TECHNISCHE UNIVERSITÄT MÜNCHEN
Fakultät für Maschinenwesen
Lehrstuhl für Luftfahrtsysteme

Aircraft Technology Assessment Using Fleet-Level Metrics

Niclas Peter Randt

Vollständiger Abdruck der von der Fakultät für Maschinenwesen
der Technischen Universität München zur Erlangung des akademischen Grades eines
Doktors der Ingenieurwissenschaften
genehmigten Dissertation.

Vorsitzender:	Prof. Prof. h.c. Dr. Dr. h.c. Ulrich Walter
Prüfer der Dissertation:	1. Prof. Dr.-Ing. Mirko Hornung
	2. Prof. Dr.-Ing. Eike Stumpf

Die Dissertation wurde am 05.10.2015 bei der Technischen Universität München
eingereicht und durch die Fakultät für Maschinenwesen am 01.06.2016 angenommen.

Abstract

Future-forecasting studies of reputable international institutions expect commercial aviation to grow by around 3 to 5% annually within the upcoming two decades. From an economic viewpoint, this development can be considered as very positive. Yet, the strong growth of aviation will inevitably have an adverse impact on the environment, if appropriate countermeasures are not taken in time. This thesis contributes to the ongoing research efforts to anticipate the future impact of the global air transport system on the environment. It focusses on the fuel-saving potential of next-generation aircraft at a system-wide level considering the global commercial air transport fleet. A methodology is introduced that quantifies the effects of novel aircraft concepts and technologies on the future fuel consumption and exhaust gas emissions production. It is found that the next-generation aircraft considered here may improve the fleet-wide fuel efficiency from the present until 2050 by up to 0.8% annually and help mitigate the growth in total fuel demand by around the same value within this period. Hence, additional measures apart from the integration of new aircraft must be taken in order to ensure an environmentally friendly development of global air traffic in the long term. The methodology developed in this thesis is also applied to assess a newly designed high-capacity transport aircraft. The assessment results reveal that with an entry into service in 2025, this aircraft can decrease the total fuel demand of the global fleet in 2050 by about 0.8%. Five percent can even be achieved under the assumption that the production rates of this aircraft are not subject to restrictions. Furthermore, it is shown that the aircraft can reduce the annual increase in fuel demand of the world fleet from 2025 until 2050 by a maximum value of around 0.2% per year.

Kurzzusammenfassung

Zukunftsstudien anerkannter internationaler Institutionen erwarten, dass der kommerzielle Luftverkehr in den kommenden 20 Jahren um etwa 3-5% jährlich wächst. Aus wirtschaftlicher Sicht ist dies als sehr positiv zu werten. Jedoch wird das starke Wachstum auch zu einer Belastung der Umwelt führen, falls angemessene Gegenmaßnahmen nicht rechtzeitig getroffen werden. Die vorliegende Arbeit liefert einen Beitrag zu laufenden Forschungsarbeiten, die sich der Bestimmung der zukünftigen Wirkung des Weltluftverkehrs auf die Umwelt verschreiben. Es wird eine Methode vorgestellt, welche die Wirkung neuer Flugzeugkonzepte und -technologien auf den zukünftigen Kraftstoffverbrauch und den Ausstoß von Abgasen quantifiziert. Mit dieser Methode wird festgestellt, dass im Zeitraum von heute bis 2050 Flugzeuge der nächsten Generation die flottenweite Kraftstoffeffizienz um etwa 0.8% jährlich vorantreiben und gleichfalls das Wachstum des globalen Kraftstoffbedarfs um etwa denselben Betrag verringern können. Um also eine langfristig umweltfreundliche Entwicklung des Luftverkehrs sicherzustellen, müssen weitere Maßnahmen neben der Integration neuer Flugzeuge ergriffen werden. Die in der vorliegenden Arbeit entwickelte Methode wird ebenfalls zur Bewertung eines neu entworfenen Großraumtransportflugzeuges angewendet. Die Bewertungsergebnisse zeigen, dass das Flugzeug mit einem angenommenen Eintrittsjahr in 2025 den Gesamtkraftstoffbedarf in 2050 realistisch um etwa 0.8% reduzieren kann. Dieser Wert kann auf bis zu 5% gesteigert werden unter der Annahme, dass die Produktionsraten zum Bau dieses Flugzeugs keinen Beschränkungen unterliegen. Schließlich wird gezeigt, dass das Flugzeug den jährlichen Anstieg des Kraftstoffbedarfs der Weltflotte von 2025 bis 2050 maximal um etwa 0.2% pro Jahr verringern kann.

