighter	Boeing 767-300F
4	Jet commuter	Embraer 190
5	Long-range freighter	Boeing 747-400F
6	Turboprop commuter	ATR-72-500
7	Mid-range	Boeing 767-300
8	Long-range	Boeing 777-200
9	Narrow-body	Airbus A320-200

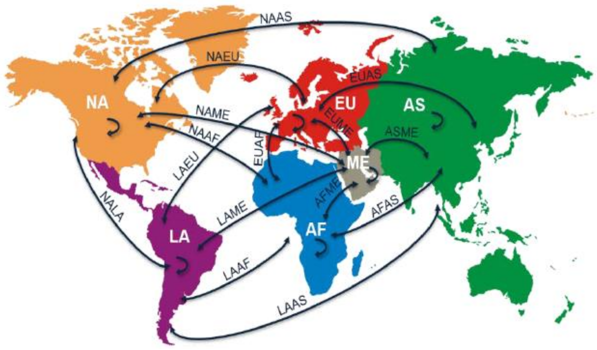

Fig. 2. FSDM Route Groups

For each route group, cluster-specific characteristic stage-lengths, seats and freight capacities were modeled based on the scheduled aircraft activities in 2008 provided by the Official Airline Guide (OAG).

1.2.3 Modeling of Next-Generation fleet

In the FSDM, the next-generation fleet (i.e. aircraft entering the fleet after 2008 to replace the initial fleet) was defined with specific entry-into-service (EIS) years as well as production limit values over time. Representative aircraft types of the next-generation fleet are shown in Table 2 together with their reference (or initial fleet) clusters and EIS year.

Table 2. Next-Generation Fleet: Cluster Data and EIS Years

Cluster ID	Ref. Cluster	Representative Aircraft Type	EIS Year
10	5	Boeing 747-8F	2011
11	7	Boeing 787-8	2011
12	2	Boeing 747-800	2012
13	8	Airbus A350-900	2015
14	9	Airbus A320-neo	2015
15	4	Embraer E-Jet E2	2016*
16	6	ATR-72-600	2019*
17	3	Boeing 787-8F	2020*
18	2	Airbus A380NEO	2021*

* = Assumed

1.2.4 Modeling of Aircraft Availability

In the FSDM, the availability of the next-generation fleet is modeled based on the aircraft production functions from the year 2008 up to the year 2021 used by [12]. These are defined in equations 1 and 2.

$$y_{nb} = 80.624x - 161052 \quad (1)$$

$$y_{wb} = 35.501x - 71128 \quad (2)$$

Equations (1) and (2) define the numbers of narrow-body aircraft and wide-body aircraft, (y_{nb} and y_{wb}, respectively) which can be produced in a year x ranging from 2007 to 2021. In the model, the production capacity of freighter is set to infinity, to accommodate the observed phenomenon of passenger aircraft being converted to freighter aircraft.

1.2.5 Determination of fleet requirements

Using the OAG data for year 2008, the flight frequencies of the initial fleet was modeled. Using the output demand (ASK and ATK) together with a scenario-defined constant seat and freight load factor of 86% and 53% respectively, the passenger traffic (*RPK*) and freight traffic (RTK) for 2008 was calculated.

Furthermore, using user-defined forecasts of market growth rates, the following year's traffic was obtained, from which the next year's output demand was calculated. This process was repeated until the target year of the analysis (not beyond 2050). The same market growth rates of [12] were used in the model for verification purpose. These are taken as constant throughout the simulation period [12]. The market growth factors used in the model are shown in Table 3.

1.2.6 Modeling of fleet operations and development

After defining the fleet of aircraft and the characteristics of the network these aircraft operate on, the next step is the fleet assignment or allocation problem which makes the aircraft "operate" on the defined network. In implementing this allocation problem, the objective function of minimizing the unit direct operating cost [$ per seat km] of each trip of the representative aircraft is used.

For the short-term analysis of aircraft operation along a route, the most common method adopted in planning is the comparison, for each candidate aircraft, of the total operating cost (TOC). As part of the TOC, the direct operating cost (DOC) approach is recommended because it helps to evaluate the performance of aircraft over the life cycle, paying attention to the aircraft utilization alongside its limit of validity [13].

