Chapter

Increasing the Emission Mitigation Potential by Employing an Economically Optimised Transport Aircraft Retirement Strategy

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Abstract

This study investigates the emission mitigation potential of retiring passenger aircraft economically at the global fleet level. In an integrated model of the air transport system, fleet turnover aspects of the global passenger aircraft fleet are defined using aircraft lifetime direct operating costs. Two fleet renewal strategies are compared in the study. The growth strategy (the baseline scenario) prioritises aircraft allocation for serving demand growth and replacing aircraft retired at the end of their design lives, before replacing those that are retired because of their operating cost disadvantage. Conversely, the replacement strategy allocates global aircraft production capacity first for replacing aircraft that are retired based on their operating cost disadvantage and those retired on reaching their design life limit, before serving growth in air travel demand. Results show that in year 2024, emission savings of three percent were achieved at the global fleet level using the Replacement Strategy, when compared to the baseline. Afterwards, due to the unavailability of newer efficient aircraft, emission savings diminish to two percent (around 40 million tonnes of CO_2). This research is useful to aviation stakeholders in having an overview of expected emission savings of the proposed strategic measure.

Keywords: fleet renewal strategies, aircraft direct operating cost, aviation emissions, emission mitigation, aircraft retirement

1. Introduction

There were around 28,000 commercial aircraft as of 2017, and out of these, 22,337 passenger jet aircraft have operations that yielded around 859 million tonnes of CO_2 [1–3]. Based on forecast of growth in air traffic, aviation emissions are also expected to grow in the long term. For example, Japan Aircraft Development Corporation [3] claimed that approximately 33,500 aircraft would be added to the global fleet over the next 20 years. The International Civil Aviation Organization [4] also claimed that a five percent growth in air traffic, compared to the projected one to two percent annual increase in aircraft fuel efficiency, would lead to the growth in emissions.

According to the International Air Transport Association [5], the air transport industry developed and has restated commitment to its aviation emission mitigation targets as follows:

i. An average improvement in fuel efficiency of 1.5% per year from 2009 to 2020

ii. A cap on net aviation 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

A combination of different measures (technology, operations, infrastructure, economic and additional technologies and biofuels) would help achieve the 2050 target of reducing net aviation CO_2 emissions by 50%, relative to 2005 levels [6]. Thus, this study proposes a strategic measure of mitigating aviation emissions by giving priority to retiring passenger aircraft at the global fleet level when they are evaluated to have an operating cost disadvantage in comparison with other aircraft. The emission mitigation potential (EMP) of the measure is also evaluated.

The next section gives an overview of measures already proposed in different studies for mitigating aviation emissions. Section III describes the methodological approach used in the study. Subsequently, two fleet renewal strategies (*Replacement Strategy* and *Growth Strategy*) are presented before analysing the potential of using the *Replacement Strategy* over the *Growth Strategy*.

2. Review of measures for mitigating aviation emissions

The process of fleet development is majorly driven by the satisfaction of demand, subject to objective conditions. These conditions include profit maximisation or return on investment, minimising operating costs especially when faced with major maintenance events, environmental constraints effected as governmental restrictions and exogenous market dynamics like aircraft demand and supply and fuel prices [7]. Furthermore, before an airline decides to add aircraft to the fleet, an evaluation period is chosen to ensure that the aircraft introduced to the global fleet either to fill capacity gap or as replacement aircraft still gives a unit cost advantage by the end of the evaluation period. Wensveen [8] claimed a planning horizon of 10 years for a typical fleet planning model, while Clark [9] and Belobaba [10] stated possible periods between 6 and 12 and 10–15 years, respectively, for the macro-approach to fleet planning.

Extensive work has been done in proposing emission mitigation measures that can be applied at the aircraft fleet level, using various fleet development tools [11–21]. A review of these studies was done by Oguntona [22]. **Table 1** summarises the measures proposed in these studies and categorises them under the broad groups of measures for mitigating aviation emissions.

Although these studies have covered essential aspects of measures proposed by the industry, there has been no consideration of prioritising aircraft economic retirement as an emission mitigation measure.

3. Method

Fleet system dynamics model (FSDM), an integrated modelling environment (IME), was developed by Randt [23] for evaluating longer-term emissions of

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Basket of measures	**Scenario measures studied**	**Dray et al. [11, 12]**	**Owen et al. [13]**	**Hassan et al. [14, 15]**	**Schilling et al. [16]**	**Ogunsina et al. [17]**	**EASA [18]**	**Winchester et al. [19]**	**ICAO [20]**	**Randt et al. [21]**
Technology, additional technologies and biofuels	Next-generation aircraft with improved technology[‡]	X	X	X	X	X	X	—	X	X
	Retrofits	X	—	—	—	—	—	—	—	—
	Performance Improvement Package (PIP) of 1% per year for all aircraft	X	X	X	—	—	X	X	—	—
	Alternative fuels	X	X	—	—	—	—	—	X	—
Infrastructure measure	ATM improvements	X	X	—	—	—	X	X	X	—
Operations measure	Early aircraft retirement	—	—	X	—	—	X	—	—	—
	Increased Load factor/ reduced frequency	X	—	—	—	—	X	—	—	—
	Others[♐]	X	—	—	—	—	—	—	—	—

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Regulatory and economic measures	Emission trading	X	—	X	—	—	X	X	—	—
	Set emission limit	—	X	—	—	—	X	X	—	—
	Fuel tax, route and airport charge	X	—	—	—	—	X	—	—	—

‡Electric, hybrid, distributed propulsion, blended-wing body, optimised counterrotating propeller, advanced turboprop, etc.
↗Surface congestion management, single-engine taxi, optimised departures, reduced cruise inefficiency, optimised approach, reduced fuel reserves, reduced tankering, increased engine maintenance, increased aerodynamic maintenance, engine wash, increased turboprop use.

Table 1.
Emission mitigation measures studied in fleet models reviewed [22].

aircraft at the global fleet level. FSDM initially used aircraft-specific fuel consumption as the performance criterion for aircraft addition to the fleet, while aircraft were retired from the fleet using functions dependent on aircraft calendar age. This aircraft retirement method was also used in some studies previously mentioned in Section 2, without inclusion of the objective functions mentioned in Section 2.

FSDM was later adapted by Oguntona et al. [24] who evaluated aircraft direct operating cost (DOC) performance in analysing the development of the global passenger aircraft fleet under a specified forecast fuel price development. The model adaptation excluded the aircraft economic retirement consideration. However, in this study, the DOC calculation method is revised while using this approach also for aircraft economic retirement considerations.

3.1 Air transportation system simplification approach

The network simplification approach used by Oguntona et al. [24] was retained, in which average distances (hereafter referred to as route groups) between and within regions were adopted.

Furthermore, the method of classifying the aircraft fleet available in year 2008 that was adopted by Randt [23] was retained while excluding aircraft types that are unlikely to be produced as well as freighter aircraft. Two generations of aircraft types were used in the model. The initial fleet aircraft clusters referred to aircraft types available in year 2008 (see **Table 2**), while next-generation aircraft (next-gen aircraft) referred to aircraft types produced afterwards (see **Table 3**). Cost improvements in the FSDM aircraft are shown in the Appendix (see **Table A-1**).

3.2 Integrated model overview

The FSDM was built in an integrated modelling environment [23]. It receives mission fuel burn values from a global fleet mission calculator (GFMC) that is based on the Base of Aircraft Data (BADA) tool [23]. The fuel performance data is then used alongside other input data in the Aircraft Lifetime Cost (ALiTiCo) module. ALiTiCo produces lifetime direct operating cost (DOC) estimates for the different entry into service (EIS) years of the FSDM aircraft. Input for ALiTiCo includes aircraft and engine characteristics as well as other parameters that vary over time and are unique to the considered FSDM flight distances. These are shown in **Table 4**.

Cluster name	Cluster acronym	Representative aircraft type
Long-range combi	LRC	Boeing MD 11
Long range heavy	LRH	Boeing 747-400
Mid-range freighter	MRF	Boeing 767-300F
Jet commuter	JC	Embraer 190
Long-range freighter	LRF	Boeing 747-400F
Turboprop commuter	TP	ATR 72-500
Mid range	MR	Boeing 767-300
Long range	LR	Boeing 777-200
Narrow body	NB	Airbus A320-200

Table 2.
Representative aircraft of the initial fleet aircraft clusters using FSDM [21].

Initial fleet aircraft	Representative next-generation aircraft type	Next-gen aircraft cluster name (acronym)	EIS year
MR	Boeing 787-8	Next-gen mid range (NGMR)	2011
LRH	Boeing 747-800	Next-gen long range heavy (NGLRH)	2012
LR	Airbus A350XWB	Next-gen long range (NGLR)	2015
NB	Airbus A320neo	Next-gen narrow body (NGNB)	2016
JC	Bombardier CS100/ Embraer E190-E2	Next-gen jet commuter (NGJC)	2016

Table 3.
Next-generation aircraft EIS [21].

