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Aircraft Fleet Renewal: Assessing Measures for Reducing CO_2 Emissions

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Abstract

This dissertation focuses on the assessment of fleet renewal measures aimed at fleet level CO_2 emissions reduction (EMR) of passenger aircraft. A research gap exists which involves the implementation of standard airline practices like Direct Operating Cost (DOC) estimation, structural retirement, and continuous improvements in airframe and engine (A&E) technologies to model longer term fleet renewal in a global context. Thus, studies on EMR involving the mentioned methods do not exist.

The existing Fleet System Dynamics Model (FSDM) was updated with an adjoining Aircraft Lifetime Cost Module (ALiTiCo) which generates lifetime DOC and structural retirement age for FSDM aircraft based on aircraft utilization and other parameters. This enables a better implementation of the airline practice of aircraft evaluation and retirement. Sensitivity tests were done using ALiTiCo before verifying that the integrated fleet model gives results compatible with historical and forecast data from similar models.

Fleet renewal measures studied are: two technological measures of continuous uptake of A&E improvements, and an assumed Future Generation Narrowbody aircraft (FGNB) with entry into service of 2035; and an operational measure of early structural retirement of narrowbody aircraft types; and an allocation of available aircraft to first fill economic retirement gap before growth gap. Using scenario analysis, CO_2 EMR caused by individual and combined fleet renewal measures in year 2050 were obtained. When combined, compared to a *Giant-leap Improvement Baseline* scenario, the measures yielded emissions reductions of 6% and 17%, without and with the FGNB, respectively.

In conclusion, emissions reduction (EMR) is facilitated by increase in market share of more-efficient aircraft in total fleet. EMR impact of early retirement of aircraft improves if more efficient are available. EMR improves when higher share of fleet is retired and higher growth in specific fuel consumption is attained. Lastly, EMR of each measure depends on the compared scenarios, and order of applied measures. Recommendations for further research include incorporating freighter aircraft in order to obtain a holistic view of the air transport system.

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Table of abbreviations

A&E	Airframe and Engine
A/C	Aircraft
ACARE	Advisory Council for Aviation Research and Innovation in Europe
ACAS	Aircraft Analytical System
ACC	Aircraft Commerce
ADOC	Additional Direct Operating Cost
AEA	Association of European Airlines
AEDT	Aviation Environmental Design Tool
AERO-MS	Aviation Emissions and Evaluation of Reduction Options Modelling System
AF	Africa (Global Region)
AF	Airframe
AFAF	Intra-Africa route group
AFLA	Africa-Latin America route group
AFNA	Africa-North America route group
AIM	Aviation Integrated Model
ALiTiCo	Aircraft Life Time Cost Module
APF	Airport Fees
APG	Airliner Price Guide
APMT	Aviation Portfolio Management Tool
APU	Auxiliary Power Unit

AS	Asia / Pacific (Global Region)
ASAF	Asia-Africa route group
ASAS	Intra Asia route group
ASK	Available Seat kilometres
ASLA	Asia-Latin America route group
ASME	Asia-Middle East route group
ASNA	Asia-North America route group
ATAF	Aircraft Technology Assessment Framework
ATK	Available Tonne kilometres
ATM	Air Traffic Management
BADA	Base of Aircraft Data
BHL	Bauhaus Luftfahrt e.V.
BPR	By-pass ratio
BWB	Blended Wing Body
CAEP	Committee on Aviation Environmental Protection
CGE	Computational General Equilibrium
CLEEN	Continuous Lower Energy Emissions & Noise
CMO	Current Market Outlook
CO_2	Carbon dioxide
COC	Cash Operating Cost
COO	Cost of Ownership
Db	decibels
DECC	Department of Energy and Climate Change
DLR	Deutsches Zentrum für Luft- und Raumfahrt

DMC	Direct Maintenance Cost
DOC	Direct Operating Cost
DSG	Design Service Goals
DSO	Design Service Objectives
DTI	United Kingdom Department of Trade and Industry
EASA	European Aviation Safety Agency
EIA	US Energy Information Administration
EIS	Entry into service
EMM	Emission Mitigation Measure
EMP	Emission Mitigation Potential
EMR	Emissions Reduction
ER	Early Retirement
ERA	Economic Retirement Age
ERA	Environmentally Responsible Aviation
ESG	Extended Service Goals
ESO	Extended Service Objectives
ETS	Emissions Trading Scheme
EU	Europe (Global Region)
EUAF	Europe-Africa route group
EUAS	Europe-Asia route group
EUEU	Intra-Europe route group
EULA	Europe-Latin America route group
EUME	Europe-Middle East route group
EUNA	Europe-North America route group

FAA	Federal Aviation Administration
FAST	Future Aviation Scenarios Tool
FC	Flight Cycles
FCECT	Fuel Consumption and Emissions Calculation Tool
FESG	Forecast and Economic analysis Support Group
FGNB	Future Generation Narrowbody aircraft
FH	Flight Hours
FLEET	Fleet level Environmental Evaluation Tool
FSC	Full service carriers
FSDM	Fleet System Dynamics Model
Future-Gen	Future-Generation
FW	Fixed Wing
GDP	Gross Domestic Product
Geogr.	Geographical
GFMC	Global Fleet Mission Calculator
GHC	Ground Handling Charges
GHG	Green House Gas
GIACC	Group on International Aviation and Climate Change
GLI	Giant-leap Improvement
GNP	Gross National Product
GREAT	Global and Regional Environmental Aviation Tradeoff
GS	Growth Strategy
HDP	High Depreciation Period
HFP	High Fuel Price

HPH	High Planning Horizon
IATA	International Air Transport Association
ICA	Initial Cruise Altitude
ICAO	International Civil Aviation Organisation
IEA	International Energy Agency
IGSM	Integrated Global Systems Model
IME	Integrated Modelling Environment
IncImp	Incremental Improvement
IPCC	Intergovernmental Panel on Climate Change
ITS	Introduction to service
JC	Jet Commuter aircraft
LA	Latin America (Global Region)
LALA	Intra-Latin America route group
LANA	Latin America-North America route group
LCCs	Low Cost Carriers
LDP	Low Depreciation Period
LFP	Low Fuel Price
LH	Long haul
LOV	Limit of Validity
LPH	Low Planning Horizon
LR	Long-Range aircraft
LRC	Long-Range Combi aircraft
LRCr	Long-range cruise
LRF	Long-Range Freighter aircraft

LRH	Long-Range Heavy aircraft
LTO cycle	Landing-Take-Off cycle
LTTG	Long Term Technology Goals
M/L-TA	Medium/Large Twin Aisle
MCTF	Maintenance Cost Task Force
ME	Middle East (Global Region)
MEAF	Middle East-Africa route group
MELA	Middle East-Latin America route group
MEME	Intra-Middle East route group
MENA	Middle East-North America route group
MERGE	Model for Evaluating Regional and Global Effects of GHG Reduction Policies
MiniCAM	Climate Assessment Model
MIT	Massachusetts Institute of Technology
MODTF	Modelling and Databases Task Force
MR	Mid-Range aircraft
MRF	Mid-Range Freighter aircraft
MTOW	Maximum Take-off Weight
NA	North America (Global Region)
NANA	Intra-North America route group
NAS	National Airspace System
NB	Narrowbody aircraft
Next-Gen	Next-Generation
NGJC	Next-Generation Jet Commuter aircraft

NGLR	Next-Generation Long Range aircraft
NGLRF	Next-Generation Long-Range Freighter aircraft
NGLRH	Next-Generation Long-Range Heavy aircraft
NGLRH2	Next-Generation Long-Range Heavy aircraft 2
NGMR	Next-Generation Mid-Range aircraft
NGMRF	Next-Generation Mid-Range Freighter aircraft
NGNB	Next-Generation Narrowbody aircraft
NGTP	Next-Generation Turboprop commuter aircraft
NO_x	Nitrogen dioxide
NPV	Net Present Value
O/D	Origin or Destination
OAG	Official Airline Guide
OECD	Organisation for Economic Cooperation and Development
OPR	Overall Pressure Ratio
PAX	Passenger
PC	Production Capacity
PIPs	Performance Improvement Packages
PLD	Payload
ppm	Parts per million
RD	Route Distance
RPK	Revenue Passenger kilometres
RS	Replacement Strategy
RTK	Revenue Tonne kilometres
SA	Single Aisle

SBW	Strut-Braced Wing
SFC	Specific fuel Consumption
SKO	Seat kilometers offered
slf	seat load factor
SMH	Small to medium haul
SRA	Structural Retirement Age
S-TA	Small Twin Aisle
TA	Twin Aisle
TOFL	Take-off field length
TP	Turboprop commuter aircraft
US or USA	United States of America
USD	United States Dollar
WWF	World Wide Fund for Nature
yearly_freq	yearly frequency

Table of symbols and subscripts

#	Number of
p	productivity
1	Referring either to the initial year of calculation or to a particular aircraft type
2	Referring either to the year following the initial year of calculation or to a particular aircraft type
i	Referring to one particular aircraft type
j	Referring to one particular route group
k	Referring to one particular year
nb	Referring to narrowbody or single-aisle aircraft types
wb	Referring to widebody or twin-aisle aircraft types

1. Introduction

1.1. Mitigation Methods for Commercial Aviation's Future Emissions

Since the 1970s when air travel liberalization began in the United States, air traffic has grown. Industry reports and forecasts claim a doubling or near-doubling of air traffic volume every 15-20 years [1–4]. As a compliment to this boom in the industry, aircraft efficiency has also improved with the advent of the turbo fan engine, such that by 2010 fuel burn per seat kilometre of the average aircraft entering the global fleet had reduced significantly by over 80% in 2010 compared to those operated in 1970 [5].

Despite this kind of improvement in aircraft efficiency to accompany the growth in air traffic, there has been an increased concern about the impact of aviation's emissions on the global environment. The International Civil Aviation Organisation (ICAO) has identified that air travel grows at a rate of about 5% per year, although fuel efficiency increased only at a lower rate of 1-2% per year [6]. Thus, if this trend remains into the future, emissions of aviation will be higher than current levels. The Intergovernmental Panel on Climate Change (IPCC) reported that carbon dioxide (CO_2) emissions from aviation accounted for 2% of total anthropogenic CO_2 emissions. Thus, given the estimated growth rate of air travel and the current action taken to reduce emissions from air travel, by 2050, the contribution of aviation to the total anthropogenic CO_2 emissions could grow to 3% [7,8], or even up to 22% [9].

Besides CO_2, aircraft also emit nitrogen oxide, water vapour and particulates [10]. Although water vapour does not have a major direct atmospheric warming effect, its emission into cold super-saturated air leads to the formation of contrails. Contrails trap heat in the atmosphere and have a warming effect close to that of carbon dioxide alone. However, there are significant uncertainties about their quantifications [10,11]. Hence, the effects of aviation on the environment are likely to be even higher than what has been estimated.

Therefore, in 2008, the aviation industry set ambitious non-binding goals on controlling the emissions from aviation while allowing an unrestricted growth of air travel. The goals are graphically shown in Figure 1.1 and are:

1. To improve fleet fuel efficiency by 1.5% per year from 2010 till 2020
2. To cap net emission from 2020 through carbon neutral growth, and
3. By 2050, to reduce the net aviation carbon emissions by half of what they were in 2005.

As can be seen from the figure, the goals are expected to be achieved by implementing a combination of measures comprising of technology, operations, infrastructure, and economic measures [5].

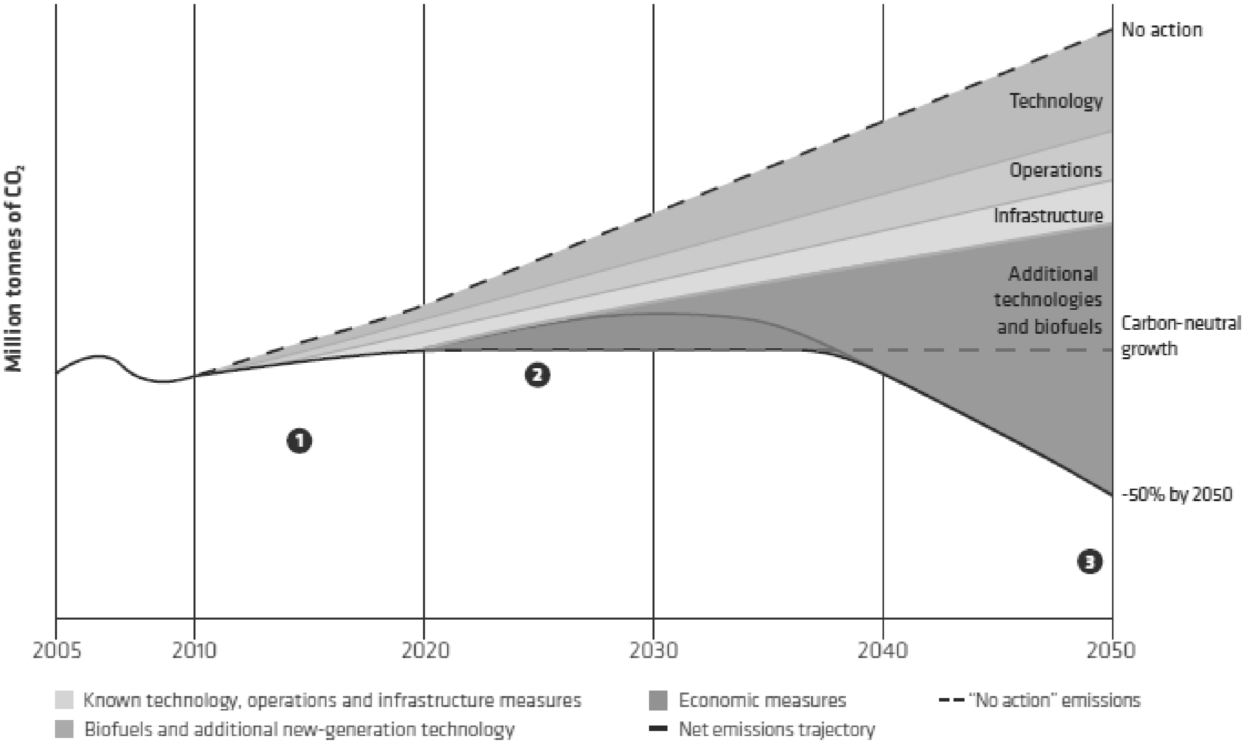

Figure 1.1 Longer-term goals of the aviation industry

Source: [5]

Technological measures proposed include evolutionary new aircraft design, new composite lightweight materials, radical new engine advances, and the development of biofuels. Operations measures include reduced auxiliary power unit (APU) usage, more efficient flight procedures, weight reduction measures, and cabin densification. Infrastructure measures include more efficient air traffic management (ATM) and airport infrastructure implementation through better en-route navigation and approaches to landing. Lastly, economic measures imply global emissions trading, and global mandatory offsetting with revenue [5,12,13]. All these measures, when combined together, are expected to improve the fuel efficiency [kg fuel burn per seat km] of the global fleet and ultimately reduce the CO_2 emissions by 50% compared to the emissions level in 2005.

1.2. Factors Affecting Global Fleet Fuel Efficiency

Many interrelated factors affect global fleet fuel efficiency. In line with the ambitious goals of the industry, aircraft airframe manufacturers and aircraft engine manufacturers have achieved significant advances. Kharina [14] reported that the average fuel efficiency of the global aircraft fleet increased at an annual rate of 1.3% per annum from 1968 to 2014. Although major improvements of 2.6% per annum occurred in the 1960s and 1980s, later improvements from 2010 to 2014 were lower at 1.1% per annum. The major drivers for the efficiency improvement were identified as increase in fuel prices which had generally translated into demand for more efficient aircraft, more liberalization which resulted in intensified price competition, a reduction in the market share of less-efficient regional aircraft, as well as the availability and influx of more efficient aircraft into the global fleet [14].

Growing aircraft demand also contributes to the fleet renewal efforts. This is aided by the growth in Low-Cost Carriers (LCCs) [4,15] which usually operate their aircraft at a higher seat density. A study conducted in 2017 showed that the average seat capacity of aircraft had increased, especially for narrowbody aircraft types that are common with LCCs [16]. On a per-seat basis, fuel efficiency of the global fleet improves by assuming that aircraft are operated at higher seat densities [17]. Therefore, the expected continued growth of LCC and their aircraft will further improve the fleet fuel efficiency of the global aircraft fleet.

However, the higher growth in air travel undermines the efforts towards fleet renewal leading to a projected growth in net carbon emissions of 3-4% per annum [8]. This low rate of fleet renewal is largely due to the average lifetime of an aircraft which is between

20 and 30 years [18]. Also, with sustained low jet fuel prices aircraft years in service could be further extended [19,20].

In addition to sustained low jet fuel prices, aircraft manufacturers give aircraft operators possibilities of keeping aging aircraft longer in service beyond their original design life. This is offered in packages like Extended Service Goals (ESG) and Extended Service Objectives (ESO) given to extend average aircraft lifetime. Groenenboom [21] reported that about 47% of Boeing 737 classics and 6% of Airbus A320 aircraft in service (roughly 700 aircraft units of both Boeing and Airbus aircraft types) were operated beyond their designed service life. Previous Design Service Goals (DSG) of the A320 was 48000 FC/60000 FH [22], whereas the ESG is now set at 60000 FC or 120000 FH.

Lastly, deferrals or cancellations of aircraft orders further force airlines to use aging aircraft and, as a result, worsen fleet fuel efficiency. This usually results from aircraft manufacturer delays in deliveries as well as not meeting contractual agreements [23].

These factors of extended service life and aircraft order deferrals or cancellations, though non-beneficial to the global fleet fuel efficiency, are part of airline strategic decisions to minimize their operating costs in response to exogenous circumstances. Likewise, achieving higher seat densities on aircraft lead to lower operating costs, however, this decision helps to improve fleet fuel efficiencies.

Therefore, despite the significant progress made in fuel efficiency, airline practices leading to extension of average aircraft age have not all favoured the overall improvement of global fleet fuel efficiency.

1.3 Scope and Goal of Thesis

This thesis work describes the method of modelling aircraft structural and economic end of life as a major component of aircraft fleet development. Major factors affecting aircraft retirement and fleet growth are identified and evaluated using scenario analysis to determine their reduction effects on fleet level emissions.

Specifically, different scenarios of fuel price development are analysed, as well as extension of aircraft design life. Additionally, airline strategy scenarios of adopting available improvements in airframe and engine (A&E) technology, as well as allocating aircraft production capacity are analysed.

However, aircraft deferrals and order cancellations are not evaluated. Neither freighter aircraft nor airline business model differences are considered in the current work. Specifically, this work contributes to scientific knowledge in the following three areas:

i. Modelling end of economic life on individual aircraft level
ii. Modelling fleet development and fuel burn
iii. Assessment of measures meant to reduce fuel burn at the fleet level.

1.4 Thesis Structure

Since the long term environmental goals of aviation earlier mentioned are evaluated at the fleet level, fleet-level assessment methodologies become necessary with which the expected impact of proposed mitigation measures can be evaluated. However, since aircraft fleet are managed by airlines, it also becomes imperative for such methodologies to correctly reflect airline fleet planning strategies and operations.

Chapter 2 therefore introduces longer-term fleet planning as a fleet development modelling method for evaluating the impact of mitigation measures and explains how this fleet planning method is different from other fleet planning methods of airlines. Afterwards, system requirements for longer-term fleet planning are explained, followed by a more detailed presentation of the macro-evaluation method as a core process of fleet development modelling.

Chapter 3 presents a literature review of studies applying different models to evaluate the impact of different emission mitigation measures (EMMs). It also provides a comprehensive overview of the methods and models used in estimating future CO_2 emissions reduction potentials and measures.

Chapter 4 then presents the Fleet System Dynamics Model (FSDM), which is an existing fleet development model. The chapter gives a description of the major capabilities and methods of the tool before this research work.

Chapter 5 describes the Aircraft Life Time Cost Module (ALiTiCo) which pre-calculates important input for the FSDM. The main input and output as well as the module sequence are presented. The chapter concludes with some verification studies to ensure reliability of the module’s output.

Chapter 6 describes the updated methods used and the additional capabilities of the yearly simulation of the integrated fleet model- FSDM.

Chapter 7 describes the calibration of the updated FSDM and the verification of the reliability of the methods integrated in the FSDM. First, fleet development forecast data by Boeing for jet aircraft is used for the calibration of the integrated fleet model. Next, global fleet development data on passenger aircraft from other comparable sources are used to verify past and forecast fleet metrics.

Chapter 8 presents scenarios of fleet renewal measures that apply the updated, calibrated and verified FSDM. The emission mitigation potential (EMP) of each scenario measure is presented.

Lastly, a conclusion of this research work and suggestions for further research are made.

2. Global Fleet Development Modelling

Given the evidence of the environmental impact of aviation, it is imperative to estimate the impact of measures designed to mitigate the emissions from commercial aviation. A prerequisite for this will be the ability to estimate longer-term aviation emissions. Therefore, this chapter explains the fleet planning practice of airlines: the different horizons it entails, factors affecting aircraft demand and end of life, and how fleet planning is generally used in global fleet development modelling through the macro-evaluation method.

2.1. Horizons in Airline Fleet Planning

Four possible fleet planning methods can be identified in aviation planning, each with its respective time horizon. The longer-term method is important to regulators and researchers of aviation activities whereas long-term, medium-term and short-term methods are majorly used by airlines. The four methods are described in Table 2-1.

Longer-term fleet planning method, covering periods of 25 to 50 years, is concerned with key features and performance criteria of a typically simplified fleet whose development is driven by forecast demand, technology and productivity. It is used to forecast requirements for aviation activities, for example, for planning investments into infrastructure and capacity, or for assessing future CO_2 emissions, to develop solutions for an efficient fleet [24]. This planning method could be applied at different geographic scales ranging from national to global applications.

For the determination of future CO_2 emissions, because of the long period, the degree of uncertainty in the results increases because of the higher likelihood of changes in the key factors influencing the results. Therefore, the use of scenarios is the best approach for gaining understanding of the evolution of longer-term futures. The IPCC defined a scenario as “a set of assumptions devised to reflect the possible development of a particular situation over time. These assumptions are used as inputs to a model that describes the manner in which an activity might develop over time” [17].

Table 2-1 Comparison of fleet planning methods

Planning Horizon	**Fleet Planning Method**	**Goal**	**Principle**
Longer-term (25 - 50 years)	Fleet development modelling method	• Environmental impact assessment of longer term aviation activity	• Determination of aviation demand using longer term aviation forecast for chosen geographic scope • Determination of fleet requirements using repeated long-term fleet planning analysis until target future year • Determining the future environmental impact of aviation activity
Long-term (>5 years; 6 - 15 years)	Macro-evaluation method	• Determination of fleet requirement (aircraft to be retired and acquired) in long term airline operations • Communication with aircraft manufacturers on improvement in future programs, product support, etc.	• Fleet requirement determined in terms of aircraft acquisition. • Aircraft acquired according to capacity gap at future point in time, considering forecast demand, required types of aircraft to serve future demand, and aircraft retirement • Operating economics (potential revenue and direct operating costs) evaluated at aircraft level
Medium-term (1 to 5 years)	Schedule-evaluation method	• Optimization of total fleet and individual aircraft • Review of options and letters of intention placed	• Allocate forecast demand to current plan/schedule after projecting into the future • Check if load factor is unreasonably low or high • Fleet requirements determined after iterations of adjusting schedule frequency, assigned aircraft itinerary structure, connect opportunities, and operating economics
Short-term (up to 1 year)	Aircraft-assignment method	• Assignment of selected/individual aircraft • Consolidation of acquisition	• Define total system in terms of origin-destination traffic demand, aircraft performance, operating economics, financial limits, and system constraints • Select and assign aircraft using computer software such that service and operating requirements, and objective function are satisfied

Source: ICAO [24]

Because of the uncertainty involved, the IPCC suggested that scenario assumptions or results ought to be consistent with industry trends and with rules that are expected to remain unchanged during the scenario period. Likewise, there ought to be internal consistencies or compatibilities with other dominating external developments [17].

Generally, two approaches to long-term fleet planning are established in literature: the macro approach, also known as the top-down approach or macro-evaluation method; and the micro approach, also known as the bottom-up approach, to fleet planning. In the macro approach, a demand forecast is used to determine the number of seats necessary to provide a certain level of service to an identified market, region or route. Different aircraft models are then evaluated within the forecast scenario for the market and operating realities so that economics can be estimated. The output is an approximate number of defined aircraft type(s) needed to provide the desired level of service [25,26].

In the micro approach to fleet planning, aircraft are evaluated on specific routes under economic forecast; competition effects of airlines are included with respect to market share and pricing powers. Since the micro approach is more detailed in its approach, it can provide more comprehensive evaluations if accurately modelled. However, the required level of detail also poses a disadvantage to this model because of time requirements as well as the difficulty in accurately predicting the actions of competitors. Therefore, the top-down approach is commonly used for long-term fleet planning [25,26].

The macro-evaluation method serves as a basis for fleet development modelling methods. However, since the methods aggregate operations of airlines, they should also reflect airlines’ responses to dominating external developments in the global air transport system.

2.2. System Coverage as Fleet Planning Requirement

The estimation and timing of aircraft demand lies at the core of fleet planning. In this regard, ICAO defined fleet planning as the act of determining future fleet requirements[1]

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[1] Types and quantity of aircraft needed in the future

and the timing of aircraft acquisitions. ICAO further recommended a system-level approach to fleet planning [24]. Thus, modelling the process of fleet development requires the consideration of many interrelated factors. Figure 2.1 shows the system interactions in airline fleet planning, based on literature findings.

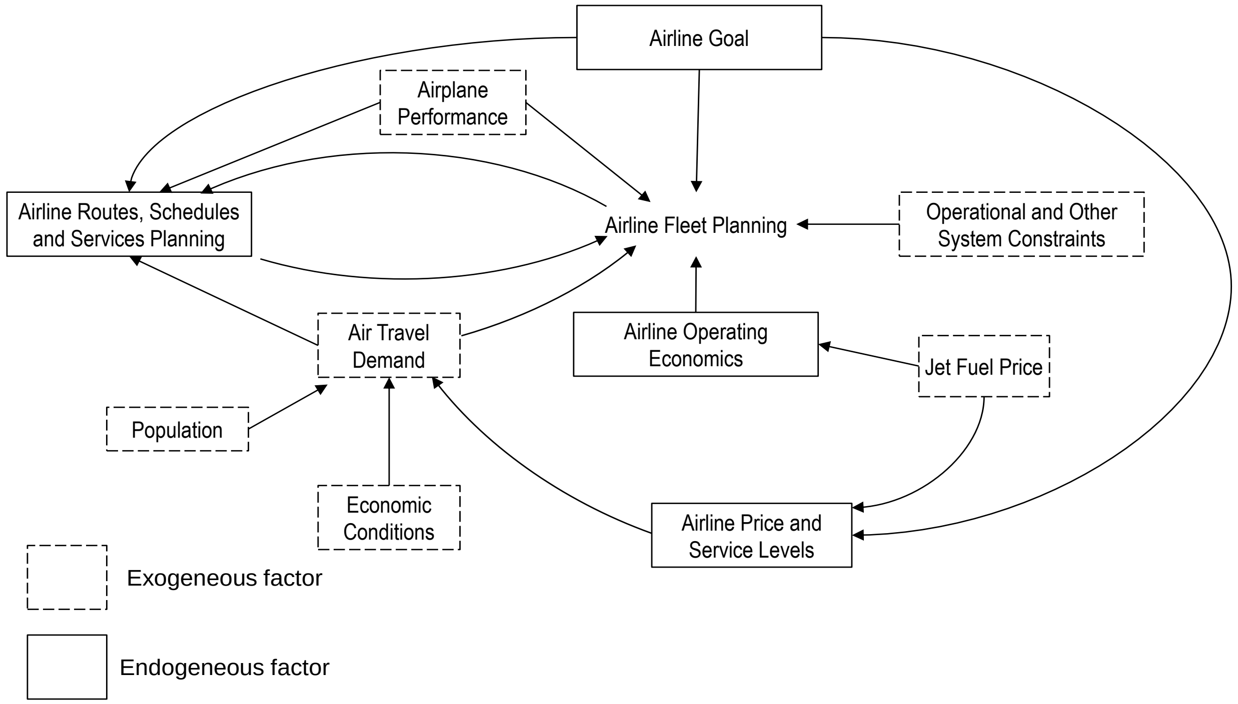

Figure 2.1 Aggregated system interactions in airline fleet planning process

Source: own depiction

Similar to global fleet fuel efficiency, a number of factors affect airline fleet planning, among which changes in oil price is a major factor [27]. Demand for new aircraft typically grows when oil prices increase, as newer aircraft types generally have more efficient fuel burn. On the other hand, incentives are reduced by low fuel prices, and below a threshold of $60/barrel the demand for new aircraft drops to a very low level [27].

Interest rates also affect aircraft demand- positive demand exists when the rates are low. Likewise, airline profitability and availability of liquidity affect demand for new aircraft. Airlines operating profitably require newer aircraft to increase their operations, and positive aircraft demand occurs when there is easy marketability of aircraft [27].

Also crucial to airline fleet planning is the aircraft acquisition method. Aircraft can be acquired either through an outright purchase or by financial lease. The share of leased aircraft in the total global fleet is projected to reach approximately 50% by 2025 [28]. However, the scope of this research does not cover methods of acquiring aircraft.

Furthermore, the demand for new aircraft is influenced by business and operational factors including operational costs reductions, supporting strong growth of air travel in and to emerging markets, and replicating successful low-cost carriers (LCC) business models. Similarly, renewing an ageing fleet (especially of US airlines), retaining market share, and strengthening competitive advantage when facing new competition provide an incentive for ordering new aircraft. Lastly, the emergence of airlines in developing countries because of the increase in the proportion of the middle class population also creates aircraft demand [29,30].

Of all the factors identified to drive demand for new aircraft, growth in air travel demand is the most crucial. Air travel demand is influenced by the economic and demographic situation in the airline's market [24], the ticket price the passenger should pay, and the competitive situation offered on the market, for example in the case of LCCs [15].

Air travel demand is therefore a major predictor of fleet requirements considered by airlines in their fleet planning process. This is because many fleet planning methods are based on anticipated Revenue Passenger kilometers (RPK) growth [31]. In addition, air travel demand is considered when planning routes and services. With increasing demand, airlines extend their network coverage to new or emerging markets and can increase the number of flights on their routes.

The planning of routes and services, a major aspect of an airline's business model, usually serves as a driver for fleet planning, for example, assuming a case of planning from scratch. The routes to be flown, including the destinations to be served, and the planned turn-around times affect the choice of aircraft. Also, planned services including planned operational costs are put into consideration in the fleet planning process. The Organisation for Economic Co-operation and Development (OECD) stated that operating costs had replaced technology as the key factor for consideration by airlines before they purchased aircraft [32]. Apart from jet fuel price, a major driver of operating costs is the level of cabin density chosen as part of the airline's product development. A higher average seat density [seats/m^2] in the aircraft cabin decreases the unit costs to the airline while reducing passenger comfort.

On the contrary, the result of an airline's fleet planning, i.e. existence or absence of aircraft with payload-range and technology capabilities (among other fleet properties), also affects the routes, schedules and services the airline can offer especially in the future.

Therefore, airlines plan their routes and services with the aim of effectively competing in existing or target markets and building up competitive strength to defend or enter these routes/markets respectively. In addition to an airline's network competitive strategies, other factors affect airline fleet planning such as aircraft technical performance (payload-range capability, technology year, etc.), operational and other system constraints (turn-around times, airport slot capacity, airport emission restrictions, exchange rates) [24,25].

From the foregoing discussion, the following endogenous factors to an airline affect its aircraft selection or fleet planning process: airline goals (projected market position), airline price and service levels, operating economics (total operating costs and revenues), as well as airline routes, schedules and services planning [24,33]. Other factors such as economic and demographic conditions affecting air travel demand, airplane technical performance, as well as operational and system constraints are exogenous to the airline industry [24,33]. This research work focuses on the influence of airline operating economics, air travel demand, airplane performance and airline routes on airline fleet planning.

2.3 Aircraft End of Life and Replacement

Given all the factors that affect what type of aircraft is added to a fleet and when this should happen best, the other side of long- and longer-term fleet planning involves what type of aircraft should be retired and when this should best happen.

The introduction of new aircraft and macro-economic factors such as crude oil price are the main factors driving or delaying retirement of aircraft globally [20], 21, 34]. High crude oil prices result in higher operating costs, fostering retirement of old inefficient aircraft. On the contrary, with low fuel prices, airlines tend to delay replacement of their older aircraft [35].

In addition, aircraft are designed with defined periods of time within which it has been tested that significant cracking including widespread fatigue damage would not occur on the aircraft. These periods, usually expressed in Flight Hours (FH) or Flight Cycles (FC), are referred to as the Design Service Goals (DSG), Design Service Objectives (DSO) or Limit Of Validity (LOV) of an aircraft [36]. Aircraft shall be withdrawn from service when they reach their LOV [37]. A possible alternative could be to extend the technical life (DSG/DSO/LOV) as is sometimes the practice of airlines especially in situations of low fuel prices [22,38,39].

Airlines usually couple aircraft retirement with replacement. Replacement could come as a result of keeping up with competition on relevant airline markets or systematically increasing capacity through profit profiling [33,35]. A review of traditional aircraft successions in the industry reveals that recent replacement aircraft are up to +20% larger, in terms of typical seat capacity, than aircraft they replace as shown in Table 2-2.

Table 2-2 Typical seating capacity of aircraft type successions

Aircraft Type	Typical Seating	Successor Aircraft	Typical Seating	Delta [%]
B747-100	366	B747-400	416	+14
B747-400	416	B747-8I	467	+12
E190	100	E190-E2	106	+6
CRJ900	90	CRJ900-NG	90	0
ATR72	68	-	70	+3
B763	261	B787-8	242	-7
A330-300	247	A330-800neo	257	+4
B772	305	B777X	365	+20
A340-300	295	A350	325	+10
B727-200	134	B737-800	162	+21
B727-200	134	A320	150	+12
B737-100	96	B737classic	149	+55
B737classic	149	B737NG	160	+7
B737NG	160	B737MAX	178	+11
A320	150	A320neo	150	0

Source: aircraft manufacturers’ websites

Furthermore, Boeing stated that aircraft retirement occurs when its end of economic life is reached, defining the later as the time when “the cost to retain and operate the airplane exceeds profits generated” [4]. This is usually due to rising maintenance costs [40] since aircraft maintenance costs account for 14-20% of cash airplane related operating costs [41].

Replacement theory defines the optimal replacement of capital equipment in a deteriorated condition as necessary when the operating cost of keeping the old equipment is higher than the long-run cost associated with investing in a new piece of equipment [42].

Applying this theory to the airline industry, airlines therefore compare the operating cost of their aircraft in the long-term planning horizon (see Section 2.1) with those of newer aircraft in deciding when an economic replacement is due.

As a result, airlines will retire their aircraft if the direct operating cost (DOC) of their aging aircraft is higher than the direct operating cost of a new available replacement aircraft. Therefore, in addition to maintenance costs, changes in fuel costs (another major cost component of aircraft DOC [41]) influence the economic retirement of aircraft. Besides operating economics, other factors also play a role like traffic volumes and market development [43].

2.4 Macro-evaluation Method: Core Process of Fleet Development Modelling

After discussing the drivers of fleet planning and its components, the next discussion focuses on the use of the macro-evaluation method in fleet development modelling. The main components include the determination of capacity gap (*Gap ASK*), the determination of the number of aircraft required (*# A/C required*), and the determination of the number of particular aircraft types (*# particular A/C types*).

This is shown in Figure 2.2.

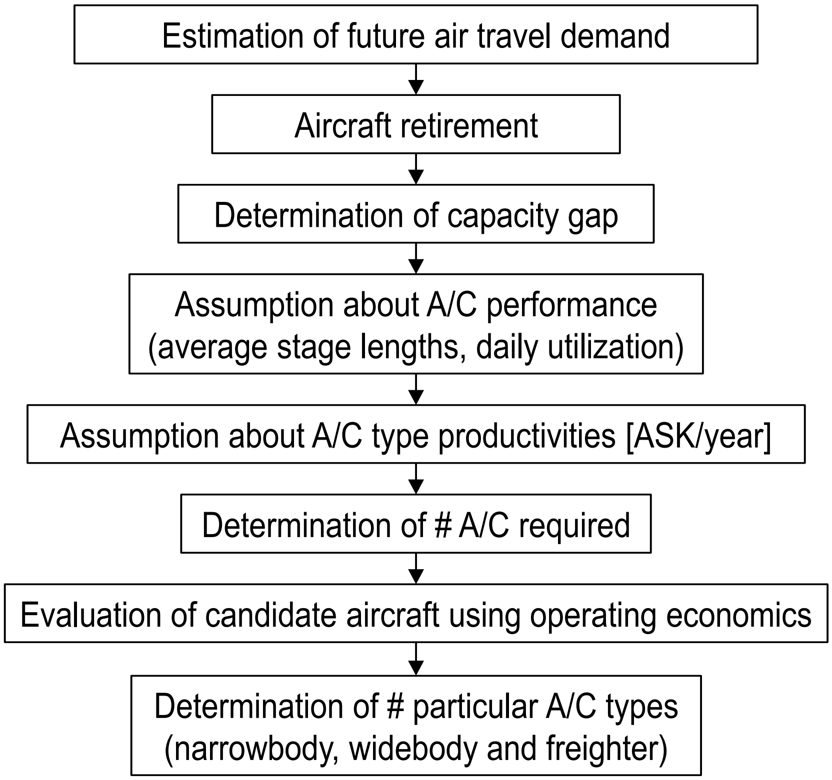

Figure 2.2 Main steps of the macro-evaluation method

Source: ICAO, Belobaba et al. and Clark [24,31,33]

2.4.1 Determination of capacity gap

Based on a set of assumptions, a certain yearly traffic growth rate is used to define the expected traffic demand RPK_2 in a following year *2* from the base year *1*. An assumed seat load factor is used to determine the capacity ASK_2 an airline is required to supply in year *2*. Thus, the capacity growth gap, the additional capacity an airline is required to supply above the current capacity ASK_1 of the base year, can be calculated as the difference between ASK_2 *and* ASK_1 as shown in Equation 2.1

$$\sum \mathbf{ASK}_{\boldsymbol{i,j,k}} - \sum \mathbf{ASK}_{\boldsymbol{i,j,k-1}} = \mathbf{Growth\ ASK}_{\boldsymbol{i,j,k}} \tag{2.1}$$

i, j, k are indices for aircraft, route, and year of evaluation, respectively;

k-1 is the previous year of analysis

Next, a retirement gap *Retirement* $ASK_{i,j,k}$ (see Equation 2.2) exists after the retirement of old inefficient aircraft. This results in a surviving fleet with reduced supply capacity ASK_2^* in year 2.

$$\sum\left(\boldsymbol{RD_{i,j,k}} \times \boldsymbol{Seats_{i,j,k}} \times \boldsymbol{yearly\_freq_{i,j,k}}\right) = \boldsymbol{Retirement\ ASK_{i,j,k}} \qquad (2.2)$$

Therefore, the capacity gap is calculated as the sum of the retirement gap and the market growth gap as shown in Equation 2.3 and Figure 2.3

$$\boldsymbol{Growth\ ASK_{i,j,k}} + \boldsymbol{Retirement\ ASK_{i,j,k}} = \boldsymbol{Gap\ ASK_{i,j,k}} \qquad (2.3)$$

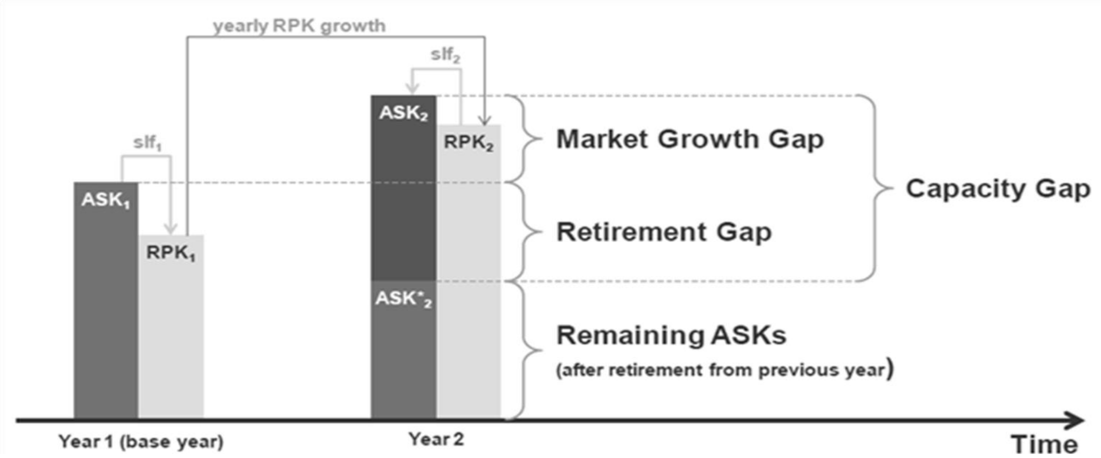

Figure 2.3 Capacity gap determination in macro-evaluation method

Source: [25,31,44]

2.4.2 Determination of number of aircraft

After determining the capacity gap on a route, airlines determine the number of aircraft that can be operated to satisfy the capacity demand gap. This is based on the airline's assumption concerning the current and future performance of candidate aircraft in terms of aircraft utilization, aircraft payload capacity and airline network stage length [31]. The number of aircraft can therefore be calculated as shown in Equation 2.1

Number of aircraft = Gap ASK / ASK per aircraft 2.1

At the end of this stage, a first round of selection is achieved based on the airline's network requirement. Aircraft are eliminated from the selection based on their payload-range capabilities. A study conducted on nine of the top airlines based on total scheduled passengers carried in 2014 revealed that best practice values for aircraft output in 2014 were 1304 million ASK per long haul[2] (LH) aircraft and 399 million ASK per short to medium haul[3] (SMH) aircraft. However, the global average values for these aircraft types were much lower, and airline values varied as shown in Figure 2.4.