Table 3. Route group growth rates [12]

Routes	**Growth Rate [% per year]**
Inter-regional routes	**Mean**
North America- Europe	3.39
North America – Latin America	4.68
North America – Asia	4.88
North America – Middle East	6.27
North America – Africa	6.20
Europe – Africa	4.86
Latin- America – Europe	5.17
Europe – Asia/ Pacific	5.81
Europe – Middle East	5.40
Middle East – Asia/Pacific	6.69
Middle East – Latin America	7.75
Middle East – Africa	6.20
Africa – Latin America	7.75
Africa – Asia/Pacific	7.67
Latin America- Asia	6.00
Regional routes	
Intra Africa	5.32
Intra Asia/ Pacific	6.18
Intra Europe	2.76
Intra Latin America	5.34
Intra Middle East	4.19
Intra North America	2.34

Thus, for an aircraft *i* flying on route *j*, the allocation problem was mathematically formulated as:

Minimize:

$$\sum_i \sum_j x_{ij} c_{ij} \qquad (3)$$

Subject to

$$\sum_i \sum_j x_{ij} \leq \sum_i x_0 \qquad (4)$$

$$\sum_i \sum_j x_{ij} . seats_{ij} \cdot RD_{ij} \cdot yearly\_freq_{ij} \leq \sum_j ASK_0 \qquad (5)$$

Equation (3) serves as the objective function to minimize the cost of operating the fleet by minimizing the direct operating cost c_{ij} of each representative aircraft of the fleet x_{ij}. The constraint in equation (4) ensures that the sum of the optimal fleet x_{ij} on each cluster and route does not exceed the sum of the initial fleet x_0 in the base year, whereas the constraint in equation (5) ensures that the capacity of the optimal fleet is comparable to the capacity ASK_0 produced by the initial fleet in the base year.

Given these two constraints, the optimizer is made to allocate the aircraft type with the minimal direct operating costs, but operating on a network to produce a capacity close to that of the initial year.

This optimization is done for the base year whereas for subsequent years, aircraft allocation to the network is implemented by computing the trip DOC for each simulated mission and ranking the aircraft flying the route based on their DOC performance.

In addition, the production intervals used in the study of [12] were used in the model as a constraint to the number of aircraft in service.

1.3 Aircraft Operating Costs Analysis

Aircraft direct operating costs are calculated using the Aircraft Life-Cycle Cost Analysis (AliCyA) tool developed at Bauhaus Luftfahrt and verified by [13,14].

The tool estimates life-cycle costs of different aircraft types based on various input parameters and as a function of the aircraft age. For a given aircraft type of defined engine type, aircraft operational entry year, stage length, seat capacity, utilization [block hours per year], block fuel capacity [kg], selected flight crew operations, world region of operation, flight type [international or domestic], and fuel price, the life-cycle costs and expected age at retirement can be calculated.

Within the tool the DOC elements: Costs of Ownership (COO), decreasing with the age of the aircraft; cash operating costs (COC), increasing with the age; and additional direct operating costs (ADOC), constant irrespective of age, are considered [13].

By estimating the operating cost of all representative aircraft[1] operating on each route group using the AliCyA tool, the clusters were ranked in order of their unit cost performance (i.e. DOC per unit seat km). Thus, using an

[1]Approximate DOC values used for clusters 1, 5, and 8 using the AliCyA tool.

aircraft ranking list, the capacity gap on each route group is filled first with aircraft of best unit direct operating cost up to the production limit of the cluster aircraft for the analysis year, before the remaining capacity on the route group is filled with the second best cluster aircraft up to its production capacity, and so on.

On the other hand, having defined the age distribution of the aircraft in the fleet, aircraft retirement is implemented by assessing aircraft specific survival curves to determine the amount of aircraft to be retired in each simulation year [12].

2 Model Verification

The cost minimization method was verified by comparing the fleet-level metrics (fleet-wide fuel burn and fleet-level CO_2) results to those of the previous method of fuel burn minimization.