	Time-dependent input	Time-independent input	
Route-independent input			
Aircraft type dependent	• EIS year • Normalised improvements in fuel costs • Normalised improvements in non-fuel COC • Normalised improvements in ADOC	• Limit of validity • MTOW • Range at LRC • Mach number • Cabin length • Cabin height • Cabin width at floor • Cabin width maximum • Take-off field length • Operating weight empty • Approach noise level • Flyover noise level • Engine dry weight	• Number of engines • Engine SFC • Number of shafts • Engine take-off power • Number of propeller blades • Propeller diameter • BPR • OPR • Number of compressor stages • Maximum thrust • Emitted pollutant NOx per LTO cycle
Environmental, macro-economic and flight-related	• Fuel price • Inflation adjustment factors • Seat load factor • Freight load factor	• Aircraft price scenario: minimum, mean or maximum • Exchange rate • Interest and insurance rates per year • Labour rate • Escalation factors • Navigation unit rate	• Threshold approach noise • Threshold flyover noise • ETS allowance per ton CO_2 • Calculation age limit • Depreciation period
Route-dependent input			
		• Flight distance	• Flight type

	Time-dependent input	Time-independent input	
	• Annual frequency	• Installed seats	
		• Belly-freight capacity	
		• Block fuel	
		• Block time	

Source: Own depiction.

Table 4.
Input to ALiTiCo.

An overview of the interlinked submodules of the updated integrated modelling approach used in this study is shown in **Figure 1**.

The integrated model depends on input data extracted from various data sources and processed in calculators to give various outputs. The final output of interest is obtained from the FSDM. The data flow in and out of the calculators is shown in **Figure 2**.

The main steps of the integrated model are shown in **Figure 3**.

The main steps of fleet renewal/development FSDM performs every calculation year are:

i. Retirement of aircraft that have reached their design life limit, evaluated in terms of their structural retirement age [years] depending on their assumed annual utilisation rates.

ii. Evaluation of aircraft before addition to fleet to fill route capacity gap.

iii. Comparison of existing aircraft with new available aircraft in terms of operating cost performance, retiring those having a cost disadvantage and replacing them with more cost-efficient ones. This is also referred to as economic retirement of aircraft.

3.3 Cost modelling approach

Direct operating costs (DOC) were estimated to comprise of cost of ownership (COO), cash operating costs (COC) and additional direct operating costs (ADOC) according to the approach of Ploetner et al. [25].

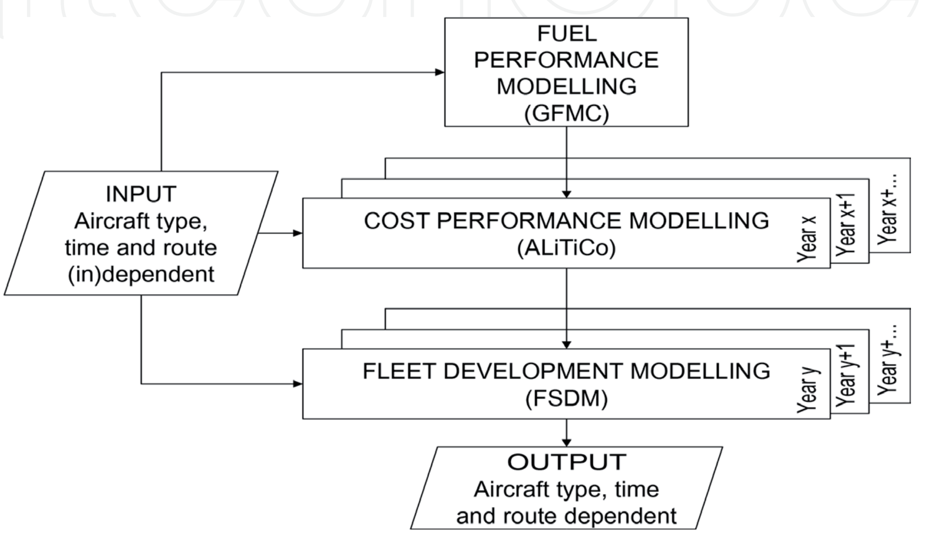

Figure 1.
Interlinked submodules of integrated model environment.

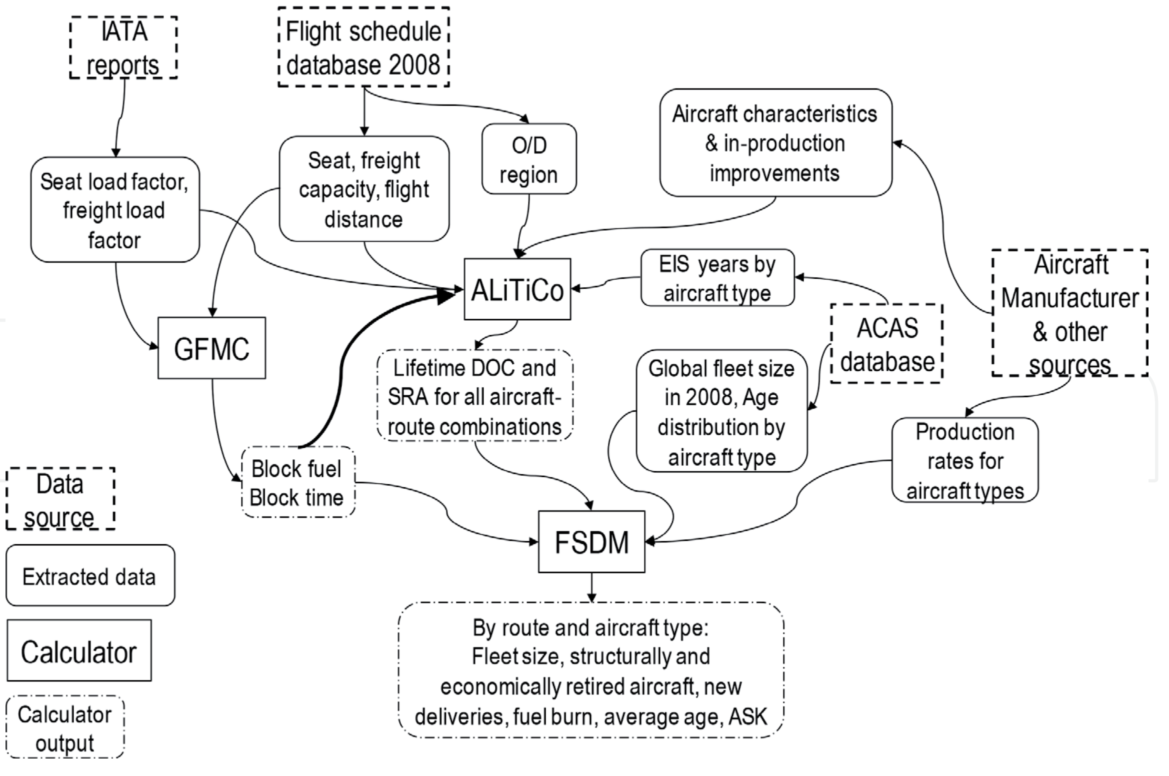

Figure 2.
Data flow in and out of GFMC, ALiTiCo and FSDM.

3.3.1 Cost of ownership

The methodology of Ploetner et al. [26] is used in this work. This approach calculates aircraft market price using aircraft parameters of range, Mach number, number of passengers, cabin volume and take-off field length based on data from year 2003 to 2008 and adjusted to year 2008 US dollars (USD). Using the relevant inflation factor [27], the costs were converted to year 2016 USD.

Given that the COO comprises of depreciation, interest and insurance, the COO development of an aircraft over time is dependent on the depreciation model chosen. In this study an exponential function model is used based on the approach of Wesseler [28]. A summary of depreciation periods of aircraft according to

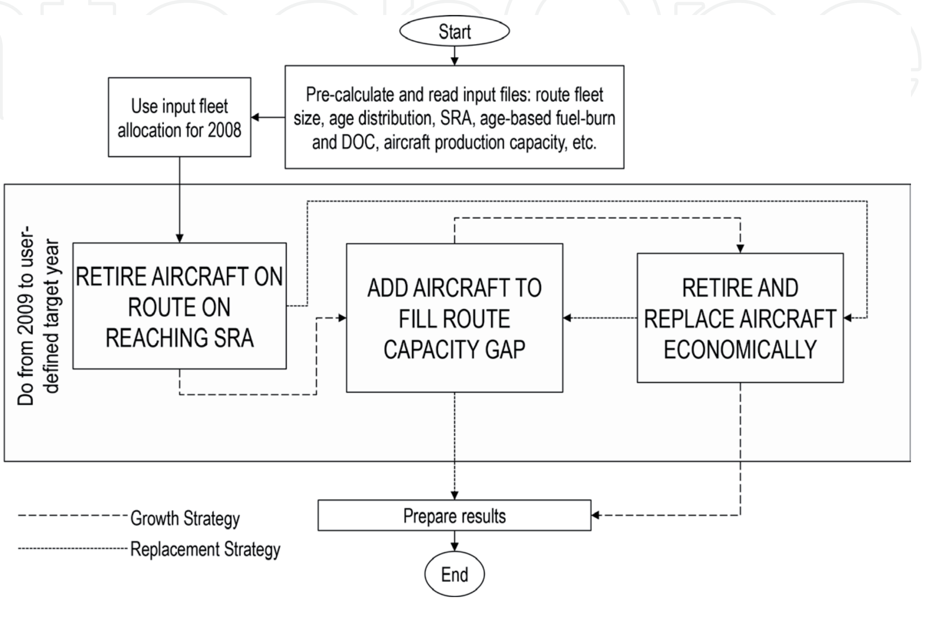

Figure 3.
Main steps in updated integrated model environment.