Danke

Die vorliegende Arbeit entstand im Rahmen meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Lehrstuhl für Luftfahrtsysteme der Technischen Universitäten München im Zeitraum von 2011 bis 2015. Zahlreiche Personen unterstützten mich während dieser intensiven Zeit – in vielerlei Form – und trugen letztlich dafür Sorge, dass ich meine Arbeit zum Erfolg führen konnte.

Zunächst danke ich meinem Doktorvater Prof. Mirko Hornung für die Möglichkeit zu dieser Arbeit, indem er mich an seinen Lehrstuhl holte und mir dann sein Vertrauen und den Raum schenkte, in welchem ich meine Ideen entwickeln und zu brauchbaren Ergebnissen führen durfte. Mein Dank gilt ebenso Prof. Eike Stumpf, der mir mit seinen Fragen und Anregungen immer wieder neue Impulse gab und ebenso ohne Zögern das Koreferat für mein Promotionsvorhaben übernahm. Herrn Prof. Ulrich Walter danke ich herzlich für die Übernahme des Prüfungsvorsitzes. Schließlich danke ich Herrn Prof. Andreas Hupfer für seine engagierte Betreuung im Rahmen meiner Mitgliedschaft bei der TUM Graduate School.

Ich hatte die große Freude, mit vielen vortrefflichen Kollegen zusammenarbeiten zu dürfen, die mich unermüdlich hinterfragten und durch so manches Tal und über manchen Berg trugen. Dabei standen mir neben dem Kollegenkreis am Lehrstuhl für Luftfahrtsysteme auch viele Wissenschaftler des Bauhaus Luftfahrt mit Rat und Tat zur Seite. In besonderer Erinnerung bleiben mir dabei Sky Sartorius, Gerald Öttl und Felix Will, die es vorbildlich verstanden, mich in ihren Büros zu ertragen. Vielen Dank Euch allen!

Der guten Seele des Lehrstuhls danke ich für ihre unentwegte Unterstützung bei allem Organisatorischen und den vielen Dingen, die weit darüber hinaus gingen. Danke, liebe Natalie!

Ohne meine ‚Army of Students‘ wäre der Erfolg meiner Arbeit niemals zustande gekommen. Neben ihren fachlich wertvollen Beiträgen bin ich allen Studenten, welche ich in ihren Forschungsprojekten begleiten durfte, aber vor allem für die vielen bleibenden Erfahrungen dankbar, die ich auf unserem gemeinsamen Weg machen durfte. Für ihren exzellenten Einsatz in ihren Studien- und Abschlussarbeiten danke ich hier ganz besonders herzlich Christoph Arnold, Christoph Assenheimer, Christoph Engelke, Jonas Ittel, Michael Iwanizki, Martin Kügler und Lennart Wache.

Der größte Dank gebührt schließlich meiner Familie: meinen Eltern, die einen unerschütterlichen Glauben an mich haben – komme, was wolle; meinen Geschwistern, die mir die bunte Vielfalt des Lebens zeigen; meiner lieben Frau, die mich trägt, egal wohin ich gehe; und meinen Kindern, die mich jeden Tag aufs Neue lehren, welche Wunder das Leben mit sich bringt.