In the previous approach implemented in the FSDM, in contrast to the objective function of minimizing the unit direct operating cost approach used in this work, the model of [12] allocated aircraft to the network in order to minimize the total fuel consumption of the global fleet in each year of simulation. The fleet composition of the cost-optimized fleet is expected to be different from that of the fuel burn-optimized fleet. This is because the fuel burn-optimized fleet includes only the evaluation of the fuel consumptions of the different missions of the fleet, whereas the DOC- or cost-optimized fleet is based on consideration of factors including but not restricted to the cost and amount of fuel consumed. Other factors included are both age-dependent such as maintenance and emissions cost of the aircraft, and age-independent factors mentioned in section 1.3. This comparative study was therefore done, for the same traffic growth factors, production intervals and load factors (seat and freight) of [12].

The development of the global fleet was compared for both optimization methods, focusing on narrow-body (NB) and wide-body (WB) aircraft types, and evaluating the effects of modeling the cost optimization function with variable fuel price.

2.1 Comparison of Fuel and Cost-optimization modeling methods

Given that long haul aircraft have a better unit cost performance on longer routes than on shorter routes, and that in a given route group, representative unique stage lengths are given for each cluster (which step was taken, to reflect the traffic operations for 2008), for a given intra-regional route, best unit cost performance for the route group comes from the next-generation long haul aircraft flying the longest distance of the intra-regional route rather than from the next-generation narrow-body aircraft flying a shorter stage length. It resulted, therefore, that in order to fill the capacity gap, the model selected the best unit-cost-performing aircraft on the route, i.e. long-haul aircraft with the highest distance in the route group to fill the route group’s capacity demand, before smaller aircraft with shorter distances are added to fill the capacity. This led to the observed decline in the share of narrow-body aircraft. However, in reality, the global fleet does not tend have such a rather strongly-declining share of narrow-body aircraft. Therefore, the proposed improvement was to have a uniform distance for all clusters within each route group.

2.2 Uniform Route Distance Method Calibration

A uniform frequency-weighted route group distance was established for each route. Over the 21 route groups, an average reduction of about 7% was observed changing from a variable route distance system to a uniform route distance system. The incorporated standardized route distance in the fleet model was first calibrated according to the fuel burn minimization function to ensure similar results of yearly fleet size, fuel burn, and CO_2 compared to the variable route distance method of [12], before using the cost minimization objective function.

3 Fuel Price Scenarios Study

Having implemented a uniform route distance method in the model, the objective function of minimizing the direct operating cost (DOC) was integrated in the model to investigate the impact of DOC minimization and various fuel price projection scenarios on fleet development and fleet development metrics.

3.1 Fuel Price Scenarios

Three fuel price scenarios were developed in the study, based on the Annual Energy Outlook 2015 (AEO2015) oil price cases [15].

3.1.1 Low Oil Price scenario

The Low Oil Price scenario is based on the Low Oil Price case of the AEO2015. It assumes that low oil price results from a combination of low demand for petroleum and other liquids in nations outside the Organization for Economic Cooperation and Development (non-OECD nations) and higher global supply. On the supply side, the Organization for Petroleum Exporting Countries (OPEC) increases its liquids market share to 51% in 2040 from 40% in 2013. Also it assumes that the costs of other liquids production technologies are lower than in the reference case [15].

Due to the high computation time needed to compute the fuel price scenarios, fuel price fluctuations were modeled for the historic phase of the projections (i.e. for years 2008-2013). However, for the scenarios phase (2014-2025) for simplification purposes, fuel price was modeled as constant, equal to the average of fuel price projections for 2020 and 2030. The jet fuel price projection for this scenario is shown in Figure 4, fluctuating from 2008 to 2013, and constant at \$1.79/gallon in the scenarios phase (2014-2025). This is shown in Figure 3.

3.1.2 High oil price scenario

The High Oil Price scenario is also based on the AEO2015 High Oil Price case. High oil prices result from a combination of higher demand for liquid fuels in non-OECD nations and lower global crude oil supply. OPEC's liquids market share averages 32% throughout the projection. Non-OPEC crude oil production expands more slowly in short- to mid-term relative to the Reference case [15]. In the scenarios phase (2014-2025) the fuel price was constant at \$4.53/gallon.