Literature source	Narrow-body aircraft	Wide-body aircraft
Association of European Airlines	14 years	16 years
Doganis	8–10 years	14–16 years
IATA	Average of 20 years	Average of 20 years

Table 5.
Summary of depreciation periods according to literature findings [29–32].

literature findings is shown in **Table 5**. In summary, depreciation periods of 8–20 and 14–20 years could be used for single-aisle and twin-aisle aircraft, respectively.

In ALiTiCo, aircraft delivery price is assumed to be constant over the simulation period. This is not the case in reality since aircraft prices are influenced by many factors including inflation, developments in price of materials, demand for aircraft, current market value and the strength of the dollar, among other factors [33]. However, the assumption simplifies the complexity of incorporating such effects. Furthermore, depreciation and interest period are assumed to be constant.

3.3.2 Cash operating cost

COC is composed of crew charges, fuel costs, direct maintenance costs (DMC), navigation charges, airport fees and ground handling charges.

3.3.2.1 Crew charges

Crew charges are based on a correlation relationship of crew salaries in 2008, supplied by EUROCONTROL [34], to maximum take-off weight (MTOW) and number of passengers on a flight. According to Wesseler [28], flight crew costs per block hour could be expressed as a function of MTOW, whereas cabin crew costs per block hour could be expressed as a function of the number of passengers. He assumed a seat density and combination of flight and senior flight attendants of a typical full-service carrier. Likewise, these costs were converted to 2016-year dollars, using the relevant inflation factors.

3.3.2.2 Fuel costs

Fuel costs are computed from fuel consumption and the respective yearly fuel prices, adjusting to 2016-year dollars. Fuel burn per trip is still modelled using the Global Fleet Mission Calculator (GFMC) based on the BADA 3 tool of EUROCONTROL also described by Randt [23]. The tool was already validated by Ittel [35]. However, given that fuel costs cover a major share of aircraft DOC, verification of fuel consumption estimates was done for the initial fleet and next-generation aircraft types considered in the model. Fuel burn on routes was not modelled to increase because of payload increase. However, conservatively higher passenger and freight payload factors of 86% and 53%, respectively, than in 2008 were assumed throughout the simulation period to ensure conformity of model results to anticipated future growth in these load factors, as verified by Randt [23].

In ALiTiCo, similar to the approach of Moolchandani et al. [36], engine overhaul or replacement is not done. Though fuel burn deterioration is mainly engine-driven, and thus does not have a linear characteristic throughout an aircraft's life, in ALiTiCo, a linear deterioration rate of 0.1% per year is assumed for simplification purposes. Considering that a deterioration of 3.5–4% is possible all through the aircraft life [37, 38], this assumption of 0.1% per year is justified.

3.3.2.3 Navigation charges

Navigation charges are based on the EUROCONTROL model using the average unit rate weighted by the number of landings in all European countries in 2008 [28]. The charges are computed in year 2016 US dollars (USD).

3.3.2.4 Airport charges

Airport charges and ground handling charges are based on the methodology of Ploetner et al. [39]. Airport charges are composed of landing charges, passenger charges, navigation aid charges, lighting charges, terminal charges and service charges. The method was based also on data from 2008. Like other cost components, the charges are computed in year 2016 US dollars.

In the fleet model, flights could be either within a region or between two regions. For flights belonging to the latter category, the average value of airport charges within both origin and destination regions is used.

3.3.2.5 Direct maintenance costs

Using available data from Aircraft Commerce [40] for the initial fleet aircraft, the method recommended by the Association of European Airlines (AEA method) [31, 32] is adopted because it uses aircraft parameters such as aircraft operating weight empty, engine bypass ratio, etc. Other parameters such as aircraft price are obtained from the ownership cost model already explained. Furthermore, for the engine price [year 1989 USD], the approach by Jenkinson et al. [41] is used, which calculates engine price in year 1995 British pounds based on specific fuel consumption [lb/lbf/h] and cruise thrust [Ma]. The engine bare price [year 1989 USD] is then obtained after the price in year 1995 British pounds is first converted to year 1995 USD and then to year 1989 USD.

The AEA method assumed mature levels of cost, i.e. after 5–7 years of operation. Using ageing function from Strohrmann [42], based on Dixon [43], DMC values for other years of the aircraft lifetime are determined. Furthermore, input labour rate value given by the AEA in 1989 is used and converted to 2016 USD. Due to lack of data, this is assumed to be constant over time and independent of route although DMC labour rate varies over time and with world region [44]. A limitation of the AEA method is that it does not hold for engines with thrust above 30 metric tonnes. Furthermore, since the method was developed to give comparable results to aircraft operated by airlines in 1989, the method cannot be directly used for next-generation aircraft considered in this work. Therefore, improvement factors are used which correlate nonfuel COC of initial fleet aircraft to next-generation ones.

Since the AEA method for computing aircraft DMC is evaluated in year 1989 USD, an inflation factor is used to adjust the costs to year 2016 USD. Direct maintenance costs per flight cycle of representative aircraft of the initial fleet, determined using AEA method, were compared with corresponding cost values published by Aircraft Commerce (ACC). This is shown in **Figure 4**.

Cost values published by ACC can be taken as representative of the industry since they are obtained from maintenance providers.[1] The difference between AEA and ACC values increased with increasing MTOW. A higher difference can be expected for aircraft with first flights made after the AEA publication. From **Figure 4**, the AEA method for DMC computation produced aircraft DMC values at most 22% higher than those of ACC. Compared to cost levels given by IATA's MCTF [45], the

[1] Correspondence on 13 February 2018 with Aircraft Commerce.

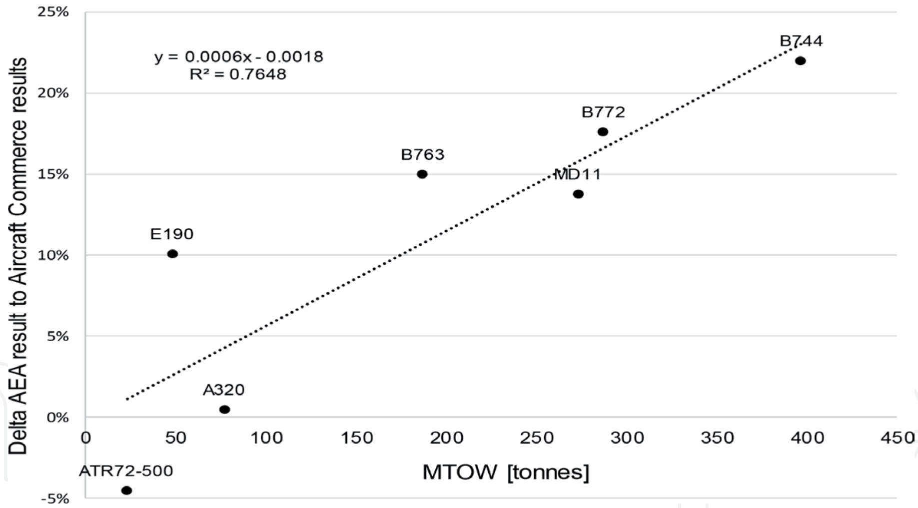

Figure 4.
DMC [$/FH] of initial fleet aircraft, comparing AEA and ACC results.

costs computed using AEA method are at most up to 40% higher. Therefore, for all initial fleet aircraft types used in FSDM, including aircraft with engine thrust above 30 metric tonnes like the B777-200, by applying a correction factor defined by the linear regression function in **Figure 4**, the cost results of the AEA method are adjusted to cost levels, resulting from Aircraft Commerce computation.

3.3.3 Additional direct operating costs

Additional direct operating costs refer to environmental airport noise and NO_x charges, as well the emission trading scheme (ETS) charges [26]. The charges were computed based on functions from Ploetner et al. [39]. The noise charges are based on defined levels of aircraft noise values for arrival as well as sideline and flyover as given by the ICAO [46]. Maximum approach and sideline and flyover noise levels of 88 and 83 EPNdB, respectively, were used. Also, a constant charge of 10 Euros per tonne of CO_2 was implemented based on Schmidt et al. [47].

4. Analysis

4.1 Longer-term fleet development strategies

If the order of implementing the last two of the three main steps of fleet renewal presented in sub-section B of the previous section is modified, two fleet renewal strategies can be defined on an FSDM route. These are shown in **Figure 5**.