Niclas Peter Randt

Bietigheim-Bissingen, im September 2016

Table of contents

Table of figures

Table of tables

Table of abbreviations

a/c	Aircraft
ACAS	Aircraft Analytical System
adv	advanced
AEDT	Aviation Environmental Design Tool
AERO	Aviation Emissions and Evaluation of Reduction Options
AERO-MS	AERO Modeling System
AF	Africa (global region)
ANCAT	Abatement of Nuisances Caused by Air Transport
APF	Airline Procedures File
APM	Aircraft Performance Model
ARPM	Airline Procedure Model
AS	Asia/Pacific (global region)
ASCII	American Standard Code for Information Interchange
ASK	Available Seat Kilometer
ATAF	Aircraft Technology Assessment Framework
ATAG	Air Transport Action Group
ATK	Available Ton Kilometer
ATM	Air Traffic Management
BAA	British Airports Authority
BADA	Base of Aircraft Data
BH	Block Hours
CEAS	Council of the European Aerospace Societies
CIA	Cross-Impact Analysis
CIS	Commonwealth of Independent States
CMO	Boeing Current Market Outlook
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CAEP	Committee on Aviation Environmental Protection
DATAR	*French:* Délégation interministérielle à l'aménagement du territoire et à l'attractivité régionale *(Office for Regional Planning of the French Government)*
DLR	*German:* Deutsches Zentrum für Luft- und Raumfahrt *(German national aeronautics and space research center)*
DoD	US Department of Defense

EASA	European Aviation Safety Agency
EDB	Aircraft Engine Emissions Databank
EC	European Commission
ECT	Emissions Calculation Tool
EIA	United States Energy Information Administration
EIS	Entry Into Service
EPA	United States Environmental Protection Agency
EU	Europe (global region)
Eurocontrol	European air traffic management authority
FAA	Federal Aviation Administration
FAP	Fleet Assignment Problem
FATE	Four-dimensional Calculation of Aircraft Trajectories and Emissions
FCCT	Fuel Consumption Calculation Tool
FCECT	Fuel Consumption and Emissions Calculation Tool
FESG	Forecast and Economic Analysis Support Group
FLF	Freight Load Factor
FLOPS	Flight Optimization System
FOI	*Swedish:* Totalförsvarets forskningsinstitut *(Swedish defense research agency)*
FOITP	Confidential Database for Turboprop Engine Emissions of the FOI
FSDM	Fleet System Dynamics Model
ft	Feet
GAMS	General Algebraic Modeling System
GFMC	Global Fleet Mission Calculator
GMF	Airbus Global Market Forecast
GDP	Gross Domestic Product
IATA	International Air Transport Association
ICA	Initial Cruise Altitude
ICAO	International Civil Aviation Organization
ID	Identification Number
IDT	Integrated Design Tool
IEEE	Institute of Electrical and Electronics Engineers
Inf	Infinite
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere
JADC	Japanese Aircraft Design Corporation
kts	Knots
LA	Latin America (global region)
LMI	Logistics Management Institute
LMINET	LMI Network

LOSU	Level of Scientific Understanding
LTO-cycle	ICAO Landing-and-Take-Off Cycle
LW	Large Widebody (aircraft category)
ME	Middle East (global region)
MH	Maintenance Hours
MSL	Mean Sea Level
MTOW	Maximum Take-Off Weight
MW	Medium Widebody (aircraft category)
NA	North America (global region)
n/a	Not applicable
NO_x	Nitrogen Oxides
O-D	Origin-Destination
OAG	Official Airline Guide
OPF	Operations Performance File
Pax	Passenger
PIANO	Project Interactive Analysis and Optimization
PM	Particulate Matter
PMTS	Probabilistic Modified Trends School
POS	Percentage of Survival
PTD	Performance Table Data
PTF	Performance Table File
RAHS	Risk Assessment and Horizon Scanning
RF	Radiative Forcing
RJ	Regional Jets (aircraft category)
ROCD	Rate of Climb or Descent
RPK	Revenue Passenger Kilometer
RTK	Revenue Ton Kilometer
SA	Single-Aisle (aircraft class)
SAGE	System for Assessing Aviation's Global Emissions
Shell	Royal Dutch Shell plc
SFC	Specific Fuel Consumption
SLF	Seat Load Factor
SMC	Single Mission Calculator
SPC	Single Production Capacity
SRI	Stanford Research Institute
SW	Small Widebody (aircraft category)
TA	Twin-Aisle (aircraft class)
TAS	True Airspeed
TEM	Total-Energy Model
TGTEF	Total Ground Track Extension Factor