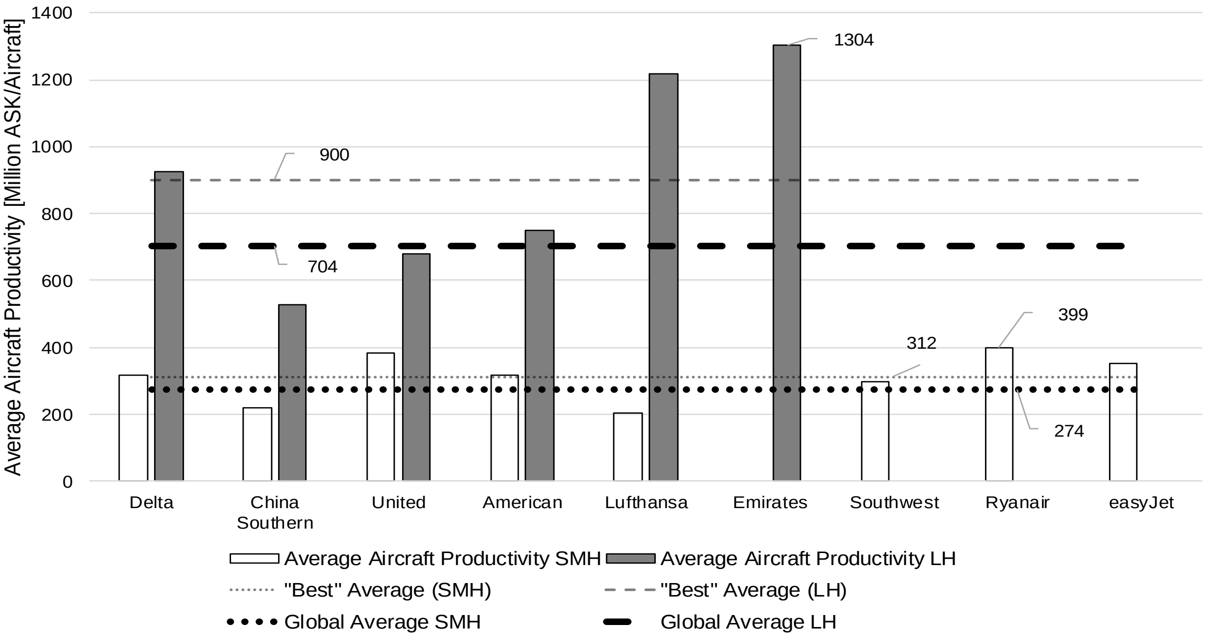

Figure 2.4 Average aircraft productivity: global average and best practice values from top airlines in 2014

Source: own depiction

2.4.3 Aircraft Evaluation Analysis

After an airline estimates the number and type of aircraft required to satisfy the capacity gap based on aircraft performance claims, the airline then makes a more detailed

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[2] Long-haul segment is one that cannot be operated by an unconverted A320 or B737 aircraft (Morrel, 2008)

[3] Short to medium haul network segment is one that can be operated by an unconverted A320 or B737 aircraft; not considered are regional jets with maximum seating capacity of not more than 100

evaluation of the candidate aircraft. Design characteristics, physical performance, maintenance needs, acquisition costs, and operating economics have to be considered [45].

Design characteristics include aircraft dimensions, weight profile, fuel capacity, seating configuration, and total volume, whereas the physical performance of aircraft includes items such as take-off and landing data, cruise and approach speeds, runway requirements, and noise performance, in addition to payload-range diagrams. Maintenance needs relate to the availability of spare parts, as well as fleet compatibility and commonality considerations, while acquisition costs include the cost of the aircraft itself plus spare parts, ground equipment needed, maintenance and flight training required, and the cost of financing together with manufacturer warranties and prepayment schedules. Factors affecting aircraft economics to be compared are the operating costs as well as the revenue [33,45].

Clark [33] recommended a project management approach using rolling wave planning process for the aircraft evaluation work. Although, the approach takes an iterative way of working, it begins with a request for technical operational and support information from aircraft manufacturers to estimate the performance and, if possible, economics of the aircraft under consideration. Basic information that could be requested relates to fuel burn and maintenance cost. Once the estimate results are considered satisfactory, the request for proposal is then submitted in which milestones are set between the airline on the one hand, and aircraft and engine manufacturers on the other.

The full set of selection criteria varies with the type of airline or leasing company carrying out the aircraft selection process. For example, for a lessor, a potential aircraft must be adaptable to a wide range of markets, whereas, that would not be a must-have for a short-haul low-cost carrier. After all responses are submitted, the evaluation team then analyses and interprets the data for the airline owner or board to decide on what aircraft to add to the fleet. Afterwards, a Letter of Intent or Memorandum of Understanding is signed before finally a Purchase Agreement is signed. It follows that the macro-evaluation method of fleet planning would produce different results for different airlines who operate different networks. Therefore, when utilizing the macro-evaluation approach in longer-term horizon fleet planning methods, it would be expected that simplifications and assumptions need to be made to model the global airline industry.

2.5 Chapter Summary

The fleet development modelling method is used to determine future aviation emissions and possible emissions reduction by repeated iterations of the macro-evaluation method from a base year to a target year. This is based on assumptions of aircraft utilization in the modelled market as short- and medium-term fleet planning results, and other assumptions, for example, on air traffic growth rate. A global fleet development model would then be expected to reflect the system interactions in airline fleet planning, for example, including the impact of aircraft utilization, and growth in air travel demand on aircraft demand and retirement. In addition, such model would also include a method of determining capacity gap between two successive years, evaluating candidate aircraft based on operating economics, and determining the number of most efficient aircraft to fill capacity gap on each network segment.

The global air transport system is complex because of its many different interacting parts. For example, differences exists between aircraft types and their performances, between markets and their macro-economic factors for a given point in time, and between airlines, especially in their networks and business models. There is an added complexity involved when considering changes in these factors over time.

As a result, no single fleet development model can completely describe all the factors, processes, interactions and methods discussed in this chapter for the global air transport system. However, fleet development models are developed to describe essential system interactions depending on the investigated mitigation measures and geographical scope. This chapter thus presented an overview of the aspects and principles to be considered in global fleet development modelling. The simplifications and approach chosen in this research work while considering the influence of airline operating economics, air travel demand, airplane performance and airline routes on airline fleet planning will be discussed in later chapters. In the meantime, a review of existing approaches to fleet development modelling is presented in the next chapter.

3 Review of Existing Approaches to Fleet Development Modelling

Evaluating future environmental impact of aviation requires using a set of assumptions within an integrated modelling environment that consists of linked submodules simulating different aspects of the aviation system [46]. The IPCC [17] reviewed studies using scenarios of long term emissions reduction. They first investigated scenarios made by the Forecasting and Economic Analysis Support Group (FESG) of the Committee on Aviation Environmental Protection (CAEP) and the United Kingdom Department of Trade and Industry (DTI) whose focus was more on fuel efficiency improvements. Studies conducted by World Wide Fund for Nature (WWF) had a broader focus including phasing out of air freight, policies to encourage mode shift to road and rail, technological options such as changes in cruise altitudes and alternative fuel sources, as well as increases in load factors and fuel tax. Studies conducted at the Massachusetts Institute of Technology (MIT) were based on time and expenditure budget forecasts produced for global passenger transport. The last study evaluated the fleet fuel burn and NO_x emissions associated with the availability of High-Speed Civil Transport fleet which are expected to displace some subsonic aircraft upon entry into service [17].

However, the scenarios investigated by IPCC included little or no consideration of economic factors like fuel price variation in the future, neither was the economic end of life of aircraft considered. Furthermore, the IPCC report did not give an overview of the reduction potential of the identified emissions reduction measures. Besides, the studies reviewed were conducted not later than 1999, before the ambitious goals of aviation were determined.

This chapter focuses on studies made after the IPCC publication. Recent studies involving integrated models for evaluating fleet-level emissions reduction are reviewed; used model methods, input scenarios, and their corresponding results are described.

The goal of the chapter is to present a summary highlighting the emissions mitigation measures investigated in the studies, the approaches taken to evaluate fleet turnover as well as essential areas of research not included in the studies.

3.1 Aviation Integrated Model

The Aviation Integrated Model (AIM) builds on a fleet turnover model in which global aviation emissions are affected by new aircraft purchases, changes to aircraft in the fleet and retirements [47]. The model produces Net Present Value (NPV) cost implications of various possible fuel burn reduction scenarios like high fuel prices, emissions trading scheme (ETS), and other policy options. Furthermore, in the model, replacement aircraft were added to the in-service fleet by a comparison of the NPV advantages or costs of replacing aircraft of various ages with new technology. The replacement aircraft offered a significant improvement in fuel efficiency of between 15-35% compared to the best existing models of the same seat capacity. Aircraft retirements followed a logistic functional form comparable to the CAEP/8 FESG retirement curves; which also affected the global aviation emissions estimates.

Dray et al [48] investigated the effect of global emissions trading on global aviation demand and emissions using the Aviation Integrated Model (AIM). Three scenarios were used, combined differently with five stringency levels of atmospheric CO_2 stabilization, each with an associated carbon price. Table 3-1 shows the assumptions of the scenarios.

Table 3-1 Global assumptions of the scenarios using AIM

Scenario	**Oil Price (year) [year 2005 $/ bbl]**	**Carbon Price at 750ppm - 450ppm stabilisation levels [year 2005 $/tonne$CO_2$]**
IGSM	88.8 (2020), 125.5 (2040)	5.6 - 80.1 (2020), 13.0 – 189.5 (2040)
MERGE	71.7 (2020), 98.0 (2040)	0.3 – 34.0 (2020), 1.2 – 118.3 (2040)
MiniCAM	62.3 (2020), 77.8 (2040)	0.3 – 28.8 (2020), 1.1 – 98.3 (2040)

Source: Author’s depiction based on [48]

The main differences in scenarios were in global distribution of GDP per capita and population annual growth, and in oil and carbon prices, with carbon prices directly affected by the level of stringency simulated.

The main technology options modelled to reduce emissions were the open rotor engine aircraft assumed to enter the fleet in 2020 and biomass-derived synthetic jet fuel, in a 20% blend with Jet A, also assumed to be available from 2020. Other mitigation options were incorporated, like retrofitting winglets on aircraft without them, an option which has a low total effect on global emissions. Also, air traffic management improvements were assumed to be non-optional in the US, European and Asian regions, resulting in a 4% decrease in total global fuel burn from 2015 to 2025. Furthermore, engine upgrade kits were assumed to have low adoption rates.

They found out that by 2050, aviation-related CO_2 emissions may range from double the 2005 level (under the most stringent atmospheric CO_2 stabilization target of 450 ppm) to five times the 2005 levels (when no emissions trading took place). They also found out that the adoption of new technologies in response to increased carbon costs resulted in approximately two-third of the total emissions reductions while the last third was because of demand reduction. Open rotor engine aircraft as new technology options were particularly incorporated into the fleet in scenarios with high oil prices to save on total fuel and carbon costs. On the other hand, biofuels, were incorporated into the fleet in high stringency scenarios, assuming they were priced at similar prices or higher than Jet A. The functionality of the emissions trading scheme was such that the expected increase in aviation CO_2 would be offset by reductions in emissions from other sectors.

Even though the studies using AIM modelled the economic evaluation of aircraft for addition to the global fleet, they incorporated neither the economic nor technical end of life of aircraft. In addition, they did not determine the emissions reduction potential of the mitigation measures implemented.

3.2 Future Aviation Scenarios Tool

Owen et al. [49] developed aviation emission scenarios to 2050 that were designed to interpret IPCC scenarios under four main families, with a further outlook to 2100.

Additionally, a scenario was developed assuming that the ambitious technology targets of ACARE would be achieved.

Their work was implemented using the Future Aviation Scenarios Tool (FAST). The global model of aircraft movements and emissions had a baseline year of 2000 and combined a global aircraft movement's database of scheduled and non-scheduled air traffic with data on fuel flow provided by a separate commercial aircraft performance tool PIANO. Aircraft were modelled using 16 types and engines, representative for the global fleet. Fleet development was fed by fleet forecast [50]. They normalised the CO_2 emissions in the base year to the International Energy Agency (IEA) total aviation fuel sales figure of 214 Tg/year. Projected traffic growth rate of ICAO/CAEP (4.3% annual average) was used until 2020; while traffic demand for each scenario was calculated using global GDP growth as the main driver in addition to the differing maturity of aviation markets in the regions.

Scenarios were defined assuming that political and societal factors affected future travel both globally and with different regional impacts. Aircraft added to the fleet after the base year (e.g. B787, A380) to replace retired older aircraft were estimated with about 20% fuel efficiency such that a fleet-wide efficiency improvement of approximately 1% $year^{-1}$ from 2000 up to 2020 was realised. Beyond 2020, ACARE technology goals and ICAO/CAEP Long-Term Technology Goals (LTTG) were used in the scenarios. Table 3-2 shows the scenarios used and their CO_2 emissions results.

Since the fleet development method implemented was based on externally predefined fleet forecast, there was a low sensitivity of fleet development to possible changes in external economic factors. Besides, their scenarios were more technologically inclined and lack considerations of other measures. For example, operational emissions mitigation measures like forced aircraft retirements or economic measures like carbon pricing were not evaluated.

Table 3-2 Scenario assumptions and CO_2 emissions results from study using FAST

Scenario	**Notes**	**Fuel Efficiency [kg/SKO] growth rate**		**CO_2 [Tg]**
		2000-2020	**2020-2050**	
A1B	Greatest growth in regions such as Africa and Latin America. Moderate infiltration of ACARE-complaint new aircraft into fleet: 5% in 2020, 25% in 2030, 75% in 2050	1% year^{-1}	1% year^{-1}	2418
A2	Lowest overall demand, lack of technological advances and intl. cooperation	1% year^{-1}	0.2% year^{-1}	1481
B1	More radical aircraft designs, materials and alternative fuels become available.	1% year^{-1}	1.3% year^{-1}	1345
B1ACARE	Same as in B1 above. Furthermore, all new A/C entering fleet are ACARE-compliant. Demand is slower, compared to other scenarios.	1% year^{-1}	2.1% year^{-1}	1025
B2	Lacks tough emissions standards and features less technological advances like in B1	1% year^{-1}	2020-2030: 1% year^{-1}; 2031-2050: 0.6% year^{-1}	1373

Source: [49]

3.3 Global and Regional Environmental Aviation Trade-off tool

Hassan et al. [51] proposed a framework, similar to the description of the Global and Regional Environmental Aviation Trade-off (GREAT) tool [52] , to assess the performance of the future National Airspace System (NAS) under different scenarios that considered varying technology, operation, and biofuel contributions to mitigate the environmental impacts of aviation.

Vehicle performance was determined for different combinations of airframes, engines, and technology packages. Seven vehicles classes of tube and wing aircraft configurations with geared fan engine were considered namely turboprop, regional jet, small single aisle, large single aisle, small twin aisle, large twin aisle and very large aircraft, simulating only domestic operations in the United States.

Technology improvements were modelled as continuous improvements in fuel efficiency and thus reduced CO_2 emissions. The best improvement at aircraft level, the N+3 technology, was to achieve a reduction of 60% in aircraft fuel consumption referenced to the B737-800 with CFM56-7B engines. Table 3-3 shows the technology considerations and their possible entries into service. Since operational efficiency improvements affect flight time, and thus fuel burn, mission fuel burn was modelled as a function of distance and flight time.

Table 3-3 Aircraft technology considerations using the GREAT tool

Technology Generations	**N+1 (2015)[1]**	**N+2 (2020)[2]**	**N+3 (2025)[1]**
Noise[3]	-32 dB	-42 dB	-52dB
LTO NO_x Emissions[4]	-60%	-75%	-80%
Cruise NO_x Emissions[5]	-55%	-70%	-80%
Aircraft Fuel Consumption[5]	-33%	-50%	-60%

[1] referenced to B737-800 with CFM56-7B engines

[2] referenced to B777-200 with GE90 engines

[3] cumulative margin relative to Stage 4

[4] relative to CAEP 6 standard

[5] relative to 2005 best in class

Source: [51]

In the framework developed, a baseline operational network and fleet composition was established. Aviation forecasts that predicted future operational growth at airports were considered. A trip distribution algorithm was applied to predict future operations along routes. Aircrafts were retired based on parametric ‘survival’ curves. Replacement aircraft were added based on capability/vehicle class, then fuel and energy consumption of the updated system network was computed.

Scenarios were based on their best estimates of available technology sets within the simulation time frame without use of biofuels and operational measures. For this, they assumed passenger demand based on the Aerospace Forecast (2013-2033) growth rates for U.S. domestic and international air travel. Results of the different scenarios in terms of the factor of increase or decrease in the fleet CO_2 emissions are shown in Table 3-4.

Table 3-4 Scenario assumptions and CO_2 emissions results using the GREAT tool

Scenario	**New Technology introduction**	**Normalised Factor in Fuel Burn and CO_2 (year 2050 compared to 2006)**
Business as usual	Not introduced	1.88
Reference-Technology-Collector	No new technology introduced, but fleet upgrades to current state of the art technology allowed	1.30
N+2 – Basic Implementation	Select N+2 technologies introduced alongside current technologies	1.08
N+2 – Moderate Implementation	More N+2 technologies introduced alongside current technologies	1.02
N+2 – Full Implementation	All available N+2 and N+3 technologies introduced	0.95

Source: [51]

Thus, Hassan et al. [51] showed that the carbon-neutral growth goal could be reached using technology improvements. However, the goal of reducing CO_2 emissions in 2050 by 50% relative to 2005 values could not be reached by technologies alone. They suggested that operational measures and alternative, sustainable aviation fuels would be needed to fill the remaining gap.

However, a more recent related study [53] suggested that the 2050 goal could be realized if other aspects were included. Such aspects included the response of passenger demand to macroeconomics, and changes in operating cost and ticket prices resulting from different scenarios of jet fuel price. The sensitivity of fleet emissions to accelerated aircraft retirements was also evaluated. This resulted in emissions savings only in the short-term; in the longer term, aircraft were replaced with those of similar efficiency. They also considered fuel consumption reduction at the fleet-level because of more advanced hybrid-electric aircraft technologies. Three classes of hybrid-electric aircraft technologies were defined: regional jet, small single aisle and large single aisle aircraft.

They investigated scenarios involving different combinations of demand, fuel prices, and technology level. They found out that, for the investigated combinations, hybrid electric aircraft had a moderate contribution in reducing CO_2 emissions relative to 2005 values. Also, from their preliminary results, a scenario involving medium demand, high energy price and medium technology performance including hybrid aircraft had a better EMP than that with low demand, medium energy price and medium performance technology in reducing CO_2 emissions towards the 2050 target. However, they found out that a scenario involving high demand could not achieve the 2050 goals of IATA.

Similar to the observations concerning other integrated models, not only was the GREAT tool used with a focus only on the U.S. market, studies using the tool neither considered aircraft end of economic life in the fleet development methodology nor identified the EMP of the each mitigation measure tested.

3.4 Fast Foreward

The German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR) fleet and fuel forecast tool, Fast Foreward (FFWD) [54] was developed to assess the impact of new aircraft technology on global CO_2 emissions of airline traffic. The tool methodology projected the development of the world fleet of commercial passenger aircraft; then, to each aircraft model in the forecast, it assigned fuel consumption and performance information. Global CO_2 emissions and traffic were then calculated by aggregating the single aircraft estimates. The model used retirement curves from ICAO’s CAEP to remove aircraft from the world fleet. The year 2008 ICAO FESG forecast was used to generate traffic growth scenario for which the number of additional aircraft needed to satisfy this growth was calculated. Additionally, IATA's traffic forecast was applied for the long run. In this way, aircraft demand consisted of fixed existing aircraft orders, with the surplus unassigned demand expected to be covered by "unfixed aircraft demand".

All aircraft models were classified into eight different aircraft size categories (51-100 seats, 101-150 seats, 151-210 seats, 211-300 seats, 301-400 seats, 401-500 seats, 501-600 seats, and 601-650 seats) and four aircraft technology groups (old technology[4],current technology[5], new technology[6], and unfixed demand). New technology aircraft were modelled to have significant CO_2 improvements compared to current technology aircraft, whereas unfixed demand (or future generation) aircraft were represented by a generic aircraft per seat category [54].

Schilling [55] reported the study conducted by the German Aerospace Centre (DLR) in cooperation with the International Air Transport Association (IATA), using FFWD, to investigate the benefits, challenges and resulting CO_2 EMP, at the world fleet level, of novel aircraft configurations and fuel technologies. The aircraft configurations were a fully electric aircraft concept, a strut-braced wing with open rotor configuration and a blended wing body configuration.

A baseline scenario for the study considered global aircraft fleet and fuel consumption development considering only evolutionary technologies as detailed by IATA [8]. The study excluded potential economically driven delays such as weaker world economics or reluctance to invest in large high-risk research and development projects. Furthermore, an underlying RPK annual growth scenario of 2.0% from 2005-2010, 5.3% from 2010-2020, 4.5% from 2020-2030, 4.0% from 2030-2040, and 3.7% from 2040-2050 was used [55].

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[4] Old technology aircraft include, for example, the MD-80 aircraft

[5] Current technology aircraft includes aircraft like A320, 737, CRJ, 767, 777, 747-400, CRJ-900

[6] New technology aircraft includes aircraft like A320neo, A350, 737max, 787, Cseries, and Mitsubishi MRJ with specified technology factors representing fuel burn improvements compared to current technology aircraft

The assumed properties of the aircraft configurations investigated and the forecast potential impact of each configuration, as well as the combination of the three, are shown in Table 3-5.

Table 3-5 Aircraft concepts and associated scenarios studied using FFWD

Aircraft Configuration Scenario	EIS	Range and Seat Properties of Introduced Aircraft	Block Fuel Burn saving potential	CO_2 saving potential on global fleet level in 2050
Fully-electric Aircraft (Electrical)	2035+	700-1000 nm, up to 200 seats	-100% compared to reference aircraft of similar size and range	Up to 15%
Blended Wing Body (BWB)	2040+	7500 nm 500 seats	-50% compared to reference aircraft of similar size and range	Approximately 1-2%
Strut-Braced Wing with Open-rotor (SBW)	2030+	3500 nm 154 seats	-29% for 2030 version up to -62% for 2045 version	Up to 7%
Electrical + BWB + SBW	2030+	700-1000 nm, 3500 nm and 7500 nm 154 seats up to 500 seats		About 20% to 25%

Source: [55]

The EMP results of the mitigation measures are in agreement with results of other studies, for example in subsection 3.4, that technological measures alone are insufficient for achieving the aspirational goals of the aviation industry.

Although the study presented by Schilling [55] evaluated fleet development at the global level, together with the evaluation of EMP of defined aircraft concepts, the aircraft retirement methodology did not give consideration to the economic and technical end of life of aircraft.

3.5 Fleet Level Environmental Evaluation Tool

Ogunsina et al. [56] described the Fleet Level Environmental Evaluation Tool (FLEET) which mimicked how a profit-seeking airline might get to use new aircraft under given conditions of market demand and environmental policy. The tool mimicked development on US domestic routes as well as international routes with origin or destination (O/D) airport in the US by taking a set of 24 aircraft, divided into six size-classes spanning four technology ages that represented all aircraft operating in the network.

The tool was set-up as a system-dynamics framework of models of aircraft technology evolution, economic and policy changes. The aircraft technology evolution model simulates the aircraft retirement and acquisition process of the airline. The model started at the assessment of the performance of each class of aircraft; using performance attributes such as number of deployed and available aircraft, average number of trips for each aircraft class, and the fraction of total market demand served by each class of aircraft in the fleet.

The number of aircraft in each seat capacity required to satisfy increasing demand was estimated using predicted demand for the following year. Afterwards, the model estimated the number of aircraft to be retired in each technology generation and each seat capacity class. The number of aircraft in each seat capacity required to satisfy increasing demand was deducted from the total number of aircraft produced in each seat class to obtain the maximum number of aircraft available to replace existing aircraft evaluated for retirement. Current aircraft were evaluated by comparing the NPV of a strategy of keeping the existing aircraft with the NPV of replacing the aircraft. The FLEET airline then followed the strategy with the higher NPV.

The replacement strategy entailed either replacing existing aircraft with available new and similar-class aircraft, or, if there is no available similar-sized aircraft, replacing with an available larger-sized aircraft. In addition, aircraft with airframes older than 40 years were retired and replaced if there was any available aircraft. In addition, the priority was to replace retired aircraft with new available same seat class aircraft, otherwise with smaller class aircraft. In case of a lack of available aircraft, the old aircraft would be retired without a replacement aircraft. In the event of a replacement of retired aircraft, the model ensured that the same total number of seats flown by the existing aircraft was provided [56].

Table 3-6 below shows the representative-aircraft and their respective classes and technology ages. The expected entry-into-service (EIS) dates for the two technology ages with the most technology improvements are also shown in Table 3-6.

Table 3-6 Representative aircraft modelled using FLEET

Aircraft Class (Seats)	**Representative-In-Class**	**Best-in-Class**	**New-in-Class {Expected EIS}**	**Future-in-Class {Expected EIS}**
Small Regional Jet (20-50)	RJ200/RJ440	ERJ145	Small Regional Jet	
Regional Jet (51-99)	RJ700	E170	CS100 {2016}	
Single Aisle (100-149)	B737-300	B737-700	B 737-700 Re-engined {2016}	Purdue Small ASAT with N+1 / N+2-level tech {2025}
Small Twin Aisle (150-199)	B 757-200	B737-800	B 737-800 Re-engined {2018}	D-8 “Double Bubble” {2024}
Large Twin Aisle (200-299)	B 767-300	A330-200	B 787 {2018}	
Large Quad Aircraft	B 747-400	B777-200ER	Large Twin Aisle {2020}	

Source: [56]

Three scenarios were investigated: *Baseline, Late EIS*, and *Low GDP* scenarios. Table 3-7 shows the scenario assumptions. They also assumed that neither airport capacity constraints nor biofuel options were implemented. Also, jet fuel prices were incorporated according to US EIA reference fuel price projections. Of the three scenarios, the *Late EIS* scenario resulted in the highest total CO_2 emissions in 2050, about 4.5 times the emissions value in 2005, because of the delay in availability of next-gen aircraft. On the other hand, the lowest total CO_2 emissions resulted from the *Low GDP* scenario, mainly due to low aircraft utilization resulting from low air travel demand.

Table 3-7 Scenarios considered using FLEET

Scenario	EIS Date of New-In-Class Aircraft	EIS Date of Future-in-Class Aircraft	GDP Growth Rate
Baseline	Expected EIS Year	Expected EIS Year	2.8% beginning in 2009 on all routes except routes with O/D in Asia which have rates of 4.3%
Late EIS	Expected EIS + 5 years	Expected EIS + 10 years	2.8% beginning in 2009 on all routes except routes with O/D in Asia which have rates of 4.3%
Low GDP	Expected EIS Year	Expected EIS Year	2% beginning in 2009 on all routes except routes with O/D in Asia which have rates of 3.07%

Source: [56]

3.6 Aviation emissions and Evaluation of Reduction Options

Belonging to the European Aerospace Safety Agency (EASA), the Aviation Emissions and Evaluation of Reduction Options (AERO) model is an economic and technical model of global air transport. The model was developed with the goal of determining aircraft technology characteristics based on fleet development, forecasting demand for air services and aircraft flights, and estimating the overall aircraft operating costs. Other goals were to calculate aircraft fuel use and engine emissions, and provide a comprehensive overview of cost and revenues of air transport and some other economic impacts.

Because of the large variety of aircraft existent, and also the difficulty of rightly predicting the specific characteristics of future aircraft, the model developers utilized a classification approach of clustering all aircraft into 9 seat bands. Furthermore, nine range bands, two aircraft purposes (passenger or cargo aircraft), and aircraft technology year were used. The engine age was classified “old”- if the first engine production year was 1991 or earlier; or “current”- if the first engine production year was 1992 or later.

A schematic overview of the sub-models comprising the updated model, Aviation emissions and Evaluation of Reduction Options Modelling System (AERO-MS), is shown in Figure 3.1.

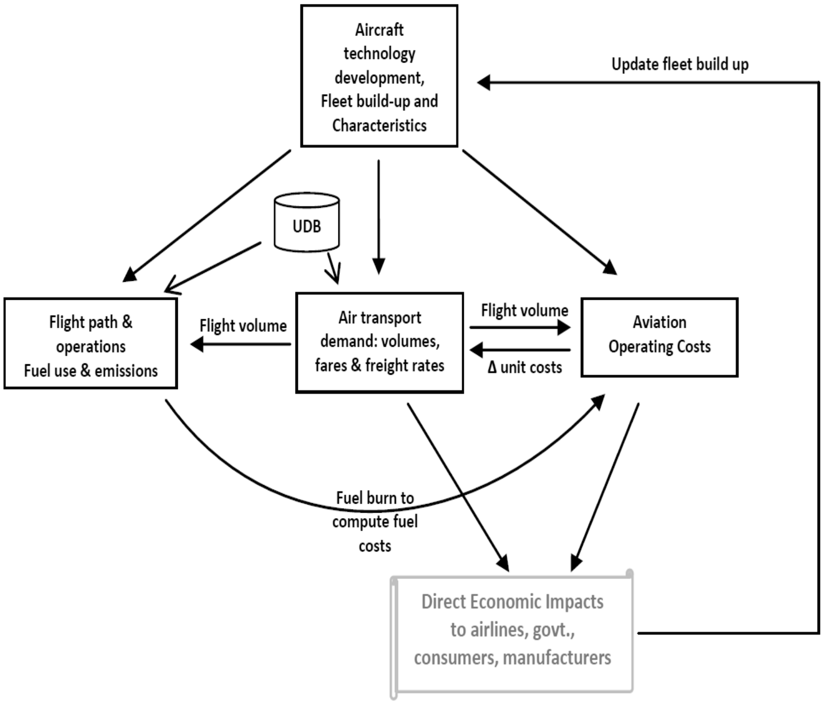

Figure 3.1 Overview of sub-models in the AERO-MS

Source: Author, based on EASA [15][15]

Thus, the global aircraft fleet was categorized using ten aircraft types (i.e. 10 combinations of range and capacity) with two possible technology levels for each aircraft type, and two possible aircraft purposes.

Fuel efficiency improvement of new aircraft technology was modelled yearly as fuel burn reduction relative to aircraft produced in the previous year. The AERO model used, among others, the PRISME dataset. From this dataset, for each seat and range band and aircraft purpose (i.e. for a generic aircraft type), an historic fleet build-up in terms of aircraft entering the fleet by purchase year (i.e. entry into service year) was retrieved. The observed sales in the PRISME dataset was then used to draw a relation of the sales over the purchase years for each generic aircraft type (GAT). From the sales, an average annual sales growth rate was determined using the last 10 years prior to 2006 (base year). The modelled aircraft entering the fleet by purchase year was then determined by combining information on annual sales with the retirement curve and an assumed maximum life span of the aircraft [15]. Table 3-8 gives information about the ten aircraft types seat and range capabilities simulated in the AERO-MS model [15].

The choice of aircraft to operate on a route was based on the direct operating cost (DOC) of the aircraft. Using aircraft operating costs, it could then result that policy scenario developments, such as emissions trading, would favour more fuel-efficient aircraft types, despite their higher ownership costs. Therefore, an aircraft choice mechanism was used which traded off the differences in ownership costs and cash operating costs.

Table 3-8 Reference aircraft and engine types considered by EASA

Reference A/C	Aircraft Type	Engine Type	Seat Band	Range band
0	C750	AE3007C	0-19	Short
1	CRJ2	GE CF-34-3B1	20-100	Short
2	A319	CFM56-5B5/P	101-150	Short
3	B738	CFM56-7B26	151-210	Short
4	B737	CFM56-7B22	101-150	Medium
5	A320	CFM56_5_A3	151-210	Medium
6	B764	CF6-80C2B7F	211-300	Medium
7	B772	PW4090	211-300	Long
8	B772	PW4090	301-500	Long
9	A380	TRENT 970-84	>500	Long

Source: [15]

The AERO model modelled two distinct business models: scheduled and non-scheduled (or charter) airlines, differentiating in terms of cost structures, fare levels, and demand response (elasticity) to fare changes. Full service carriers (FSCs) were modelled in the "scheduled" category while low cost carriers (LCCs) were included in the "charter" category, because of their similar cost levels, fares, load factors, demand elasticities and aircraft utilization [15].

In the AERO-MS, scenarios and policy options were tested. The former referred to autonomous developments with respect to air transport and flight activities, whereas the later referred to a variety of financial, technological and operational measures. The CAEP8 moderate (CAEP8-M) scenario was used. Four variant scenarios were defined: one on an optimistic technology and operational improvement (*OTI*), two on the effect of an oil price improvement (*Ef_OPI1* and *Ef_OPI2*) and one on the observed demand reduction between 2007 and 2009 in North America and Europe.

The variant scenario *Ef_OPI1* modelled the price elasticity of demand if average fare increased by 12.5% from 2006 to 2026 while the variant scenario *Ef_OPI2* modelled the gross national product (GNP)-related effect of an increased oil price. The CAEP8-M scenarios included estimates of fuel price. However, the effects of price elasticity of demand and GNP reduction were not modelled.

Table 3-9 summarises the assumptions and some results of the CAEP8-M scenario and the variant scenarios *OTI, Ef_OPI1 and Ef_OPI2* investigated using the model.

In addition, economic and financial policies as well as regulation and operation policies were applied. Financial policies tested include in the order of efficiency: fuel taxation of 0.5 US$ per kg of fuel, route charges per aircraft-km by aircraft type and technology level, airport charge per aircraft movements, and additional ticket and value-added taxation to airlines and air transport clients, respectively, by applying a global increase in fares and freight rates. Regulation and operation policies used include the scrapping of all aircraft with a certification year or purchase year older than 25 years. Another policy used was an additional fuel technology improvement (AFTI) [% p.a.] from 2007 to 2026 with a percentage increase in price of new aircraft from 2016 for each 1% additional fuel improvement. Others were a reduction in purchase price of new aircraft purchased within two years of technology availability, and percentage reduction of part of detour factor in excess of 1 (%RD), accounted for by percentage increase in route charges.

Table 3-9 Assumptions and selected results of scenarios studied by EASA

Parameter	**Base year (2006‡) value**	**CAEP8-M 2016 (OTI) {Ef_OPI1} [Ef_OPI2]**	**CAEP8-M 2026 (OTI) {Ef_OPI1} [Ef_OPI2]**	**CAEP8-M 2036**
Average Global Growth in Passenger Traffic		2006-2016: 5.1% per annum*	2016-2026: 4.8% per annum*	2026-2036: 4.4% per annum*
Average Passenger Load Factor	75%*	78%*	81%*	81%*
Fuel efficiency annual improvement of new aircraft		0.96% (1.5%)	0.96% (1.5%)	0.96%
Global ATM Efficiency Improvement		1.0%	1.4%	1.4%
Aircraft Utilization Improvement		-	10%	-
Fuel price	65 US$ per barrel	90 US$ per barrel (90 US$ per barrel) {90 US$ per barrel} [90 US$ per barrel]	109 US$ per barrel (122.7 US$ per barrel) {109 US$ per barrel} [109 US$ per barrel]	115 US$ per barrel
GNP Reduction			{-7% relative to what GNP would have been without oil price increase}	
RESULTS: % Change Relative to Base Year				
Fuel burn and CO_2 emissions		+45%	+111% (+95%)	+210%
Fuel/RTK		-13%	-24%	-32%

[*] with variations in growth across route groups

‡ Fuel burn: 188.5 Mt; CO_2 emissions: 595.2 Mt; Fuel/RTK: 0.33 kg/tonne-km

Source: [15]

In addition to the possibility of selecting a demand response model that reflects the price elasticity of demand, the AERO-MS user had the possibility of also selecting a technology response model. Since the aircraft choice mechanism was inclined to disfavour the dominant preference for fuel-efficient aircraft when a measure or policy that assumed higher aircraft technology improvements was used, disabling the aircraft choice mechanism further reduced the total fuel use. Still, enabling demand response while disabling aircraft choice mechanism retained maximum fuel technology improvement being reinforced by a reduced demand.

Given the above variety of policies, several combinations of policies were made and tested in combination with scenarios. A summary of the assumptions and relevant results from the policy combinations which produced the highest fuel reductions in the CAEP8-M 2026 scenario (earlier described) are shown in Table 3-10.

3.7 Aviation Portfolio Management Tool

The Federal Aviation Administration, National Aerospace Security Agency and Transport Canada developed the Aviation Portfolio Management Tool (APMT). According to ICAO [44], the main goal of developing the tool was "to develop a critically needed ability to characterize and quantify the interdependencies among aviation-related noise and emissions, impacts on health and welfare, and industry and consumer costs, under different policy, technology, operational, and market scenarios."

The APMT-Economics, a module of the APMT, has two modes. It can:

- generate forecast mix of aircraft operations by aircraft type for future years by applying FESG fleet and operations forecasts directly. Therefore, the mix of new aircraft introduced to the fleet in forecast years was sensitive to the forecasts of aircraft operating costs. This is referred to as the Economics-led mode.
- use the forecast mix of aircraft operations by aircraft type for future years generated by other models – for example supplied by MODTF after applying the FESG fleet and operations forecasts. This is referred to as the Operations-led mode.