The *Growth Strategy* prioritises aircraft allocation for serving demand growth and replacing aircraft retired at the end of their design lives, before replacing those that are retired because of their operating cost disadvantage. This strategy is assumed a status quo strategy used in the airline industry. This is because aircraft manufacturers claim that more than half of aircraft deliveries forecast for the next two decades are to accommodate growth in air travel demand (ATR, 65%; Embraer, 63% and 56%[2]; Boeing, 57%; Airbus, 63%) rather than replace existing aircraft (ATR, 35%; Embraer, 37% and 44%; Boeing, 43%; Airbus, 37%).[3] This is also

[2] For 70–130 seat jet segment and turboprop segment, respectively.

[3] Values derived from ATR's turboprop market forecast 2016–2035, Embraer's market outlook 2017, Boeing current market outlook 2017–2036 and Airbus Global Market Forecast 2017–2036.

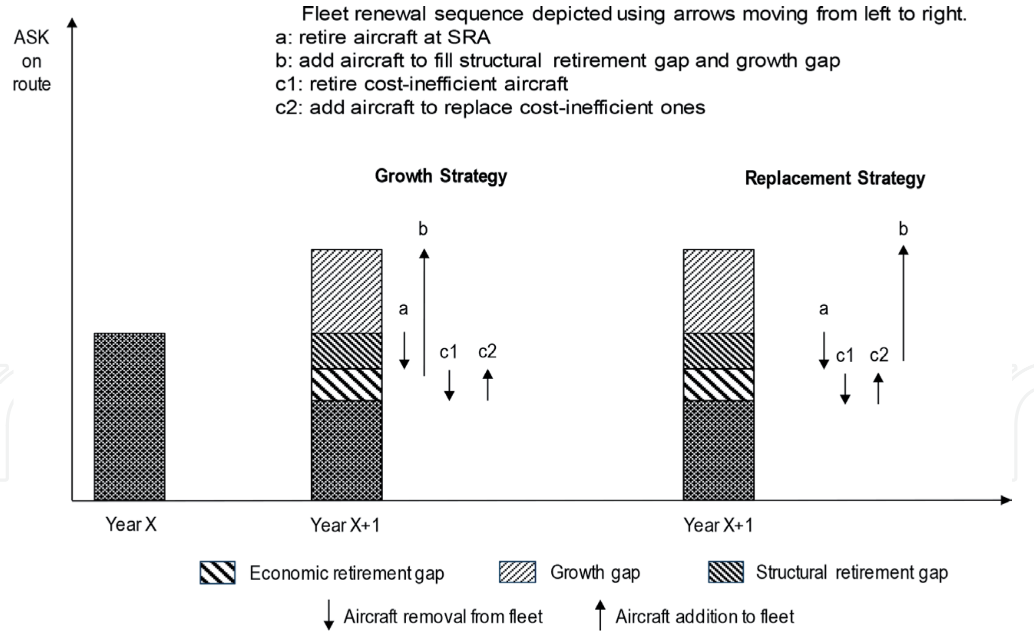

Figure 5.
Strategies for fleet renewal on a route.

assumed because airlines tend to delay replacement of their older aircraft when jet fuel prices are low [48], meaning that a complete economic retirement of aircraft has not been performed industry-wide.

Conversely, a more radical strategy, the *Replacement Strategy*, allocates global aircraft production capacity first for replacing aircraft that are retired based on their operating cost disadvantage and those retired on reaching their design life limit, before serving growth in air travel demand.

4.2 Calibration using growth strategy

FSDM was calibrated to generate fleet composition results similar to Boeing's forecast for 2036 while reflecting verifying the historical development for the jet aircraft fleet.

4.2.1 Assumed input

Passenger and freight load factors from 2008 to 2016 are taken from IATA reports [49], without differentiating between route groups. While passenger load factor increased from 76% in 2008 to 80.3% in 2016, freight load factor reduced from 46% in 2008 to 43% in 2016. In 2017, freight load factor is assumed to be slightly higher due to the entry of LCCs into the cargo business and other reasons given by JADC [50]. After 2017, freight load factor is assumed to be stable at 47.7%. However, the development in freight traffic is beyond the scope of this work. In addition, JADC [50] forecasts that passenger load factor is set to increase from 80.3% in 2016 to 83.3% in 2036.

Fuel prices (with units in year 2016 US dollars) were derived for years 1968 until 2016 using US GDP deflator values [27] and US Gulf Coast Kerosene-Type Jet Fuel Spot Price [51]. It was assumed that jet fuel prices were constant until year 1990 since there was no major difference between the average US Kerosene-Type Jet Fuel Wholesale and Resale Price by Refiners between 1978 and 1990 [52].

For years 2016–2036, low- and high-fuel price scenarios by Boeing are used as shown in **Figure 6**. The scenario of fuel price that was used in the Boeing CMO was not stated. The low-fuel price forecast assumed that fuel price in 2030 would

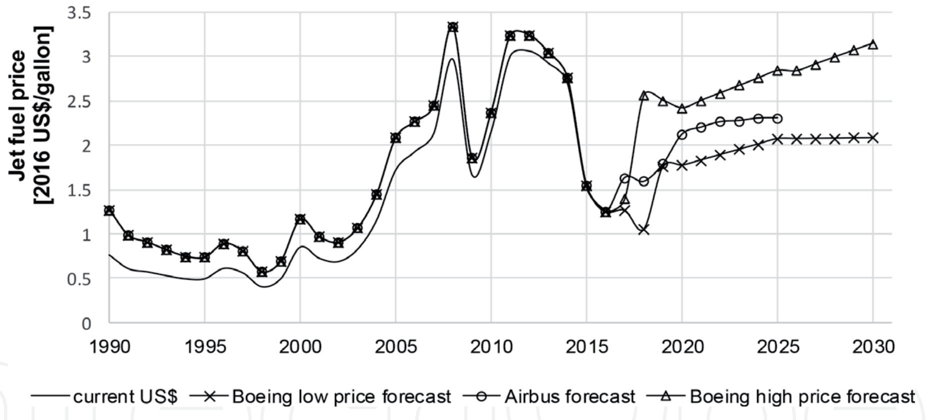

Figure 6.
Historical and forecast fuel price scenarios by Airbus and Boeing [27].

be similar to 2005 price levels. On the other hand, Boeing's high-fuel price scenario assumes that fuel price in 2018 will rise close to 2008 price level while further rising beyond 2012 price level in 2030. Same RPK growth factors on route groups were assumed for both fuel price scenarios as given in the CMO report. Fuel prices after 2030 are assumed to be stable at 2.08 and 3.1452016 US dollars per gallon in the low and high-fuel price forecasts, respectively.

These fuel price scenarios differ from Airbus fuel price forecast which assumes medium fuel price close to 2010 price levels in 2025 [53] (see **Figure 6**).

Maximum aircraft upgauge was assumed to be 20%. In addition, the utilisation of an aircraft type is modelled to vary between route groups, with a possibility of increasing annually. According to Boeing [54], passenger airplane utilisation increased between 2008 and 2015. A study of the growth in airplane utilisation at aircraft cluster level between year 2008 and 2014 revealed that the growth occurred mostly for turboprop commuter, jet commuter, narrow-body and mid-range aircraft cluster between years 2008 and 2014, whereas long-range aircraft utilisation increased between 2012 and 2014 [55]. For a given year, an increase in airplane utilisation results in lower unit costs and trip costs because fixed ownership costs are spread over an increased number of trips [56]. Considering that portions of flight crew and cabin crew costs as well as maintenance costs are possible components of fixed costs [9], it is assumed that higher airplane utilisation results in lower direct operating costs. Therefore, the unit DOC of a particular aircraft type with the same payload varies with different levels of utilisation on different route groups.

A fleet forecast also uses an assumption on development of aircraft productivity, which, according to Evans and Johnson [57], is influenced by load factor, average block speed, annual utilisation and number of seats per aircraft. Because the updated FSDM is not capable of modelling dynamically changing average block speed or number of seats per aircraft every year, aircraft productivity growth is modelled as growth in annual flight frequencies.

In their forecast, Boeing assumed older aircraft would have lower utilisation compared to newer aircraft [58]. Although an increase in passenger load factor is expected as explained above, additional annual ASK productivity growth of aircraft is modelled for next-generation aircraft as 0.9% as used by Evans and Johnson [57], with the exception of next-generation regional aircraft assumed to have a higher annual growth rate of 1.3%. For initial fleet aircraft, a lower annual growth rate of 0.35% is assumed according to Boeing's assumptions. The 0.35% growth rate is adopted from the assumption of Forsberg [59]. These values are considered conservative when considering the compound annual growth rates of initial fleet aircraft productivity between 2008 and 2014 as evaluated by Bellhäuser [55].

Lastly, after 2022, production capacity of all aircraft types is assumed to grow at an annual rate of 4.7%, same as Boeing's projected worldwide growth rate for air passenger traffic. This growth rate is arguably reasonable because over the period from 2008 to 2016, total aircraft production capacity has also grown at an average of 4.7% per year.