TH	Turn-around Hours
TIA	Trend-Impact Analysis
TPC	Total Production Capacity
TUM LLS	*German:* Lehrstuhl für Luftfahrtsysteme der Technischen Universität München *(Institute of Aircraft Design of the Technical University of Munich)*
UH	Utilization Hours
UHC	Unburned Hydrocarbons
UK DTI	Department of Trade and Industry of the United Kingdom
UN	United Nations
US	United States of America
UNFCCC	UN Framework Convention on Climate Change
w/	with
w/o	without
WWLMINET	World Wide LMI Network

Table of symbols

Symbols in Latin script

a	$year$	Age of aircraft
ASK	$seat \cdot km$	Transport supply (passengers)
ATK	$ton \cdot km$	Transport supply (freight)
BH	h	Block hours
d	km	Great circle distance between an O-D pair
D	N	Drag
E	J	Energy
f	-	Number of flight frequencies
FB	kg	Fuel burn
fgr	%	Rate of growth in freight transport demand
flf	%	Freight load factor
FMD	km	Flight mission distance
g	m/s^2	Gravitational acceleration
h	$m; ft$	Altitude
MH	h	Maintenance hours
m	kg	Mass
n	-	Number of aircraft units
p	-	Number of passengers transported
pgr	%	Rate of growth in passenger transport demand
plf	%	Payload factor
POS	%	Percentage of survival
RD	km	Route distance
RF	W/m^2	Radiative forcing
RPK	$seat \cdot km$	Transport demand (passengers)
RTK	$ton \cdot km$	Transport demand (freight)
s	$seat$	Number of seats
sfc	$kg/(seat \cdot km)$; $kg/(ton \cdot km)$	Specific fuel consumption
slf	%	Seat load factor
t	s	Time
t	ton	Tons of freight capacity
T	N	Thrust
$TGTEF$	-	Total ground track extension factor

TH	h	Turn-around hours
UH	h	Utilization hours
v	$m/s\,;kts$	Speed

Symbols in Greek script

α	-	MH/BH-ratio
β	-	Retirement coefficient

Table of subscripts

0	Addressing the standard or reference value
1	Addressing the initial year of calculation
2	Addressing the year of calculation following the initial year
I	Addressing the first retirement coefficient
II	Addressing the second retirement coefficient
ask	Addressing an ASK-specific variable
atk	Addressing an ATK-specific variable
ext	Addressing an artificially extended variable
i	Addressing one particular flight route or route group
j	Addressing one particular aircraft unit, type, or cluster
k	Addressing one particular flight
kin	Addressing the kinetic value
max	Addressing the maximum possible value
pot	Addressing the potential value
TAS	Addressing the true airspeed
$total$	Addressing the total value

Glossary

Aircraft fleet	A →*system* being composed of a distinct number of aircraft units.
Air transport system	The *air transport system* is considered here as a →*system* of aircraft (referred to as →*aircraft fleet*) that operates on a particular network of air routes. Airports are explicitly not included in this definition. Authorities of the air traffic management →*system* are only accounted for indirectly by considering their influence on the way aircraft are legally allowed to be operated.
Environment	The *environment* comprises all "circumstances, objects, and conditions that will influence the completed →*system*; they include political, market, cultural, organizational, and physical influences as well as standards and policies that govern what the →*system* must do or how it must do it." (IEEE, 1996, p. 3) As a result, the *environment*, as defined here, is always part of a more extensive environment, and is therefore referred to as the *relevant environment* as well. The *relevant environment* is constituted by a compilation of →*environmental factors*. (Huss and Honton, 1987b, p. 21)
Environmental factor	An *environmental factor*, also referred to as *driving force* (van der Heijden, 2005, p. 103) or *external factor* (O'Brien and Meadows, 2013, p. 647), is one specific part of the →*environment*. That is, a certain number of *environmental factors* together form and define the →*environment*. Consequently, *environmental factors* have a certain kind of influence or impact on the →*system* under consideration. Depending on the respective →*scenario*, each *environmental factor* holds a certain *future state, outcome* (Wright *et al.*, 2013, p. 634), or *projection* (Gausemeier *et al.*, 1998, p. 115).
Operational environment	The *operational environment* pertains to the →*relevant environment* "in which a →*system* or component is intended to be used." (IEEE, 1990, p. 52) It therefore sets the (physical, legal, etc.) boundary conditions of the way a →*system* is operated.
Requirement	A *requirement* is "a [...] capability needed by a user to solve a problem or achieve an objective." (IEEE, 1990, p. 62)
Scenario	*Scenarios* are "focused descriptions of fundamentally different futures presented in coherent script-like or narrative fashion." (Schoemaker, 1993, p. 15) As such, they are "accessible to and sharable by diverse stakeholders." (Go and Carroll, 2004, p. 53) *Scenarios* are neither "states of nature nor statistical predictions," (Schoemaker, 1993, p. 196) but "multiple, but equally plausible" (van der Heijden, 2005, p. 9) descriptions of potential states of the →*environment* used to better understand the future uncertainties thereof.
Scenario building	*Scenario building* addresses all activities involved in "speculating about the uncertainty surrounding the future […]" and "envisaging a few