Table 3-10 Assumptions and results from scenario-policy combination studies by EASA

Scenario-Policy combination	**Description of Scenario-policy**	**% change relative to CAEP8-M 2026 total fuel burn**	**2026 Fuel Use [Mt]**	**2026 CO_2 Emissions [Mt]**	**% change relative to base year total fuel burn**
FTI-1% 07-26 AP2% RD50% RC+200% NoAC	AFTI: 1% per year from 2007-2026; 2% price increase of new aircraft for each 1% additional fuel improvement; %RD: 50%; 200% increase in route charges; demand response; no aircraft choice mechanism	-14.1%	341.37	1077 Mt	81.9%
FTI-1% 07-26 AP2% RD50% RC+200% NoAC No DR	AFTI: 1% per year from 2007-2026; 2% price increase of new aircraft for each 1% additional fuel improvement; %RD: 50%; 200% increase in route charges; no aircraft choice mechanism; no demand response	-10.9%	354.08	1117 Mt	88.6%
FTI-1.5% 07-26 AP2% RD 75% RC+300% NoAC	AFTI: 1.5% p.a. from 2007-2026. 2% price increase of new aircraft for each 1% additional fuel improvement; %RD: 75%; 300% increase in route charges; demand Response; no aircraft choice mechanism.	-20.1%	317.52	1002 Mt	69.2%
FTI-1.5% 07-26 AP2% RD 75% RC+300% NoAC NoDR	AFTI: 1.5% p.a. from 2007-2026; 2% price increase of new aircraft for each 1% additional fuel improvement; %RD 75%; 300% increase in route charges; no aircraft choice mechanism; no demand response	-15.9%	334.21	1055 Mt	78.1%

2006 Fuel burn: 188.5 Mt; CO emissions: 595.2 Mt; Fuel/RTK: 0.33 kg/tonne-km; AFTI: Additional Fuel Technology Improvement; %RD: percentage reduction of part of detour factor in excess of 1

Source: [15]

From an established database of air transport demand, supply and costs, APMT-Economics projected the future aviation operating costs, demand projections and capacity requirements, fleet development projections, and fleet assignment to an aggregate set of operations.

Within the APMT-Economics functionality, changes in costs to air carriers were translated into changes in air fares, leading to an adjustment of air transport demand. Based on a translation of changes in unit costs to changes in fares, the partial equilibrium between air transport demand and supply was approximated within the APMT-Economics module [44].

Winchester et al. [57] evaluated the impact of a climate policy, specifically, the American Clean Energy and Security Act of 2009, on aviation emissions trading enacted in the US. For their work, they used the partial equilibrium model, *APMT-Economics*, in combination with the Emissions Prediction and Policy Analysis, *EPPA*. An economy-wide or computable general equilibrium (CGE) model estimated the impact of the policy on fuel prices and economic activity, while the APMT-Economics model was used to estimate changes in aviation carbon dioxide emissions and operations.

Two offset possibilities were considered to capture the uncertainties concerning evolution of the offsets market and the impact of competition from foreign emissions trading programmes. To incorporate emissions trading in other regions, it was assumed that developed nations (excluding the US) gradually reduced emissions to 50% below 1990 levels by 2050 and China, India, the Former Soviet Union, and South America would begin curtailing emissions in 2030 [57].

Using a reference demand growth benchmarked to ICAO/GIACC (2009) forecasts for the year 2012 till 2050, it was assumed in the base scenario that aircraft fuel efficiency would rise by 1% p.a. and airspace management improvement would be implemented in the US and then in other regions in 5-year lag. Furthermore, they assumed detour reductions relative to great circle distances of 3% and 10% in 2015 and 2025, respectively in the US; and five years later for other regions. Compared to 2006 base year value, 2050 CO_2

emissions were 142% higher. Policy scenarios were then tested, by applying climate policies in the regions [57].

Table 3-11 summarizes the policy scenarios studied, showing relevant assumptions and results.

Table 3-11 Scenarios considered using APMT-E

Scenario	**CO_2-e[7] price ($/t$CO_2$-e)**			**GDP-induced demand change % relative to base scenario**			**Fuel price change (% relative to base scenario)**			**CO_2 emissions % change relative to base year**
	2015	2030	2050	2015	2030	2050	2015	2030	2050	
F1[a]	7.27	13.09	28.69	-0.1	-0.4	-1.0	3.26	2.67	2.76	125%
F2[b]	7.79	14.03	30.73	-0.1	-0.5	-1.2	6.96	7.25	10.20	119%
M1[c]	21.31	38.39	84.07	-0.3	-1.0	-1.8	9.95	10.50	15.61	123%
M2[d]	22.25	40.07	87.08	-0.3	-1.1	-2.0	20.86	24.12	37.98	83%

a: Full offsets with no aviation multiplier, i.e. without considering non-CO_2 effects

b: Full offsets with an aviation multiplier, i.e. considering non-CO_2 effects

c: Medium offsets with no aviation multiplier i.e. without considering non-CO_2 effects

d: Medium offsets with an aviation multiplier i.e. considering non-CO_2 effects

Source: [57]

3.8 ICAO Environmental Report 2016 Scenarios

ICAO's CAEP [58] assessed the present and longer-term impact and trends of aircraft noise and engine emissions starting from a base year of 2005 till a target year of 2050. Their study was conducted using United States Federal Aviation Administration's (FAA) Aviation Environmental Design Tool (AEDT), EUROCONTROL's IMPACT and the FAST model.

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[7] CO_2-e: CO_2 equivalent

The Aviation Environmental Design Tool (AEDT) is a software tool that evaluates environmental consequences of aviation in terms of fuel consumption, emissions, noise, and air quality based on input fleet and schedules. It can be used for analysis at airport level to global level [59]. The model implemented aircraft retirement using FESG retirement curves and aircraft addition based on future fleet forecast and replacement databases that list replacement aircraft available for each seat class and stage length [60].

IMPACT is a modelling platform for both noise and fuel/emissions of aviation. IMPACT used, as input, the output from the Aircraft Assignment Tool (AAT) and produced noise and emissions estimates. The European Commission, EASA and EUROCONTROL developed AAT. AAT took, as input, existing demand and fleet forecast, and translated it into a forecast of movements by particular aircraft types on specific airport pairs. It retired aircraft based on retirement curves and allocated aircraft for growth and replacement based on fleet forecast and specified market shares. The geographical scope of the modelling could range from single airport pair to global operations. IMPACT integrated the Advanced Emissions Model (AEM) and the SysTem for AirPort noise Exposure Studies (STAPES). The former was based on the Boeing Fuel Flow Method2 (BFFM2), and estimated emissions by aircraft type, and total emissions; whereas the later estimated population around airport affected by noise [61].

Measures considered to reduce fuel burn include contribution of aircraft technology, improved ATM, and operational improvements resulting from better infrastructure use. The analysis was centred on emissions from international aviation. Given that international and domestic aviation represented 65% and 35% of global aviation traffic in 2010, with projected values of 70% and 30% for 2050, values of global aviation emissions in 2005 and 2050 were calculated using their results, with the 2005 values extrapolated based on this information [58].

An RPK annual growth rate of 4.9% between 2010 and 2030 was assumed, with nine scenarios of fuel efficiency improvement developed to simulate the contribution of aircraft technology improvement to emissions reduction. An aircraft fuel efficiency improvement scenario of 1.4% together with ATM and operational improvements resulted in 1039 Mt more CO_2 emission above the net emissions values estimated for 2020. Thus, to achieve the carbon neutral growth target as from 2020, the contribution of alternative jet fuels (AJF) from feasible stocks to fuel replacement and GHG trends was investigated. The most effective scenario assumed production ramp ups for AJF in 2050 to fully replace petroleum-derived jet fuel. This scenario resulted in global aviation emission in 2050 growing by a factor of less than one and a half compared to the estimates for 2005.

3.9 Fleet System Dynamics Model

The "Fleet System Dynamics Model" (FSDM) [62,63], a global fleet development model was developed at the Institute of Aircraft Design, Technical University of Munich. Like for previous tools earlier described, the main methods and investigated scenarios using the FSDM, as well as corresponding results are described in this section. A more detailed description of the capabilities of the model is given in Chapter 4, because the model is further extended in this present work.

The model is based on nine aircraft types representing nine clusters of aircraft (afterwards referred to as the initial fleet aircraft) which produced at least 0.1% of the global ASK in the year 2008 (base year) operating on 21 global route groups. After 2008, next-generation (next-gen) aircraft with improved fuel efficiencies, whose availabilities were defined by production functions, were assumed to replace the initial fleet aircraft to fill the capacity gap according to the macro-evaluation fleet planning method.

Aircraft operated on the route network and were added to the fleet with the objective of minimizing the specific fuel consumption (SFC) [kg fuel burn per seat km] of each trip of the representative aircraft used. On the other hand, aircraft were retired from the fleet using retirement curves also used in the AIM tool (see Section 3.1).

Randt et al. [63] evaluated the impact of next-gen aircraft in reducing the global fleet emissions and fuel consumption. Scenarios of technology advancements of next-gen aircraft were developed, representing future developments in fuel efficiency of the aircraft clusters. Three improvement scenarios were evaluated: low improvement rates ('BAD'), the mean rates ('BASIC'), and high rates ('BEST').

The initial fleet aircraft considered are shown in Table 3-12.

Table 3-12 Representative aircraft of the initial fleet aircraft clusters using FSDM

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

Source: [63]

The fuel efficiency values assumed for the next-gen aircraft are shown in Table 3-13.

Table 3-13 Next-Generation aircraft EIS and scenario fuel efficiency improvement

Initial Fleet A/C	Representative Next-Generation Aircraft Type	Next-Gen Aircraft Cluster Name (Acronym)	EIS Year	Fuel Efficiency Improvement		
				Bad	Basic	Best
LRF	Boeing 747-8F	Next-Gen Long Range Freighter (NGLRF)	2011		-16%	
MR	Boeing 787-8	Next-Gen Mid-Range (NGMR)	2011	-14%	-16%	-20%
LRH	Boeing 747-800	Next-Gen Long-Range Heavy (NGLRH)	2012		-16%	
LR	Airbus A350XWB	Next-Gen Long Range (NGLR)	2015	-13%	-18%	-20%
NB	Airbus A320-neo	Next-Gen Narrowbody (NGNB)	2016	-10%	-15%	-20%
JC	Bombardier CS100 / Embraer E190-E2	Next-Gen Jet Commuter (NGJC)	2016	-10%	-16%	-20%
TP	-	Next-Gen Turboprop (NGTP)	2019*	-10%	-15%	-20%
MRF	Boeing 787-8F	NextGen Mid-Range Freighter (NGMRF)	2020*			
LRH	Airbus A380neo	Next-Gen Long-Range Heavy_2 (NGLRH2)	2021*	-10%	-12%	-16%

Source: [63]

However, among next-generation aircraft there is no information that the NGLRH2 and NGTP in Table 3-13 would be produced.

It was concluded that in a zero-fuel efficiency improvement scenario, fuel consumption could increase as high as 90% as compared to the base year (2008), whereas for the BAD, BASIC and BEST scenarios, the fuel consumption in 2035 increased by 76%, 73%, and 68% respectively, as compared to year 2008 [63].

3.10 Summary of Fleet Development Studies

A comparison of the studies described in Sections 3.1 to 3.9 highlighting the emission mitigation measures (EMMs) as part of the overarching basket of measures in terms of emissions mitigation measures evaluated is shown in Table 3-14. It should be noted that macro-economic effects are also included among EMMs although these are not listed in the industry explanations of the mitigation measures.

Table 3-15 summarizes the different studies reviewed, the measures of their baseline and strictest scenarios, the type of fleet CO_2 emissions estimated, i.e. full-flight emissions or fuel life-cycle emissions, and the respective percentage change in the fleet emissions in the target year relative to base year.

Due to the differing underlying scenario assumptions and model methods, the results of neither the baseline nor strictest scenarios could be quantitatively compared.

For example, while Dray et al [48] evaluated fuel life-cycle CO_2 emissions, other studies evaluated full-flight CO_2 emissions. Besides, the studies by Hassan et al. [51, 52], Ogunsina et al. [56], and Winchester et al. [57] were focused on USA domestic and international flights while the others had a global geographic scope.

Another essential difference lies in the assumptions made for each EMM studied. For example, while Schilling [55] assumed fully electric aircraft that are not yet operational, Randt et al. [63] studied next-generation aircraft that are already operational like the Boeing 787-8.

Lastly, the differing base and target years of the studies hinder a quantitative comparison of the study results.

Table 3-14 Emissions reduction measures studied in fleet models reviewed

High-level measures	**Scenario Measures studied**	**Dray et al 2010**	**Owen et al. 2010**	**Hassan et al 2015, 2017**	**Schilling et al 2016**	**Ogunsina et al 2017**	**EASA 2010**	**Winchester et al 2013**	**ICAO 2016**	**Randt et al 2015**
Technology, additional technologies and biofuels	Next-Generation Aircraft with improved technology‡	X	X	X	X	X	X	-	X	X
	Retrofits	X	-	-	-	-	-	-	-	-
	Increased maintenance	X	-	-	-	-	-	-	-	-
	PIP of 1% per year for all A/C	X	X	X	-	-	X	X	-	-
	Alternative Fuels	X	X	-	-	-	-	-	X	-
Infrastructure measures	ATM Improvements	X	-	-	-	-	X	X	X	-
Operations measures	Delayed A/C EIS	-	-	-	-	X	-	-	-	-
	Forced Aircraft retirement	-	-	X	-	-	X	-	-	-
Economic measures	Emissions Trading	X	X	X	-	-	X	X	-	-
	Fuel tax, route & airport charge	X	-	-	-	-	X	-	-	-
Macro-economic effect	RPK Growth changes/differences in specified regions	X	X	X	-	X	X	X	-	X
	Jet fuel price changes/differences	X	-	X	-	X	X	X	-	-

‡: electric, hybrid, open-rotor, distributed propulsion, etc.

However, despite these differences, all the studies, except results presented by Hassan et al. [53], were agreeable that the 2050 emissions mitigation goal was still not achievable by the evaluated combinations of measures.

Table 3-15 Baseline and strictest scenario assumptions and results from studies reviewed

		Baseline Scenario		Strictest Scenario	
Study	**Base year - Target Year (Geogr. scope, CO_2 type)**	**Description**	**CO_2 emissions % change in target year relative to base year (estimates)**	**Scenario Description**	**CO_2 emissions % change in target year relative to base year (estimates)**
Dray et al. 2010	2005 – 2050 (Global, fuel life-cycle CO_2 emissions)	MIT's IGSM scenario, with no emissions trading scheme	480% (3000 Mt)	MIT's IGSM scenario of high oil prices and high rates of economic growth in US, western Europe, and low levels of economic growth in the developing world, high carbon prices at high stringency levels (450ppm) of carbon trading. Aircraft technology available in final simulated year are open rotor engine aircraft and biofuel	200% (1200 Mt)
Owen et al. 2010	2000 – 2050 (Global, full-flight CO_2 emissions)	Fuel Efficiency grows at 1% per year from 2000 to 2050	350% (2418 Mt)	Aircraft technology available in final simulated year complying with ACARE targets: aircraft fuel efficiency [kg/seat km offered] reduction of 83% compared to base year. Demand growth is slower	150% (1025 Mt)
ICAO 2016	2005 – 2050 (Global, full-flight CO_2 emissions)	Fleet renewal. No technology and operational improvement	600% (3750 Mt)	Fuel efficiency grows at 1.4% per year. Improved ATM and infrastructure use, petroleum-based jet fuel completely replaced by alternative jet fuel	140% (940 Mt)
EASA 2010	2006-2026 (Global)	CAEP8-M 2026	111% (1255 Mt)	FTI-1.5% 07-26 AP2% RD 75% RC+300% NoAC	69.2% (1002 Mt)
Hassan et al. 2015	2006 – 2050 (USA, full-flight CO_2 emissions)	Business as usual, no new technology introduced	190%	Aircraft technology available in final simulated year complying with CLEEN, ERA and FW program targets of aircraft fuel consumption reduction of 60% compared to B737-800 with CFM 56-7B engines	90%

Table 3-15 (continued)

Hassan et al. 2017	2006 – 2050 (USA, full-flight CO_2 emissions)	FAA's baseline forecast: 2.5% annual demand growth	140%	Low Demand, Medium Energy Price, Medium Performance + Hybrid	35%
Winchester et al. 2013	2006-2050 (USA domestic plus intl. flights, full-flight CO_2 emissions)	ICAO/GIACC (2009) forecasts	142%	M2	111%
Schilling et al. 2016	2005-2050 (Global, full-flight CO_2 emissions)	Global aircraft fleet and fuel consumption development considering only evolutionary technologies as detailed by IATA	450%	Electric Aircraft + Strut-braced wing + Blended wing body	350%
Randt et al. 2015	2008-2025 (Global, full-flight CO_2 emissions)	Zero-fuel improvement	90%	"Best" Fuel Efficiency Improvement by Next Generation Aircraft	68%
Ogunsina et al. 2017	2005-2050 (USA domestic plus intl. flights, full-flight CO_2 emissions)	Baseline	390%	Low-GDP	240%

3.11 Summary of Fleet Development Models

Table 3-16 summarizes the rules for fleet development in the reviewed models. Different rules were used to define aircraft addition to the fleet. Most models (e.g. GREAT and FFWD) predefined aircraft to replace specified aircraft on routes, for example, based on fleet forecast. Others (e.g. AIM and FLEET) were based on evaluation of DOC or NPV of operating aircraft, whereas FSDM was based on fuel burn performance of aircraft.

Table 3-16 Fleet development rules for aircraft addition and removal

Model Blocks		AIM	FAST	GREAT	FFWD	FLEET	AERO-MS	APMT-E	AEDT	IMPACT AAT	FSDM
Aircraft Selection Criterion	Operating cost	-	-	-	-	-	X	X	-	-	-
	Fuel burn	-	-	-	-	-	-	-	-	-	X
	NPV	X	-	-	-	X	-	-	-	-	-
	Predefined	-	X	X	X	-	-	-	X	X	-
Aircraft Retirement Criterion	Survival Curves	X	U	X	X	-	X	X	X	X	X
	Economic Retirement including DOC or NPV estimation	-	-	-	-	X	-	-	-	-	-

U: Unknown.

However, aircraft retirement was mostly based on aircraft retirement curves, except FLEET which retired aircraft based on the NPV of keeping the aircraft as compared to the NPV of replacing it with an available new aircraft.

According to IPCC [17], the results of scenarios are only as reliable as the reliability and consistencies of its assumptions and methods with industry trends, as well as its compatibility with other dominating external developments. Despite the vast coverage of the reviewed tools in modelling future fleet development, some inconsistencies and incompatibility with industry trends, practices, and external developments have been observed.

Specifically, no study or fleet model method implemented aircraft economic retirement and aircraft selection simultaneously based on direct operating costs. Also, none of the models implemented aircraft structural retirement.

Although FLEET implemented an NPV approach to both aircraft phase-in and phase-out decisions, it did not consider fleet development at a global geographic scale. Besides, although the NPV method is useful for investment appraisals, with the advantage of considering the time value of money[8], the DOC method is the most common less complicated method for evaluating current and future aircraft's economic performance for the aircraft decision and selection process [33,65,66].

Therefore, it is necessary to conduct a study implementing a global assessment of fleet development and fleet-level emissions consistent with airline industry practice of analysing direct operating costs, incorporating design service life, extended service life and economic life considerations of aircraft, as well as the continuous incremental improvement in airframe and engine technologies. More so, a combination of these industry methods with a sensitivity to the dominating external influence of fuel price developments is lacking.

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[8] George Brown College [64] defined the time value of money as the principle that a certain amount of money has a different buying power at different points in time.

Lastly, the assessment of the EMP of the identified EMMs is currently lacking and would be useful to policy makers in knowing the expected emissions mitigation benefit of proposed environmental policies related to the IATA basket of measures. Aviation stakeholders like aircraft manufacturers and airlines would also have an overview of expected emissions savings of each measure.

The FSDM has already functional capabilities for integrating these aspects into the fleet-level assessment process. The next chapter evaluates the existing capabilities of the FSDM.

4. Previous Capabilities of FSDM

This chapter describes the core capabilities and methods used in the FSDM prior to this thesis. The FSDM fulfils the requirement of a fleet model to have a system dynamics capability. This enables the estimation of stocks of aircraft additions, and retirements, as well as fleet size and emissions per year, route and aircraft type, in order to assess measures for reducing CO_2 emissions from the global air transport system.

4.1 Global Fleet and Route Network Representation

In the model, every aircraft type which produced at least 0.1% of the global ASK in the year 2008 (base year) belonged 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 have been shown in Table 3-12 whereas the constituent aircraft in each aircraft cluster are listed in Table A-1 [67]. 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 21 route-groups, as shown in Figure 4.1.

Figure 4.1 FSDM route groups

Source: [67]

In the FSDM, next-generation aircraft, i.e. new aircraft types entering the fleet after 2008 to replace the initial fleet, were defined with specific entry-into-service (EIS) years (see Table 3-13).

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

4.2 Modelling of Aircraft Availability

The availability of the initial fleet aircraft for addition to the global in-service fleet was based on the actual maximum production capacities of the manufacturers of the respective aircraft comprising the aircraft clusters [68].

In the FSDM, the availability of the next-generation fleet was modelled based on the aircraft production functions from the year 2008 up to the target year defined by the user. In the study by Randt et al. [63], the following production functions were used:

$$y_{nb} = 80.624x - 161052 \tag{4.1}$$

$$y_{wb} = 35.501x - 71128 \tag{4.2}$$

Equations (4.1) and (4.2) define the numbers of narrow-body aircraft and wide-body aircraft, (y_{nb} and y_{wb}, respectively) which can be produced in a year ranging from 2008 to 2021. The production functions could be assumed to further extend to year 2050 given the expected continued increase in demand for airplanes.

In the model, the production capacity of freighter aircraft was set to infinity, to accommodate the observed phenomenon of passenger aircraft being converted to freighter aircraft.

4.3 Determination of Fleet Requirements

Using the OAG data for 2008, the seat and freight capacities as well as sector lengths of the initial fleet was modelled. Using the capacity supply (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) demand for 2008 was calculated.

Furthermore, using user-defined forecasts of market growth rates, the following year's RPK and RTK traffic demand was obtained, from which the next year's ASK and ATK capacity supply was calculated using the assumed seat and freight load factors. This process was repeated until the target year of the analysis. Market growth rates were derived from forecasts, for example, of Boeing Current Market Outlook reports.

4.4 Modelling of Fleet Assignment and Development

The fleet assignment or allocation problem makes the aircraft "operate" on the defined network. In solving this allocation problem, the objective function of minimizing the specific fuel consumption [kg fuel burn per seat km] of each trip of the representative aircraft was used.

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

Minimize $\sum_i \sum_j \mathrm{x}_{ij} fuelburn_{ij}$ subject to *first constraint*

$$\sum_{\boldsymbol{i}} \sum_{\boldsymbol{j}} \boldsymbol{x_{ij}} \leq \sum_{\boldsymbol{i}} \sum_{\boldsymbol{j}} \boldsymbol{x_{0,_{ij}}} \tag{4.3}$$

and *second constraint*

$$\sum_{\boldsymbol{i}} \sum_{\boldsymbol{j}} \boldsymbol{x_{ij}.seats_{ij} \cdot RD_{ij} \cdot yearly\_freq_{ij}} \leq \sum_{\boldsymbol{i}} \sum_{\boldsymbol{j}} \boldsymbol{ASK_{0,_{ij}}} \tag{4.4}$$

The objective function was to minimize the fuel burn while operating the fleet by minimizing the trip fuel burn $fuelburn_{ij}$ of each representative aircraft of the fleet x_{ij}. The *first constraint* ensured that the sum of the optimal fleet x_{ij} on each cluster and route did not exceed the sum of the initial fleet x_0 in the base year. In addition, the *second constraint* ensured that the capacity of the optimal fleet was comparable to the capacity ASK_0 produced by the initial fleet in the base year.

Given these two constraints, the optimizer[9] was made to allocate the aircraft type with the minimal fuel burn, but operating on a network to produce a capacity close to that of the initial year. This optimization was done for the base year whereas for subsequent years, aircraft allocation to the network was implemented by computing the trip fuel burn for each simulated mission and ranking the aircraft flying the route based on their fuel burn performance. In addition, the aircraft production capacities used in the study of Randt et al. [63] were used in the model as a constraint to the number of aircraft in service.

4.5 Aircraft Market Entry and Exit

To fill ASK and ATK capacity gaps using aircraft, it is imperative that the capacity gap is first obtained. ASK gap is computed based on the macro-evaluation method of fleet planning (see section 2.4).

4.5.1 Determining added aircraft based on capacity gap

Based on section 2.4, the ASK-gap and ATK-gap consist of retirement and growth gap. Thus, a forecast market growth or decrease rate is anticipated, based on the set of assumptions used, to result in the need for more or less aircraft in the calculated year, respectively.

For the calculation year 2008, ASK-gap was estimated after solving the fleet assignment problem, whereas for subsequent years; this was implemented after aircraft retirement.

In the case of a negative capacity gap, aircraft clusters with the worst fuel burn performance in the route were removed from the fleet, whereas, a positive capacity gap implied aircraft clusters with the best fuel burn performance were added to the fleet. Given a certain ASK-gap on a certain route j, the model calculates the number of aircraft to be added to the fleet in service using the seats, freight, distance and frequency properties of the best ASK-ranked aircraft. The number of added aircraft units x_{PAX} or $x_{freight}$ of the corresponding best-ranking aircraft to fill the capacity gap in a next year y_2 was computed from the total number of flights of the passenger or freighter aircraft on the route.

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[9] MATLAB® optimizer *fmincon*

The total number of flights by a best-ranking passenger aircraft *i* flying a route *j* is

$$\boldsymbol{u\_y2_{i,j}} = \frac{\boldsymbol{ASKgap\_y2_{i,j}}}{\boldsymbol{seats_{i,j} \cdot distance_{\ i,j}}} \qquad (4.5)$$

$$\boldsymbol{x_{PAX_{i,j}}} = \frac{\boldsymbol{u\_y2_{i,j}}}{\boldsymbol{frequency_{i,j}}} \qquad (4.6)$$

For *u,* the freight capacity of the computed passenger aircraft was also computed as growth ATK.

$$\boldsymbol{growthATK\_y2_{PAX\ A/C_j}} = \sum_{i} \boldsymbol{freight_{PAX\ A/C_{i,j}} \cdot distance_{i,j} \cdot u_{y2_{i,j}}} \qquad (4.7)$$

The *growth*ATK_y2$_{\text{PAX A/C}}$ was taken into consideration when computing the ATK-gap for the next year y_2.

In a similar way, the model computed the ATK-gap for *y2* as the difference between the forecast ATK for the respective route in the next year *y2* and the current ATK of the fleet in the current calculated year. For the calculation year 2008, ASK-gap was estimated after solving the fleet assignment problem, whereas for successive years; this was implemented after aircraft retirement. The current ATK of the fleet in the current calculated year was however composed not only of the ATK capacity of the freighter aircraft, but also the ATK capacity of the passenger aircraft used to fill ASK capacity in the next calculated year *y2.*

$$\begin{aligned} \boldsymbol{ATKgap\_y2_j} &= \boldsymbol{forecastATK\_y2_j} \\ &\quad - \left(\sum_{i} \boldsymbol{ATK_{y1_{Freighter\frac{A}{C}_{i,j}}}} + \boldsymbol{growthATK_{y2_{PAX\frac{A}{C}_j}}} \right) \qquad (4.8) \end{aligned}$$

Based on the share of aircraft clusters in a route, the ATK-gap on a route can be distributed among the aircraft clusters flying on the route. The total number of flights by a best-ranking freighter aircraft *i* flying a route *j* is

$$\boldsymbol{v\_y2_{i,j}} = \frac{\boldsymbol{ATKgap\_y2_{i,j}}}{\boldsymbol{freight\_capacity_{i,j} \cdot distance_{\ i,j}}} \qquad (4.9)$$

$$\boldsymbol{x_{freight_{i,j}} = \frac{v\_y2_{i,j}}{frequency_{i,j}}} \qquad (4.10)$$

4.5.2 Considerations of aircraft production capacities

The number of added aircraft units can be constrained by the consideration of production capacities of the aircraft clusters. If single production capacities (SPC) of aircraft were considered, the number of added aircraft was checked so that the single production capacity of the aircraft cluster was not exceeded. If this is the case, x_{PAX} or $x_{freight}$ is taken as calculated. Otherwise, x_{PAX} or $x_{freight}$ is reduced by a factor which is the ratio between the single production capacity and the sum across all the routes for each aircraft cluster.

Therefore, for a next-generation passenger or freighter aircraft, if:

$$\boldsymbol{\sum_j x_{new\ cluster_{i,j}} > SPC_{new\ cluster_i}} \qquad (4.11)$$

$$\boldsymbol{x_{new\ cluster_{i,j}} = x_{new\ cluster_{i,j}} \cdot \frac{SPC_{new\ cluster_i}}{\sum_j x_{new\ cluster_{i,j}}}} \qquad (4.12)$$

The reduction in x_{PAX} or $x_{freight}$ led to a reduction in the total ASK and ATK capacity of the calculated aircraft, therefore the shortfall was catered for by using the next best aircraft in the route in terms of fuel burn.

If the production capacity (PC) of single aisle and twin aisle aircraft were taken as the constraint i.e. in a certain year, total number of all SA or all TA aircraft could not exceed the availability described in section 3.9.4., for next-generation aircraft cluster, if

$$\boldsymbol{\sum x_{SA\ A/C\ clusters} > PC_{SA\ A/C\ cluster}} \qquad (4.13)$$

$$\boldsymbol{x_{next\ gen.\ ,SA\ A/C_{i,j}} = x_{next\ gen,SA\ A/C_{i,j}} \cdot \frac{PC_{SA\frac{A}{C}}}{\sum_j x_{next\ gen.\ ,SA\frac{A}{C}_{i,j}}}} \qquad (4.14)$$

$$\boldsymbol{x_{initial\ fleet,SA\ A/C_{i,j}} = x_{initial\ fleet,SA\ A/C_{i,j}} \cdot \frac{PC_{SA\frac{A}{C}} - \sum_j x_{next\ gen.\ ,SA\frac{A}{C}_{i,j}}}{\sum_j x_{initial\ fleet,SA\frac{A}{C}_{i,j}}}} \qquad (4.15)$$

Also, if

$$\sum \boldsymbol{x}_{\boldsymbol{TA\ A/C\ clusters}} > \boldsymbol{PC}_{\boldsymbol{TA\ A/C\ cluster}} \quad (4.16)$$

$$\boldsymbol{x}_{\boldsymbol{next-gen.\ cluster,TA\ A/C}_{\boldsymbol{i,j}}} = \boldsymbol{x}_{\boldsymbol{next-gen.\ cluster,TA\ A/C}_{\boldsymbol{i,j}}} \cdot \frac{\boldsymbol{PC}_{\boldsymbol{TA}\frac{\boldsymbol{A}}{\boldsymbol{C}}}}{\sum_{\boldsymbol{j}} \boldsymbol{x}_{\boldsymbol{next\ gen.cluster,TA}\frac{\boldsymbol{A}}{\boldsymbol{C}}_{\boldsymbol{i,j}}}} \quad (4.17)$$

$$\boldsymbol{x}_{\boldsymbol{initial\ fleet,TA\ A/C}_{\boldsymbol{i,j}}} = \boldsymbol{x}_{\boldsymbol{initial\ fleet,TA\ A/C}_{\boldsymbol{i,j}}} \cdot \frac{\boldsymbol{PC}_{\boldsymbol{TA}\frac{\boldsymbol{A}}{\boldsymbol{C}}} - \sum_{\boldsymbol{j}} \boldsymbol{x}_{\boldsymbol{next\ gen.,TA}\frac{\boldsymbol{A}}{\boldsymbol{C}}_{\boldsymbol{i,j}}}}{\sum_{\boldsymbol{j}} \boldsymbol{x}_{\boldsymbol{initial\ fleet,TA}\frac{\boldsymbol{A}}{\boldsymbol{C}}_{\boldsymbol{i,j}}}} \quad (4.18)$$

If the two conditions were to hold at the same time, then the corresponding statements would also apply.

4.5.3 Determining aircraft retirements based on age

In the model by Randt [67], aircraft are retired using logistic S-curves which give the percentage of surviving aircraft belonging to a fleet depending on aircraft age. Using retirement curves is a method well used in many of the fleet development models as shown in Table 3-16.

5. Aircraft Life-Time Cost Modelling

As explained in Section 4.4, aircraft performance in terms of trip fuel burn per seat-km was crucial to the fleet assignment and development process of the fleet development model by Randt. However, as explained in Sections 2.3 and 2.4, the estimation of aircraft operating costs is more crucial for the process.

Furthermore, the estimation and monitoring of the life-time cost of every aircraft in an airline's fleet is crucial to the airline's operations and fleet planning exercise [47]. In this current work, trip Direct Operating Cost (DOC) per seat-km is evaluated as the cost metric driving aircraft assignment to routes and retirement from routes. DOC is defined as costs associated with flying an airplane, i.e. airplane-related cost [65]. Direct operating cost is the sum of cost of ownership (COO), cash operating cost (COC), and additional direct operating cost (ADOC) [69].

According to Bradshaw [70] and Clark [33], COC is used to compare aircraft operated by an airline by highlighting aircraft use and variable cost trends. They both claimed that airlines would likely be willing to pay similar prices for similar aircraft, so that aircraft price related costs become irrelevant. However, when considering the economic replacement of aircraft, it becomes important to consider the low ownership cost of aging aircraft against the high ownership costs disadvantage of new ones, in addition to their cash operating costs [15,31]. Therefore using the DOC method alone, without the indirect operating cost (IOC) component is sufficient for airlines' airplane decision processes.

This chapter explains how the components of Aircraft Life-Time Direct Operating Cost are structured in ALiTiCo- a tool used to compute life time DOC of aircraft for use in modelling aircraft introduction to fleet as well as retirement from fleet in the FSDM.

5.1 Choosing a Period for Aircraft Evaluation

In line with the fleet planning process of airlines, an evaluation period would be chosen to ensure that an 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 [45] claimed a planning horizon of 10 years for a typical fleet planning model; while Clark [33] and Belobaba [31] stated possible periods between 6-12 and 10-15 years, respectively for the macro-approach to fleet planning. Therefore, any period within these boundaries is acceptable. It should be noted that the given periods fall within or close to the period when aircraft maintenance costs are relatively stable (from the 7th till the 12th operational year of an aircraft), also regarded as the mature period of an aircraft [71,72].

5.2 Cost of Ownership

Several methods exist for calculating the cost of ownership of a certain aircraft type. For example, Jenkinson et al. [73] and van Bodegraven [65] stated that some cost methods ignore interest and insurance calculations. However, they both agree to combining these components with depreciation to have a better perspective on aircraft cost of ownership.

The methodology of Ploetner et al. [69] 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. Using the relevant inflation factor [74], the costs were converted to year 2016 US dollars.

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. According to Clark [33] and IATA [75], most airlines use the straight line model, however, in this thesis an exponential function model is used based on the approach of Wesseler [76]. Shortening the depreciation period leads to a steeper drop of the COO, and so a lowering of the minimum lifetime DOC of the aircraft, and as a result, a lower DOC value at the end of its maximum lifetime as compared to when the depreciation period spans more years. Therefore, a shorter depreciation period leads to an extension in aircraft age at economic replacement. Depreciation periods limited to 14 years for narrowbody aircraft and 16 years for widebody aircraft were recommended by Association of European Airlines (AEA) [77,78]. Similarly, Doganis claimed depreciation periods of 14-16 years for wide-body aircraft and 8-10 years for narrow-body aircraft [79]. However, IATA reported aircraft depreciation periods of mostly 20 years were used in the airline industry, irrespective of aircraft type [75]. A summary of depreciation periods are shown in Table 5-1. In summary, depreciation periods of 8 to 20 years and 14 to 20 years could be used for single aisle and twin aisle aircraft, respectively.

Table 5-1 Summary of depreciation periods according to literature findings

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

Source: [75,77–79]

In ALiTiCo, aircraft delivery price is assumed 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 [80]. However, the assumption simplifies the complexity of incorporating such effects. Furthermore, depreciation and interest period are assumed the same.

5.3 Cash Operating Cost

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

5.3.1 Crew charges

Crew charges are based on a correlation relationship of crew salaries in 2008, supplied by EUROCONTROL [81], to MTOW and number of passengers on a flight. According to Wesseler [76], 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.

5.3.2 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 [67]. The tool was already validated by Ittel [82]. However, given that fuel costs cover a major share of aircraft DOC, an extensive verification of fuel consumption estimates was done for the initial fleet and next-generation aircraft types considered in the model. This verification (presented in Table B-1) was done to ensure the estimates of the simulated representative aircraft types agree with data published in industry-reports or by aircraft manufacturers. 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 [67]. The assumed passenger load factor will be later compared to the anticipated future load factors to ensure acceptable error estimation of the assumption.

In ALiTiCo, similar to the approach of Moolchandani et al. [83], engine overhaul or replacement is not done. Aircraft fuel burn deterioration without engine replacement was also modelled by Lee, Wilson and Pasurka Jr. [84] through the use of an aircraft age multiplier. They assumed a deterioration rate of 0.3% per year. However, considering deterioration values from other sources, a rate of 0.3% per year is high, knowing that an aircraft could be operated for up to 40 years. For example, IPCC [17] stated a 4% maximum deterioration, above which engine overhaul would take place. Furthermore, whereas Kelaidis et al. [85] claimed a 3.5% deterioration as a high engine degradation level, Wulf [86] claimed a maximum of 4% all through the aircraft life. 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.

5.3.3 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 [76]. The charges are computed in year 2016 US dollars.

5.3.4 Airport charges and ground handling charges

Airport charges and ground handling charges are based on the methodology of Ploetner et al. [87]. 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.

Ploetner et al. [87] found out that landing charges and passenger related charges have the highest share in airport charges, passenger charges were particularly high in Europe and the Southwest Pacific region (which is a part of the region Asia in FSDM). In addition, local noise and local emissions charges, being mostly charged in the same regions, affected the total airport charges of these regions. To confirm the high airport charges available in Europe, Oxford Economics stated that in 2010, among the world's 100 largest airports measured by the number of domestic and international passengers handled, London Heathrow Airport had the highest airport charges [88].

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 O/D regions are used.

5.3.5 Direct maintenance costs

Having described, in the previous sections and subsections of this chapter, the approaches and assumptions taken for other cost components, DMC calculation approach, verification and benchmarking is presented in this section.

5.3.5.1 Reference data selection

Different methods exist for the calculation of aircraft DMC as shown in the depiction by Boeing [41] in Figure 5.1.

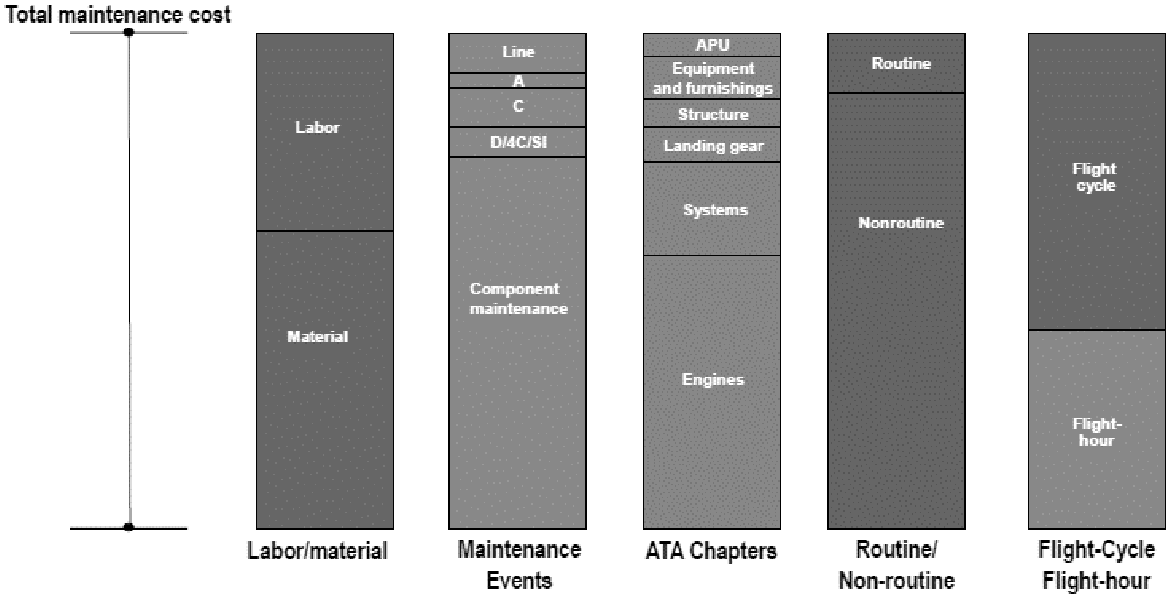

Figure 5.1 Different ways to view total maintenance costs of aircraft

Source: Boeing [41]

As the ways of viewing maintenance costs are different, published values of maintenance costs differ depending on the components considered, fleet considered, age of the fleet, calculation year and operating conditions [89].