4.2.2 Model calibration objective

Boeing assumed in their forecast that some trends would continue. For example, they assumed that new markets that had previously been either unreachable or unprofitable, especially those that can be served by small wide-body aircraft, would open up [58]. Although the opening up of new markets is not modelled in FSDM, the effect of liberalisation, in terms of increased air traffic, is considered. These assumptions led to a forecast that the share of wide-body aircraft would increase from 19% in 2016 to 21% in 2036. As shown in **Figure 7**, this growth is driven by the growth in small twin-aisle aircraft.

This calibration work, therefore, has an objective goal of a higher preference for wide-body aircraft over narrow-body aircraft in 2050. Boeing categorised aircraft types into three groups. However, the method used in doing this was not explained. **Table 6** shows how FSDM aircraft clusters compare to the classifications.

Boeing also categorised the B777X, A350–1000 and B787–10 as M/L-TA aircraft which would be already in operation in year 2036. In the fleet model, however, these future aircraft types are not modelled as unique representative aircraft. This is mainly because the fuel burn performance of these aircraft types cannot be determined using the BADA version used in this work. Besides this, there is uncertainty about the future production capacities of these future aircraft types. Production capacities were assumed for the B777X and included in that of the NGLR, whereas, since the other two aircraft types are related to existing FSDM representative aircraft, special production capacities are not included. As a result, for calibration purposes, the production capacity share of the B777X in the NGLR is deducted from the total delivered aircraft in this aircraft cluster and its corresponding aircraft category (i.e. the S-TA) and added to the number of aircraft belonging to the category M/L-TA.

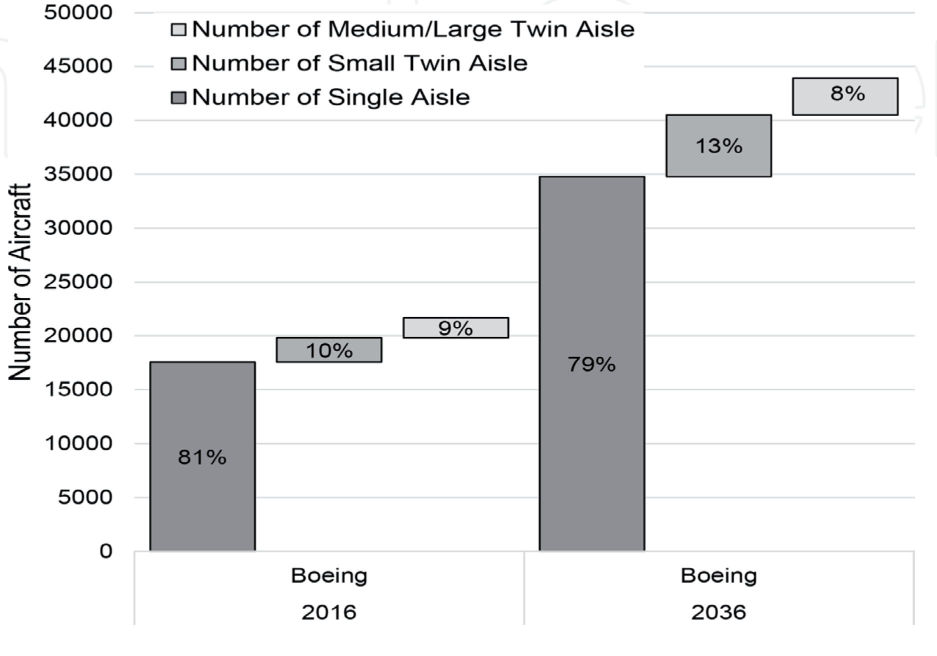

Figure 7.
Fleet size and composition according to Boeing in 2016 and 2036 [58].

Boeing category	FSDM aircraft cluster
Single aisle (SA)	JC, NB, NGJC, NGNB
Small twin aisle (S-TA)	MR, NGMR, NGLR
Medium/large twin aisle (M/L-TA)	LRC, LRH, LR NGLRH

Table 6.
Comparison of Boeing CMO to FSDM aircraft classification.

Fleet composition in year 2036 is dependent primarily on the choice of aircraft during introduction to fill the capacity gap. Apart from cost improvements modelled in the aircraft, aircraft preference depends on fuel price (FP), depreciation period (DP) and planning horizon (PH) assumed during aircraft evaluation. To have a simplified approach in calibration, these variables are applied without differentiating between single- and twin-aisle aircraft. Upper and lower boundaries for the variables are shown in **Table 7**.

Because of the high number of combinations possible if intermediate values of these variables are observed, simplifications are made in the calibration process by using only combinations involving the boundary values. Moreover, further assumptions were made in terms of cost improvements due to the increase in aircraft utilisation, leading to a preference for S-TA and M/L-TA. These are shown in the Appendix (see **Table A-2**). For each fuel burn scenario, four combinations of DP and PH are used for calibration.

4.2.3 Calibration results

The calibration results are shown in **Figure 8** for years 2008, 2016 and 2036. Because the long-term development is of interest, yearly changes in the results are not shown.

In 2008, FSDM's total fleet size, which is taken from the ACAS database, was 3% less than that of Boeing because the latter considered more aircraft types (e.g. twin-aisle aircraft like Ilyushin IL-86 and Lockheed L-1011 and single-aisle aircraft like Sukhoi Superjet 100,Yakovlev Yak-42, Mitsubishi MRJ, Dornier 328JET, Fokker 70, F28 and BAe 146). As a result, FSDM's SA fleet size was 10% less than that of Boeing. When weighted by their 75% share in the total aircraft fleet size, a difference of 7% results. Furthermore, for the S-TA and M/L-TA aircraft categories, respectively, with approximately 12% share each, percentage differences in fleet size estimates by Boeing and FSDM of 60 and 4% were estimated. When weighted by fleet size, differences of 7 and 0% result for the S-TA and M/L-TA, respectively. Therefore, a maximum difference of 7% is estimated between the fleet sizes in each category, when weighted by fleet share, based on Boeing's data and those of the FSDM simulation year.

In 2016, some of these aircraft types, especially single aisles, not considered in FSDM initial fleet were in limited service. Therefore, the share of single-aisle aircraft

Variable	Low boundary	Upper boundary
Fuel price scenario	Boeing low fuel price	Boeing high fuel price
Depreciation period	14 years	20 years
Planning horizon	7 years	15 years

Table 7.
Upper and lower boundary values of calibrated variables.

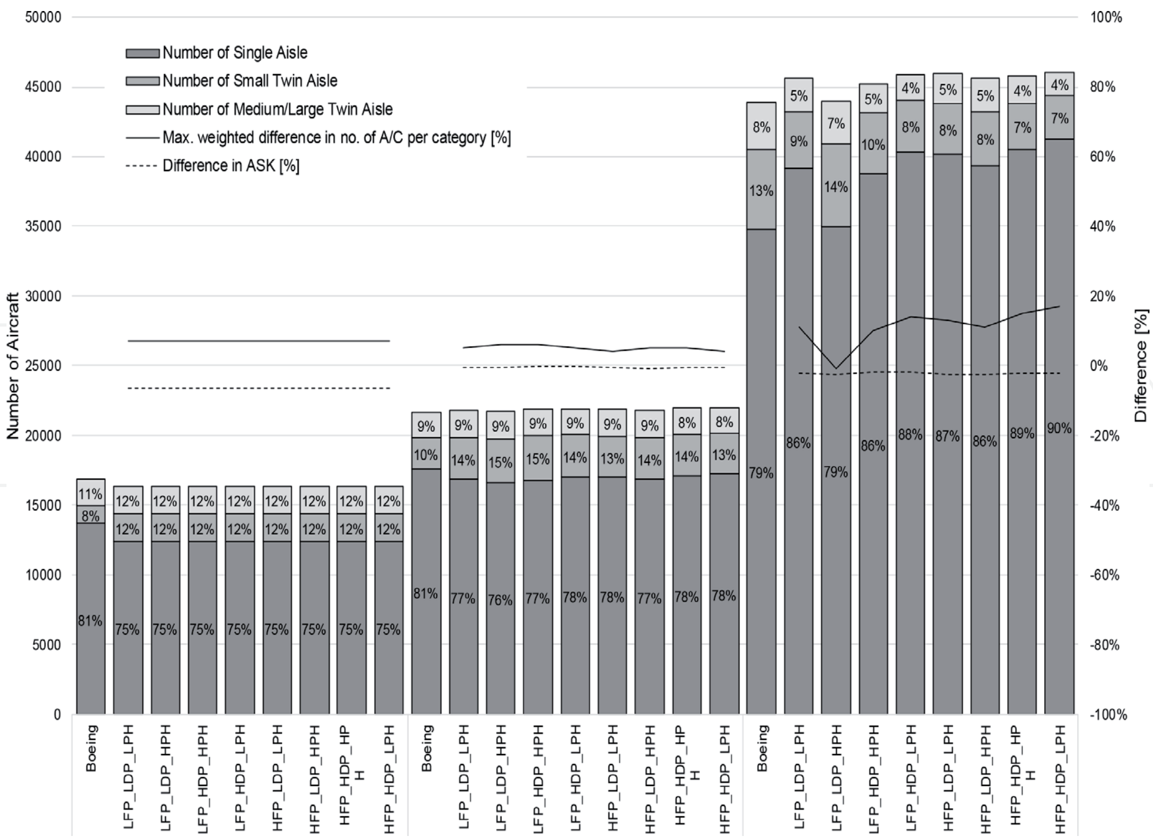

Figure 8.
Calibration results.

between 2008 and 2016 is expected to have increased slightly over the period. As a result, in 2016, FSDM produced a slightly higher share of single-aisle aircraft compared to 2008, although the share of single-aisle aircraft did not change in Boeing's data from 2008 to 2016. In 2016, the difference between the numbers of aircraft in each category based on Boeing's data and those of the FSDM in 2016 ranges between −6 and 43%. However, when weighted by fleet share, there was a 6% maximum difference in fleet size estimates by FSDM and Boeing for each aircraft category.