	different possible future outcomes for the situation under scrutiny." *Scenario building* is "the necessary foundation for →*scenario planning*." (Martelli, 2001)
Scenario planning	*Scenario planning* is a management technique that decision-makers use "to articulate their mental models about the future and thereby make better decisions." (Georgantzas and Acar, 1995)
System	A *system* is a collection of components that cooperate in an organized way to achieve some desired result, i.e., the →*requirements*. (Hull *et al.*, 2011, p. 4) It is "an integrated composite of people, products, and processes that provide a capability to satisfy a stated need or objective." (DoD, 2001, p. 3) A *complex system* is characterized by an increased amount of system components that interact with each other in a way to achieve the overall system functionality. (Haskins, 2006, p. 22)
System Dynamics	*System Dynamics* is an approach to modeling the dynamics of →*systems* that feature a strong mutual interaction. The main principle of *System Dynamics* is to describe →*complex systems* by applying feedback loops. Stocks and flows are the basic elements of a *System Dynamics* model. They help describe how a →*system* is connected by feedback loops, which create the nonlinearity that frequently exists in modern-day problems. Computer software is used to implement a *System Dynamics* model. Running 'what-if' simulations to test certain policies on such a model can greatly aid in understanding how the →*system* changes over time. (Definition adapted from Seel (2012, p. 3257))

1. Introduction

DESPITE various drastic events and economic downturns that have occurred in the past, the global commercial air transport industry has experienced significant rates of growth within the last decades. This has undoubtedly proven the existence of a continuously increasing demand for air travel worldwide. When referring to the most prominent aviation-related future forecasting studies currently available, one can conclude that there is obviously a broad consensus among business analysts that commercial aviation will further grow within the upcoming decades.

Figure 1-1 shows the forecasted development of the global amount of revenue passenger kilometers (RPKs) as published by some of the most influential aviation stakeholders and research institutes. The figure clearly reveals that almost all studies assume a doubling of the global RPKs within the next 20 years.

1.1 Aviation climate goals

While from a purely economic point of view, a further growth of the air transport sector may represent a desirable condition, the resultant impact on the environment must obviously not be neglected. In fact, growth and environmental impact mitigation constitute the two top-level goals, both of equal importance, which the air transport industry must pursue in order to ensure a sustainable future development.

With this in mind, the global air transport industry has proclaimed a strategic path towards sustainable development and environmental protection. Here, one prominent example is the envisaged reduction of carbon dioxide (CO_2) emissions produced by the world fleet of commercial transport aircraft due to jet fuel burn. In 2009, the International Air Transport Association (IATA) defined three major development milestones for the period between 2009 and 2050. (IATA, 2009, p. 3) Figure 1-2 schematically illustrates these three milestones:

1. An average improvement in fuel efficiency of 1.5% p.a. from 2009 to 2020 (***IATA 1***)
2. A cap on aviation CO_2 emissions from 2020 also referred to as "carbon-neutral growth" (***IATA 2***)
3. A reduction in CO_2 emissions of 50% by 2050 relative to 2005 levels (***IATA 3***)