Different aircraft DMC values quoted from different sources such as IATA's Maintenance Cost Task Force (MCTF), Aircraft Commerce (ACC), ESG Aviation Services' Airline Monitor (ALM), and the Airliner Price Guide (APG) were compared, comparing aircraft only when reported years are similar.

It must be noted that values by IATA referred to an average within the respective aircraft families of the 20 airlines reporting; whereas, the values by ACC referred to specific aircraft types; although the specific aircraft could be assumed to dominate these families. Data from APG were from the Form 41 of the American Department of Transport. Also, the sample size used in the estimation by Airline Monitor are assumed to be from the USA, whereas the ACC database assumed a sample size from other markets.

The results are shown in Figure 5.2.

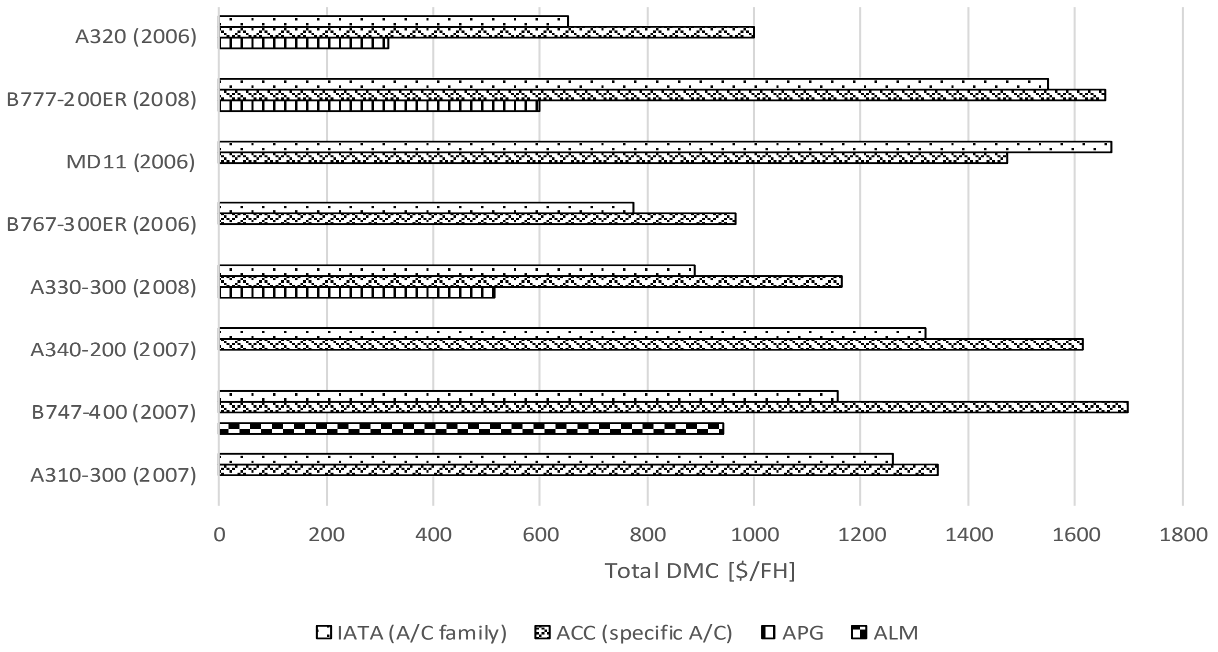

Figure 5.2 Selected aircraft DMC based on four sources in same evaluated year
Source: [90], other sources[10]

The results show that cost values by Aircraft Commerce were generally about 21% above values by the IATA's MCTF. However, as will be shown in the next subsection, values by Aircraft Commerce are about 22% below values assumed by the Association of European Airlines. In addition, because FH DMC values are available for all evaluated aircraft of the initial fleet using the ACC source, the ACC data is chosen as the reference for the DMC computation model.

5.3.5.2 DMC computation method selection

Different methods exist for the computation of DMC of aircraft. For example, Wesseler [76] presented an approach based on evaluating contributions from the different ATA chapters of an aircraft whereas Aircraft Commerce presented an approach based on Maintenance events [90].

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[10] ACC and APG database accessed by subscription at BHL, The Airline Monitor Vol. 21 No. 3 Copyright 2008

For this research work, the main requirements for the DMC calculation method to be used are the following:

i. Calculation year (incorporating inflation rates of calculation year)
ii. Possibility to change maintenance labour rates
iii. Use of aircraft parameters
iv. Sensitivity to flight hours per flight cycle
v. Provision for both turbofan and turboprop engines
vi. Cost adaptation to aircraft age

Using available data from Aircraft Commerce for the initial fleet aircraft, the method recommended by the Association of European Airlines (AEA method) [77,78] is considered the best DMC computation method because it uses aircraft parameters such as aircraft Operating Weight Empty, Engine By-Pass Ratio, etc. Other parameters such as aircraft price is obtained from the ownership cost model already explained. Furthermore, for the engine price [year 1989 USD], the approach by Jenkinson et al. [73] 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 [year1989$] 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 assumes mature levels of cost, i.e. after 5-7 years of operation. Using aging function from Strohmann [91], based on Dixon [72], DMC values for other years of the aircraft lifetime are determined. Furthermore, input labour rate value given by AEA in 1989 is used and converted to 2016 US Dollars. 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 [92]. 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 non-fuel COC of initial fleet aircraft to next-generation ones.

Since the AEA method for computing aircraft DMC is evaluated in year 1989 US dollars, an inflation factor is used to adjust the costs to year 2016 US dollars.

5.3.5.3 AEA DMC method verification using Aircraft Commerce data

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 5.3.

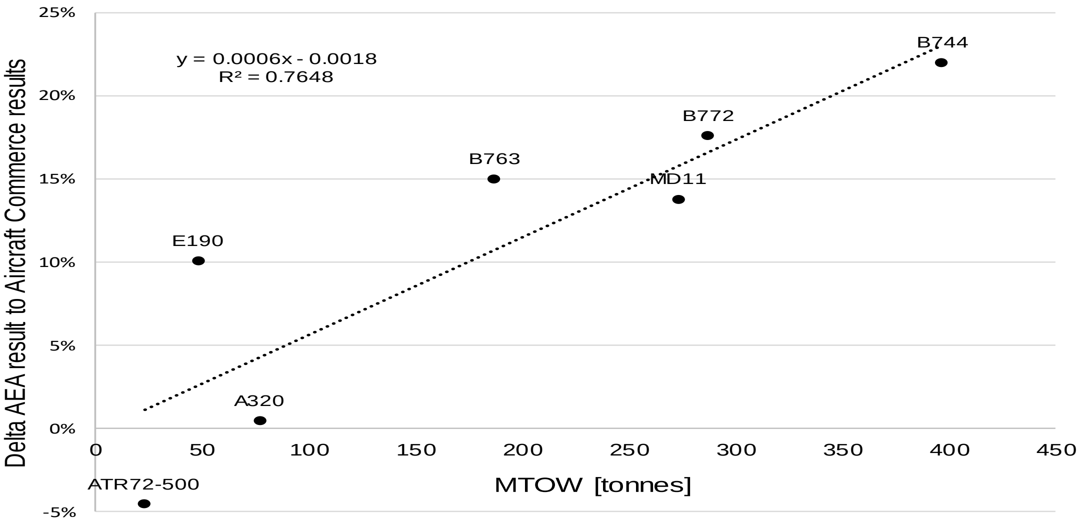

Figure 5.3 DMC [$/FH] of initial fleet aircraft, comparing AEA and ACC results

Source: own calculation

Cost values published by ACC can be taken as representative of the industry since they are obtained from maintenance providers[11]. 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 the figure, 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, the 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 5.3, the cost results

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[11] Correspondence on 13th February 2018 with Aircraft Commerce

of the AEA method are adjusted to cost levels resulting from Aircraft Commerce computation.

In summary, the concept of DMC calculation method verification is depicted in Figure 5.4. The method uses same input data that was used in Aircraft Commerce computations, and compares the results from Aircraft Commerce with those using the applied AEA method. An MTOW-dependent correction factor is then applied to the DMC result of the AEA methodology.

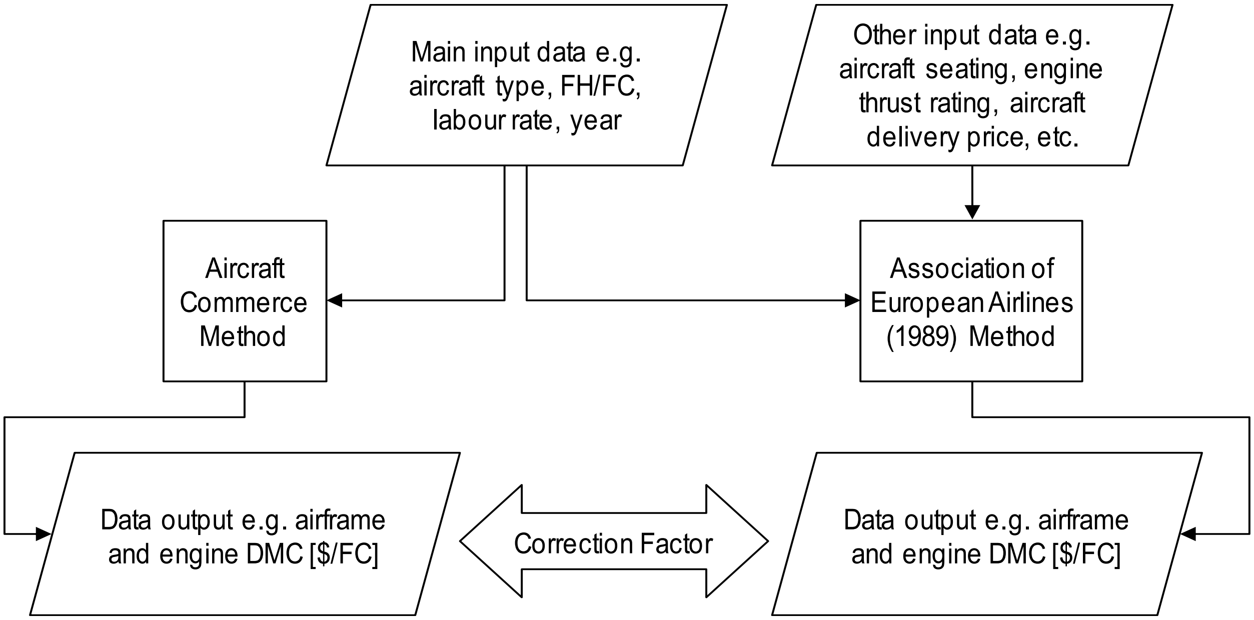

Figure 5.4 Validation method for aircraft DMC calculation

Source: own depiction

5.4 Additional Direct Operating Costs

Additional direct operating costs refer to environmental airport noise and NO_x charges, as well the emissions trading scheme (ETS) charges [69]. The charges were computed based on functions from Ploetner et al. [87]. The noise charges are based on defined levels of aircraft noise values for arrival as well as side line and flyover as given by ICAO [93]. Maximum approach and side line and flyover noise levels of 88 and 83 EPNdB, respectively were used. Although the ETS charges no longer apply, an assumed constant charge of 10 Euros per tonne CO_2 was implemented on all flights with O/D in the EU based on Schmidt et al. [94] to evaluate the impact of such carbon-pricing measure.

5.5 Aircraft LifeTime Cost Module

ALiTiCo is a tool that uses the cost calculation methods described above in determining Lifetime Direct Operating Costs of aircraft for defined mission characteristics and aircraft entry into service years. The tool can be used for both initial fleet and next-generation aircraft as well as future-generation aircraft that are not yet in service.

5.5.1 Module sequence

For a given aircraft flight on a route, the module sequence for computing aircraft lifetime DOC is shown in Figure 5.5.

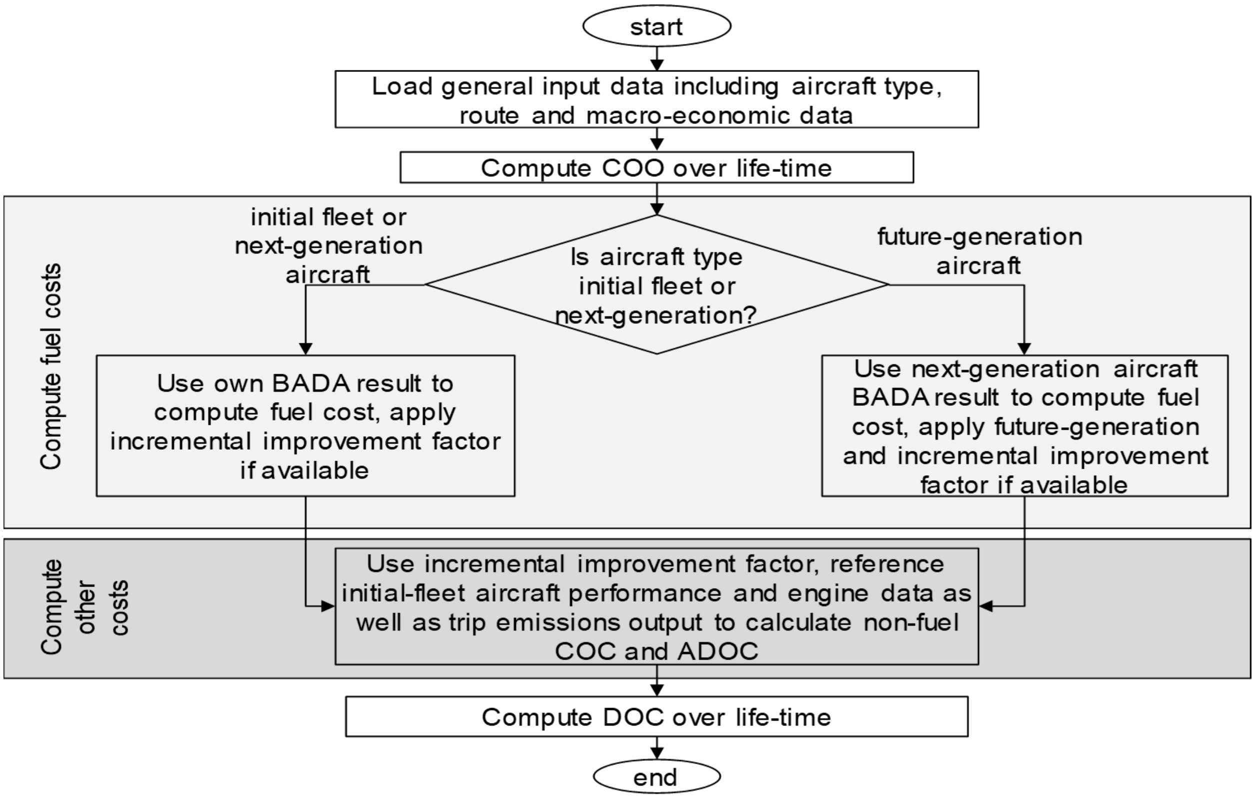

Figure 5.5 ALiTiCo module sequence for computing aircraft lifetime DOC

Source: own depiction

5.5.2 Main uses of the module

There are two main uses of the module. The main use of the ALiTiCo module is to estimate, for each aircraft type's EIS year, the aircraft lifetime DOC, aircraft lifetime fuel-burn, and structural retirement age (SRA) as input for the fleet model.

EIS year, aircraft lifetime DOC, and structural retirement age (SRA) are used in the aircraft phase-in and phase-out process of the FSDM. In addition, aircraft lifetime fuel-burn results are used in computing fleet-level fuel burn and CO_2 emissions.

ALiTiCo can also be used as a stand-alone tool in evaluating the earliest year for an aircraft to be replaced given its entry-into-service year and available replacement aircraft. The age of the investigated aircraft at the earliest economic replacement year is termed the economic retirement age (ERA). Here, as described in Section 2.3, an investigated aircraft is considered due for economic replacement if its DOC is greater than the DOC of an available replacement aircraft. This comparison is done not only for the ERA, but also over the evaluation period (see Section 5.1 for more on evaluation period). An available replacement aircraft is assumed to possess the cost improvement characteristics assumed for the aircraft in its year of introduction.

5.5.3 Module input

Two types of input data are supplied to ALiTiCo: aircraft type dependent data, and aircraft type independent data. Aircraft type dependent input data are either time-dependent or time-independent; and at the same time either route-dependent or route-independent. As shown in Figure 5.5, incremental improvement factors [%] are used for the calculation of fuel costs, non-fuel COC and ADOC of aircraft. A normalized factor (*NF*) [%] is defined as a function of an improvement factor using the equation below.

$$NF = 100\% - Improvement\ Factor \tag{5.1}$$

Table 5-2 shows how these factors are applied for different DOC components and aircraft generations.

Table 5-2 Reference aircraft considered for applying normalized factors

Aircraft Generation	Reference aircraft for normalized factors	
	Fuel cost	Other costs
Initial-fleet	Same aircraft	Reference initial-fleet aircraft
Next-generation	Same aircraft	
Future-generation	Reference next-gen. aircraft	

Source: own depiction

Thus, for a particular aircraft generation with a defined reference aircraft shown in Table 5-2 and normalized factor $NF_{A/C\text{-}Gen}$, each cost component $cost_{A/C\text{-}Gen}$ is defined from the cost component estimate of the reference aircraft $cost_{ref\ A/C}$ using the equation below.

$$cost_{A/C-Gen} = NF_{A/C-Gen} \cdot cost_{ref\ A/C} \tag{5.2}$$

Table 5-3 shows the aircraft type dependent input to ALiTiCo categorised according to their assumed variability over time and flight distance.

Table 5-3 Aircraft type dependent input to ALiTiCo

	Time Dependent Input	Time Independent Input	
Route Independent Input	• EIS year • Normalized improvements in fuel costs • Normalized improvements in non-fuel COC • Normalized 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 NO_x per LTO cycle
Route Dependent Input	• Annual frequency	• Installed seats • Belly-freight capacity • Block fuel • Block time	

Source: own depiction

Table C-1 to Table C-4 contain seat and freight capacities of aircraft used in the FSDM, based on OAG 2008 data. Table C-5, Table C-7, and Table C-8 show other aircraft type dependent input used in ALiTiCo.

EIS year information of the initial fleet aircraft type is listed in Table C-6. Aircraft EIS year is based on the age distribution of the initial fleet aircraft in 2008 taken from the Aircraft Analytical System (ACAS) database and also used by Randt [67]. A maximum life time of 40 years was used similar to the approach of Moolchandani et al [83]. Therefore, if in 2008 an aircraft cluster has aircraft units aged 40 years and above, the earliest EIS year of such cluster would be 1968. Aircraft type independent data are environmental, macro-economic, and flight-related data. These are also either time-dependent or time-independent; and they are either route group dependent or route group independent. These are shown in Table 5-4. Actual input values are listed in Table C-9.

Table 5-4 Environmental, macro-economic and flight-related input to ALiTiCo

	Time Dependent Input	**Time Independent Input**
Route Independent Input	• 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

Source: own depiction

For simplification purposes, flights on all route groups (intra and inter-regional) are considered as international. As a result, applicable cost functions for international flights are applied in computing airport fees (APF) and ground handling charges (GHC). A review of air traffic in 2008 based on OAG data shows that more than 50% of all intra-regional ASK were international flights, except in North America (4%) and Latin America (30%).

However, for intra-regional flights in North America using the NB in 2008, 2% difference in APF was estimated between national and international flights; whereas in Latin America where traffic was 85% less in 2008, 25% difference was in APF was estimated. This may be due to differences in unit rates per passenger levied at airports [87]. Flight distances of the route groups are given in Table D-1 alongside other characteristics.

5.5.4 Module output

If ALiTiCo is used to generate input data for the fleet model, the main outputs from ALiTiCo are structural retirement age (SRA) also known as the utilization-dependent design life (design life limit), and life time trip DOC of aircraft. If the module is used as a stand-alone tool, it can also be used to determine the economic retirement age of an aircraft, given a set of aircraft considered to economically replace the investigated aircraft.

5.6 Module Sensitivity Tests

As identified in Section 2.2, different factors affect the fleet development process, including aircraft age at economic retirement. The main airline economic and operational factors expected to influence the economic retirement of an aircraft are investigated. The goal of the sensitivity test on the Aircraft Lifetime Cost Module (ALiTiCo) is therefore to determine if expected sensitivities of the module to the main factors are demonstrated.

5.6.1 Sensitivity to continuous cost improvements of in-production aircraft

Improvements made on in-production aircraft are aimed at reducing operating costs of aircraft for airlines. These improvements are incremental for in-production aircraft, whereas “giant-leap” improvements are incorporated in novel aircraft types [95]. When incremental improvements are integrated in in-production aircraft, certain cost components are improved. For example, for the A330 aircraft program, over a period up to 20 years after entry into service, incremental improvements resulting in a 20% reduction of airframe direct maintenance costs were achieved [95].

In the same manner, improvements modelled in the FSDM are both incremental improvements and giant-leap improvements- the former are modelled in in-production aircraft while the latter are modelled as new aircraft clusters. In order to isolate the effect of continuous improvement in airframe and engine technologies, a scenario with a fuel price constant at 2014 levels (2.8 year 2016 USD per gallon) is assumed for every year of the sensitivity calculation. Continuous improvements of in-production aircraft over time result in a reduction of first year DOC of new available in-production aircraft over time. When compared to older aircraft, newer improved aircraft have a cost advantage leading to an earlier economic retirement of the older aircraft.

An example is given in Figure 5.6. The diagram shows unit costs of a Long-Range Heavy aircraft, aged 28 years in 2008 (i.e. EIS in year 1980), operating on a typical trans-Atlantic flight. Economic retirement occurs when the lifetime trip DOC of an aircraft in service (solid line) is continuously greater than the first year DOC (dashed line and dotted line) of a replacement aircraft. The assumed aircraft utilization allows the aircraft to be operated for 40 years based on the design life.

Based on this example, if continuous improvements are not considered (solid dotted line), the FSDM airline could not replace the aircraft economically by the same aircraft type in the same generation until the structural retirement age (SRA). However, when in-production improvements are considered, the aircraft could be economically retired and replaced by an available incrementally improved same-generation aircraft as from year 2000. Also from Figure 5.6, the same aircraft could be economically retired from service as from year 2012 in order to be replaced by its available next-generation aircraft.

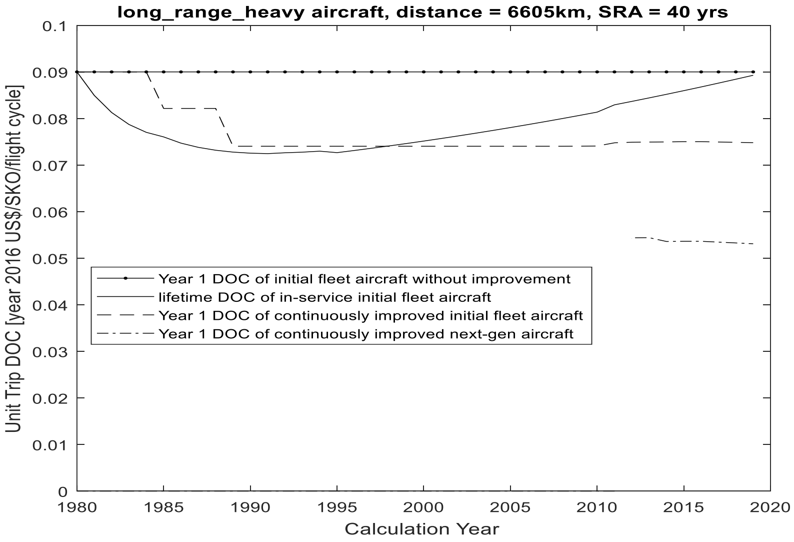

Figure 5.6 Lifetime unit trip DOC of LRH and NGLRH

Source: own depiction

5.6.2 Sensitivity to fuel price fluctuations

To test for this sensitivity, unit trip DOC of long-range heavy aircraft operating on a typical trans-Atlantic route was modelled using the historical fuel price increase from 2002 (0.9 year 2016 USD per gallon) to 2008 (3.3 year 2016 USD per gallon).

This was then compared with a scenario in which fuel price was constant at year 2002 level throughout the simulation period. As noted by Dray and Evans [46], economic retirement and replacement of inefficient aircraft is influenced by high fuel prices so that a scenario of increased fuel price results in higher unit costs and enables earlier economic retirements. This is shown in Figure 5.7. With EIS of 1990 (right panels), assuming no change in fuel price (panel d), economic retirement could happen as from the 32nd year of operation.

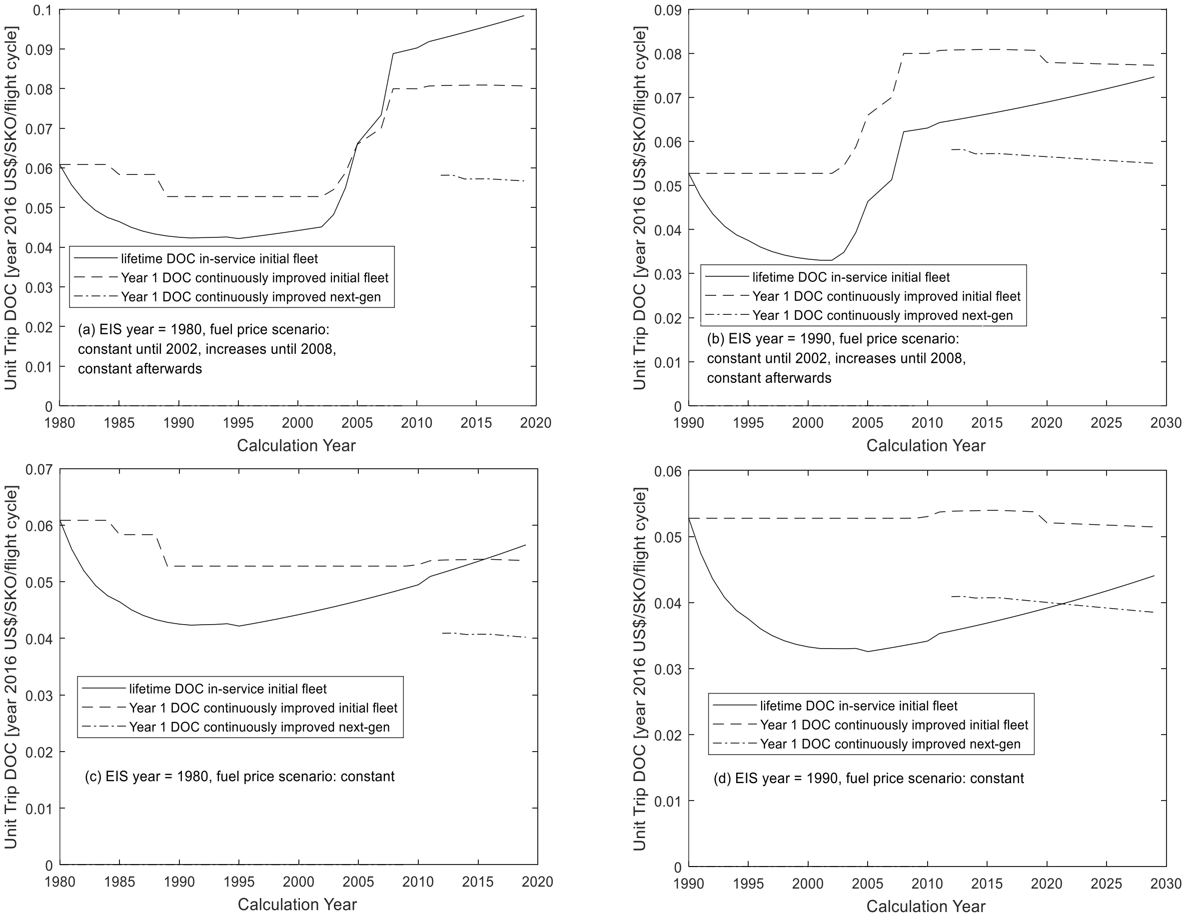

Figure 5.7 DOC of LRH and NGLRH with different EIS, under two fuel price scenarios

Source: own depiction

However, with a fuel price increase from the 12th to the 18th year of service (panel b), economic retirement and replacement with the NGLRH can occur as from its 22nd year of operation.

Similarly, for an aircraft 10 years older (left panels), economic replacement with an improved same-generation aircraft could happen from the 36th year of service (panel c). This could also happen earlier in the aircraft's 32nd year of service when replacing with the NGLRH (panel c). However, assuming the fuel price increase, replacement with the improved same generation aircraft could already take place in the aircraft's 26th year of service (panel a).

5.6.3 Sensitivity to DMC increase

Canaday [96] reported that DMC/FH of airlines increased by 12% from 2010 to 2014, or about 1.7% annually in real terms. Likely causes identified were higher costs of OEM parts, fewer suppliers of many MRO materials and components, and testing and tooling equipment becoming more expensive. Therefore, a sensitivity test was conducted to investigate the effect of higher DMC on aircraft lifetime unit trip DOC and aircraft ERA. This is shown in Figure 5.8 for a long-range heavy aircraft with EIS year of 1990 operating on a trans-Atlantic flight. Similar to the approach used in the previous sensitivity tests, effects of other factors were made constant to isolate the effect of rising DMC on aircraft lifetime costs. Constant fuel price at year 2002 level was used for both simulations.

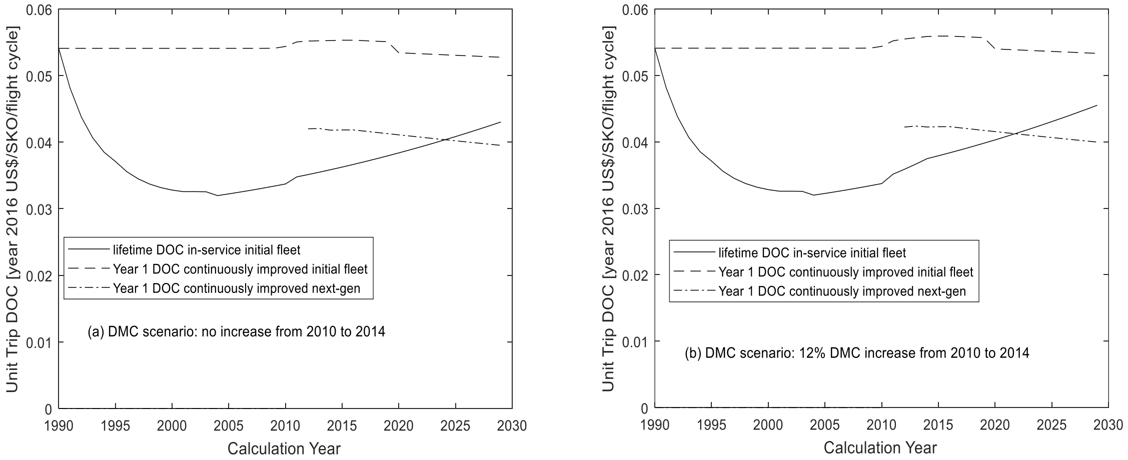

Figure 5.8 DOC of LRH and NGLRH with different EIS; under two DMC scenarios

Source: own depiction

Similar to rising fuel costs, higher DMC increases unit costs and enables earlier economic retirement and replacement of inefficient aircraft. In the left panel, only the effects of aging on airframe and engine DMC, identified in section 5.3.5.2, are considered. On the other hand, in the right panel, the additional external effects described by Canaday [96] are assumed, resulting in an annual 3% increase in DMC from 2010 to 2014. The increase in aircraft flight hour DMC enables an earlier economic replacement with next-generation long-range aircraft in the 32nd year of operation in comparison to a previous possible retirement and replacement with next-generation aircraft in the 34th year of operation.

5.6.4 Sensitivity to route group

As explained in sections 5.3.4 and 5.4, flights to or from Europe and Asia have higher airport charges and ADOC (noise, ETS, and local emissions charges). The sensitivity of ALiTiCo results to route groups is shown in Figure 5.9. The figure shows the variation in unit and trip cost of NGNB aircraft in 2036 with the intra-regional route groups. Trip costs, averaged over a 15-year planning horizon, increase with increasing flight distance. In addition, unit costs generally reduce over distance. However, higher ADOC and airport charges on intra-European and intra-Asia Pacific flights lead to higher trip DOC and unit trip DOC on these routes. On other inter-regional flights with origin or destination region being Europe or Asia Pacific, spikes in unit costs can be expected.

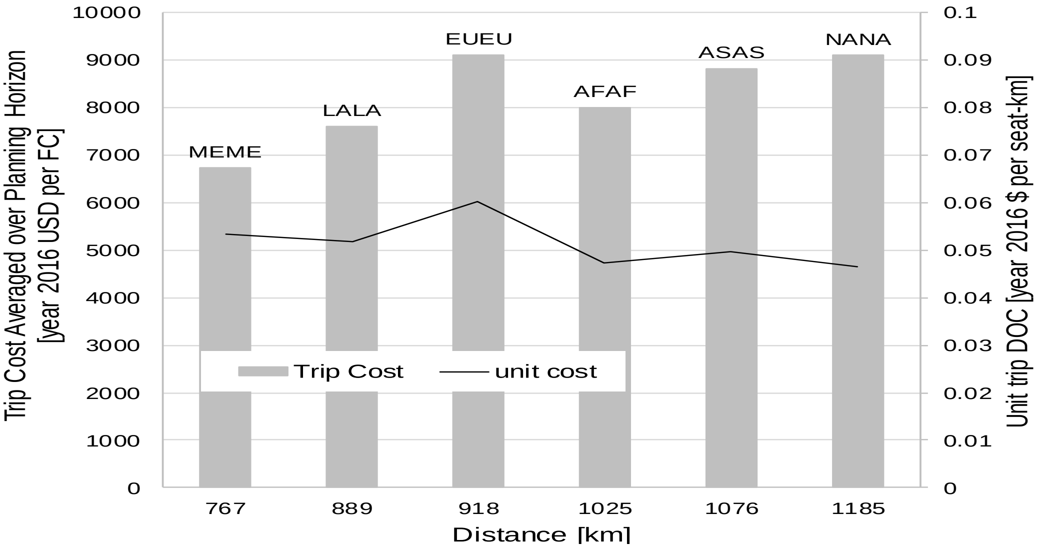

Figure 5.9 Costs of NGNB with constant seating on intra-regional routes, 2036

Source: own depiction

5.6.5 Sensitivity to depreciation period

Lastly, ALiTiCo module is tested for its sensitivity to the aircraft depreciation period chosen. Of the three cost components of DOC, the COO has the highest flexibility in terms of the higher range of depreciation periods for both narrowbody and widebody aircraft. Therefore, the chosen depreciation period affects the overall lifetime DOC development, which eventually affects the cost efficiency of an aircraft compared to another over a particular evaluation period. A higher depreciation period leads to a gentle drop in the COO which increases the DOC at later years of operation of an aircraft (see section 5.2). This implies a lower preference for such aircraft to the cost-minimizing FSDM airline.

5.7 Chapter Summary

The core contribution of this research, that is, aircraft lifetime direct operating cost modelling, has been explained. Mainly, ownership costs, fuel costs, and maintenance costs components change as an aircraft stays longer in service. Additional direct operating cost may also change on certain routes. ALiTiCo, the Aircraft Life Time Cost module, takes input from various parameters dependent and independent on route, time, environment, macro-economics and aircraft. These inputs are used in calculating the life-time costs of the 12 FSDM aircraft types for different entry into service years, and operating on the 21 different route groups.

The module is built using verified methods for computing aircraft ownership costs, fuel costs, airport fees, navigation charges, crew costs, ground-handling charges, and additional direct operating cost. A direct maintenance cost component, which was added in this work, was verified in this chapter. Lastly, results of the module, being used in the stand-alone mode, show expected sensitivities to changes in fuel price, DMC, route groups, and continuous incremental cost improvement in A&E technologies. In the cost modelling, escalations in airport charges, navigation charges, crew charges, DMC, noise charges and ETS charges are assumed to not increase or escalate over time.

The next chapter explains further the functionality of ALiTiCo in terms of its integration in the integrated modelling environment (IME), as well as other capabilities integrated into the FSDM.

6. Integrated Model Overview and FSDM Additional Capabilities

The FSDM was built in an IME called the Aircraft Technology Assessment Framework (ATAF) [67]. An overview of the interlinked submodules of the updated integrated modelling approach used within this thesis is shown in Figure 6.1.

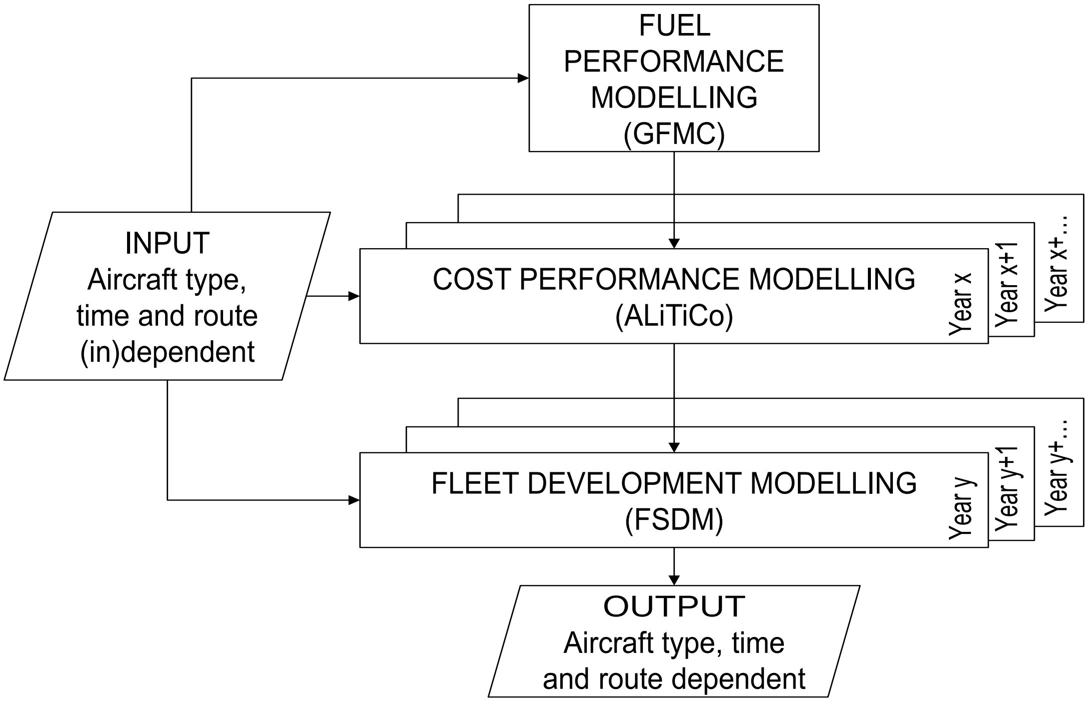

Figure 6.1 Interlinked submodules of thesis integrated model environment

Source: own depiction

The integrated model consists primarily of the modelling of fleet fuel performance, fleet cost performance, and fleet development. The integrated model depends on input data extracted from various data sources and processed in calculators to give various output. The final output of interest are obtained from the FSDM calculator. The data flow in and out of the calculators, as well as the main steps of the integrated model are shown in Figure 6.2 and Figure 6.3, respectively.