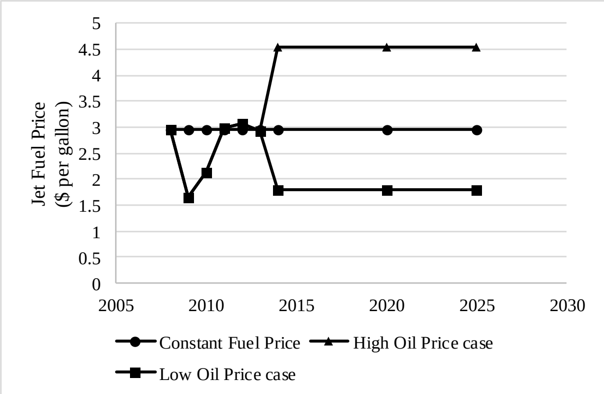

Fig. 3. Jet Fuel Price: Projections and Simulations to 2025

3.1.3 Constant fuel price scenario

A constant fuel price scenario was used to compare the DOC optimization results to those of the fuel burn optimization method. It assumed a constant fuel price of \$2.96/gallon from 2008 till 2025.

3.2 Effect of DOC optimization

Using the uniform route distances, the aircraft production interval as well as the market growth factors earlier determined, the fleet development was evaluated in order to determine the effect of DOC optimization compared to fuel burn (FB) optimization.

The fuel burn and CO_2 emissions for DOC optimization were normalized to the ASK levels achieved using fuel burn optimization within the simulated period. The results showed that DOC optimization resulted in higher estimates of fuel burn and CO_2 emission; an average of 9% over the simulated period.

Figure 4 shows the resulting CO_2 emissions of the fleet resulting from the two optimization methods using the same market growth factors of [12], both based on uniform route group distances; and the DOC minimization simulating for a constant fuel price of \$2.96/gallon within the simulated period.

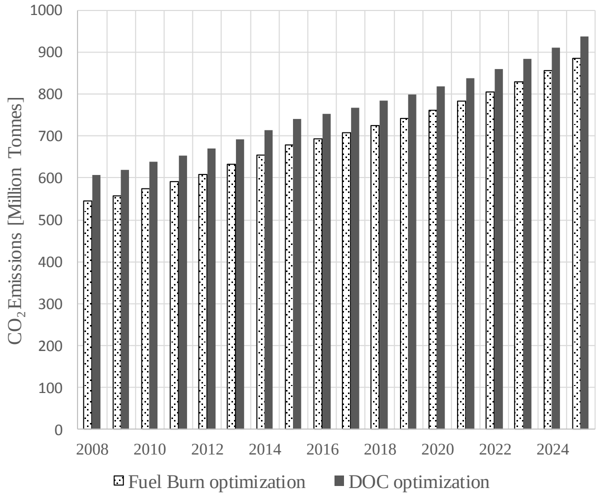

Fig. 4. CO_2 Emissions Comparison for Fuel Burn and DOC Optimization

3.2 Effect of Fuel Price Projections on Fleet Development

The effect of the fuel price projections on fleet development using DOC optimization is shown in Figure 5.

A higher fuel price resulted in an increase of the narrow-body fleet and a decrease in the wide-body fleet, and vice versa. This shift from wide-body aircraft to narrow-body aircraft with an increase in the fuel price was mostly prominent on three route groups with a uniform route group distance between 3000km and 5000km.

In the low fuel price scenario, because of their seat density, wide-body aircraft similar to A350-900 and B787-9 are better ranked in terms of unit DOC performance on distances between 3000km and 5000km than narrow-body aircraft similar to A320neo and B737max. However, as a result of their lower share of fuel cost in the direct operating cost (FC-DOC ratio), narrow-body aircraft similar to A320neo and B737max are less affected by a fuel price increase than wide-body aircraft similar to A350-900 and B787-9. As a result, on routes with distance between 3000km and 5000km, in the high fuel price scenario, the narrow-body aircraft have a lower unit DOC, and become better ranked, than the wide-body aircraft in filling capacity gap.