In 2036, the difference in fleet size estimates by FSDM and Boeing for each aircraft category ranged from −51 to 19% depending on the combination of calibration variables used. However, when weighted by fleet share, there was a maximum difference of 17% in fleet size estimates by FSDM and Boeing for each aircraft category. The calibration results in terms of ASK show a good comparison to Boeing's forecast. In years 2008, 2016 and 2036, maximum differences in ASK of −7, −1 and −3%, respectively, were attained.

For both fuel price forecasts used, of the four combinations of DP and PH possible, the combination of low depreciation period (LDP) and high planning horizon (HPH) gives results closer to Boeing's forecast. Therefore, this combination is used in the remaining steps of this study. The most comparable result to the jet fleet composition forecast by Boeing is obtained using the low-fuel price (LFP) scenario in the LDP and HPH combination. In other words, this combination has the lowest maximum difference between the numbers of aircraft in each category based on Boeing's data and those resulting from the FSDM in 2036.

Furthermore, from **Figure 8**, it can be seen that an increase in jet fuel price from Boeing's low- to high-price scenarios leads to a "slightly" different fleet composition in 2036. This primarily results from a change in the ranking and introduction of cost-efficient aircraft on the route groups, leading to an increase in the number and share of narrow-body aircraft. Because, unlike wide-body aircraft, narrow-body aircraft are less sensitive to fuel price, a higher jet fuel price has less impact in increasing their unit DOC. As a result, narrow-body aircraft are more competitive than their wide-body counterparts are, especially when compared on the design range of the former. This result is in agreement with the claim by Rutherford [60] that aircraft with four engines like the B747 and A380 were less fuel-efficient than fuel-efficient twinjets like the A350–900 and B787–9 even on trans-Pacific routes for which the former are designed. Therefore, in a high-fuel price scenario like that of Boeing, fleet phase-in decisions will favour less of NGLRH. Furthermore, given that fuel prices change over time, the comparative cost performance of the aircraft differs over time.

4.3 Verification using growth strategy

4.3.1 Verification of historical fleet fuel burn and fuel efficiency

Based on calculation results by Wasiuk et al. [61], IATA [49, 62] and Dray et al. [63], estimates of past passenger aircraft fuel burn in million tonnes are compared with results from FSDM. FSDM estimates are in average 5% above the estimates of Dray et al. and 7% below IATA's estimate for year 2016. However, FSDM's estimate of fleet fuel burn in 2016 is 1% below that of the IATA. Using the approach explained by Dray et al. [63], IATA's values used here are reduced by 9.6% because, unlike the IATA reports, freighter aircraft are not included in this work. Another 5% was deducted to account for unscheduled flights that were included in IATA reports. For the fuel efficiency results, IATA's fuel burn data was combined with ICAO's ASK data. In 2016, FSDM exactly reproduces fuel efficiency data by the IATA and ICAO. Fuel burn performance of the global passenger aircraft from year 2008 to 2016 is shown in **Figure 9**.

4.3.2 Verification of historical fleet unit cost and average age

Fleet unit cost development is dependent on development in fuel unit cost [64]. The developments in cost per ASK (CASK), fuel price and average aircraft age are shown in **Figure 10**.

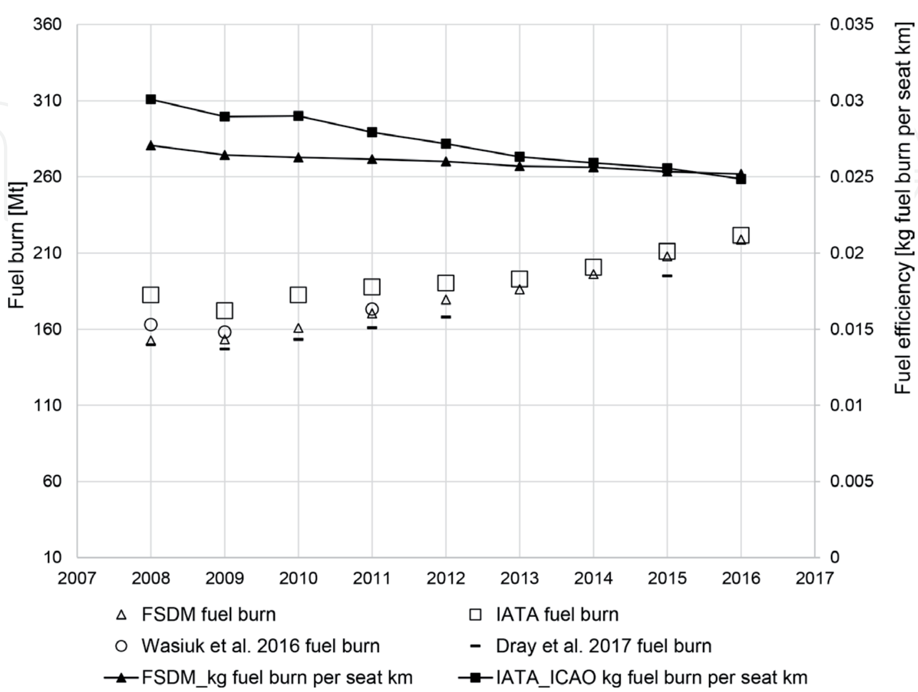

Figure 9.
Passenger aircraft fuel burn and fuel efficiency 2008-2016.

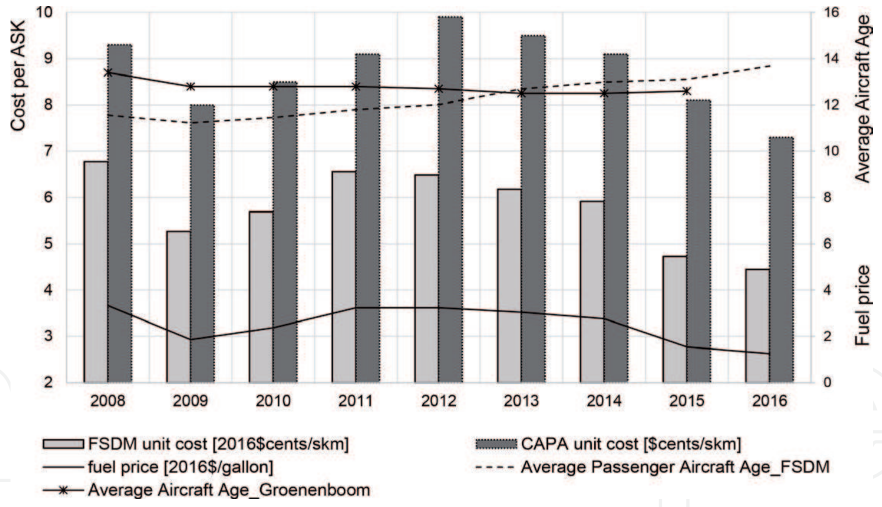

Figure 10.
Fuel price, unit cost, and average age of global pax fleet: 2008-2016. Source: Own calculations [65].

Data on aircraft unit cost used for verification was obtained from Centre for Asia Pacific Aviation [64]. A comparable unit cost drop between 2014 and 2016 can be observed for both FSDM results (25%) and CAPA data (20%). Likewise, the trend of the cost development throughout the period is comparable for both FSDM and CAPA, although absolute values are not equal. Although Groenenboom [65] recorded that the average age of passenger aircraft slightly decreased between 2010 and 2015, it does not precisely give the age for passenger aircraft. Average age of the passenger aircraft fleet depends on the rate of aircraft additions to the fleet, compared to retirements from the fleet. In addition, the average fleet age depends on jet fuel price. Lower fuel prices encourage airlines to keep older aircraft longer in service, especially when travel demand is strong [66, 67], thereby increasing the average fleet age. Therefore, a slight increase in the average age of the fleet accompanies a decrease in the price of fuel from year 2012 to 2016.