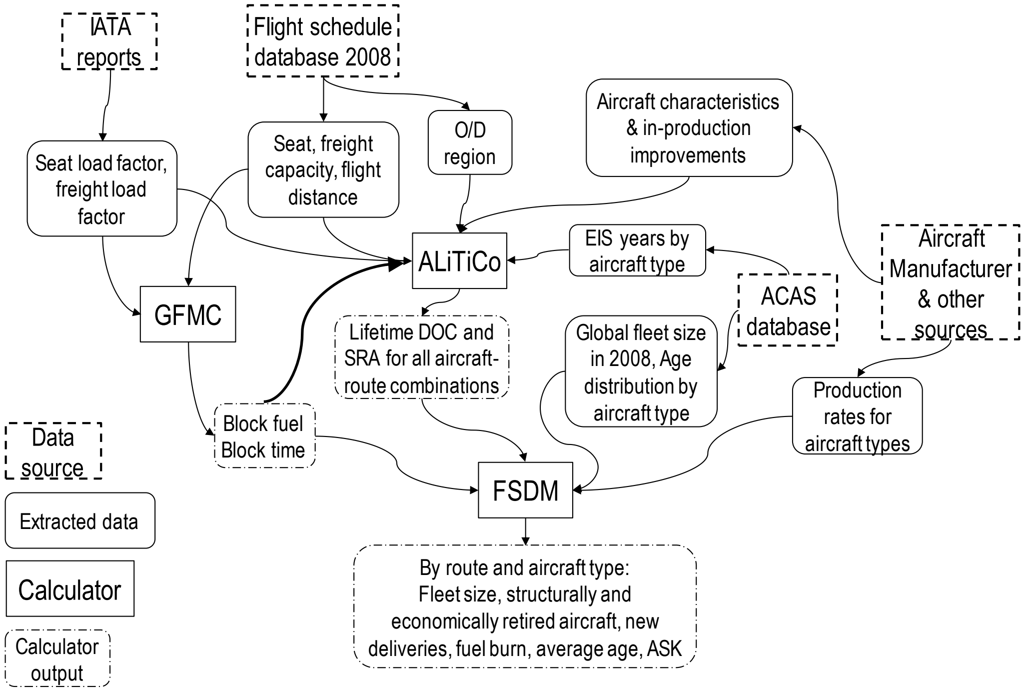

Figure 6.2 Data flow in and out of GFMC, ALiTiCo and FSDM

Source: own depiction

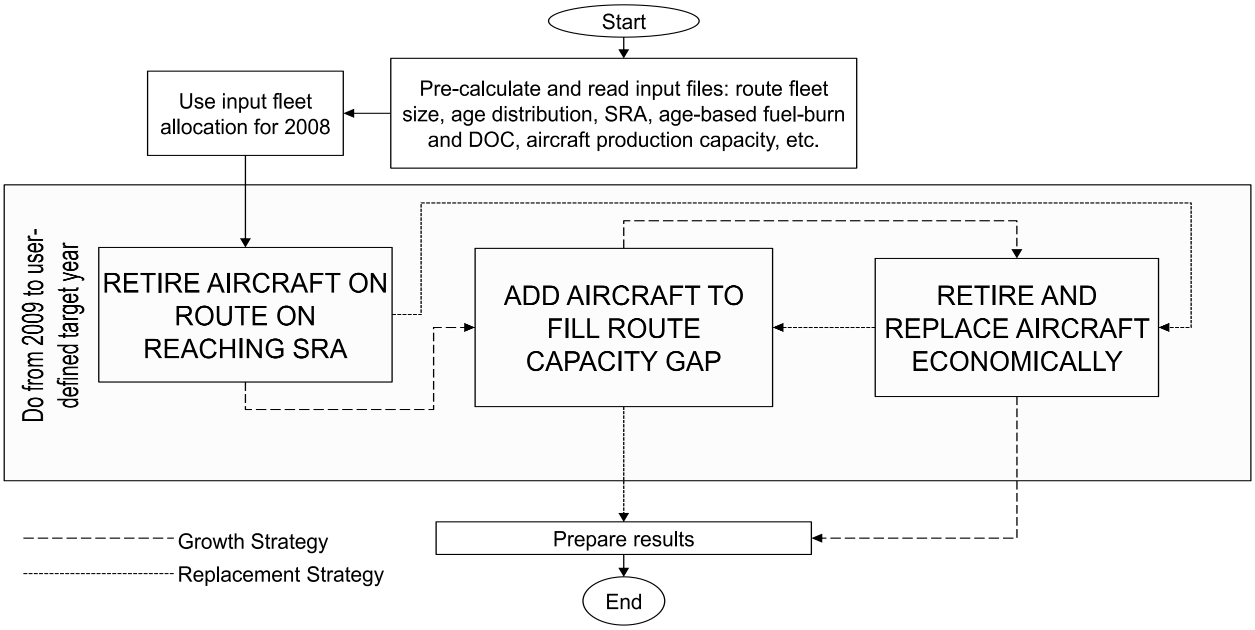

Figure 6.3 Main steps in updated integrated model environment

Source: own depiction

The main steps of the FSDM carried out every calculation year are:

i. retirement of aircraft based on structural life requirements,
ii. addition of aircraft to fill route capacity gap, and
iii. economic retirement and replacement.

Depending on the strategy for allocating aircraft production capacity, the order of the last two steps could be reversed.

The data preparation and pre-calculation of SRA and DOC have been explained in Chapter 5. Fuel burn is obtained using the GFMC and, age-based fuel burn and other costs are determined using ALiTiCo. The remaining part of this chapter describes the additional capabilities incorporated into the FSDM.

6.1 Modelling of Structural Retirement and Economic Replacement

In the model by Randt, aircraft retirement was implemented based on the age of the aircraft, using the probability of survival defined by S-curves. This resulted in each aircraft being retired based on age irrespective of its utilization. The disadvantage of this approach is that aircraft units of a particular aircraft type are retired without considering the differences in utilization and operating costs pertinent to particular routes.

However, in this research work, it is assumed that aircraft units of the same aircraft type have equal fleet age distribution only in the calculation start year. This assumption was made because there was no reliable data on age of different aircraft types flying on each FSDM route group in year 2008. And in subsequent years, the age distribution of the aircraft types on each route changes depending on the differences in the assumed utilization and cost structure on the routes.

Implementing a methodology of DOC-based fleet development requires the definition of the retirement rule of an aircraft in service. An economic and structural retirement approach is taken every simulation year. The structural retirement process is given in Figure 6.4. In this process, a maximum age of aircraft is defined so that aircraft older than 40 years are retired, following the approach of Moolchandani et al. [83].

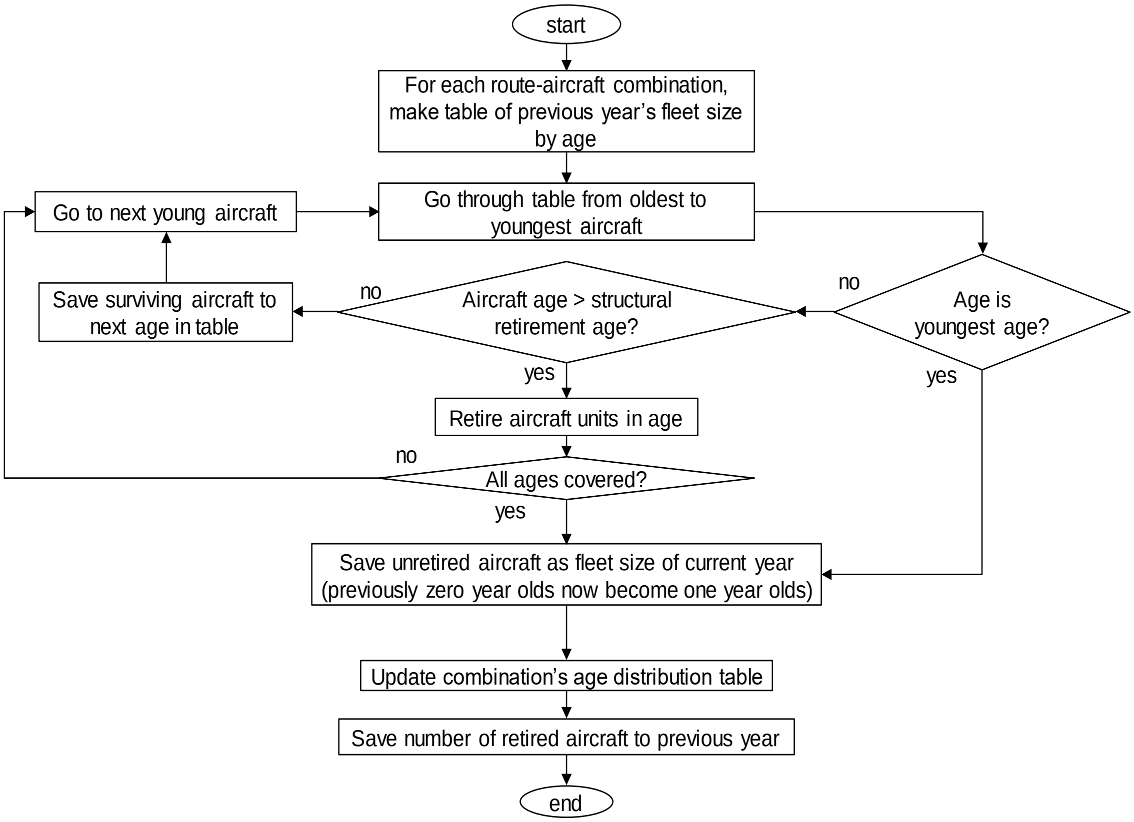

Figure 6.4 Aircraft structural retirement process on route

Source: own depiction

If, based on the utilization of an aircraft on a defined route, its structural retirement age is reached before the maximum age, the aircraft is retired based on structural (i.e. LOV) requirements. Therefore, structural retirement is done on each route depending on the aircraft's utilization (limited by its design life limit). The design life is defined based on LOV values (units in FC or FH) for each aircraft type.

The aircraft economic retirement and replacement process is shown in a flow chart in Figure 6.5.

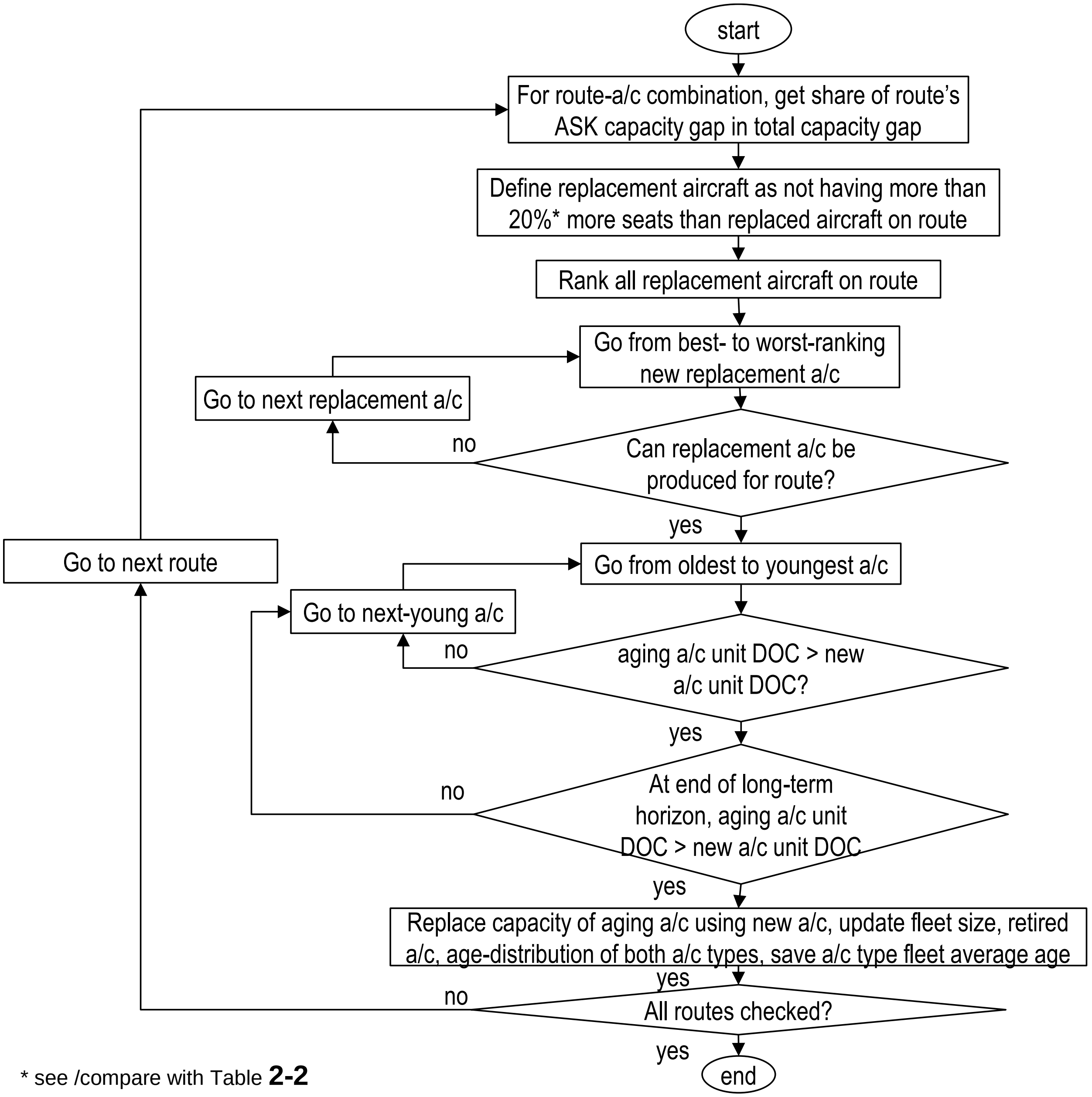

Figure 6.5 Aircraft economic retirement and replacement process

Source: own depiction

An aging aircraft on a certain route is economically retired by comparing its unit trip DOC in the current year to the unit trip DOC of other replacement aircraft available that year. A replacement aircraft is either the same aircraft equipped with the best available technological advancement in the simulation year, or another aircraft with a similar seating capacity and better unit trip DOC. Therefore, every simulation year, the age-specific unit trip DOC of each aircraft type is compared to other available similarly designed and more cost-efficient aircraft[12].

The economic retirement and replacement process differs from the structural retirement process in that the former retires aircraft based on operating costs, whereas the latter retires aircraft based on aircraft utilization-dependent design life limit. Structural retirement and economic retirement can be implemented independently so that two strategies or cases of the fleet renewal process can be investigated. The two strategies are shown in Figure 6.6.

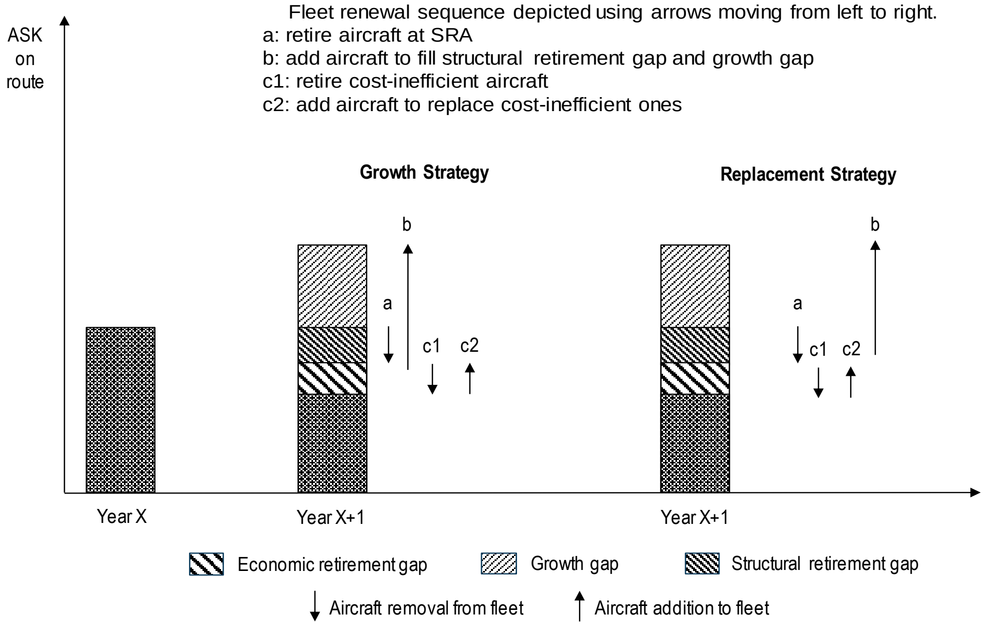

Figure 6.6 Strategies for fleet renewal on a route

Source: own depiction

Growth Strategy: Priority for structural retirement and growth, less priority for economic replacement

In this case, economic retirement and replacement is done using available aircraft left over from filling structural retirement and growth gap. This fleet development strategy is

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[12] In this version of FSDM, reassignment of aircraft between routes is not implemented. Therefore, an aircraft operates on its assigned route until it is retired from service.

primarily implemented in FSDM because it is assumed that global fleet development is driven by travel demand growth above the influence of ensuring economic retirement and replacement of inefficient aircraft. This is assumed because most aircraft manufacturers agree that a higher percentage of aircraft would be delivered over the next 20 years to serve air travel demand growth (ATR: 65%, Embraer: 63% and 56%[13], Boeing: 57%, Airbus: 63%) rather than serve as aircraft replacement (ATR: 35%, Embraer: 37% and 44%, Boeing: 43%, Airbus: 37%)[14].

Replacement Strategy: *Priority for both structural and economic retirement gaps before growth*

In this case, aircraft production capacity is first for filling both retirement gaps, before growth gap is filled. Although an airline may follow this strategy for a short-term, e.g. Allegiant Airlines [97] and Uzbekistan Airways [98] put the retirement and replacement of their old inefficient aircraft as a short-term higher priority than the expansion of their capacity and network, it is not considered to be the long term practice of the airline industry. However, there is a possibility of the strategy resulting in a more efficient fleet because more aircraft that are inefficient are retired. More studies on this strategy are done later in the model application (Chapter 8).

6.2 Aircraft Evaluation for Introduction on Unified Route

The process of aircraft evaluation has been described in section 2.4.3. In the previous work done by Randt [67], aircraft were operated on their most frequently operated route distance within each route group. That is, on a typical intra-north American route for example, narrowbody aircraft had a mean flight distance of 1333 km, whereas a long-range aircraft had a mean flight distance of 3324 km, implying flights between two different airport pairs. The nature of the aircraft introduction to fill the capacity gap implied that the performance of the two aircraft were compared on different routes, whereas in the airline

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[13] For 70-130 seat jet segment and turboprop segment, respectively

[14] Values derived from ATR's TURBOPROP MARKET FORCAST 2016-2035; Embraer's MARKET OUTLOOK 2017, Boeing CURRENT MARKET OUTLOOK 2017-2036, and Airbus Global Market Forecast 2017-2036.

practice of aircraft evaluation, the performance of the two aircraft would be compared on the same route.

Therefore, as explained in a previous work by the author [99], a uniform frequency-weighted route group distance is established for each route. Although a certain level of detail is lost in which the number of origin-destination connections previously considered is no longer incorporated in the model, a comparable transport performance is still produced by the reduced complexity (See Table D-1). In addition, the same approach was used in the AERO-MS model [15]. The process of economically introducing aircraft to fill capacity gap is shown in Figure 6.7. Main new aspects of the process are further explained below.

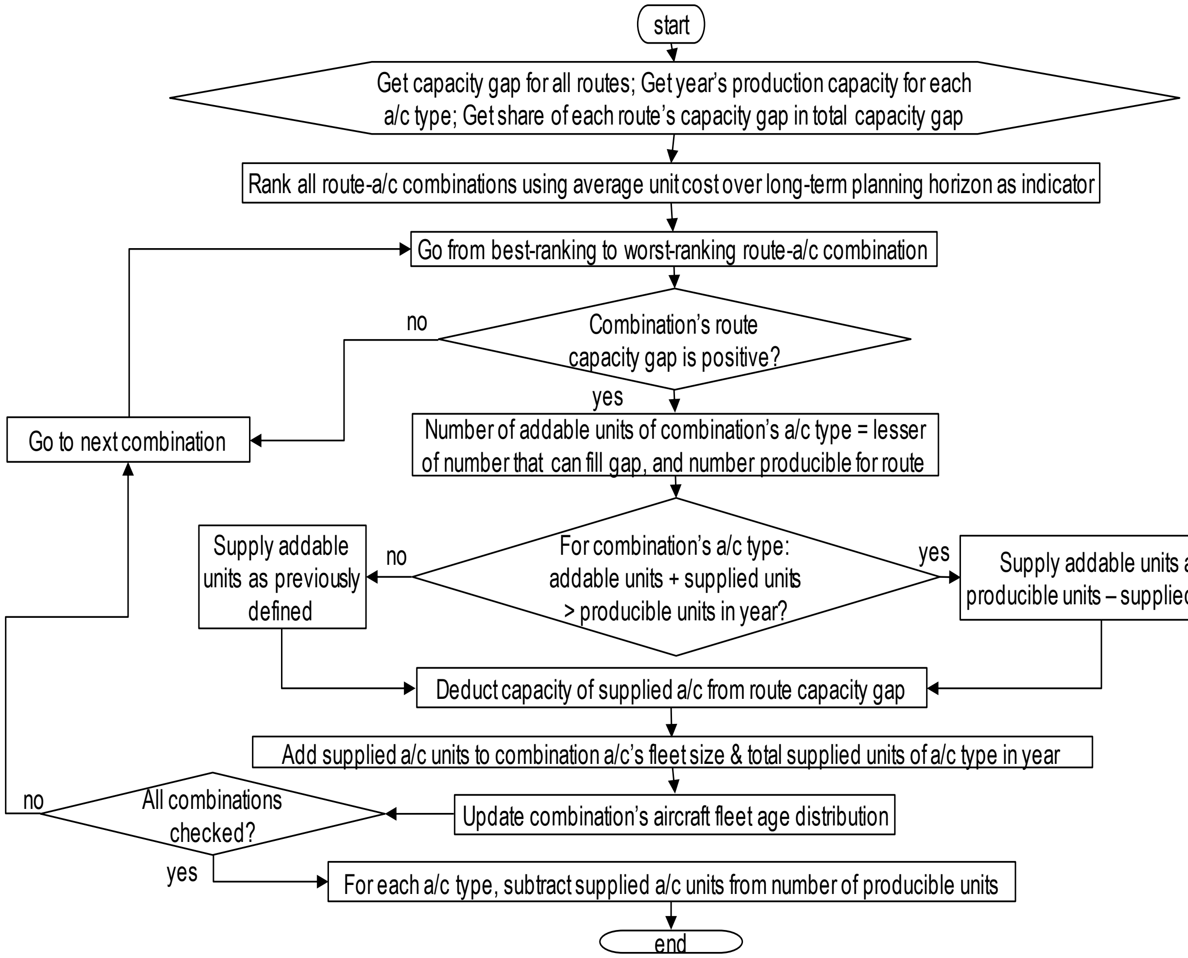

Figure 6.7 Process of aircraft economic introduction to fill capacity gap

Source: own depiction

6.2.1 Average unit cost over long term planning horizon as indicator

Using the unified route system, the unit costs of aircraft are compared before introduction on each route. The model uses the average unit trip DOC for each aircraft type over a longer-term planning horizon. Figure 6.8 shows the unit costs of the FSDM next-generation passenger aircraft on a typical route between Europe and the Middle East (flight distance = 3638 km), assuming a depreciation period of 14 years and 16 years for narrow body and wide body aircraft, respectively. Furthermore, the average jet fuel price level in 2017 of 1.63 2016 USD per gallon is assumed.

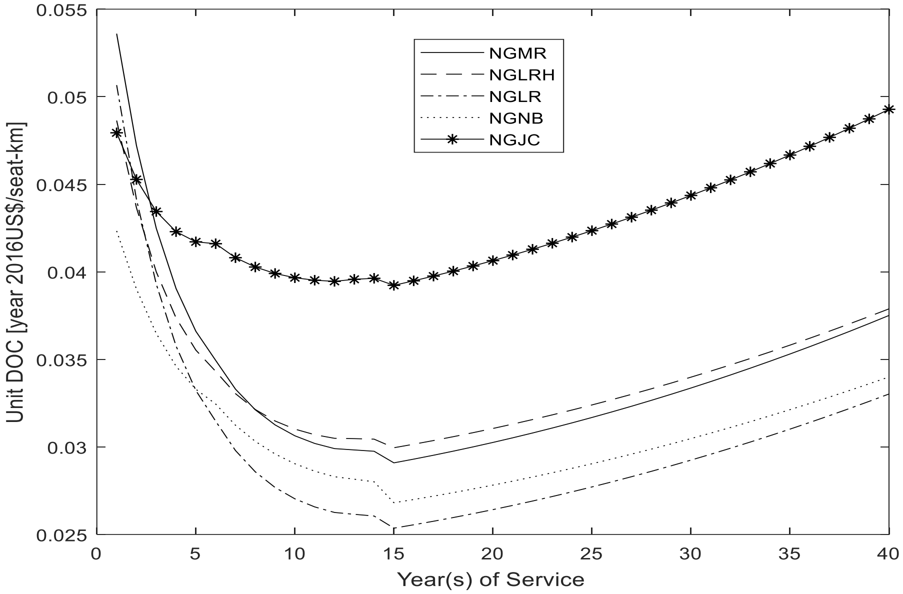

Figure 6.8 DOC of next-gen aircraft: variation with aircraft operational life

Source: own depiction

Although wide body aircraft are subject to similar depreciation periods and aging effects, the developments of the unit costs over the aircraft operational life are different, subject to aircraft properties. For example, a higher number of engines on the NGLRH compared to the NGLR results in higher engine maintenance costs in the former than in the latter. Hence, NGLRH has a gentle-descending DOC curve when compared to the NGLR aircraft. Furthermore, the NGLR has a higher share of ownership costs in the total DOC than the NGMR. Depreciation of the aircraft ownership costs therefore results in a steeper lowering of the DOC curve for the NGLR compared to the NGMR. Therefore, even though the NGLRH has lower unit costs than the NGLR in the first year of service, it has higher unit costs after the fifth year of operation.

As a result, an aircraft that has the lowest unit cost in its first year of service may not have the lowest costs at the end of the planning horizon. Therefore, instead of using operating costs in an aircraft's first year of service, using the average costs over the planning horizon is a better approach ensuring a minimization of operating costs, similar to airline practice.

6.2.2 Aircraft production capacity allocation to route

Once aircraft types available for introduction on routes have been evaluated, the capacity gaps on each route are then calculated. The method of calculating the capacity gaps described in section 2.4.1 holds except that the retirement gap is now split into economic retirement gap and structural retirement gap. Although an economic retirement gap exists, this is not considered a part of the capacity gap being filled by aircraft introduction. Rather, the economic retirement gap is filled directly (arrow c2 in Figure 6.6) after aircraft economic retirement (arrow c1 in Figure 6.6). This is because a slightly different approach is used when adding aircraft to fill the capacity gap as compared to when adding aircraft during economic retirement and replacement.

Therefore for each route, the share of the capacity gap in the year's total capacity gap is determined and used when allocating the production capacity of an aircraft type among the routes.

Before adding new aircraft, the model then keeps a record of the units of each aircraft type that can be produced for each route. This method ensures that routes with higher forecast travel demand (e.g. flights to and from Asia-Pacific) have a higher priority in aircraft delivery, and at the same time, routes with lower demand have aircraft allocated to them.

For every added unit of a particular aircraft type, the stock of producible aircraft reduces; however, capacity demand is filled up to the maximum aircraft production capacity assumed for the calculation year.

6.2.3 Age distribution managed on routes

Once aircraft have been added to a route, the age distribution of the aircraft type's fleet on the route is updated. This enables the calculation of an aircraft type's fleet average age. This enhancement of managing the addition and retirement of aircraft at route level enables the evaluation of policies that, for example, are implemented at regional or route group level.

6.3 Incremental and Giant-Leap Improvements for In-production Aircraft

When investigating economic retirement of aircraft, improvements on in-production aircraft are also instrumental to the gradual reduction of trip DOC in the global fleet. Thus, not only giant-leap improvements by next-generation aircraft are to be considered, but also incremental improvements available on in-production aircraft. Although, after production, in-service improvements here defined as performance improvement packages (PIPs) are also available, these improvements are not modelled due to the lack of available data on the level of in-service improvements carried out globally.

Therefore, FSDM assumes that all aircraft added to the fleet in a particular year carry the improvements available in that cluster for the respective year. Some improvements are offered as options on in-production aircraft; for example, Armonia cabin on ATR 72-500 [100]. However, some have become standard on in-production aircraft; for example winglets on B737NG [101] and 737MAX, and sharklets on A320neo aircraft [102,103].

Assumed improvements in the aircraft types are shown in Table E-1 based on literature.

6.4 Other Model changes

Other changes are made in the model as explained in the following subchapters.

6.4.1 Exclusion of freighter and two next-generation aircraft

Since freighter aircraft conversion methodology is not modelled in the updated FSDM, both initial fleet and next-generation freighter aircraft were not considered in the updated FSDM. Although freighter aircraft selection also considers direct operating cost, 60% - 70% of freighter airplane deliveries would be freighter conversions [104]. Besides, the share of freighter aircraft in the global commercial aircraft fleet is small (10%) and they carry about 40% of air freight. As a result, RTK growth is not considered.

Furthermore, among next-generation aircraft the NGLRH2 and NGTP in Table 3-13 are not considered because it is less likely that these aircraft types would be introduced.

6.4.2 Aircraft reallocation on route

Because of the change from a varied mission distance to a uniform route group distance, as mentioned in section 6.2, a reallocation of the fleet was done using the Matlab optimizer as explained in [99]. Additionally, after fleet reallocation, routes were checked and necessary swapping of aircraft was done to ensure that the aircraft allocated to every route had sufficient range to fly the route’s distance. As an example, 38 NB units were swapped from AFNA to ASAS. In return, equivalent capacity was taken from the ASAS to the AFNA route using the MR. Table F-1 shows the size of the initial fleet aircraft allocated to the different route groups.

6.4.3 Aircraft production capacity update

Aircraft production is sensitive to aircraft demand [105], and as a result, based on historical data, does not progress linearly. Production capacity of initial fleet aircraft had previously followed values given by Ploetner et al. [68], while equations given in section 4.2 were used for next-generation aircraft. However, production behaviour of aircraft manufacturers were further studied using historic and planned deliveries until the year 2022 available from industry literature.

With dwindling demand, aircraft manufacturers have ramp-downed production capacities and deliveries of some current-generation aircraft before first delivery and ramped-up production of next-generation aircraft scheduled to be available later. An example of this strategy can be seen with Boeing’s 777/777X [105]. However, manufacturers could perform both simultaneously; i.e. ramping down and ramping up production of current-generation and next-generation aircraft, respectively. This usually happens with high demand for both generations of aircraft. Examples of this strategy can be seen with Boeing’s 737NG/737MAX and Airbus’ A330ceo/A330neo [106–108].

A representation of yearly production rates for narrow-body aircraft is shown in Figure 6.9, while for mid-range and long-range aircraft types, respective production rates are shown in Figure 6.10. Actual numbers for all aircraft types are given in Table F-2. After 2022, production capacity of all aircraft types is assumed to grow at an annual rate of 4.7%, which is Boeing's projected worldwide growth rate for air passenger traffic between 2017 and 2036. This is slightly higher than the observed 4.4% average annual growth rate in total aircraft deliveries between 2008 and 2018.

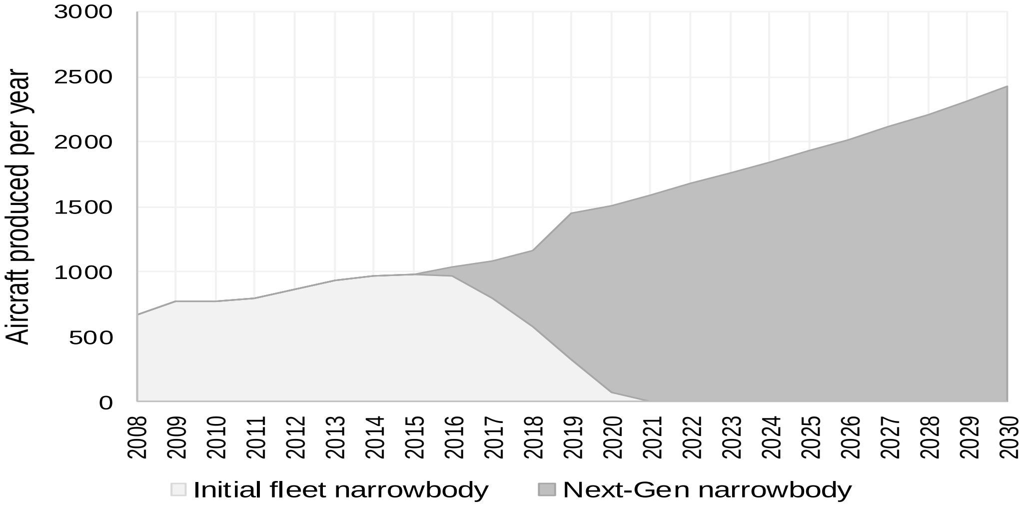

Figure 6.9 Production ramp-down and ramp-up of NB and NGNB

Source: own depiction

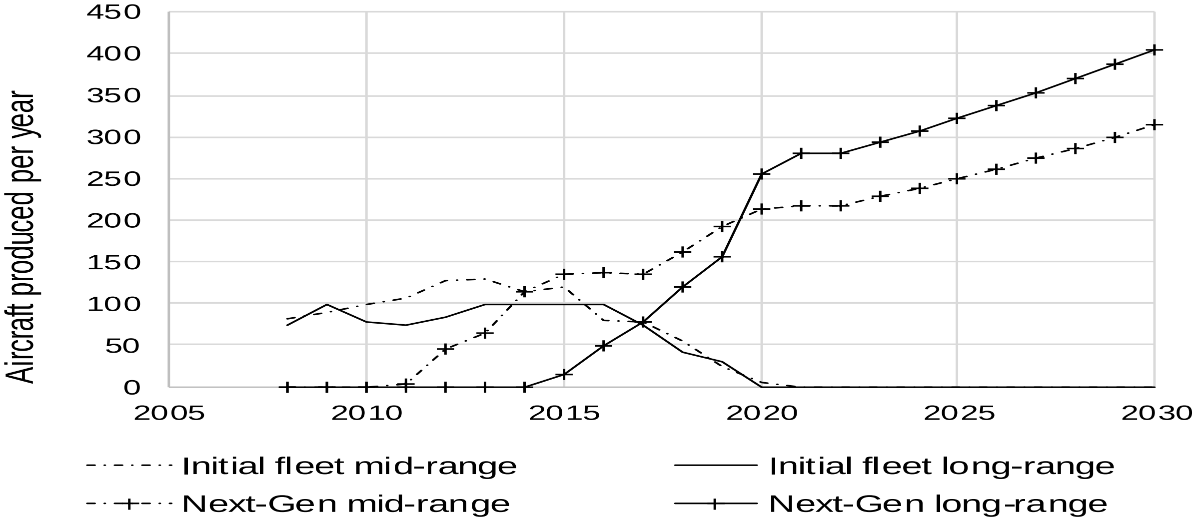

Figure 6.10 Production ramp-down and ramp-up of MR, NGMR, LR and NGLR

Source: own depiction

6.5 Chapter Summary

The main additional capabilities of the integrated model, specifically, the updated FSDM, and the accruing benefits of the enhancements are summarized in Table 6-1. Compared to the previous state of the FSDM and the work by Randt [67], the main capabilities are connected to the added submodule for fleet cost performance modelling- ALiTiCo.

Table 6-1 Main capabilities integrated in updated FSDM

Previous State	New Capability	Description of Capability	Expected Benefits
Fuel performance, i.e. fuel burn per seat km, as parameter for aircraft addition to fleet	Additional aircraft evaluation parameter: DOC	FSDM airline can introduce aircraft not only based on fuel burn per seat km but also based on unit trip DOC	• Evaluation of how externalities of fuel price scenarios affect aircraft selection and resulting fleet development
To fill capacity gap on a route group, different aircraft are compared on different flight distances	Aircraft evaluation implemented on unified route group	To fill capacity gap on a route group, unit cost performance of different aircraft are compared on same flight distance	• Better aircraft selection based on comparable selection criteria. • Model assumption closer to reality: aircraft selection is dependent on route distance and unit operating cost
Retirement based on aircraft age (survival curves), irrespective of route group	Aircraft retirement at route group level	Retirement based on route-specific aircraft utilization, design limit of validity, and externalities like fuel price, etc.	• Fleet development sensitive to effect of externalities and aircraft utilization

7. Fleet Model Calibration and Verification

The updated FSDM includes inter-relating components and methods that were presented and verified for input-output reliability in the previous chapters. In this chapter, the integrated model comprising the FSDM is tested for reliability of model results. This is done in two stages. First, historical and forecast data from industry are used to calibrate model variables to arrive at comparable jet aircraft fleet size and composition results. Next, using fleet parameters such as CO_2 emissions and fuel efficiency, the development of the global passenger aircraft fleet is verified in comparison to studies with similar methodology to the updated FSDM.

Calibration simply involves the adjustment of model variables within reasonable limits to arrive at comparable outcomes from reliable and comparable sources such as from Boeing CMO reports. These outcomes are mainly fleet size and composition from the year 2008 to 2016 as well as forecast results for year 2036.

Model verification then involves the comparison of main results, for example, fleet level CO_2 emissions, of the calibrated model to that of other reliable and comparable sources.

7.1 Calibration Using Jet Aircraft Fleet Development Data

This section relates to the calibration of the updated FSDM and the verification of jet aircraft fleet size and composition results using available past data from the year 2008 until 2016, as well as forecast data for 2036, both provided in Boeing Current Market Outlook (CMO) reports and some other reports evaluating global air transport. In order to reduce complexity, some variables are assumed constant throughout the simulation period. Since the goal of updating the FSDM in this research work is to evaluate the longer-term potential of measures for reducing aviation emissions, calibration efforts focus on comparing model results with forecast data while verifying the historical development for the jet aircraft fleet.

In this subsection, the input used in the calibration process are first explained. Next, the model calibration objectives are described based on Boeing CMO forecast data for jet aircraft fleet development; after this, different calibration inputs and their results are described using Boeing's data for years 2016 and 2036. Lastly, other jet aircraft fleet metrics are verified.

7.1.1 Additional input used for calibration and verification

Boeing Current Market Outlook (CMO) includes data on growth in RPK, excluding RPK of turbo-prop aircraft, on routes that are adaptable to the route groups of the FSDM. The fleet size accuracy of FSDM jet passenger aircraft is evaluated using CMO reports published in years 2009 to 2017[15]. In doing this, historical and forecast RPK growth rates at route groups[16] are used as published in the CMO reports. Past RPK growth rates on routes are shown in Table F-3, while Table F-4 presents forecast RPK growth rates between the route groups until 2036 according to Boeing [4].

Passenger and freight load factors from 2008 to 2016 are taken from IATA reports [109], 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 [110]. 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 research. In addition, JADC [110] forecasts that passenger load factor is set to increase from 80.3% in 2016 to

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[15] It should be noted that Boeing changed their aircraft classification system as from 2012, shifting the A350-900 from the medium twin-aisle category to the small twin-aisle category.

[16] RPK development in Rest of the World was assumed to cover equally traffic connecting Africa, Asia and Middle East with Latin America.

83.3% in 2036. Passenger and freight load factors used for calibration to Boeing's data are given in Table F-5. Over the simulation period, the assumed seat load factor of 86% used for the fuel burn estimation (see Section 5.3.2) has a maximum average error of 5% per year from the passenger load factors used for calibration.

Fuel prices (with units in year 2016 US dollars) were derived for years 1968 until 2016 using US GDP deflator values [74] and U.S. Gulf Coast Kerosene-Type Jet Fuel Spot Price [111]. It was assumed that jet fuel prices were constant until year 1990 since there was no major difference between the average U.S. Kerosene-Type Jet Fuel Wholesale/Resale Price by Refiners between 1978 and 1990 [112].

For years 2016 to 2036, low and high fuel price scenarios by Boeing are used as shown in Figure 7.1. 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 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 can be 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 3.145 2016-US Dollars per gallon in the low and high fuel price forecasts, respectively.