Also, at a higher fuel price, the fleet wide fuel burn increases compared to the low fuel price scenario, this is as a result of the increase in the quantity of narrow-body aircraft allocated to the fleet instead of wide-body aircraft on routes between 3000km and 5000km.

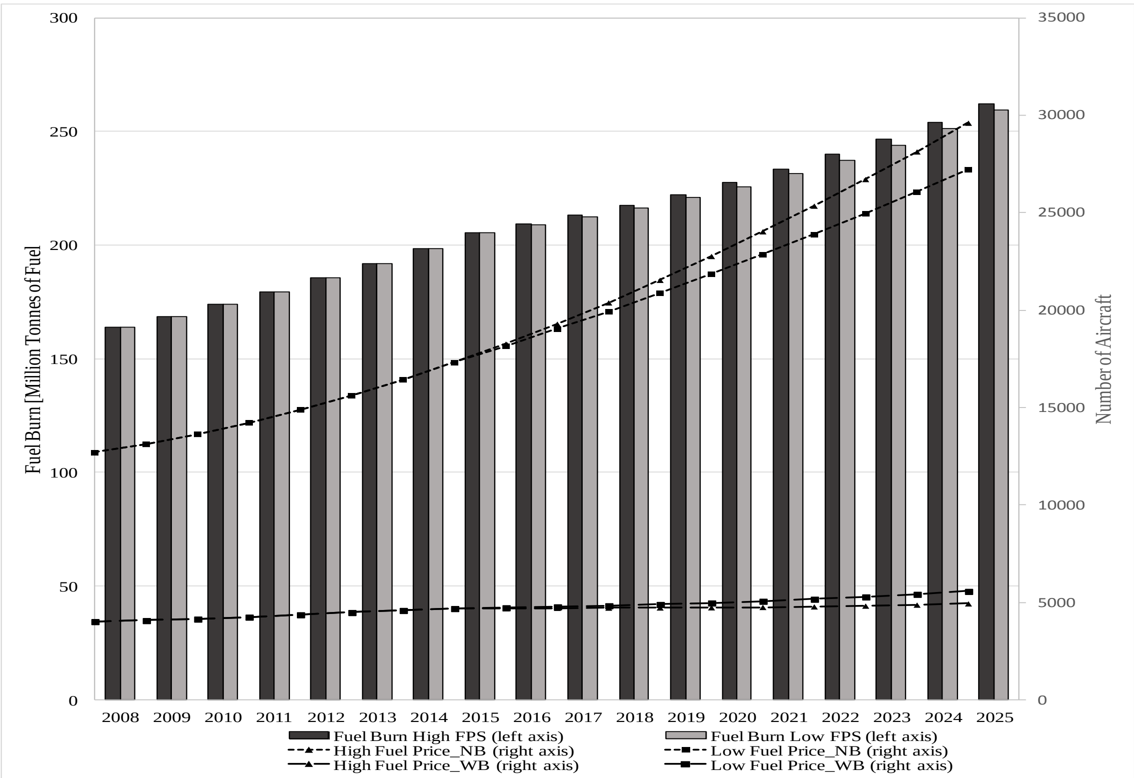

Fig. 5. Fleet Development and Fuel Burn for High and Low Fuel Price Scenarios

4 Conclusion

This study investigated the advantage of a proposed fleet allocation method based on direct operating cost minimization, for use in a fleet development model. The problem focus was the impact of fuel price projections on fleet development and fleet level metrics. Using the same user-defined aircraft production capacities, seat and freight load factors, and traffic growth rates projection as used by [12], uniform route group distances was defined.

DOC minimization was estimated to result in a higher global fleet-wide fuel burn and CO_2 emissions. Also, at a high fuel price, the cost-optimized fleet allocated more narrow-body aircraft, whereas more wide-body aircraft were allocated at a lower fuel price.

The use of cost optimization therefore gave the advantage of investigating the impact of fuel price changes on fleet development and fleet level metrics.

5 Outlook

Given that the results of this study are in broad agreement with other estimations of emissions, a next step to this study will be to incorporate other operating economic aspects, especially relating to aircraft retirement.

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