Other aviation associations like the Air Transport Action Group (ATAG, "The right flightpath to reduce aviation emissions") and governmental institutions like the European Commission ("Flightpath 2050") have adopted these milestones afterwards. (ATAG, 2011; European Union, 2011)

Furthermore, IATA presented a way to achieve these goals by suggesting a "four-pillar strategy" composed of measures that refer to (1) the use of improved technology, (2) the implementation of effective operations, (3) the creation of an efficient infrastructure, and (4) the introduction of economic incentives for aviation stakeholders to reduce their environmental impact. However, IATA did not make any precise suggestion in terms of how this strategy might actually be implemented.

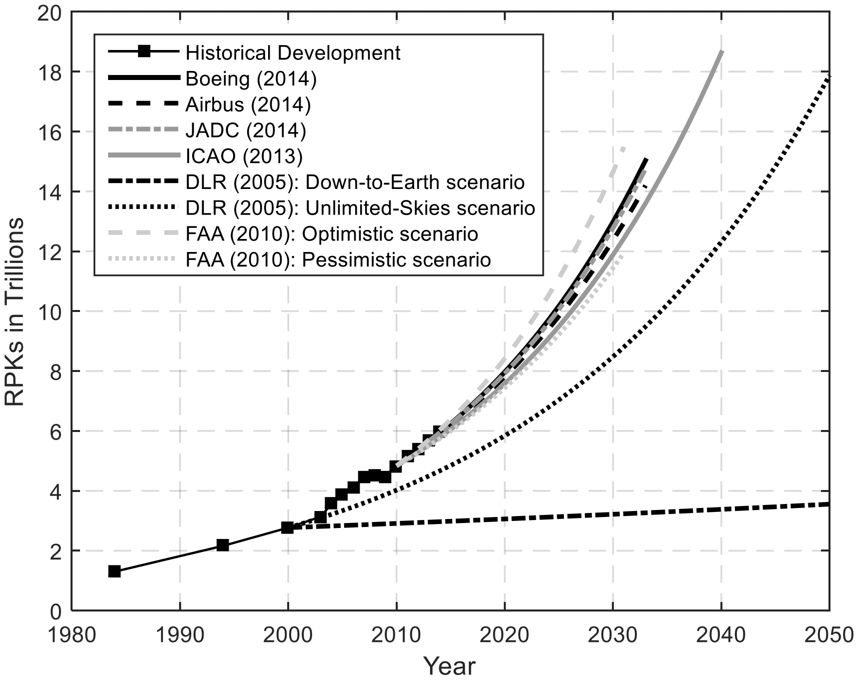


Figure 1-1 **Historical and predicted development of global RPKs**
Data sources: Airbus S.A.S. (2014a), Berghof et al. (2005), Boeing Commercial Airplanes (2014a), FAA (2010a), ICAO (2013), ICAO (2014), JADC (2014)

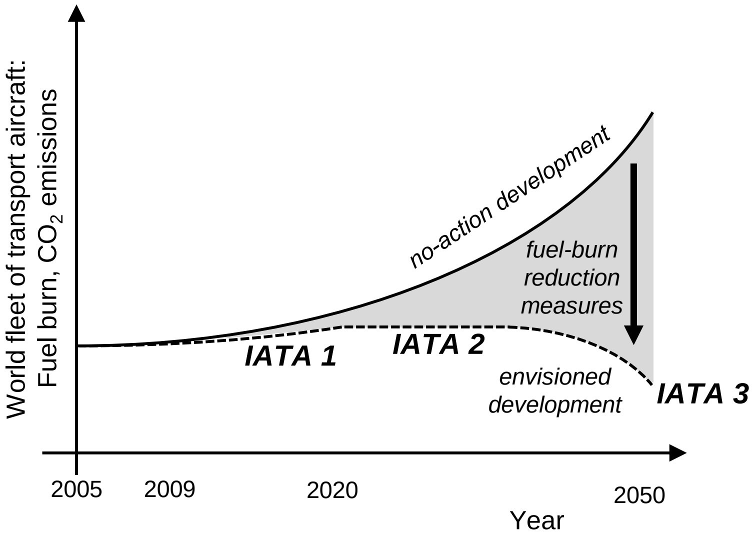


Figure 1-2 **Key milestones for reducing fuel consumption and CO_2 emissions of the global commercial air transport industry: aviation climate goals**
Image source: author's creation based on IATA (2009)

This thesis is therefore aimed at contributing to the ongoing research efforts by focusing on the quantification of the contribution of technological measures to reduce the environmental impact of the global air transport industry with particular focus on fuel burn and associated CO_2 emissions.