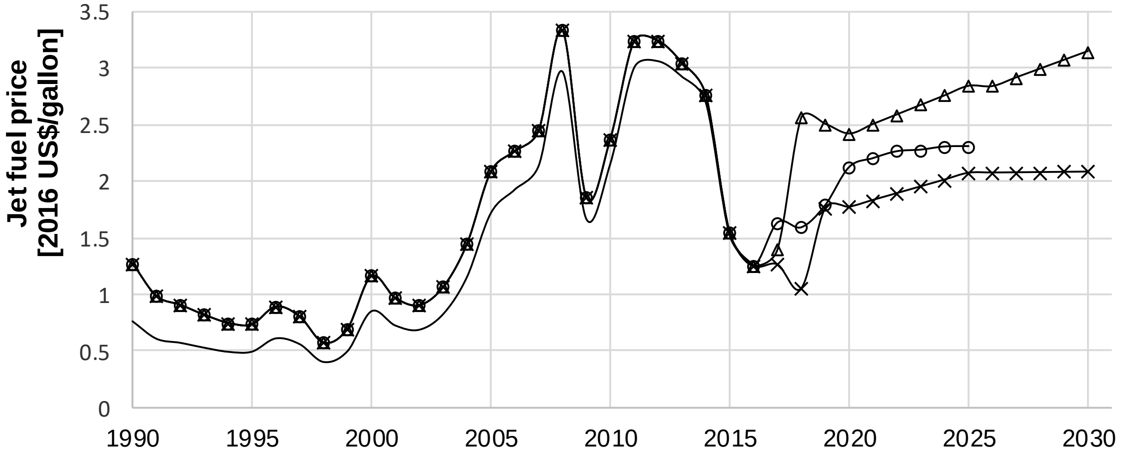

Figure 7.1 Historical and forecast fuel price scenarios by Airbus and Boeing

Source: own depiction based on [74]

These fuel price scenarios differ from Airbus fuel price forecast which assumes medium fuel price close to 2010 price levels in 2025 [113] (see Figure 7.1).

As explained in section 2.3, a maximum aircraft upgauge was set at 20%. In addition, the utilization of an aircraft type is modelled to vary between route groups, with a possibility of increasing annually. According to Boeing [40], passenger airplane utilization increased between 2008 and 2015. A study of the growth in airplane utilization at aircraft cluster level between year 2008 and 2014 revealed that the growth occurred mostly for turboprop commuter, jet commuter, narrowbody and mid-range aircraft cluster between years 2008 and 2014; whereas long-range aircraft utilization increased between 2012 and 2014 [114]. For a given year, an increase in airplane utilization results in lower unit costs and trip costs because fixed ownership costs are spread over an increased number of trips [115]. Considering that portions of flight crew and cabin crew costs as well as maintenance costs are possible components of fixed costs [33], it is assumed that higher airplane utilization results in lower direct operating costs. Therefore, the unit DOC of a particular aircraft type with the same payload varies with different levels of utilization on different route groups.

A fleet forecast also uses an assumption on development of aircraft productivity, which, according to Evans and Johnson [116], 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 utilization compared to newer aircraft [4]. 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 [116], 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 [117]. 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 [114].

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.

7.1.2 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 widebody aircraft would open up [4]. Although the opening up of new markets is not modelled in FSDM, the effect of liberalization, 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 7.2, this growth is driven by the growth in Small Twin Aisle aircraft.

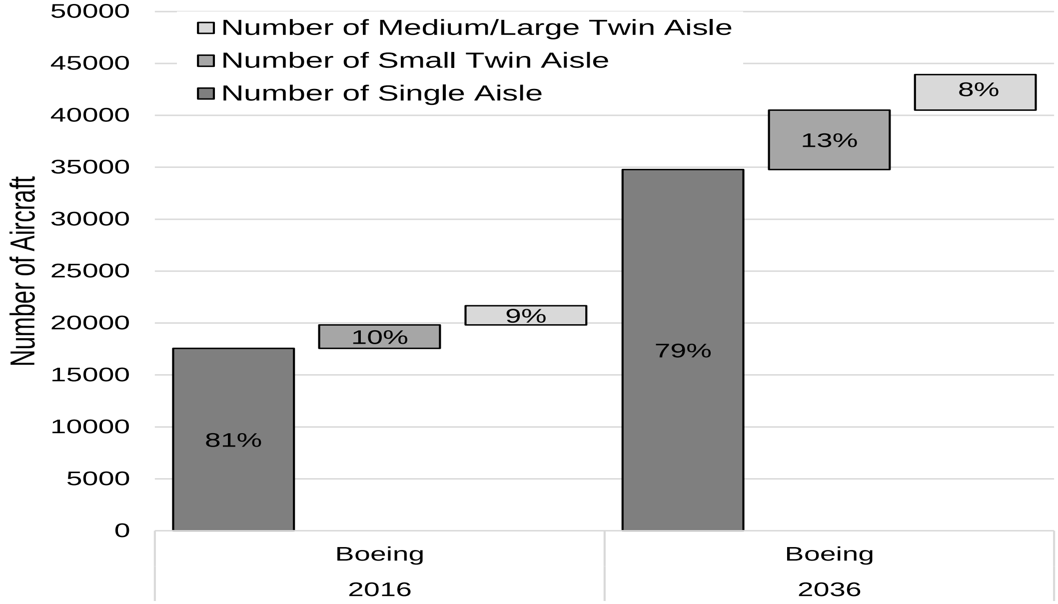

Figure 7.2 Fleet size and composition according to Boeing in 2016 and 2036

Source: [4]

This calibration work, therefore, has an objective goal of a higher preference for widebody aircraft over narrowbody aircraft in 2050. Boeing categorised aircraft types into three groups. However, the method used in doing this was not explained. Table 7-1 shows how FSDM aircraft clusters compare to the classifications.

Table 7-1 Comparison of Boeing CMO to FSDM aircraft classification

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

Source: own depiction

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. Beside 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.

7.1.3 Calibration results

Fleet composition in year 2036 is dependent primarily on the choice of aircraft for filling 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 7-2.

Table 7-2 Upper and lower boundaries values of calibrated variables

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

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 utilization leading to a preference for S-TA and M/L-TA (see section 7.1.1). These are shown in Table E-2. For each fuel burn scenario, four combinations of DP and PH are used for calibration. The calibration results are shown in Figure 7.3 for years 2008, 2016, and 2036. Because the long-term development is of interest, yearly changes in the results are not shown.

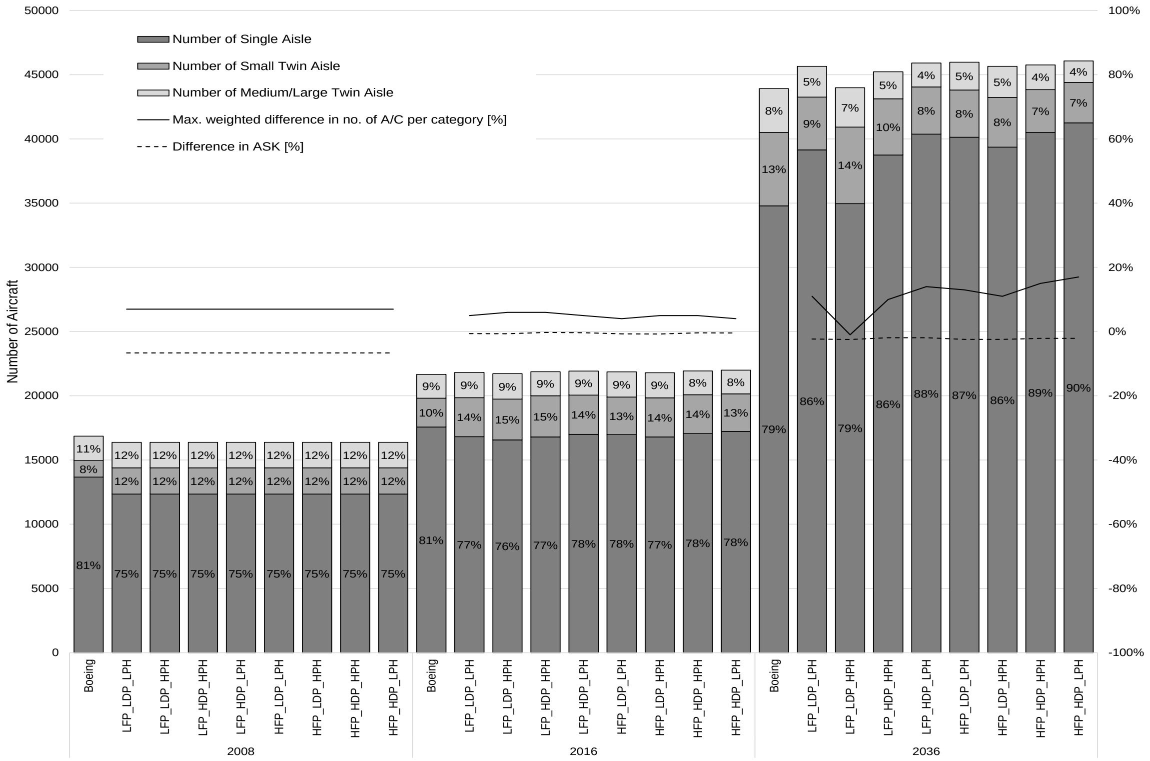

Figure 7.3 Calibration results

Source: own calculations

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 (for example, twin-aisle aircraft like Ilyushin IL-86 and Lockheed L-1011; and single-aisle aircraft like Suhkoi 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% was estimated. When weighted by fleet size, differences of 7% and 0% results 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 between 2008 and 2016 are 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 range 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 forecast used, of the four combinations of DP and PH possible, the results from 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 thesis. 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 7.3, 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 narrowbody aircraft. Because, unlike widebody 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, narrowbody aircraft are more competitive than their wide-body counterparts are, especially when compared on the design range of the former.

Because of their cost efficiencies, next-generation aircraft could have a share of more than 70% of the total fleet size in year 2036. Therefore, the cost-efficiency ranking of next-generation aircraft is decisive in effecting the change in the fleet's composition.

Moving from a low- to high-fuel price scenario, on some short haul routes, NGNB take precedence over NGMR and NGLR while NGMR take precedence over NGLRH. On some medium-haul routes, NGLR rank better than other aircraft.

Considering only route groups where there is a change in the cost performance of next-generation aircraft when a higher fuel price scenario is used, the ranking of these aircraft clusters available for EIS in 2036 are shown in Figure 7.4.

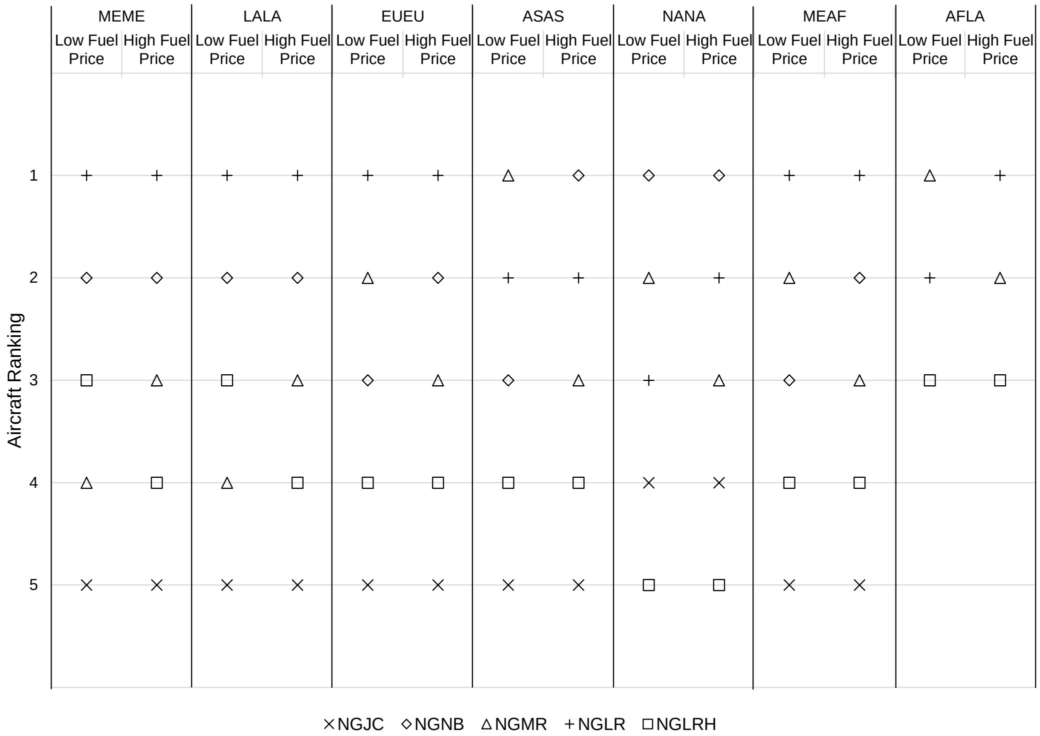

Figure 7.4 Next-gen. aircraft ranking on routes subject to jet fuel price

Source: own calculations

This result is in agreement with the claim by Rutherford [118] 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 differ over time.

Moreover, changes to DP and PH affects the preference or disfavour of twin-aisle over single-aisle aircraft. By observing the lifetime DOC of aircraft (for example, see Figure 6.8), the combination of reduction in COO and increase in COC of aircraft results in the U-shaped development. Thus, since twin-aisle aircraft have a higher share of COO in the DOC than single-aisle aircraft do, a reduction in the DP (keeping other factors constant) leads to a steeper fall in the DOC in the early years of the twin-aisle aircraft compared to the single-aisle aircraft. As a result, a lower DP results in a preference for twin-aisle aircraft.

In addition, because changes to the COO have a higher impact on the DOC of twin-aisle aircraft than the single-aisle aircraft (see Section 6.2.1 for more explanation), a higher planning horizon leads to a lower average cost of the former compared to the later. Thus, a higher PH results in a preference for twin-aisle aircraft above single aisle aircraft.

7.1.4 Calibration conclusion

Like Dray et al [119] observed, a source of variability in the results of fleet models is the input scenario data. Boeing's forecast covers, amongst others, underlying dynamics like liberalization and airport infrastructure investment. As a result, they assumed the trend of liberalization and airport infrastructure investment will continue [4]. These trends not only result in increased air travel demand, but also the opening up of new markets that had previously been either unreachable or unprofitable, especially those that can be served by small widebody aircraft. However, in the FSDM, since liberalization and airport infrastructure investments are not explicitly modelled in terms of what new routes and mission distances[17] would be newly created, it is not possible to capture these dynamics and their impacts. Only the effect of liberalization, in terms of increased air traffic, is considered in the FSDM. Besides, the aircraft utilization assumption used by Boeing was not stated. Therefore, variations in fleet size results can be expected.

In summary, in addition to the total fleet size, the calibration results show that the fleet model reliably reproduces the fleet composition forecast of the Boeing CMO report, assuming the combination of a low fuel price scenario, low depreciation period and a high planning horizon.

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[17] In the FSDM, route groups and mission distances are assumed constant over the simulation period.

7.2 Verification Using Global Passenger Aircraft Fleet Development Data

Having calibrated the fleet model using the development of the global passenger jet aircraft, more results of the model are verified using other available data and results from comparable studies on global passenger aircraft fleet development.

7.2.1 Verification of historical fleet supply capacity

The supply capacity provided by all passenger aircraft in the FSDM (i.e. all aircraft considered in section 7.1 plus the Turbo prop aircraft) is compared with IATA and ICAO [120] data for year 2008 to 2016. IATA's data were obtained from IATA reports[18]. The development of the global passenger aircraft ASK is shown in Figure 7.5.

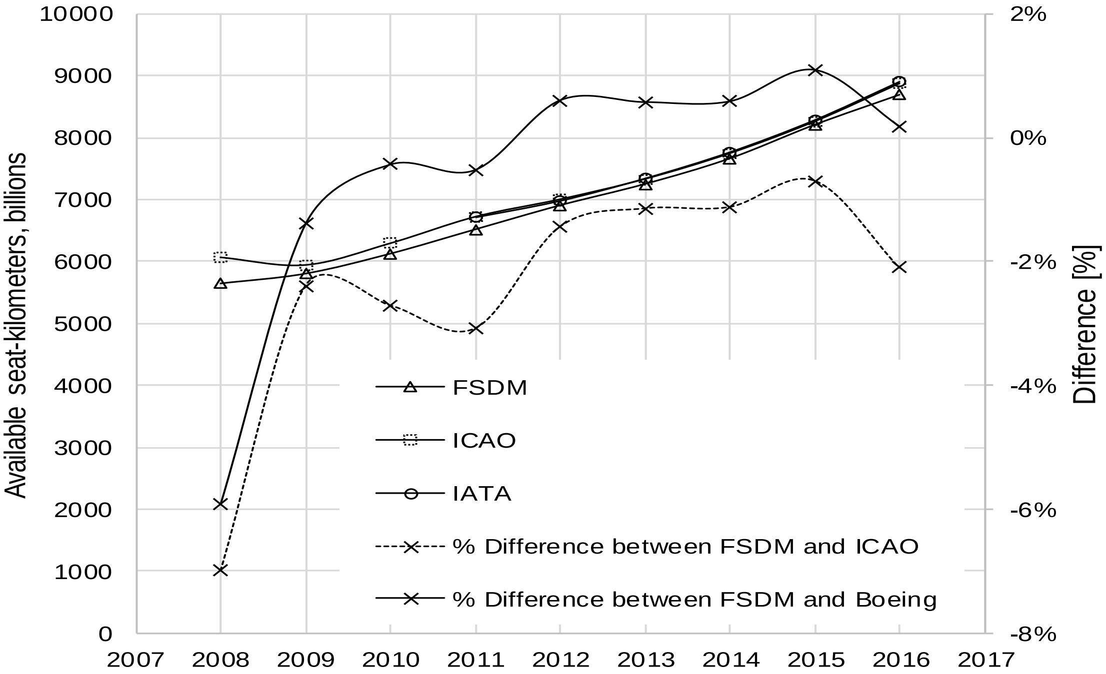

Figure 7.5 Global passenger aircraft ASK

Source: own calculations, [4,40,120]

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[18] Economic Performance of the Airline Industry: 2014 mid-year report, 2015 End-year report, and 2017 Mid-year report.

From the figure, it could be verified that the fleet supply capacity result of the FSDM for years 2008 till 2016 shows a good correlation to the global trend. Although a difference of about 7% was made in the initial year as explained in Section 6.2, FSDM gives an ASK approximately 2% below ICAO's historical data for year 2016 [120]. In addition, the supply capacity as shared by the aircraft types in 2016 is shown in Figure 7.6. The results show that FSDM representation of the turboprop aircraft in 2016 reproduces IATA's historical data [121].

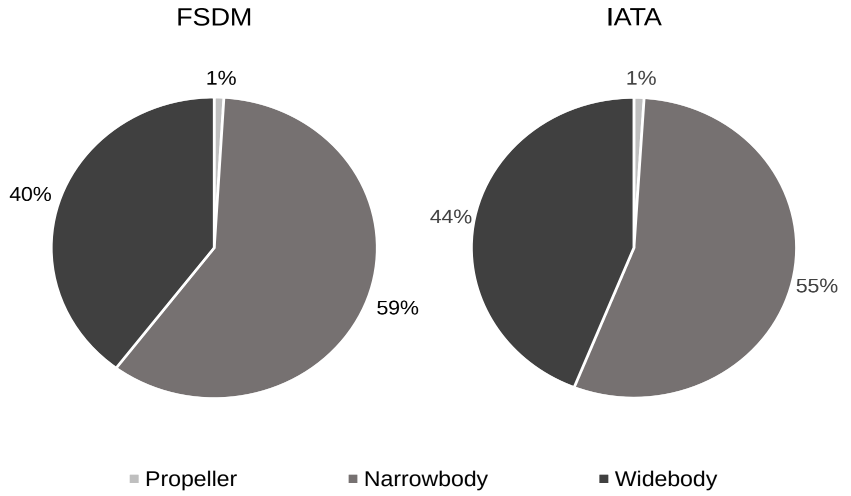

Figure 7.6 2016 global ASK share by passenger aircraft type

Source: own calculations, [121]

7.2.2 Verification of historical fleet fuel burn and fuel efficiency

Based on calculation results by Wasiuk et al. [122], IATA [109,121], and Dray et al. [119] estimates of 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. However, FSDM's estimate of fleet fuel burn in 2016 is 1% below that of IATA. Using the approach explained by Dray et al. [119], 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 IATA and ICAO. Fuel burn performance of the global passenger aircraft from year 2008 to 2016 is shown in Figure 7.7.

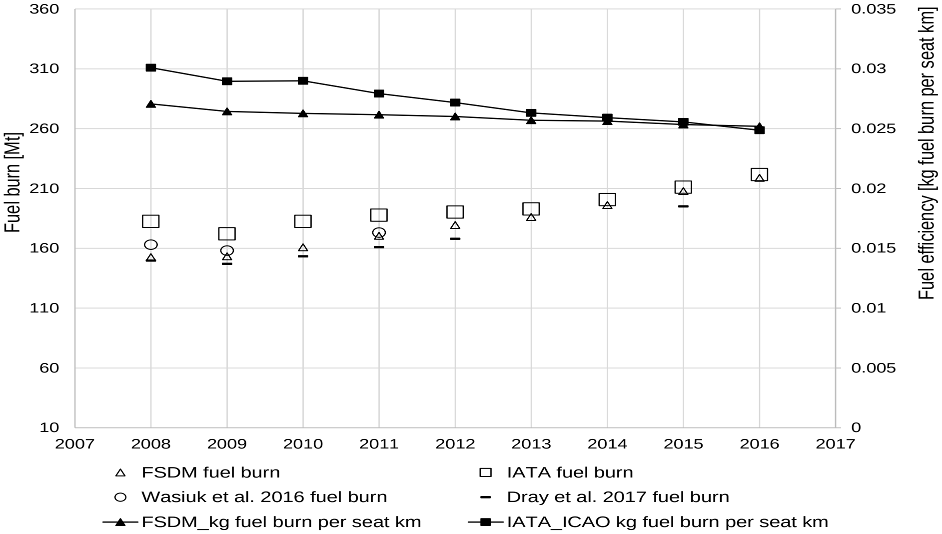

Figure 7.7 Passenger A/C fuel burn and fuel efficiency 2008-2016

Source: own calculations, [109,121]

7.2.3 Verification of historical fleet unit cost and average age

Fleet unit cost development is dependent on development in fuel unit cost [123]. The development in cost per ASK (CASK), fuel price and average aircraft age are shown in Figure 7.8.

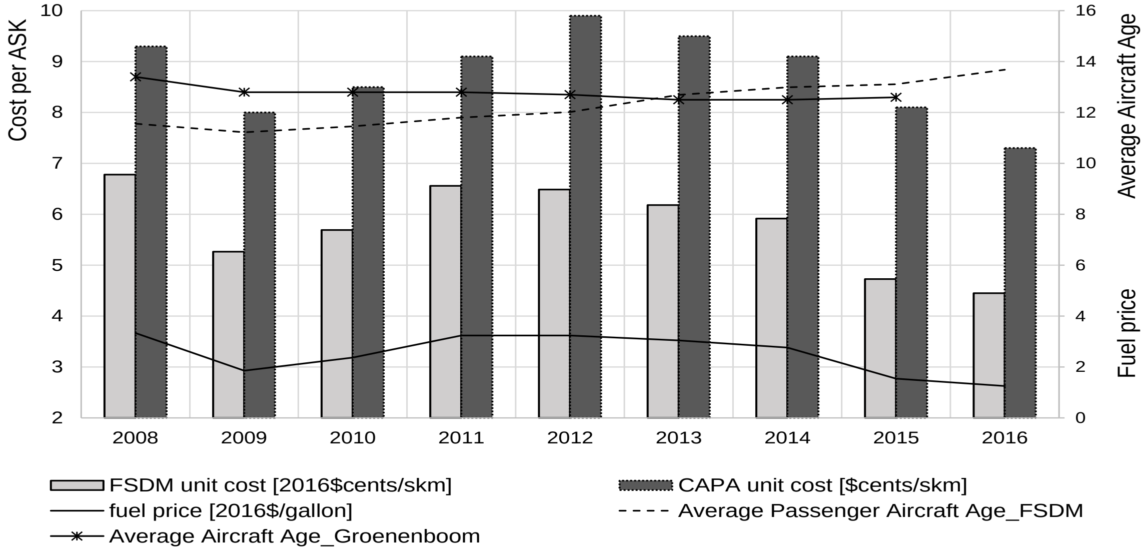

Figure 7.8 Fuel price, unit cost, and average age of global pax fleet: 2008-2016

Source: own calculations, [21[123]]

Data on aircraft unit cost used for verification was obtained from CAPA [123]. 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 [21] 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 [124,125] 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.

7.2.4 Verification of forecast fleet fuel burn and air passenger traffic

After verifying FSDM's results on past fleet development of the global passenger aircraft, the next step is to verify the reliability of the model in estimating future emissions and air passenger traffic of the global passenger aircraft fleet.

For forecasts until 2050, passenger load factor is assumed steady at 2036 levels. Dray et al. [119] updated AIM to AIM2015 and used the UK Department of Energy and Climate Change (DECC) historical and forecast oil price levels [126]. 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. [119]. In the SSP2 baseline scenario, zero carbon prices were assumed, so that ETS costs were set to zero. The assumptions in aircraft utilization, 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 7.9 shows the jet fuel price development of the SSP2 Baseline scenario, while Figure 7.10 shows estimates of fuel burn and air traffic in 2050 relative to 2015 from Dray et al. [119] and using FSDM. Because the long-term development is of interest, yearly changes in the results are not shown.

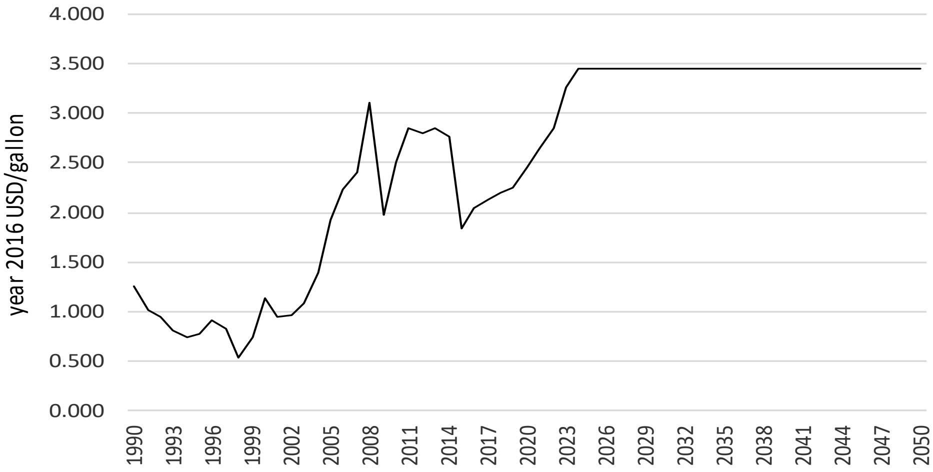

Figure 7.9 Jet fuel price development in the SSP2 baseline scenario

Source: own calculations, based on [119]

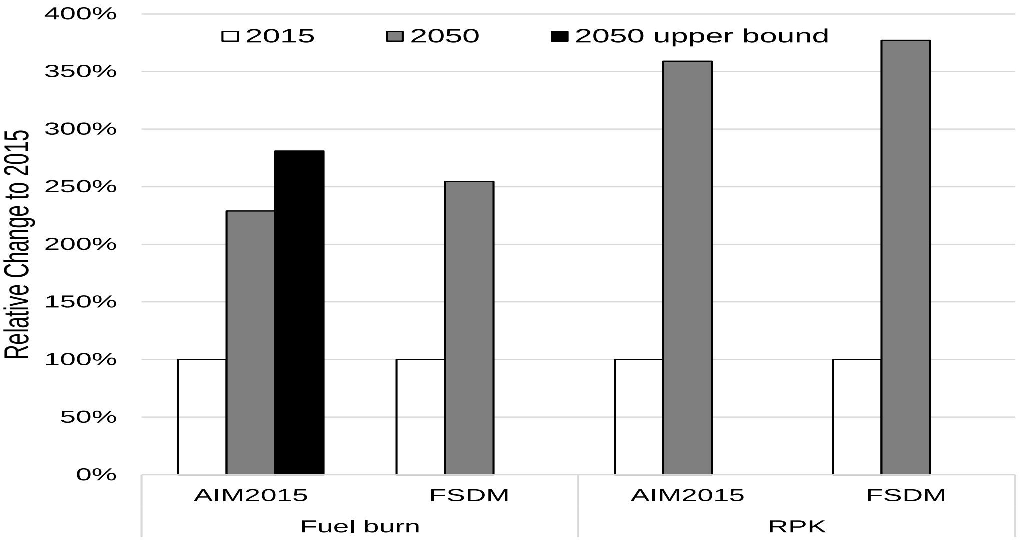

Figure 7.10 Verification of forecast passenger aircraft fuel burn and traffic

Source: own calculations, based on [119]

Dray et al [119] 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 utilization used in both models as noted by Dray et al. [119]. However, since the fleet size, composition and capacity forecast ability of FSDM has been tested, this difference can be neglected.

7.2.5 Sensitivity of model results to EU-ETS

To evaluate the effect of the European Union Emissions Trading Scheme (EU-ETS) on model results, the input of Section 7.2.4 was retained, except that ETS trip costs were not set to zero. Model results for 2050 are compared for the two scenarios with and without carbon pricing.

The fuel burn results show that charging a fee of 10€ per tonne CO_2 in the EU-ETS slightly reduces the fleet-level emissions in 2050 by 0.04%. In addition, the total DOC of the fleet in 2050 is 0.4% higher in the carbon-pricing scenario. This is because of the higher cost that are imposed on routes that have O/D in the EU. As a result, the assumption of EU-ETS as part of ADOC (see Section 5.4) makes no significant change to the model results.

7.3 Chapter Summary

The global system of air passenger transport is very complex because of the quantity and variety in its constituent aircraft and airlines. For example, there are variations in airline business models, fleet planning strategies, aircraft types and their seating capacities, and stage lengths per aircraft type. Characteristics of each inter and intra-regional origin-destination airport pair like stage length, air travel demand, flight frequency, and charging structures vary. In addition, macroeconomic factors like prices of fuel also have significant impact on the system. Much more complexity results from the fact that these airlines and aircraft, as well as the external influences change over time.

As a result, modelling the historical and future fleet development of the global passenger aviation system is a complex work that requires methodological simplifications and assumptions that comply with dominating external developments.

The assumptions and methods developed in this research work have been tested and verified by maintaining comparable input used in other works and comparing the corresponding results of FSDM to those of the other models. The results of the verification studies described in this chapter reveals good consistency of FSDM results with those of other similar works.

Therefore, the method proposed in this research work of estimating future passenger aircraft fleet composition, supply capacity and emissions based on structural retirement, and economic retirement and replacement is considered valid based on the calibration and verification results.

8. Fleet Model Application

Having calibrated and verified the results of the fleet model based on past and forecast values from industry and academic literature, the updated FSDM is applied using operational and technological fleet renewal measures in scenarios that are expected to reduce fleet level emissions.

8.1 General Input for Fleet Model Application

The following input description applies to the scenarios modelled in this chapter. Past and forecast RPK growth factors are used as given by Boeing [4]. 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 in Section 7.1.1.

Past fuel price until 2016 and forecast prices by Airbus until 2025 are used as shown in Figure 7.1. 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 defined in 7.1.1. Furthermore, calibration input such as cost improvement assumptions are retained for all application scenarios. Lastly, all passenger aircraft types (including Turboprop aircraft) of the FSDM are modelled. Table C-1 to Table F-5 contain input data used in the FSDM.

8.2 Baseline Scenarios

Four baseline scenarios are developed. The first, named the *No Action* scenario, proposes a future with neither incremental improvements in airframe and engine (A&E) technologies nor next-generation aircraft types. Thus, only initial fleet aircraft, excluding the LRC, are available for fleet growth with an assumed annual production capacity increase of 4.7% from 2008 values. To assess the impact of incremental improvements available on initial fleet aircraft, the second baseline scenario applies the first fleet renewal measure, Incremental Improvements in A&E technologies, to the initial fleet aircraft. This scenario, which also assumes the annual production capacity of the *No Action* scenario, is termed the *Initial Fleet plus Incremental Improvement Baseline* scenario.

The third baseline scenario imagines a situation in which aircraft manufacturers do not make incremental improvements, so that aircraft, which are available for introduction, have the same fuel and cost performance over their production lifespan. In this scenario, fuel and cost performance improvements are available only when successor aircraft with giant-leap improvements are available. This is termed *Giant-leap Improvement Baseline*. The fourth baseline scenario, *Giant-leap plus Incremental Improvement Baseline*, applies the incremental improvements measure to initial fleet and next-generation aircraft. 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 between the second and fourth baseline.

Based on the reasons given in section 6.3, the *Giant-leap plus Incremental Improvement Baseline* is used as a standard baseline scenario for assessing EMP of individual fleet renewal measures in sections 8.3 to 8.5. When the measures are combined (see section 8.6), the *Giant-leap Improvement Baseline* is used as the reference scenario. Incremental improvements refer to all improvements shown in Table E-1, excluding those comparing each aircraft to its previous aircraft generation.

For the first two baseline scenarios, year 2050 ASK is 14% lower than that of the last two baseline scenarios. This suggests that a higher growth rate in producing the initial fleet aircraft annually would be needed to reach the level of ASK estimated in the third and fourth baselines. However, this also suggests that the CO_2 emissions results of the *No Action* scenario are conservative. From the results of the baseline scenarios, the operation of incrementally improved next-generation aircraft lowers the emissions in 2050 by 14% compared to the *No Action* scenario. The results also show that a complete integration of incremental improvements on available aircraft would reduce fleet level emissions in year 2050 by 2%, when considering next-generation aircraft only (i.e. third and fourth Baselines); and by 4%, considering only initial fleet aircraft (first and second Baselines).

The results of the baseline scenarios until year 2050 are shown in Figure 8.1.

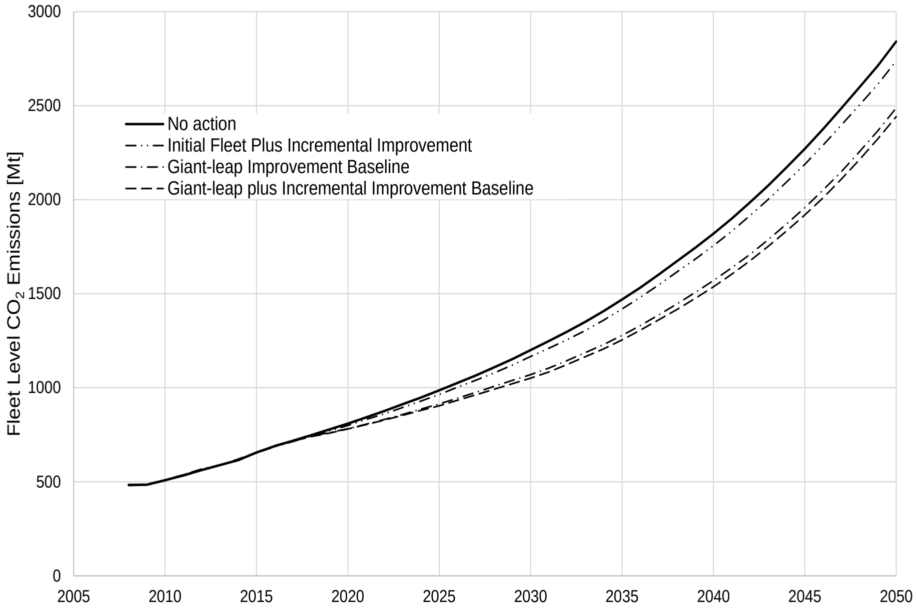

Figure 8.1 CO_2 emissions results of baseline scenarios

Source: own calculation

This benefit is small because planned incremental improvements in any aircraft generation have not been significantly above 5%. The EMP reflect the increasing market share of more-efficient aircraft in the fleet. This potential would be even greater if in-service improvements on aircraft otherwise known as Performance Improvement Packages (PIPs), which are beyond the scope of this research, are considered.

8.3 Early Retirement of Narrowbody Aircraft Cluster

Aircraft life extension, especially for NB, was identified in section 1.2 as a factor inhibiting improvements in fleet level efficiency. Therefore, a what-if scenario is developed to investigate the emission mitigation potential (EMP) if aircraft operators for this aircraft cluster did not carry out service life extension. This is also a form of early aircraft retirement, though different from previously identified early retirement (ER) measures- i.e. aggressive retirement of single-aisle aircraft investigated by Hassan et al. [53], and regulation and operations policies involving retirement of aircraft older than 25 years, as presented by EASA [15].

Three scenarios are evaluated:

a. *Giant-leap plus Incremental Improvement Baseline* Scenario: This is the same as in section 8.2. Limit of Validity values used for the FSDM aircraft types are shown in Table C-5.

b. *NB at DSG* Scenario: In this scenario, aircraft belonging to the initial fleet narrowbody aircraft cluster (NB) are operated with a service life limit of 48000 FC/ 60000 FH. Other parameters are left the same as in the Baseline scenario.

c. *NB and NGNB at DSG* Scenario: In this scenario, NB and NGNB are operated with a service life limit of 48000 FC/ 60000 FH. Other parameters are left the same as in the Baseline scenario.

Retiring narrowbody aircraft at 48000 FC/ 60000 FH instead of 60000 FC/ 120000 FH results in a higher sum of structurally retired aircraft. This increase is caused mainly by the increase in the number of NB and NGNB units retired. This result is shown in Figure 8.2.

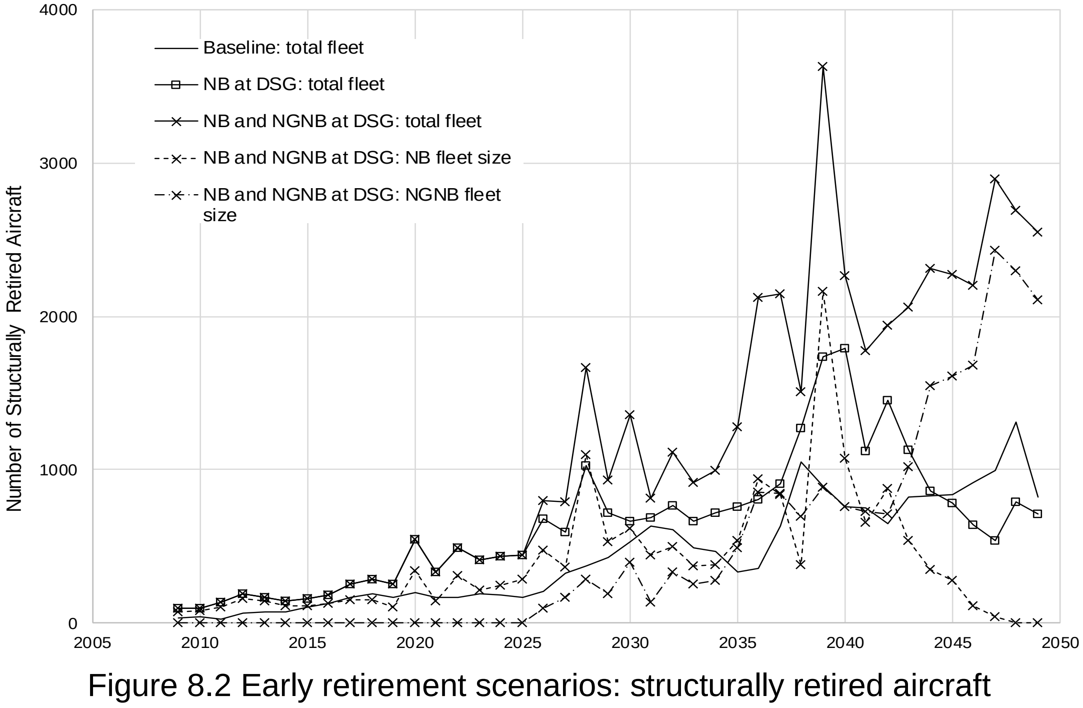

Figure 8.2 Early retirement scenarios: structurally retired aircraft

Source: own calculation

Furthermore, in the early retirement scenarios, when a higher amount of the narrowbody fleet is retired, the aircraft type's average age drops. As a result, a younger fleet operates with less emission. This can be seen in Figure 8.3. Compared to the baseline, retiring NB at 48000 FC/ 60000 FH leads to a 2.4% reduction in fleet level CO_2 emissions in year 2050; whereas, additionally retiring NGNB at the same service limit increases the EMP to 2.5% compared to the baseline. Similar to the results obtained by Hassan et al. [53], the minimal gain in EMP is a result of the lack of more efficient aircraft to replace the NGNB.