4.3.3 Verification of forecast fleet fuel burn and air passenger traffic

Next, the reliability of the model in estimating future emissions and air passenger traffic of the global passenger aircraft fleet is verified.

For forecasts until 2050, passenger load factor is assumed steady at 2036 levels. Dray et al. [63] updated AIM to AIM2015 and used the UK Department of Energy and Climate Change (DECC) historical and forecast oil price levels [68]. In this verification study, the DECC medium oil price forecast was used. A review of the historical prices [year 2016 USD per gallon] between 1990 and 2015 shows that jet fuel prices were approximately 21% above DECC oil prices. The fuel price development according to the DECC has a price level in 2036 and beyond which is even higher than Boeing's high-fuel price forecast.

Furthermore, from year 2015, RPK growth rates of 3.8% per year were used in this verification process according to the SSP2 baseline scenario of Dray et al. [63]. In the SSP2 baseline scenario, zero carbon prices were assumed, so that ETS costs were set to zero. The assumptions in aircraft utilisation, load factor and technology improvements used for arriving at Boeing's future fleet composition are retained. As a result, the basic giant-leap technological improvements assumed were similar. Incremental improvements were excluded since they did not assume incremental technological improvements. **Figure 11** shows the jet fuel price development of the SSP2 baseline scenario.

Figure 12 shows estimates of fuel burn and air traffic in 2050 relative to 2015 from Dray et al. [63] and using FSDM. Because the long-term development is of interest, yearly changes in the results are not shown.

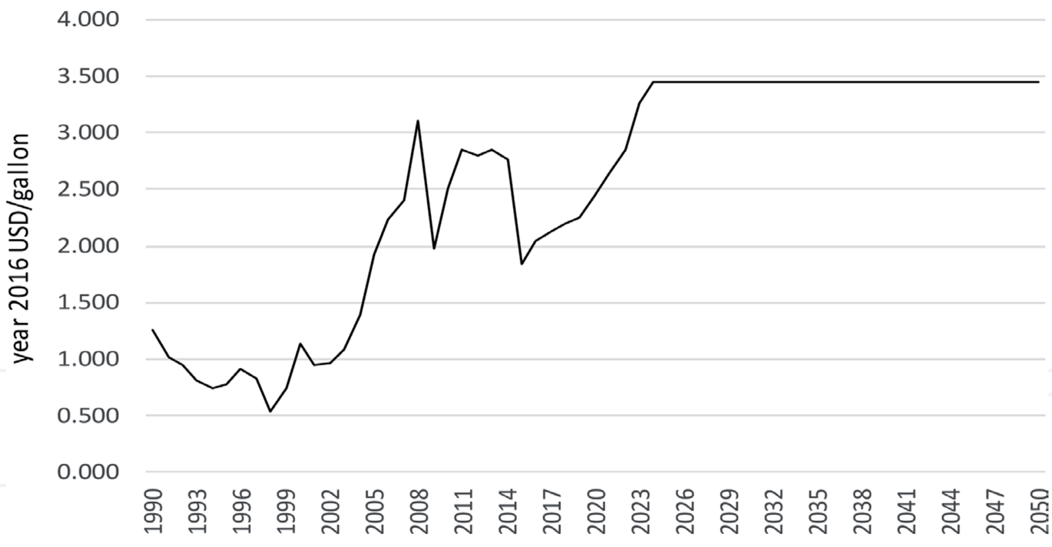

Figure 11.
Jet fuel price development in the SSP2 baseline scenario. Source: Own calculations, based on [63].

Dray et al. [63] obtained a range of results in the fleet fuel burn depending on the modelled scenario for future technology. FSDM's forecast fuel burn falls between their forecast boundaries as shown in the figure. Furthermore, there is a slight difference between the relative developments of RPK for the two models. This may be due to different input assumptions on aircraft size and utilisation used in both models as noted by Dray et al. [63]. However, since the fleet size, composition and capacity forecast ability of FSDM have been tested, this difference can be neglected.

4.4 Emission mitigation potential of the retirement strategy

4.4.1 General input for analysis

Past and forecast RPK growth factors are used as given by Boeing [58]. After 2036, the annual growth rates are assumed constant at 2036 levels. Assumptions on seat and freight load factor are the same as in the verification according to Boeing's forecast. Past fuel price until 2016 and forecast prices by Airbus until 2025 are used

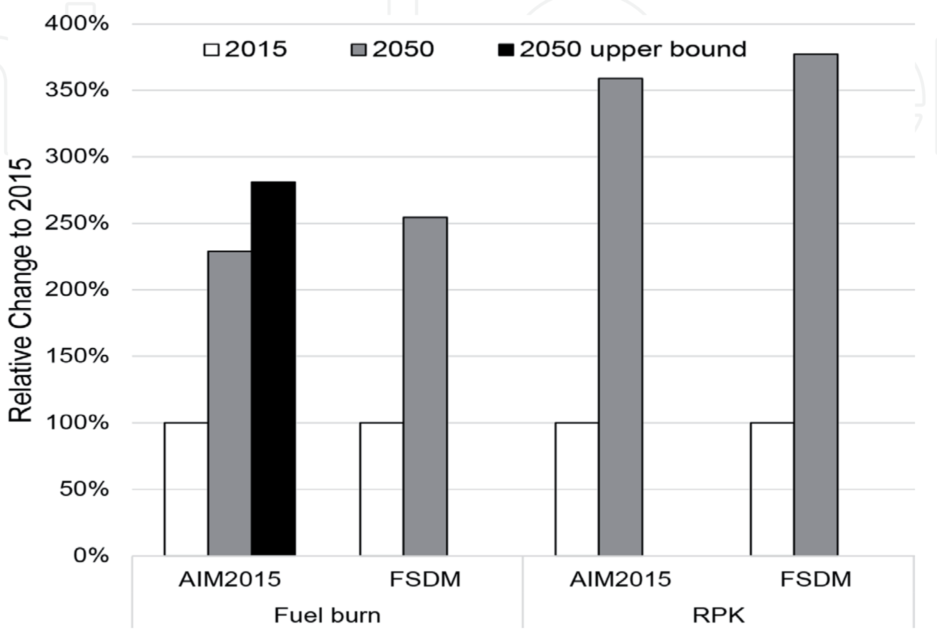

Figure 12.
Verification of forecast passenger aircraft fuel burn and traffic. Source: Own calculations, based on [63].

as shown in **Figure 6**. Fuel price after 2025 is assumed to increase annually by 0.1%, reaching 2.53 year 2016 US dollars per gallon in year 2050.

Fleet planning horizon and aircraft depreciation period are kept at 15 and 14 years, respectively. Aircraft production capacity and annual productivity are as earlier described. Furthermore, calibration input such as cost improvement assumptions is retained for all application scenarios.

5. Definition of scenarios

A baseline scenario is assumed which is named *giant-leap plus incremental improvement baseline*. This scenario assumes that incremental improvements are applied to initial fleet and next-generation aircraft. Thus, it assumes that airlines always integrate the latest available fuel and cost improvements on aircraft programmes when adding new available aircraft to the fleet. The actual state of CO_2 emissions from passenger air transport is expected to be similar to this baseline if in-service improvements on aircraft otherwise known as Performance Improvement Packages (PIPs), which are beyond the scope of this research, are considered. Incremental improvements refer all improvements shown in the Appendix (see **Table A-1**), excluding those comparing each aircraft to its previous aircraft generation.

Whereas the *Growth Strategy* has been used in the FSDM calibration and verification and is the strategy used for the baseline scenario, the *Replacement Strategy* is evaluated as a strategic measure to determine emission reduction benefits at the fleet level. Other assumptions of the baseline scenario are kept, except the fleet renewal sequence.

6. Results

Prioritising filling retirement gaps above growth gap implies that more aircraft production capacity is used for replacing economically inefficient aircraft. Compared to the *Growth Strategy*, the *Replacement Strategy* generates a higher wave of aircraft economic retirement. Between 2008 and 2050, the *Replacement Strategy* retires 7% more aircraft economically than the *Growth Strategy*. Between 2008 and 2024, the *Replacement Strategy* retires approximately 65% more aircraft economically and 44% more aircraft both economically and structurally. This can be seen in **Figure 13**.

However, in year 2024, few years after the JC, MR, LR and NB would be out of production; only a 3% improvement in CO_2 emissions is realised using the *Replacement Strategy* compared to the *Growth Strategy*.

From **Figure 14**, the two benefits of the *Replacement Strategy* until 2024 can be seen—a maximum of 2% higher share of retired aircraft in the fleet and a slightly longer year-on-year growth in fleet specific fuel consumption (SFC). However, because these improvements are minimal, the CO_2 emission improvement in the *Replacement Strategy* is also limited to about 3% in year 2024.