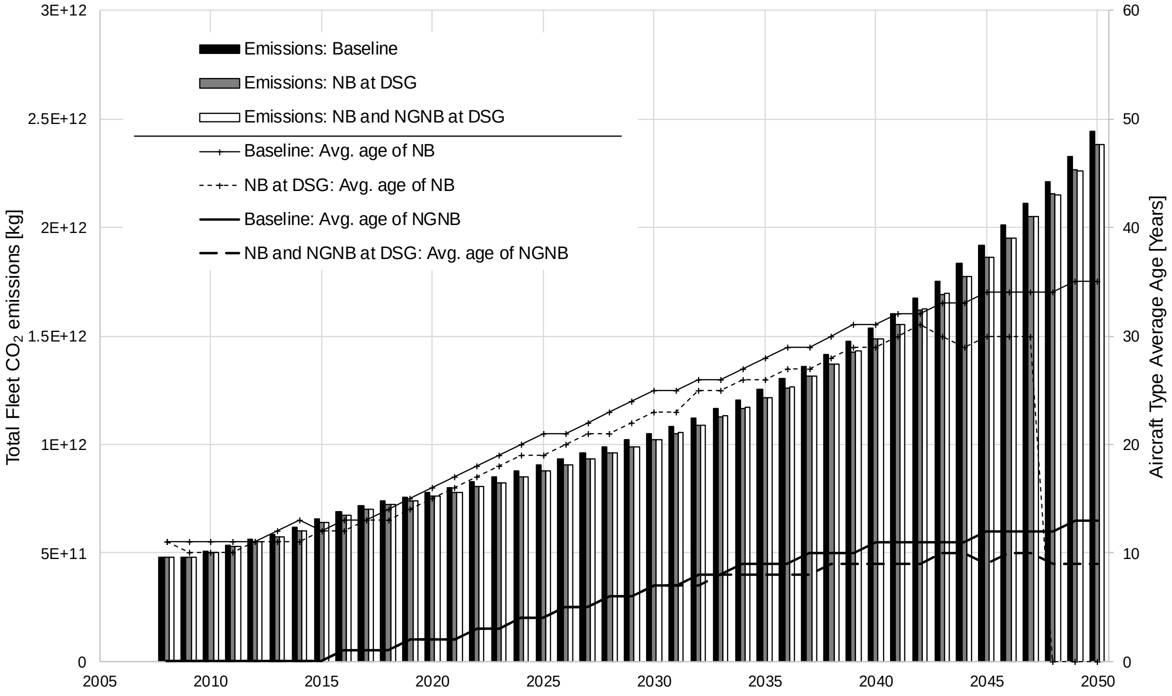

Figure 8.3 Early retirement scenarios: yearly CO_2 emissions, average aircraft type age

Source: own calculation

8.4 Prioritizing New Aircraft Deliveries for Replacement before Growth

New available aircraft are used for filling either the replacement capacities or growth capacity. As a result, two airline fleet planning strategies for using new aircraft deliveries were identified in Section 6.1. Based on these strategies, the *Replacement Strategy* scenario assumes that new aircraft deliveries are prioritised to completely fill both structural and economic retirement gaps before filling the capacity growth gap. On the other hand, the growth strategy scenario assumes that capacity growth gap is completely filled before filling the two retirement gaps.

Whereas the *Growth Strategy* has been used in the FSDM calibration and verification, and is the strategy used for the Application Baseline scenarios, the *Replacement Strategy* is evaluated as an operational measure to determine emissions reduction benefits at the fleet-level.

Prioritizing 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 8.4.

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 realized using the *Replacement Strategy* compared to the *Growth Strategy*.

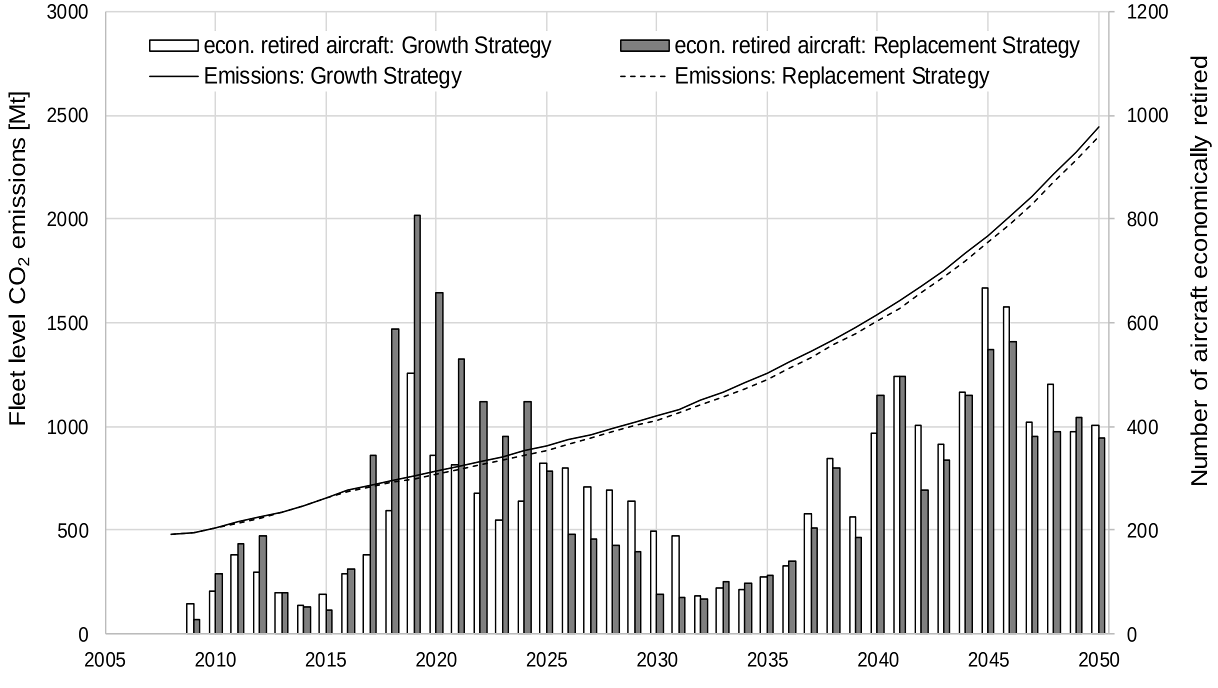

Figure 8.4 Growth and Replacement Strategy: Number of aircraft economically retired and fleet level CO_2 emissions

Source: own calculation

From Figure 8.5, 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 SFC. However, because these improvements are minimal, the CO_2 emissions improvement in the *Replacement Strategy* is also limited to about 3% in year 2024.

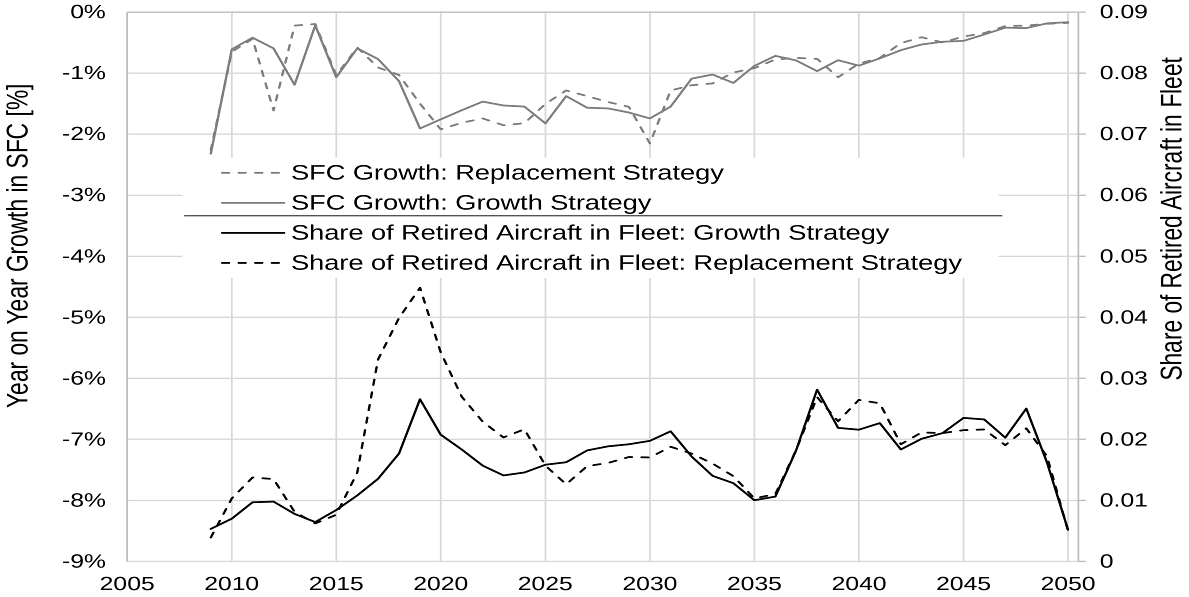

Figure 8.5 Growth and Replacement Strategy: Share of retired aircraft in fleet and Year-on-Year growth in specific fuel consumption

Source: own calculation

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 results 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.

8.5 Future Generation Narrowbody Aircraft Available 2035+

In Sections 8.3 and 8.4, the absence of a more fuel- and cost-efficient aircraft after 2024 was explained as the reason for a deterioration of the fleet emissions savings. Therefore, an additional scenario is tested. This scenario uses the *Replacement Strategy* of fleet development and further assumes a future generation aircraft is available from year 2035. The aircraft is named the Future Generation Narrowbody aircraft (FGNB), thus the scenario name *Replacement Strategy + FGNB*. The FGNB is assumed to have a 15% improvement in trip fuel burn and 14% improvement in non-fuel COC per trip over the NGNB. Furthermore, the FGNB is assumed to replace the NGNB on the production line using a simultaneous ramp-down and ramp-up period of six years, similar to that between the NGNB and its preceding generation aircraft. This is shown in Figure 8.6.

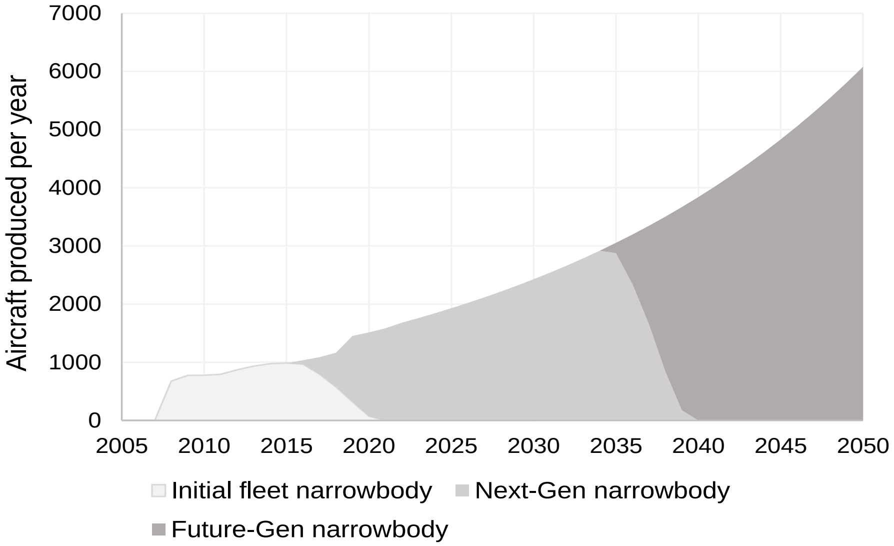

Figure 8.6 Production ramp-down and ramp-up of three narrowbody aircraft generations

Source: own calculation

8.5.1 Emissions reduction benefit of FGNB and *Replacement Strategy*

Irrespective of fleet renewal strategy, operating the FGNB reduces fleet level emission in 2050 by about 8-9%. Based on its assumed design specification, the FGNB has a lower average unit trip DOC than, and therefore replaces the NGNB and NGLR, which were introduced first on routes below 7000 km before the advent of the FGNB.

The developments in emissions and economically retired aircraft are shown in Figure 8.7.

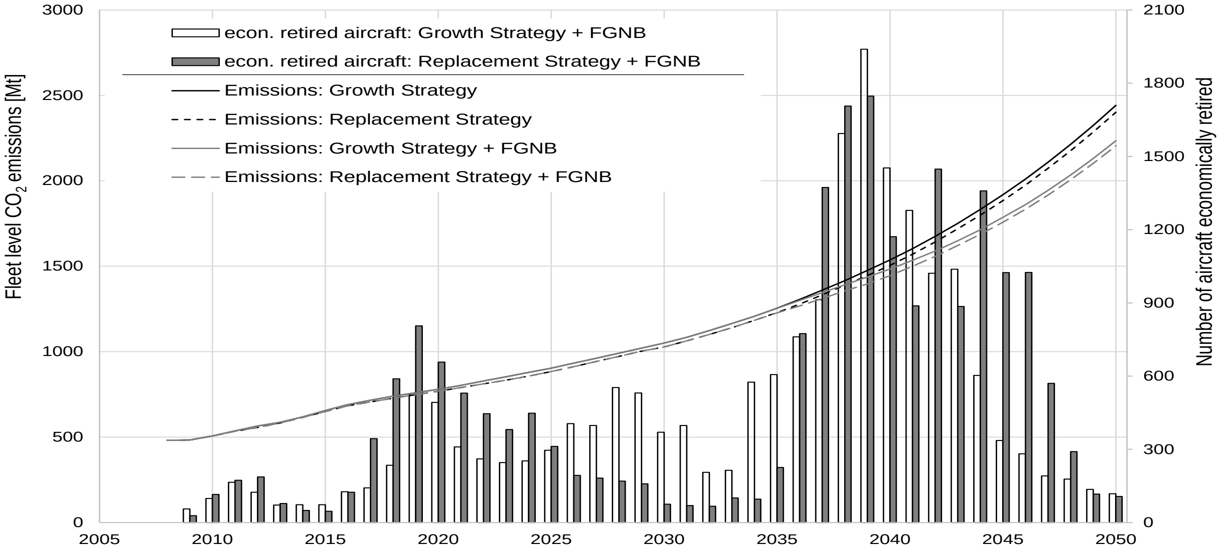

Figure 8.7 Growth and Replacement Strategy with FGNB: Number of aircraft economically retired and fleet level CO_2 emissions

Source: own calculation

From the figure, the emission reduction increases over time from the EIS of the FGNB, reflecting the continuously increasing market share of the FGNB in the fleet. The DOC of the next-gen and future gen A/C on short haul distances are shown in Figure 8.8.

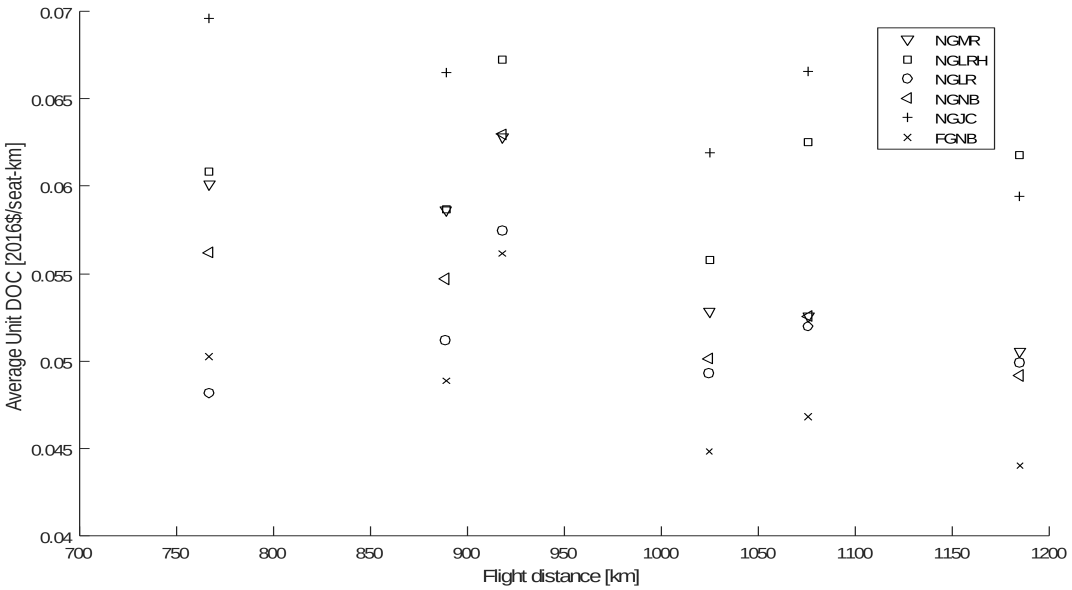

Figure 8.8 Year 2050 costs of next- and future-gen A/C over short haul distances

Source: own calculation

Figure 8.9 also shows the average unit trip DOC of the next-gen and future gen A/C in 2050.

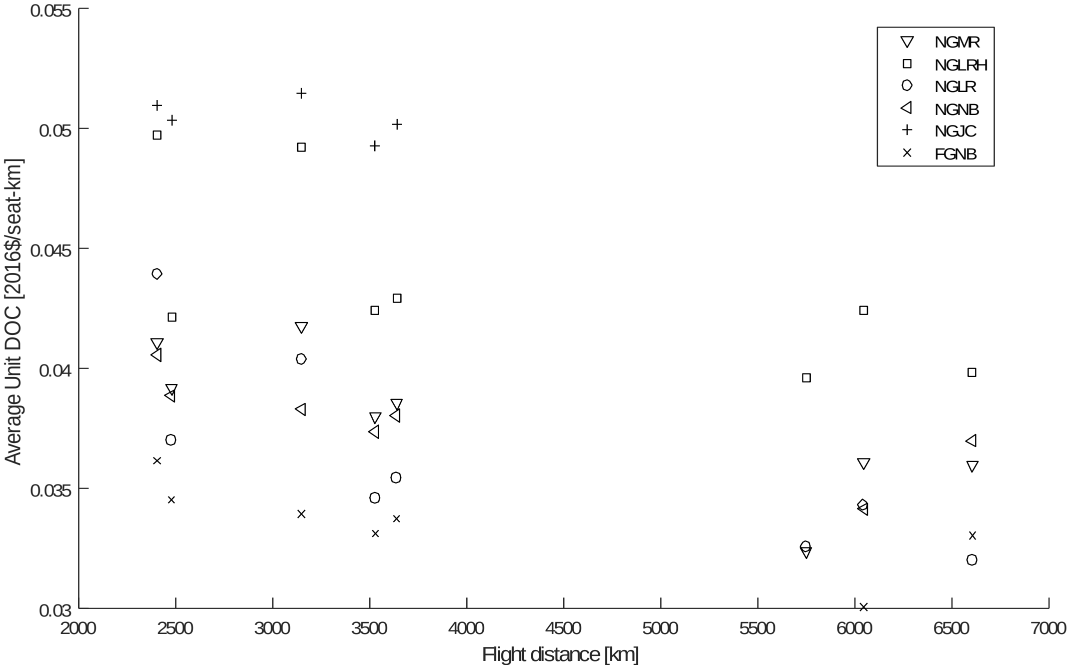

Figure 8.9 Year 2050 costs of next- and future-gen aircraft over medium haul distances

Source: own calculation

8.5.2 Emissions reduction impact of FGNB plus early Narrowbody retirement

The emissions reduction impact of retiring all three narrowbody aircraft generations earlier at a service life limit of 48000 FC/ 60000 FH is evaluated next. For this, two scenarios are tested using all 13 FSDM aircraft: one with NB, NGNB, and FGNB having a service life limit of 60000 FC/ 120000 FH, and another with the three aircraft having a service life limit of 48000 FC/ 60000 FH; each scenario being run using both *Growth Strategy* and *Replacement Strategy*.

Figure 8.10 shows the CO_2 emissions and structurally retired aircraft using both scenarios with the *Growth Strategy* (GS) and *Replacement Strategy* (RS). Over the simulation period, the scenario with early aircraft retirement has a higher number of structurally retired aircraft (see Figure 8.10 for an example using *Growth Strategy*).

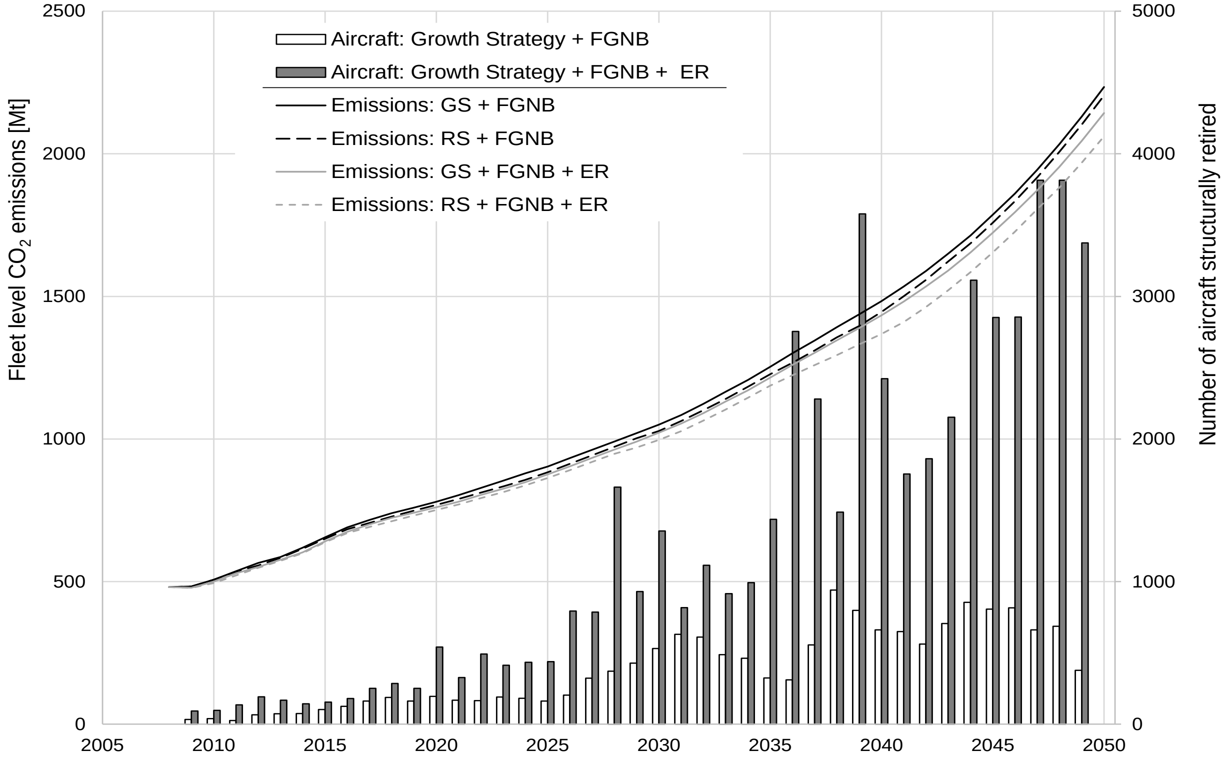

Figure 8.10 Early retirement scenarios including FGNB: CO_2 emissions and aircraft structurally retired

Source: own calculation

The most-efficient aircraft types available replace the retired aircraft, leading to an improvement in the global fleet's fuel efficiency. By 2050, the *Growth Strategy* scenario with an early retirement of the three generations of the narrowbody aircraft produces a 4% reduction, as compared to 6% using the *Replacement Strategy*.

The higher emissions mitigation effect comes from the use of the available FGNB as the replacement aircraft. In addition, given the assumption of growth in aircraft utilization (see later part of section 7.1.1), there is an additional reduction in CO_2 emissions based on the early structural retirement of future-generation narrowbody aircraft.

8.6 All Technological and Operational Measures Combined

The emission reduction effects of all EMMs simultaneously applied in this chapter are evaluated, with and without the FGNB, and compared to the *Giant-leap Improvement Baseline* scenario. The measures are:

- two technological measures:
    - Incremental improvement, abbreviated as IncImp, in airframe and engine technologies,
    - Future Generation Narrowbody aircraft (FGNB) available from 2035
- one operational measure:
    - early retirement (ER) of NB, NGNB, and FGNB at service life limit of 48000 FC/ 60000 FH, and
- one strategic measure:
    - prioritising new aircraft deliveries for replacement before capacity growth, otherwise known as the *Replacement Strategy* (RS).

8.6.1 All measures combined excluding the FGNB

When applied together to the fleet model in a scenario, IncImp, ER, and RS, produce a 6% reduction in CO_2 emissions, compared to the *Giant Leap Improvement Baseline* scenario. As was found in Section 8.5.2, the EMP of each measure depends on the compared scenarios and the order of applying measures in each scenario.

For example, if the IncImp measure is assumed to be applied first, the ER measure could be applied before or after the RS measures.

In Table 8-1, the effect of ER is evaluated before that of RS, whereas in Table 8-2, the application order is reversed for the two measures.

Table 8-1 CO_2 reduction analysis of individual measures; ER applied before RS

Scenario ID	**Measure**	**Measure combination Scenario**	**Year 2050 Fleet CO_2 emissions [Mt]**	**Relative reduction**
1	GLI Baseline	GS + GLI	2488	-
2	IncImp	GS + GLI + IncImp	2442	2%
3	ER	GS + GLI + IncImp + ER	2380	2%
4	RS	RS + GLI + IncImp + ER	2336	2%

GS: Growth Strategy; RS: Replacement Strategy; GLI: Giant leap improvement; IncImp: Incremental Improvement; ER: Early retirement

Source: own calculation

Table 8-2 CO_2 reduction analysis of individual measures; RS applied before ER

Scenario ID	**Measure**	**Measure combination Scenario**	**Year 2050 Fleet CO_2 emissions [Mt]**	**Relative reduction**
1	GLI Baseline	GS + GLI	2488	-
2	IncImp	GS + GLI + IncImp	2442	2%
3	RS	RS + GLI + IncImp	2401	2%
4	ER	RS + GLI + IncImp + ER	2336	3%

GS: Growth Strategy; RS: Replacement Strategy; GLI: Giant leap improvement; IncImp: Incremental Improvement; ER: Early retirement

Source: own calculation

From the two tables, the EMP of the Early Replacement (ER) measure could range from 2%, if Growth Strategy is the underlying fleet renewal strategy (see section 8.3), to 3%, if

Replacement Strategy is the underlying strategy. Likewise, the Replacement Strategy has an EMP of about 2% whether or not the ER measure is included.

8.6.2 All measures combined including the FGNB

Figure 8.11 shows the emissions result using all four measures applied together in one scenario, in comparison to the *Giant-Leap Improvement Baseline*. Up to year 2034, before the entry into service of the FGNB aircraft, all measures, when combined, give approximately a 7% reduction in fleet level CO_2 emissions. After the service entry of the FGNB aircraft, in year 2050, the combined measures give a 17% reduction compared to the *Giant-leap Improvement Baseline*.

Similar to the findings from section 8.6.1, relative EMP of the individual EMMs depend on the procedure of implementing the measure combination scenarios. Assuming again that the IncImp measure is given, similar to the approach of the previous section, six orders for applying the remaining three measures are possible, thus broadening the range of the EMP for each measure.

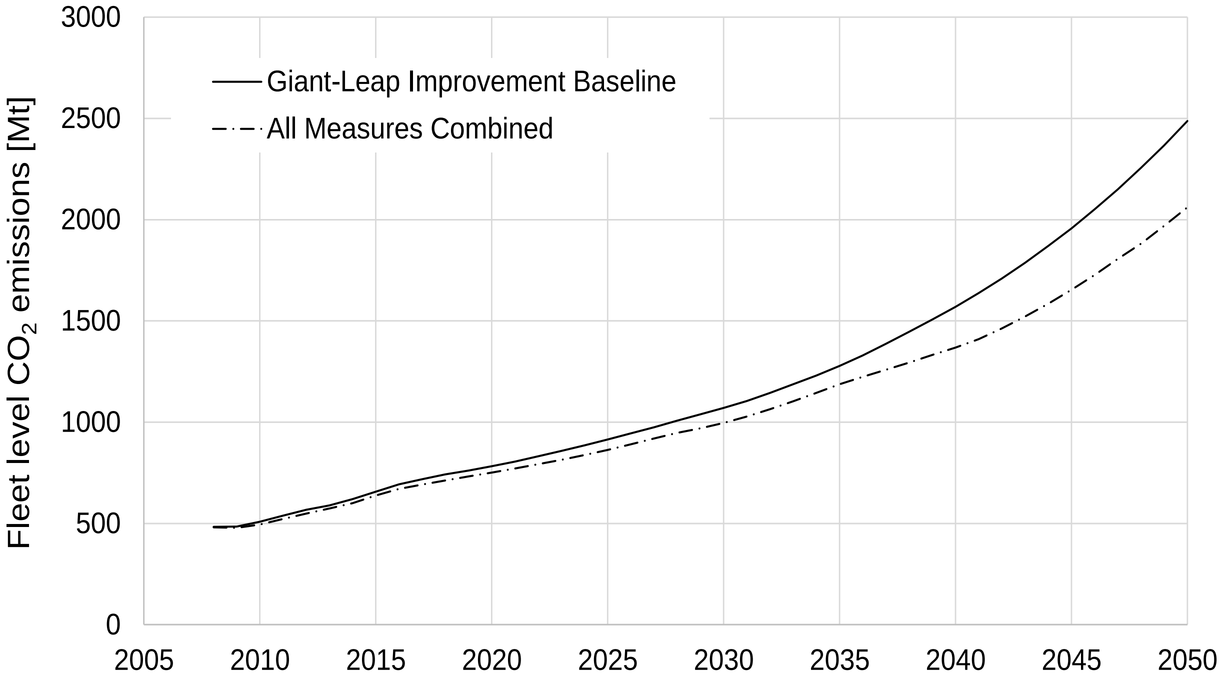

Figure 8.11 CO_2: Giant-leap Improvement Baseline and All Measures Combined

Source: own calculation

As an example, the FGNB can be applied before RS, which is also applied before ER. In this case, the relative CO_2 emissions reduction effects of 8%, 1%, and 6% are observed for the EMMs FGNB, RS and ER, respectively in year 2050.

This is shown in Table 8-3. Table G-1 to Table G-5 show similar analyses of other possible permutations of the FGNB, RS, and ER measures.

Table 8-3 CO_2 reduction analysis of individual EMM; application order: FGNB, Replacement Strategy, Early Retirement

Scenario ID	**Measure**	**Measure combination Scenario**	**Year 2050 Fleet CO_2 emissions [Mt]**	**Relative reduction**
1	GLI Baseline	GS + GLI	2488	-
2	Incremental Improvement	GS + GLI + IncImp	2442	2%
3	FGNB	GS + GLI + IncImp + FGNB	2234	8%
4	Replacement Strategy	RS + GLI + IncImp + FGNB	2204	1%
5	Early Retirement	RS + GLI + IncImp + FGNB + ER	2061	6%

GS: Growth Strategy; RS: Replacement Strategy; GLI: Giant leap improvement; IncImp: Incremental Improvement; FGNB: Future Generation Narrowbody aircraft; ER: Early retirement

Source: own calculation

8.7 Model Application Summary

Four EMR measures were applied to the model, one operational, one strategic and two technological measures. The model application results show that the technology measures have a higher emission mitigation potential than the other measures.

A range exists in the emissions reduction impact of the measures, depending on the compared scenarios and the order of the applied measures. The range of reduction in CO_2 emissions of the individual fleet renewal measures, relative to the *Giant-Leap*

Improvement Baseline are summarized in Table 8-4. Key lessons learned from the model application studies relevant for fleet renewal are also added in the table.

Table 8-4 Summary of EMM applied to fleet model, with and without FGNB

CO_2 Emissions Mitigation Measures	**Impact without FGNB in 2050‡**	**Impact with FGNB in 2050‡**	**Lesson Learned for Fleet Renewal**
Improvement in Airframe and Engine Technologies	Main difference: incremental improvements; Reduction in CO_2 emissions: 2%	Main difference: FGNB Reduction in CO_2 emissions: 8% - 11%	Emissions reduction facilitated by increase in market share of more-efficient aircraft in total fleet
Early Narrowbody Aircraft Structural Retirement Main difference in scenarios: NB aircraft retired at 48000 FC/ 60000 FH instead of 60000 FC/ 120000 FH	Reduction in CO_2 emissions: 2% - 3%	Reduction in CO_2 emissions: 2% - 6%	Mitigation impact of early retirement of aircraft improves if more efficient are available
Replacement Strategy Main difference in scenarios: *Replacement Strategy* instead of *Growth Strategy*	Reduction in CO_2 emissions: 2%	Reduction in CO_2 emissions: 1% - 3%	Emissions reduction improves when higher share of fleet is retired and higher growth in SFC is attained
All measures combined	Reduction in CO_2 emissions: 6%	Reduction in CO_2 emissions: 17%	Reduction effect of each measure depends on the compared scenarios and order of the applied measures

‡ compared to the *Giant-Leap Improvement Baseline*

The relative contributions of the four fleet renewal measures in year 2050 are shown in Figure 8.12, assuming the Incremental Improvement measure is always applied and evaluated first.

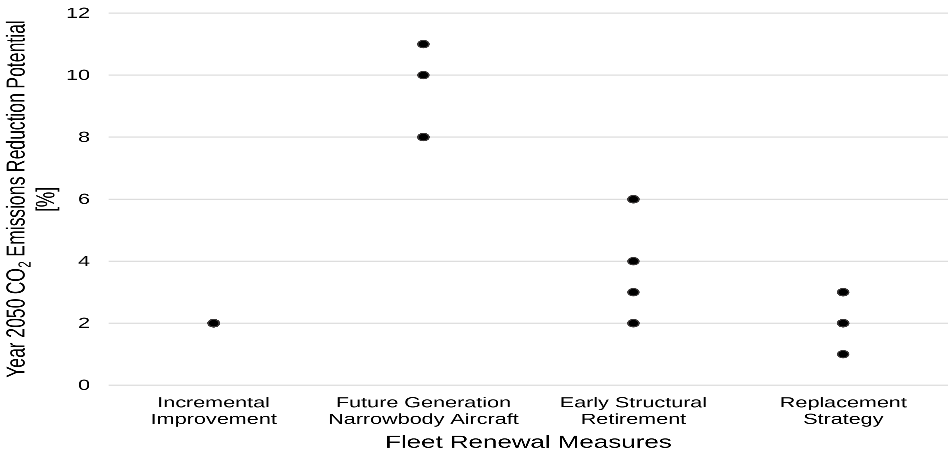

Figure 8.12 All Measures Combined: relative CO2 emissions reduction of individual measures

Source: own calculation

Compared to the *No Action* scenario, a 27% reduction is attained in year 2050 when all measures are combined. This is shown in Figure 8.13.

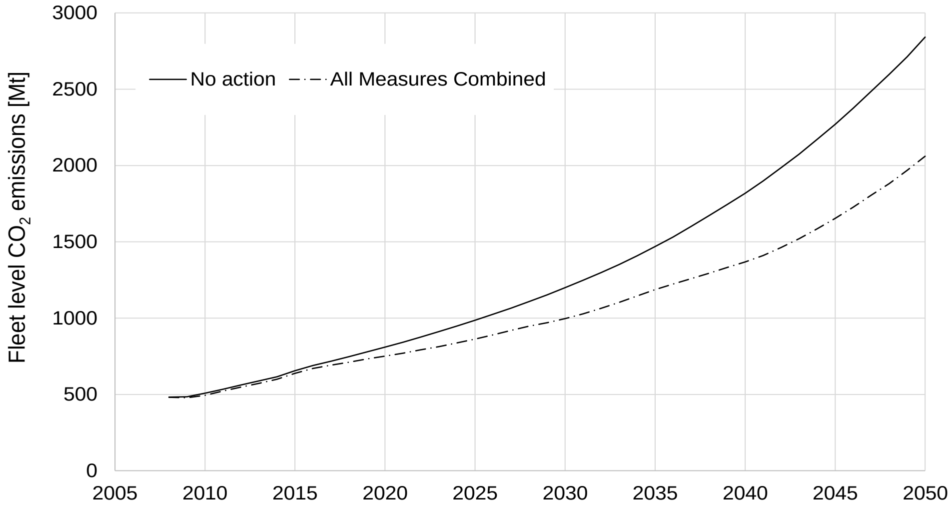

Figure 8.13 CO_2 emissions: *No Action* and All Measures Combined

Source: own calculation

9. Summary and Outlook

The task of estimating future fleet level emissions of air transport and possible reduction measures and their corresponding impact using integrated assessment modelling has been the focus of this research work. Although several studies have been conducted in this field, using about seven integrated models having a global geographical scope, no work has been done at the global fleet level using a fleet development framework of aircraft retirement based on design service life and a comparative estimation of direct operating cost of new versus aging aircraft. Furthermore, no work has been done which takes into consideration the EMP of measures studied in this work.

Focusing on passenger aircraft, the Aircraft Lifetime Cost module (ALiTiCo), pre-calculator for an extended version of the Fleet System Dynamics Model (FSDM), was developed and verified. The results of the extended model showed good consistency with past data on fleet size and composition as well as fuel burn, cost, fleet average age, and transport capacity by aircraft type from 2008 to 2016. The model was calibrated using Boeing's Current Market Outlook (CMO) for jet aircraft fleet forecast for 2017 to 2036. The effect of Boeing's low and high fuel price development on future fleet composition and size was investigated. With a high fuel price, there is a higher share of fuel-efficient next-generation narrowbody and small widebody aircraft in the fleet, while the share of medium/large widebody aircraft reduces. Generally, smaller efficient aircraft replace larger inefficient ones. Furthermore, fleet CO_2 emissions and air passenger traffic forecast until 2050 were verified using results from the AIM2015 model.

One operational, one strategic and two technological fleet renewal measures were investigated for their fleet emission reduction impact using the fuel price forecast by Airbus' Global Market Forecast in 2017, and air traffic forecast by Boeing's CMO in 2017. Scenarios were investigated for early structural retirement of the different generations of narrowbody aircraft at Design Service Goals, instead of Extended Service Goals. Another fleet renewal strategy was tested by allocating aircraft production capacity first for filling replacement gaps before growth gap. As technological measures, scenarios of continuous uptake of available or planned improvements in airframe and engine technologies were tested. Furthermore, a Future-Generation Narrowbody aircraft was assumed available from 2035 with similar giant-leap improvement and production capacity as the A320neo was to the A320ceo.

In year 2050, the four measures combined led to a fuel burn and CO_2 emissions reduction of 17% compared to the *Giant-Leap Improvement Baseline* and 27%, compared to the *No Action* scenario.

The following are the recommendations for further research related to this research work using FSDM:

- Since freighter aircraft were not included in this work, extending the method presented in this work to evaluate air cargo transport using both passenger and freighter aircraft would help to give a complete view of commercial air transport's CO_2 emissions. This would cover aspects such as long-term cargo aircraft fleet planning, including freighter conversion, cargo aircraft retirement and an estimation of freighter aircraft lifetime DOC. More can be seen in the *Cargo Forecast Methodology* section of JADC's forecast [110].
- The effect of fuel price on air travel demand was not included in this work. Inclusion of such elasticities would further help to understand the effect of fluctuations in jet fuel price on emissions from commercial aviation.
- Including the effect of increasing passenger load factor on fuel burn: in order to save computational time spent using the Global Fleet Mission Calculator, the increase in passenger load factor from 76% in 2008 to 83.3% in 2050 (see section 7.1.1) was assumed to have a negligible effect on aircraft fuel burn. While this may be negligible for regional aircraft, the effect for larger aircraft could be significant at the fleet-level as shown by Dray et al. [119].
- In the strategy of filling up retirement gap before growth gap, the process of replacing aircraft on a route does not give a priority to aircraft types with higher annual flight frequencies. This was done assuming aircraft production capacity would be sufficient in meeting the basic demand for all aircraft types per year. On

the other hand, providing replacement aircraft on a route group each year, first for more utilized aircraft before less utilized ones would better reflect airline fleet planning strategies.

- Dynamic route group development capturing the effect of liberalization: The current model does not model dynamic route group development for the sake of computation time. Modelling a dynamic route group will imply changing the mission distance of each route group over the simulation period, which would also imply modelling fuel burn by aircraft every simulation year. This would significantly increase the computation time. The effect of liberalization could, however, also be captured by modelling more static distances or O/D pairs per route group instead of the current assumption of one O/D pair per route group.
- Dynamic Aircraft Utilization impact on Structural Retirement Age: In the current version of ALiTiCo, the SRA of an aircraft is determined by the annual flight frequency of the aircraft at entry into service, which, for simplification reasons, is assumed constant throughout the lifetime of the aircraft. If the same aircraft type enters into service a year after with significantly higher annual frequency, the SRA would be shorter accordingly. However, in airline practice, it is possible for the aircraft with EIS in the previous year to have a higher frequency a year after. This would have a corresponding reduction impact on the aircraft's SRA. However, this aspect of dynamic aircraft utilization is not included in the current build-up of ALiTiCo.
- Airline business models: The current single global airline of the FSDM could be split to have characteristics of the two main business models: FSCs and LCCs. Differences in the cost structures of the two business models could be integrated into the aircraft lifetime cost module. However, a method of simulating the competition between the two airline types would also be needed.
- Cabin Densification: Although not analysed at fleet level for emissions reduction potential, cabin densification has been identified as an operational measure for fuel efficiency in the airline industry [12,127]. An advantage of a cost-driven fleet development process is the inclusion of aircraft economics considerations in the aircraft evaluation process. This requires a comparison of aircraft on a given route

in terms of unit direct operating cost per passenger comfort offered. It also requires industry practice-compliant assumptions on seat capacities of the different FSDM aircraft types on the different route groups.

What-if scenarios could be formulated that as from a certain year, the global airline industry would plan its fleet with aircraft evaluated and configured to offer a comparable level of passenger comfort depending on the kind of market served. Therefore, as soon as they are available, aircraft are allowed to compete on short and medium haul routes at defined average seat densities, irrespective of their size.

Configuring aircraft to offer comparable level of passenger comfort would imply that the number of seats installed on certain aircraft types would increase while others may not. However, despite the increase in installed seats, these scenarios could also assume that irrespective of aircraft size, seat payload factors are maintained on all flights. As a result, the emission mitigation potential (EMP) of cabin densification can be analysed.

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Appendix A: Constituent Aircraft Types of FSDM Initial Fleet Aircraft Clusters

Table A-1 OAG aircraft types belonging to FSDM aircraft types

Aircraft Cluster Acronym	**Constituent Aircraft OAG Specific Aircraft Name**
LRC	Boeing (Douglas) MD-11 Passenger, Boeing747 (Mixed Configuration), Boeing 747-400 (Mixed Configuration)
LRH	Airbus A380-800 Passenger, Boeing 747 (Passenger), Boeing 747-300/747-100/200 Sud (Pax), Boeing 747-400 (Passenger), Boeing 777-300 Passenger
JC	Airbus A318, Avro RJ100, Avro RJ85, Boeing 727 (Freighter), Boeing 737 (Freighter), Boeing 737-200 Passenger, Boeing 737-600 Passenger, Canadair Regional Jet, Canadair Regional Jet 200, Canadair Regional Jet 700, Canadair Regional Jet 900, Embraer 170, Embraer 175, Embraer 190, Embraer RJ 135/140/145, Embraer RJ 145, Fokker 100, Tupolev TU134
TP	ATR 72
MR	Airbus A300-600 Passenger, Airbus A310 Passenger, Airbus A330, Airbus A330-300, Boeing 757 (Passenger), Boeing 757-200 (winglets) Passenger, Boeing 757-200 Passenger, Boeing 757-300 Passenger, Boeing 767-300 Passenger, Tupolev TU-204 /tu-214
LR	Airbus A330-200, Airbus A340, Airbus A340-200, Airbus A340-300, Airbus A340-500, Airbus A340-600, Boeing 767-400 Passenger, Boeing 777-200 Passenger, Boeing 777-200LR, Boeing 777-300ER, Ilyushin II-96 Passenger
NB	Airbus A318 /319/ 320 /321, Airbus A319, Airbus A320, Airbus A321, Boeing (Douglas) MD-80, Boeing (Douglas) MD-81, Boeing (Douglas) MD-82, Boeing (Douglas) MD-83, Boeing (Douglas) MD-88, Boeing (Douglas) MD-90, Boeing 717-200, Boeing 737 Passenger, Boeing 737-300 Passenger, Boeing 737-400 Passenger, Boeing 737-500 Passenger, Boeing 737-700 (winglets) Passenger, Boeing 737-700 Passenger, Boeing 737-800 Passenger, Boeing 737-900 Passenger, McD- Douglas DC9 30 /40 /50, Tupolev TU154

Appendix B: Verification of Single Mission Calculator

The Single Mission Calculator was verified using published data and the results are presented here.

Table B-1 Verification of Fuel Burn Model

Long Range Combi: MD-11				
Reference Specification (PLD, stage length, ICA)	**Model Specification (A/C and mission), unless specified 1PAX@90 kg**	**Reference Fuel Burn Value [kg]**	**BADA Fuel Burn Value [kg]**	**Delta**
298 PAX @100 kg, 10/5 taxi time; 4925 nm	29.8 tons, 15 mins taxi time, step climb, 9121 km, 35000 ft ICA	75569 [128]	78591	4%
298 PAX @100 kg, 10/5 taxi time; 5123 nm	29.8 tons, 15 mins taxi time, step climb, 9488 km	78520 [128]	82346	5%

Table B-1 (continued)

Long-Range Heavy: B747-400				
Reference Specification (PLD, stage length, ICA)	**Model Specification (A/C and mission), unless specified 1PAX@90 kg**	**Reference Fuel Burn Value [kg]**	**BADA Fuel Burn Value [kg]**	**Delta**
1852 km	416 PAX, 1852 km, 34700 ft ICA, step climb, 20 mins taxi time	22097.2 [129]	21539	-3%
5556 km	416 PAX, 5556 km, 34700 ft ICA, step climb, 20 mins taxi time	59576.9 [129]	59153	-1%
375 seats, 4427 nm	375 PAX, 8199 km, 34700 ft ICA, step climb, 20 mins taxi time	97170 [130]	87118	-10%
416PAX, 6000 nm, ICA 34700 ft	416 Pax, 11112km, 34700 ft ICA, step climb, 20 mins taxi time	124051.2 [131]	123420	-1%
11112km	416 Pax , 11112km, 34700 ft ICA, step climb, 20 mins taxi time	128170.8 [129]	123420	-4%
416PAX, 6000 nm, ICA 34700 ft	416 Pax, 11112km, 34700 ft ICA, step climb, dist. Correction factor, 20 mins taxi time	124051.2 [131]	130266	5%

Table B-1 (continued)

Jet Commuter: E190				
Reference Specification (PLD, stage length, ICA)	**Model Specification (A/C and mission), unless specified 1PAX@90 kg**	**Reference Fuel Burn Value [kg]**	**BADA Fuel Burn Value [kg]**	**Delta**
207 nm, 20 mins taxi-time, 22800 lbs PLD	383.4 km, 30000 ft ICA, 10.34 tons, 20 mins taxi time	1941 [132] includes wind effect	1571	-19%
500 nm, 9+5mins taxi-time, 98 PAX @ 100kg	926 km, 14 mins taxi time, 9.8 tons PLD, 30000 ft ICA	2762 [133]	2975	7.7%
600 nm, FL 350, 98 seats	8.82 tons, 1111.2 km, step climb ICA 35000 ft, 20 mins taxi time	3147 [134]	3214	2%
607nm, 20 mins taxi-time, 22800 lbs PLD,	1124 km, 30000 ft ICA, 10.34 tons, 20 mins taxi time	3667 [132,132] includes wind effect	3490	-5 %
806 nm, 90 seats	90 seats, 1492.7 km, 30000 ft ICA, 20 mins taxi time	4330 [130]	4374	1%
1000 nm, 9+5mins taxi-time, 98 PAX @ 100kg	1852 km, 14 mins taxi-time, 9.8 tons PLD, 30000 ft ICA	4909 [133]	5329	8.5%

Table B-1 (continued)

TurboProp Commuter: ATR 72-500

Reference Specification (PLD, stage length, ICA)	Model Specification (A/C and mission), unless specified 1PAX@90 kg	Reference Fuel Burn Value [kg]	BADA Fuel Burn Value [kg]	Delta
200 nm, 68 PAX@95 kg, 4 min taxi-time	370.4 km, 6.46 tons, 4 mins taxi time, step-climb, 22000 ft ICA	617 [135]	632	2%
300 nm, 68 PAX@95 kg, 4 min taxi-time	555.6 km, 6.46 tons, 4 mins taxi time, step-climb, 22000 ft ICA	858 [135]	905	5%

Mid-Range Aircraft: B767-300

Reference Specification (PLD, stage length, ICA)	Model Specification (A/C and mission), unless specified 1PAX@90 kg	Reference Fuel Burn Value [kg]	BADA Fuel Burn Value [kg]	Delta
1200 nm, 261 seats	2222.4 km, 23.49 tons; 35000 ft ICA, 20 mins taxi time, step climb	12877.2 [136]	12924	0 %
217 seats, 3322 nm	217 seats, 6152 km, 35000 ft ICA, 20 mins taxi time, step climb	37680 [130]	32729	-13%

Table B-1 (continued)

Long-Range Aircraft: B777-200				
Reference Specification (PLD, stage length, ICA)	**Model Specification (A/C and mission), unless specified 1PAX@90 kg**	**Reference Fuel Burn Value [kg]**	**BADA Fuel Burn Value [kg]**	**Delta**
1000 nm	1852 km, 35000 ft ICA, 27.45 tons, 20 mins taxi time, step climb	16364 [129]	14991	- 8%
2000 nm	3704 km, 35000 ft ICA, 27.45 tons, 20 mins taxi time, step climb	29226 [129,129]	27764	-5%
2500 nm	4630 km, 35000 ft ICA, 27.45 tons, 20 mins taxi time, step climb	36027 [129]	34054	- 5%
3000 nm	5556 km, 35000 ft ICA, 27.45 tons, 20 mins taxi time, step climb	43143 [129]	40562	-6 %
305 seats, 5210 nm, 25 mins	35000 ft ICA, 9649 km, 27.45 tons, 25 mins taxi time, step climb	76840 [90]	72997	-5 %
5500 nm	10186 km, 35000 ft ICA, 27.45 tons, 20 mins taxi time, step climb	82067 [129]	74510	-9 %

Table B-1 (continued)

Narrowbody Aircraft: A320

Reference Specification (PLD, stage length, ICA)	Model Specification (A/C and mission), unless specified 1PAX@90 kg	Reference Fuel Burn Value [kg]	BADA Fuel Burn Value [kg]	Delta
250 nm	13.5 tons, 463 km, 33000 ft ICA; 20 mins taxi time	2497 [129]	2173	-13 %
500 nm	13.5 tons, 926 km, 33000 ft ICA; 20 mins taxi time	3661 [129]	3453	-6%
937 nm, 159 seats	159 seats, 1735 km, 33000 ft ICA, 20 mins taxi time	6200 [130]	5758	-7%
1000 nm, 150 seats	13.5 tons, 1852 km, 33000 ft ICA; 20 mins taxi time	6080 [137]	6066	0%
1000 nm	13.5 tons, 1852 km, 33000 ft ICA; 20 mins taxi time	6027 [129]	6066	1 %
1500 nm	13.5 tons, 2778 km, 33000 ft ICA; 20 mins taxi time	8332 [129]	8729	5%
2000 nm	13.5 tons, 3704 km, 33000 ft ICA; 20 mins taxi time	10866 [129]	11422	5%
2176 nm, 150 seats	150 seats, 4030 km, 33000 ft, 20 mins taxi time	12890 [130]	12363	-4%
2500 nm	13.5 tons, 4630 km, 33000 ft ICA; 20 mins	13441 [129]	14109	5%

Table B-1 (continued)

Next-Generation Mid-Range Aircraft: B787-8

Reference Specification (PLD, stage length, ICA)	Model Specification, unless specified 1PAX@90 kg	Reference Fuel Burn Value [kg]	BADA Fuel Burn Value [kg]	Delta
1200 nm	2222.4 km, 23.49 tons; 35000 ft ICA, 20 mins taxi time, step climb	16389.1 [129]	15635	-4.6%
1200 nm	2222.4 km, 23.49 tons; 35000 ft ICA, 20 mins taxi time, step climb	13111.3 [129,138]	13555	3.4%

Next-Generation Long-Range Heavy: B747-8I

Reference Specification (PLD, stage length, ICA)	Model Specification, unless specified 1PAX@90 kg	Reference Fuel Burn Value [kg]	BADA Fuel Burn Value [kg]	Delta
	42.03 tons, 13500 km, 37000 ft ICA, 20 mins taxi time, step climb	142977 [139]	154292	8%
11110 km, 410 seats	11110 km, 410 PAX, 37000 ft ICA, 20 mins taxi time, step climb	124361.5 [140]	120219	3.4%

Table B-1 (continued)

Next-Generation Long-Range Aircraft: A350-900

Reference Specification (PLD, stage length, ICA)	Model Specification (A/C and mission), unless specified 1PAX@90 kg	Reference Fuel Burn Value [kg]	BADA Fuel Burn Value [kg]	Delta
2000 nm, 314 seats	3704 km, 314 PAX, 36000 ft ICA; 32 mins taxi-times	28261 [141]	25577	-9%
2000 nm, 314 seats	3704 km, 314 PAX, 33000 ft ICA; 32 mins taxi-times	28261 [141]	27169	-4%
293 seats @115.8 kg per person, 3200 nm, taxi out 20mins, taxi-in 12 mins,	33.929 tons PLD, 6647 km, 36000 ft ICA; 32 mins taxi-times	45264 [142]	45031	-0.5%
293 seats, 3699nm, 20 min/22 min (LHR-ATL)	293 seats @ 115.8 kg, 7680 km, 42 mins taxi time, 36000 ft ICA	53284 [142]	52025	-2%
4000 nm, 314 seats	314 PAX, 7408 km, 36000 ft, 32 mins taxi time	50869 [141]	49222	-3%

Table B-1 (continued)

Next-Generation Narrowbody Aircraft: A320neo

Reference Specification (PLD, stage length, ICA)	Model Specification (A/C and mission), unless specified 1PAX@90 kg	Reference Fuel Burn Value [kg]	BADA Fuel Burn Value [kg]	Delta
1000 nm, 150 seats	13.5 tons, 1852 km, 33000 ft ICA; 20 mins taxi time	5168 [137,143]	5232	1%

Next-Generation Jet Commuter: E190-E2

Reference Specification (PLD, stage length, ICA)	Model Specification (A/C and mission), unless specified 1PAX@90 kg	Reference Fuel Burn Value [kg]	BADA Fuel Burn Value [kg]	Delta
806 nm, 90 seats	90 seats, 1492.7 km, 30000 ft ICA, 20 mins taxi time	3637.2 [130]	3678	1%

Appendix C: Aircraft Parameters Used as Input to GFMC, ALiTiCo, and FSDM

Table C-1 Seat capacities of FSDM initial fleet aircraft types

Route Group	LRC	LRH	JC	TP	MR	LR	NB
AFAF	285	370	83	69	219	271	139
AFLA	270	359	0	0	187	251	0
AFNA	0	447	0	0	223	291	172
ASAF	0	375	0	0	214	285	0
ASAS	260	372	72	69	245	296	150
ASLA	0	382	0	0	213	262	0
ASME	276	381	85	0	223	283	157
ASNA	290	381	0	0	239	288	142
EUAF	280	344	106	72	237	277	154
EUAS	256	372	75	72	213	288	139
EUEU	20	379	76	69	216	277	153
EULA	273	400	0	0	247	281	149
EUME	294	362	92	72	222	271	148
EUNA	243	351	72	0	221	275	100
LALA	294	338	78	65	200	258	142
LANA	0	384	54	64	204	254	143
MEAF	0	374	79	0	230	274	144
MELA	0	0	0	0	205	293	152
MEME	0	381	87	68	222	261	143
MENA	0	430	0	0	211	307	118
NANA	27	383	58	65	193	299	135

Table C-2 Seat capacities of FSDM next-generation aircraft types

Route Group	NGMR	NGLRH	NGLR	NGNB	NGJC
ALL ROUTES	242	467	315	165	97

Table C-3 Freight capacities [Tonnes] of FSDM initial fleet aircraft types

Route Group	LRC	LRH	JC	TP	MR	LR	NB
AFAF	44	16	0	0	11	13	1
AFLA	41	15	0	0	9	0	0
AFNA	0	15	0	0	12	10	0
ASAF	0	15	0	0	13	17	0
ASAS	54	24	3	1	13	22	1
ASLA	0	15	0	0	13	8	0
ASME	54	25	6	0	11	20	2
ASNA	45	19	19	0	11	21	1
EUAF	43	17	1	0	9	15	1
EUAS	41	20	7	0	11	14	4
EUEU	86	24	1	1	8	18	2
EULA	46	15	0	0	10	17	4
EUME	46	27	3	1	14	20	2
EUNA	47	16	8	0	9	17	0
LALA	46	17	1	0	13	17	6
LANA	0	15	3	0	11	19	2
MEAF	0	20	0	0	12	19	1
MELA	0	0	0	0	12	15	0
MEME	0	19	2	2	10	17	3
MENA	0	16	20	0	12	15	0
NANA	85	14	0	0	8	18	2

Table C-4 Freight capacities [Tonnes] of FSDM next-generation aircraft types

Route Group	NGMR	NGLRH	NGLR	NGNB	NGJC
ALL ROUTES	14	20	34.9	4	2

Table C-5 Aircraft design and cabin parameters

Aircraft Acronym	Engine	LOV [FH]	LOV [FC]	MTOW [Tonnes]	OEW [tonne]	Range [km]	Cruise Speed [Ma]	TOFL [m]	Cabin length [m]	Cabin height [m]	Max. cabin width [m]	Cabin floor width [m]
LRC	PW4460	150000	40000	273.29	128.81	12571	0.83	3115	46.52	2.413	5.71	5.52
LRH	CF6-80C2B1F	165000	35000	396.8	180.44	11456	0.85	2820	57.64	2.41	6.1	5.87
JC	CF34-10E6	80000	80000	47.79	27.9	4445	0.82	2107	25.76	2	2.74	2.58
TP	PW127F	125000	56000	22.8	12.95	2669	0.45	1290	19.81	1.92	2.57	2.26
MR	PW4060	150000	75000	186.88	90.011	7890	0.8	2652	40.36	2.87	4.72	4.64
LR	GE90-90B	160000	60000	287	138.1	14305	0.84	3000	49.1	2.87	5.86	5.82
NB	CFM56-5B4	120000	60000	77	39	5700	0.78	2190	27.5	2.22	3.7	3.45
NGMR	Trent 1000-A	200000	66000	227.93	117.80	15190	0.84	2821	42.29	2.49	5.74	5.35
NGLRH	GEnx-2B67	165000	35000	447.7	220.13	14815	0.84	3230	63.25	2.16	6.09	5.87
NGLR	CF6-80E1A2	304000	19000	268	115.7	14075	0.84	3033	51.8	2.21	5.61	5.4
NGNB	CFM56-5B4	120000	60000	77	39	6900	0.78	2190	27.5	2.22	3.7	3.45
NGJC	CF34-10E6	80000	80000	51.8	28.18	5278	0.82	1620	25.91		2.74	2.58

Table C-6 Fleet size of initial fleet aircraft type by EIS year

EIS Year	LRC	LRH	JC	TP	MR	LR	NB
2008	0	0	191	33	36	128	615
2007	0	1	170	15	29	123	619
2006	0	6	237	6	41	94	491
2005	0	5	285	8	39	81	426
2004	0	17	266	7	53	83	390
2003	0	15	264	15	63	103	447
2002	0	20	264	14	92	103	575
2001	0	13	200	13	89	110	522
2000	0	47	164	24	105	125	541
1999	1	55	135	19	109	95	462
1998	3	36	76	20	90	95	301
1997	5	23	38	11	77	58	179
1996	6	19	32	26	99	30	164
1995	7	27	37	27	116	24	208
1994	4	47	56	27	143	20	275
1993	4	52	49	25	172	5	412
1992	1	49	42	27	167	1	458
1991	2	52	22	14	144	1	363
1990	0	40	25	6	97	0	284
1989	2	12	11	0	102	0	249
1988	0	9	32	0	58	0	204
1987	2	21	20	0	48	0	170
1986	4	10	26	0	34	0	128
1985	2	5	58	0	19	0	39
1984	1	6	59	0	19	0	31
1983	0	0	0	0	0	0	0
1978-1982	32	25	470	0	3	0	148
1973-1977	7	6	206	0	0	0	46
1968-1972	0	1	72	0	0	0	96
Sum	**83**	**619**	**3507**	**337**	**2044**	**1279**	**8843**

Table C-7 Engine parameters

Aircraft	Dry Weight [Tonne]	No. of engines	sfc at max cruise [lb/lbf/h]	No. of shafts	BPR	OPR	Number of compressor stages, including fan stages	Max. Thrust [tonne]	A/C approach Noise level [EPNdB]	A/C flyover Noise level [EPNdB]	NO_X per LTO cycle [kg/LTO]
LRC	4.273	3	0.45	2	4.8	32.4	16	27.21	103.4	95.7	35.65
LRH	4.441	4	0.642	2	5.1	30.13	19	25.92	103.3	99.8	42.88
JC	1.678	2	0.64	2	5.4	25.6	13	8.39	91.8	83.4	5.9
TP	0.481	2	0.459	3	5	25	3	8.15	92.2	80.2	1.82
MR	4.273	2	0.578	2	4.7	29.7	16	27.21	100.2	93.5	28.19
LR	7.892	2	0.552	2	8.4	39.7	14	42.62	98	90.3	52.81
NB	2.38	2	0.596	2	5.9	27.1	14	12.02	94.4	85.3	9.01

Table C-8 Turboprop aircraft additional properties

Engine take-off Power [1000 SHP]	Number of propeller blades	Propeller Diameter [m]
2.75	6	3.93

Table C-9 Environmental and macroeconomics related input

Variable	**Value**
Aircraft price scenario	mean
Flight type	international
Exchange rate Euro to USD in 2008	1.33
DMC inflation conversion factor from 1989to 2008 USD	1.54
ETS charge [Euro per tonne CO_2]	10
Navigation charge unit rate [EUR]	64.38
Aircraft maximum lifetime [years]	40
Maximum approach noise level [EPNdB]	88
Maximum flyover noise level [EPNdB]	83
Interest rate [%/year]	4
Insurance rate [%/year]	0.2
Fuel price escalation rate [%/year]	0
Airport charges escalation rate [%/year]	0
Navigation charges escalation rate [%/year]	0
Crew cost escalation [%/year]	0
Maintenance charges escalation [%/year]	0
Noise charges escalation rate [%/year]	0
Emission charges escalation rate [%/year]	0
ETS charges escalation rate [%/year]	0
Depreciation period [years]	14

Appendix D: Verification of FSDM Transport Capacity in Base Year 2008

Table D-1 Route Group ASK comparison and flight distance

Route Group Name	Route Group Distance [km]	OAG ASK	FSDM ASK	delta
AFAF	1,025	6.270E+10	6.902E+10	10%
AFLA	5,749	1.800E+09	1.670E+09	-7%
AFNA	7,478	1.410E+10	1.578E+10	12%
ASAF	7,103	2.750E+10	2.329E+10	-15%
ASAS	1,076	1.171E+12	8.152E+11	-30%
ASLA	10,220	4.100E+09	2.803E+09	-32%
ASME	3,527	1.696E+11	3.098E+11	83%
ASNA	9,374	3.858E+11	4.140E+11	7%
EUAF	3,147	1.765E+11	3.412E+11	93%
EUAS	6,044	5.081E+11	8.907E+11	75%
EUEU	918	7.552E+11	6.580E+11	-13%
EULA	8,292	2.204E+11	2.219E+11	1%
EUME	3,638	1.410E+11	1.775E+11	26%
EUNA	6,605	5.549E+11	5.544E+11	0%
LALA	889	1.872E+11	1.536E+11	-18%
LANA	2,404	2.242E+11	2.290E+11	2%
MEAF	2,478	4.890E+10	4.337E+10	-11%
MELA	11,999	2.600E+09	2.328E+09	-10%
MEME	767	4.620E+10	4.225E+10	-9%
MENA	10,290	4.580E+10	4.609E+10	1%
NANA	1,185	1.244E+12	6.272E+11	-50%
sum		5.992E+12	5.639E+12	-6%

Appendix E: Incremental and Giant-Leap Cost Improvements of FSDM Aircraft Types

Table E-1 Incremental and Giant-Leap Cost Improvements of FSDM Aircraft Types

Aircraft Cluster	Cost Improvements from Cluster Introduction To Service [%]		
(Earliest EIS Year)	Fuel Cost	Non-fuel COC	ADOC
Long-Range Combi (1973)	Cruise Performance Improvement Package: -4% [144]		
Long-Range Heavy (1973)	Interior changes, aerodynamics and engine: -25% [145] Engine: -12% [145] PW4000 94-inch Upgrade Package: -1% [146]	B747-400 entry into service: -26% [147,148]	
Jet commuter (1968)	E190 EIS: -18% [149,150]; Aerodynamic enhancements: -2% [151]	E190 Improvement compared to previous aircraft in cluster: -25%; Maintenance improvement: -5% [152,153]	
Turboprop commuter (1990)	use of ARMONIA cabin: -0.6% [154]		

Table E-1 (continued)

Aircraft Cluster	Cost Improvements from Cluster Introduction To Service [%] sources		
(Earliest EIS Year)	Fuel Cost	Non-fuel COC	ADOC
Mid-Range (1984)	Adopted from A330 improvement: -2% [95]	Adopted from 20% and 5% A330 A&E DMC reduction [95]: -20%	
Long-Range (1991)	PIP: -1% [155] Upgrade package: -2% [156]	-3.4% [157]	-3.4% [157]
Narrow-body (1968)	A320 improvement compared to previous aircraft in cluster: -16.6% [43,129];	Compared to previous aircraft in cluster: -7.9% [43]	Average improvement adopted from B737-800: -2.5% [157]
	Other improvements including wingtip fence and sharklets: -3.5% [157]	Average improvement adopted from B737-800: -2.5% [157]	
Next-Gen Mid-Range (2011)	Compared to previous generation: -20% [158,159]; Trent 1000 TEN: -2% [160,161]	Compared to previous generation: -10% [137]	
Next-Gen Long-Range Heavy (2012)	Compared to previous generation: -16% [162], -3.5% [163]	Compared to previous generation: -3% [147]	
Next-Gen Long-Range (2015)	Compared to previous generation: -25% [143]; Trent XWB-84-Enhanced Performance: -1% [164]; Sharklets: -1.4% [165]	Compared to previous generation: -25% [143]	
Next-Gen Narrow-body (2015)	Compared to previous generation: -15% [163]; PW engine improvement: -2% [143]	Compared to previous generation: -14% [166]	
Next-Gen Commuter (2016)	Compared to previous generation: -17.3% [167]	Compared to previous generation: -10% [168]	Lower noise: -2% [169]

Table E-2 Additional Aircraft Cluster Cost Improvements Assumed During Calibration

Aircraft Cluster	**Cost Improvements [%]**		
	Fuel Cost	**Non-fuel COC**	**ADOC**
LRH	-4%	-7%	
MR	-1.8%	-3.6%	
LR	-2%	-2%	
NGMR	-14.9%	-9.8%	
NGLR	-15%	-5%	

Appendix F: Other Input for Model Calibration and Verification

Table F-1 Initial fleet aircraft allocation to route groups

Route Group	Aircraft Type						
	LRC	LRH	JC	TP	MR	LR	NB
AFAF	0	0	485	24	0	0	0
AFLA	2	0	0	0	0	0	0
AFNA	0	0	0	0	20	0	0
ASAF	0	0	0	0	0	26	0
ASAS	0	0	0	0	1508	0	767
ASLA	0	2	0	0	0	0	0
ASME	0	0	1124	0	0	0	0
ASNA	0	0	0	0	200	206	0
EUAF	0	0	989	0	0	0	0
EUAS	0	0	203	0	0	134	1313
EUEU	0	0	0	313	0	0	3277
EULA	0	0	0	0	250	0	0
EUME	81	0	346	0	0	0	0
EUNA	0	0	0	0	0	582	0
LALA	0	0	0	0	0	0	878
LANA	0	0	0	0	0	0	885
MEAF	0	0	0	0	66	0	0
MELA	0	0	0	0	0	2	0
MEME	0	0	361	0	0	0	0
MENA	0	15	0	0	0	18	0
NANA	0	601	0	0	0	311	1723

Table F-2 Aircraft production capacities over time

	LRH	**JC**	**TP**	**MR**	**LR**	**NB**	**NGMR**	**NGLRH**	**NGLR**	**NGNB**	**NGJC**
2008	12	216	109	82	74	676	0	0	0	0	0
2009	10	185	110	89	98	774	0	0	0	0	0
2010	18	142	112	99	78	777	0	0	0	0	0
2011	26	137	99	107	73	793	3	0	0	0	0
2012	30	120	93	127	83	870	46	12	0	0	0
2013	25	116	103	129	98	933	65	5	0	0	0
2014	30	92	83	114	99	975	114	11	0	0	0
2015	27	101	88	119	98	986	135	12	14	0	0
2016	28	108	80	79	99	967	137	12	49	68	12
2017	15	101	80	77	74	795	136	12	78	292	17
2018	12	83	120	54	42	576	162	0	120	588	52
2019	8	60	120	25	30	322	193	0	156	1131	94
2020	8	0	120	5	0	72	213	0	256	1441	150
2021	8	0	120	0	0	0	218	0	312	1584	240
2022	8	0	120	0	0	0	218	0	312	1680	240

Source: own depiction, based on Aircraft manufacturers' websites, flightglobal, bizjournals, forecastinternational, ainonline

LRC has zero production capacity over time; after 2022, production capacity increases at 4.7% per year.

Table F-3 Annual airline passenger growth rates (RPKS): 2008- 2016

Route Group	2008 - 2009	2009 - 2010	2010 - 2011	2011 - 2012	2012 - 2013	2013 - 2014	2014 - 2015	2015 - 2016
AFAF	5.5%	10.9%	4.9%	6.8%	-1.5%	5.4%	4.6%	6.3%
AFLA	25.0%	26.7%	10.9%	19.1%	8.7%	11.0%	5.8%	13.3%
AFNA	39.6%	29.0%	0.7%	10.8%	-3.5%	2.6%	1.8%	4.9%
ASAF	-23.9%	37.1%	5.4%	-21.4%	-10.5%	-9.9%	-1.5%	2.9%
ASAS	1.1%	14.3%	11.1%	10.0%	9.9%	7.5%	9.4%	9.5%
ASLA	25.0%	26.7%	10.9%	19.1%	8.7%	11.0%	5.8%	13.3%
ASME	17.6%	17.8%	9.9%	6.5%	13.2%	9.1%	11.6%	12.7%
ASNA	-7.2%	8.3%	10.4%	6.2%	2.0%	4.1%	7.3%	8.1%
EUAF	2.0%	5.7%	-1.0%	4.7%	0.0%	4.3%	4.6%	0.4%
EUAS	-8.0%	4.7%	5.1%	6.6%	-0.1%	4.6%	6.6%	2.7%
EUEU	-5.4%	2.4%	3.0%	2.6%	5.5%	6.5%	4.8%	7.9%
EULA	-1.3%	0.2%	4.3%	8.8%	3.7%	2.7%	5.4%	6.3%
EUME	13.9%	9.6%	6.6%	16.1%	10.6%	7.2%	15.0%	7.2%
EUNA	-6.2%	3.2%	2.8%	0.6%	2.0%	4.7%	2.7%	5.2%
LALA	2.9%	26.6%	12.3%	7.0%	6.8%	6.0%	4.7%	2.2%
LANA	-4.1%	7.5%	4.4%	12.6%	6.6%	8.4%	9.0%	2.6%
MEAF	32.0%	10.8%	8.3%	23.2%	4.4%	5.8%	10.9%	5.0%
MELA	25.0%	26.7%	10.9%	19.1%	8.7%	11.0%	5.8%	13.3%
MEME	8.3%	13.6%	5.7%	-7.2%	12.9%	6.2%	11.5%	13.5%
MENA	40.7%	10.0%	10.1%	13.4%	10.8%	16.6%	19.7%	12.0%
NANA	-6.1%	3.4%	3.2%	0.9%	1.4%	3.2%	4.6%	3.9%

Table F-4 Annual passenger traffic growth rates (RPKS): 2016- 2036

	Africa	**Asia Pacific**	**Europe**	**Latin America**	**Middle East**	**North America**
Africa	**6.5%**					
Asia Pacific	6.7%	**5.9%**				
Europe	4.7%	4.5%	**3.2%**			
Latin America	7.2%	6.7%	4.3%	**6.2%**		
Middle East	7.6%	6.4%	5.3%	6.9%	**5.2%**	
North America	5.9%	3.7%	2.9%	5.6%	5.0%	**2.6%**

Table F-5 Seat and Freight Load Factors used for Calibration to Boeing Results

Year	Seat Load Factor	Freight Load Factor
2008	76.1%	46%
2009	76.2%	39%
2010	78.7%	47.7%
2011	78.5%	48%
2012	79.4%	45%
2013	79.7%	46%
2014	79.9%	45.8%
2015	80.3%	44.1%
2016	80.3%	42.9%
2017-2036	0.182% growth rate compared to previous year	47.7%
2036-2050	83.3%	47.7%

Appendix G: CO_2 Reduction Analysis of Individual EMR Measures

Table G-1 CO_2 reduction analysis of individual measures, application order: Replacement Strategy, FGNB, Early Retirement

Scenario ID	**Measure**	**Measure combination Scenario**	**Year 2050 Fleet CO_2 emissions [Mt]**	**Relative reduction**
1	GLI Baseline	GS + GLI	2488	-
2	Incremental Improvement	GS + GLI + IncImp	2442	2%
3	Replacement Strategy	RS + GLI + IncImp	2401	2%
4	FGNB	RS + GLI + IncImp + FGNB	2204	8%
5	Early Retirement	RS + GLI + IncImp + FGNB + ER	2061	6%

GS: Growth Strategy; RS: Replacement Strategy; GLI: Giant leap improvement; IncImp: Incremental Improvement; FGNB: Future Generation Narrowbody aircraft; ER: Early retirement

Table G-2 CO_2 reduction analysis of individual measures, application order: Early Retirement, FGNB, Replacement Strategy

Scenario ID	**Measure**	**Measure combination Scenario**	**Year 2050 Fleet CO_2 emissions [Mt]**	**Relative reduction**
1	GLI Baseline	GS + GLI	2488	-
2	Incremental Improvement	GS + GLI + IncImp	2442	2%
3	Early Retirement	GS + GLI + IncImp + ER	2380	2%
4	FGNB	GS + GLI + IncImp + ER + FGNB	2143	10%
5	Replacement Strategy	RS + GLI + IncImp + ER + FGNB	2061	3%

GS: Growth Strategy; RS: Replacement Strategy; GLI: Giant leap improvement; IncImp: Incremental Improvement; FGNB: Future Generation Narrowbody aircraft; ER: Early retirement

Table G-3 CO_2 reduction analysis of individual measures, application order: FGNB, Early Retirement, Replacement Strategy

Scenario ID	**Measure**	**Measure combination Scenario**	**Year 2050 Fleet CO_2 emissions [Mt]**	**Relative reduction**
1	GLI Baseline	GS + GLI	2488	-
2	Incremental Improvement	GS + GLI + IncImp	2442	2%
3	FGNB	GS + GLI + IncImp + FGNB	2234	8%
4	Early Retirement	GS + GLI + IncImp + FGNB + ER	2143	4%
5	Replacement Strategy	RS + GLI + IncImp + FGNB + ER	2061	3%

GS: Growth Strategy; RS: Replacement Strategy; GLI: Giant leap improvement; IncImp: Incremental Improvement; FGNB: Future Generation Narrowbody aircraft; ER: Early retirement

Table G-4 CO_2 reduction analysis of individual measures, application order: Replacement Strategy, Early Retirement, FGNB,

Scenario ID	**Measure**	**Measure combination Scenario**	**Year 2050 Fleet CO_2 emissions [Mt]**	**Relative reduction**
1	GLI Baseline	GS + GLI	2488	-
2	Incremental Improvement	GS + GLI + IncImp	2442	2%
3	Replacement Strategy	RS + GLI + IncImp	2401	2%
4	Early Retirement	RS + GLI + IncImp + ER	2336	3%
5	FGNB	RS + GLI + IncImp + ER + FGNB	2061	11%

GS: Growth Strategy; RS: Replacement Strategy; GLI: Giant leap improvement; IncImp: Incremental Improvement; FGNB: Future Generation Narrowbody aircraft; ER: Early retirement

Table G-5 CO_2 reduction analysis of individual measures, application order: Early Retirement, Replacement Strategy, FGNB

Scenario ID	**Measure**	**Measure combination Scenario**	**Year 2050 Fleet CO_2 emissions [Mt]**	**Relative reduction**
1	GLI Baseline	GS + GLI	2488	-
2	Incremental Improvement	GS + GLI + IncImp	2442	2%
3	Early Retirement	GS + GLI + IncImp + ER	2380	2%
4	Replacement Strategy	RS + GLI + IncImp + ER	2336	2%
5	FGNB	RS + GLI + IncImp + ER + FGNB	2061	11%

GS: Growth Strategy; RS: Replacement Strategy; GLI: Giant leap improvement; IncImp: Incremental Improvement; FGNB: Future Generation Narrowbody aircraft; ER: Early retirement

Appendix H: List of student thesis supervised

1. Bellhäuser, L. (2016). *Aircraft Productivity Analysis and Fleet Development Planning*. Master Thesis
2. Cui, A. (2016). *Introducing Aircraft Assignment and Retirements in Fleet Modelling based on Operating Economics*. Master Thesis (Report No. LS-MA 16/16-EX)

Appendix I: Publications in the context of this thesis

1. Oguntona, O. 2020. Longer-Term Aircraft Fleet Modelling: Narrative Review of Tools and Measures for Mitigating Carbon Emissions from Aircraft Fleet. *CEAS Aeronaut J* **11,** 13–31 (2020). https://doi.org/10.1007/s13272-019-00424-y
2. Oguntona, O., Ploetner, K., Rothfeld, R., Urban, M., and Hornung, M. 2019. Impact of Airline Business Models, Market Segments and Geographical Regions on Aircraft Cabin Configurations. *Journal of Air Transport Studies*. 10, 1 (Jan. 2019), 1-38. DOI:https://doi.org/10.38008/jats.v10i1.8.
3. Ploetner, K., Rothfeld, R., Urban, M., Hornung, M., Tay, G., and Oguntona, O., 2017. Technological and Operational Scenarios on Aircraft Fleet-Level towards ATAG and IATA 2050 Emission Targets. *AIAA Aviation 2017*, Denver, USA. Available: http://bit.ly/2tJJ4Ay
4. Oguntona, O., Cui, A., Ploetner, K., and Hornung, M. 2016. Fleet Development Planning of Airlines: Incorporating the Aircraft Operating Economics Factor. *International Council of Aeronautical Sciences (ICAS) 2016*, Daejeon, South Korea. Available: http://bit.ly/2ucQEY5
5. Oguntona, O., Ploetner, K., and Hornung, M., 2016. Average Aircraft Output and Capacity Calculations in Airline Fleet Planning. *AGIFORS Scheduling and Strategy Planning Study Group Meeting*, Istanbul, Turkey
6. Oguntona O., 2015. Fleet Composition Decision of Airlines: Process and Principles. *12th Aviation Student Research Workshop*, Amsterdam, The Netherlands