However, after year 2024, having attained a more cost-efficient and fuel-efficient fleet than in the *Growth Strategy*, the growth in ASK over time and the absence of more efficient aircraft result in fewer numbers of aircraft being retired by the *Replacement Strategy*. On the other hand, in the *Growth Strategy*, the fleet in year 2024 is not as efficient, thereby giving a possibility of better fleet renewal afterwards. Between 2025 and 2050, the *Growth Strategy* retires 4% more aircraft both economically and structurally than the *Replacement Strategy*. Therefore, compared to the *Growth Strategy*, the *Replacement Strategy* gives a lower EMP of 2% in 2050.

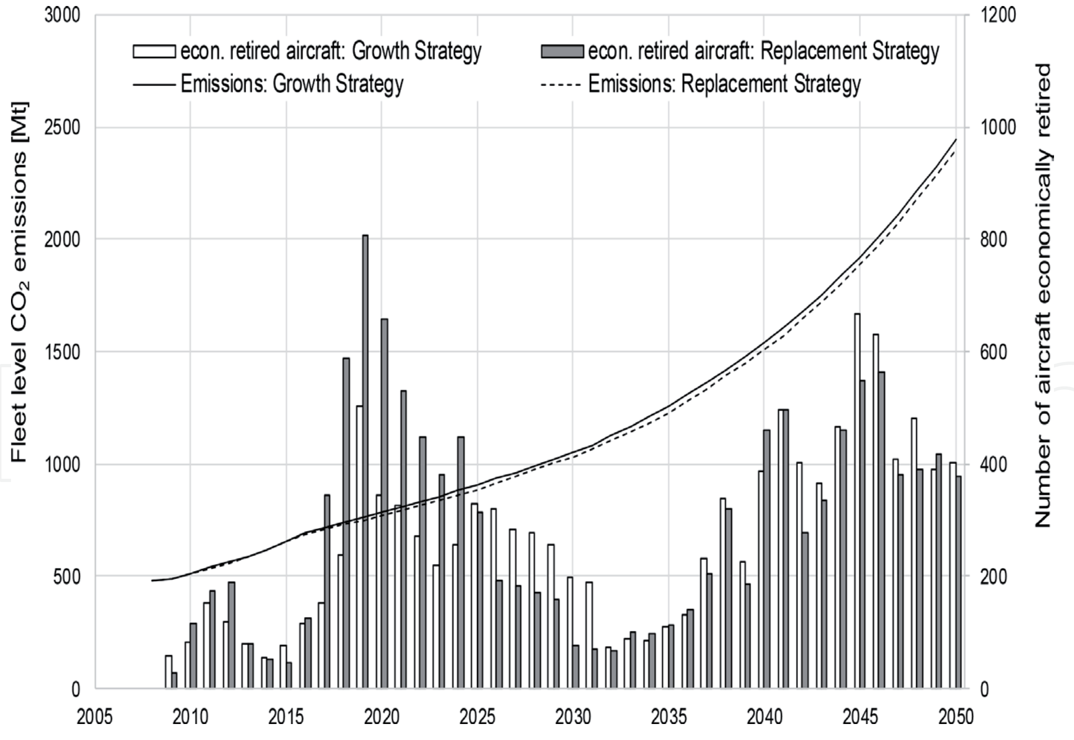

Figure 13.
Growth and replacement strategy: Number of aircraft economically retired and fleet level CO_2 emissions.

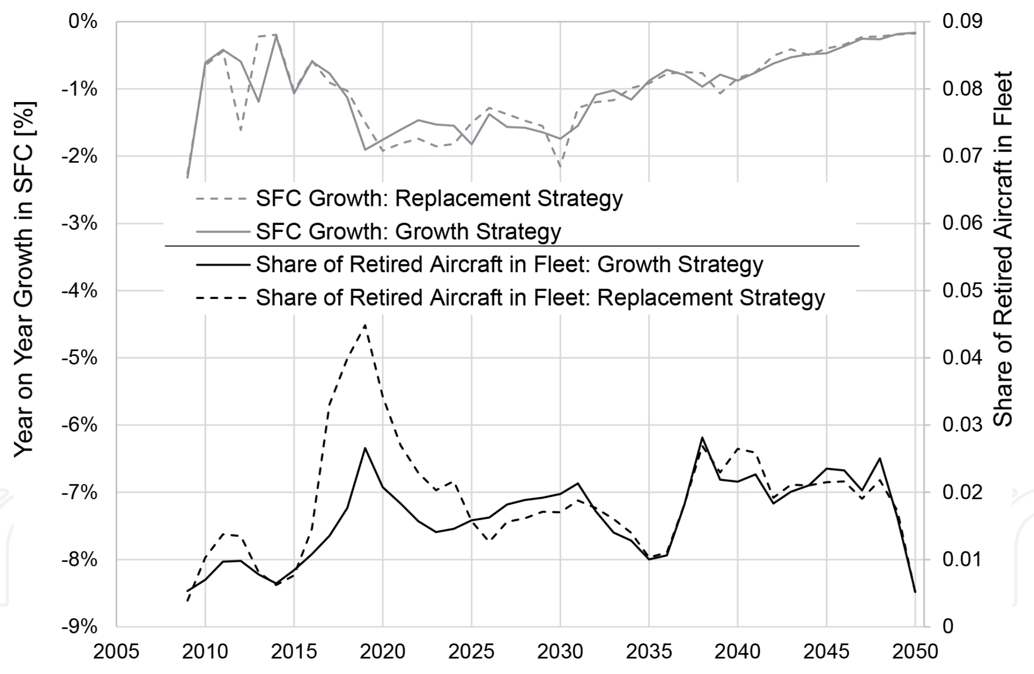

Figure 14.
Growth and replacement strategy: Share of retired aircraft in fleet and year-on-year growth in specific fuel consumption.

7. Conclusion

From the last fleet-level emission results of **Figure 13**, there is an identified short-term benefit of the *Replacement* Strategy. However, in the long term, the benefits reduce because the absence of newer more cost-efficient aircraft. Despite this diminished benefit, about 2% of the emissions (40 Mt. CO_2) could be saved at the global fleet level in year 2050 by using this fleet renewal strategy. Therefore, in order to achieve higher mitigation potentials, there is need for additional technological measures, in terms of more cost-efficient aircraft, with entry to service as from 2024.

As an outlook, having known the emission mitigation potential of the proposed *Replacement Strategy*, the cost analysis, i.e. advantage or disadvantage, of this measure should also be evaluated. Lastly, this study does not include effects of ticket price elasticity of fuel price changes.

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Appendix A

See Tables A-1 and A-2.

Aircraft cluster (earliest EIS year)	Cost improvements from cluster introduction to service [%]		
	Fuel cost	**Nonfuel COC**	**ADOC**
Long-range combi (1973)	Cruise performance improvement package: −4% [69]		
Long range heavy (1973)	Interior changes, aerodynamics and engine: −25% [70] Engine: −12% [70] PW4000 94-inch upgrade package: −1% [71]	B747–400 entry into service: −26% [72, 73]	
Jet commuter (1968)	E190 EIS, −18% [74, 75]; aerodynamic enhancements, −2% [76]	E190 improvement compared to previous aircraft in cluster, −25%; maintenance improvement, −5% [77, 78]	
Turboprop commuter (1990)	Use of ARMONIA cabin: −0.6% [79]		
Long range (1991)	PIP, −1% [80]; upgrade package, −2% [81]	−3.4% [82]	−3.4% [82]
Narrow body (1968)	A320 improvement compared to previous aircraft in cluster: −16.6% [83, 84] Other improvements including wingtip fence and sharklets: −3.5% [82]	Compared to previous aircraft in cluster: −7.9% [83] Average improvement adopted from B737–800: −2.5% [82]	Average improvement adopted from B737–800: −2.5% [82]
Next-gen mid range (2011)	Compared to previous generation, −20% [85, 86]; Trent 1000 TEN, −2% [87, 88]	Compared to previous generation: −10% [89]	
Next-gen long range heavy (2012)	Compared to previous generation: −16% [90], −3.5% [91]	Compared to previous generation: −3% [73]	

Aircraft cluster (earliest EIS year)	Cost improvements from cluster introduction to service [%]		
	Fuel cost	**Nonfuel COC**	**ADOC**
Next-gen long range (2015)	Compared to previous generation, −25% [92]; Trent XWB-84-enhanced performance, −1% [93]; sharklets, −1.4% [94]	Compared to previous generation: −25% [92]	
Next-gen narrow body (2015)	Compared to previous generation, −15% [91]; PW engine improvement, −2% [92]	Compared to previous generation: −14% [95]	
Next-gen commuter (2016)	Compared to previous generation: −17.3% [96]	Compared to previous generation: −10% [97]	Lower noise: −2% [98]

Table A-1.
Incremental and giant-leap cost improvements of FSDM aircraft types.

Aircraft cluster	Cost improvements [%]		
	Fuel cost	**Nonfuel COC**	**ADOC**
LRH	−4%	−7%	
MR	−1.8%	−3.6%	
LR	−2%	−2%	
NGMR	−14.9%	−9.8%	
NGLR	−15%	−5%	

Table A-2.
Additional aircraft cluster cost improvements assumed during calibration.

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