1.2 Aviation and the environment

The impact of aviation on the environment is manifold and has been an intensely investigated and discussed topic among researchers for several decades. In order to categorize the various types of environmental effects of aviation, Figure 1-3 depicts a commonly used scheme. Here, the environmental impact of aviation is fundamentally divided into effects related to aircraft

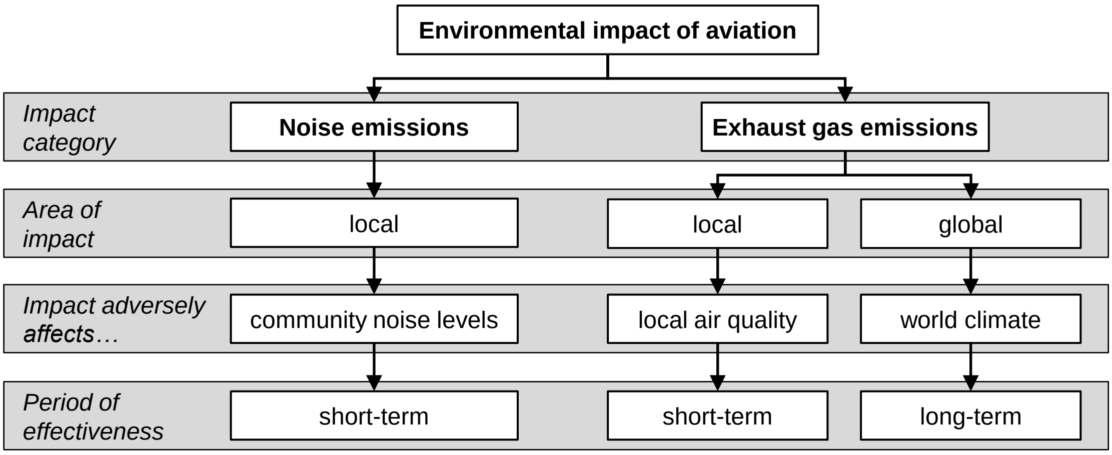


Figure 1-3 **Environmental impact of aviation: Overview**
Image source: author's creation based on Egelhofer (2008, p. 2)

noise emissions and due to exhaust gas emissions of aircraft engines. These two impact categories can hence be considered as a direct consequence of aircraft operation procedures, as they only occur once an aircraft is being operated on the ground and in the air.

While noise emissions primarily affect the local environment and its community noise levels in the vicinity of an airport, exhaust gas emissions have an influence on both the local environment, leading to a reduction of the local air quality and therefore presenting a potential health hazard towards the local population, and the world climate at a global level. Regarding the period of effectiveness of each impact category, exhaust gas emissions own the potential of influencing the world climate in the long term while their impact also features short-term effects at a local level (e.g., local wind may disperse gaseous emissions quickly around wider areas). This also applies to the impact of noise emissions that is only effective during a very limited period of time.

For reasons of simplification, the scheme shown in Figure 1-3 ignores effects that are an indirect result of aircraft operations. Important to mention here are especially the adverse effects on the local water quality in waterways, rivers, and wetlands surrounding airports (Marais and Waitz, 2009, pp. 408ff) that occur due to aircraft deicing procedures, fuel spills, and further reasons. (BAA, 2003) In addition, there are numerous noise and gaseous emission producers in and around airports such as ground-handling vehicles, fuel storages, and aircraft maintenance facilities. Finally, ground-based traffic on motorways and railways is induced near airports to transport air passengers and airport visitors to and from airports.

1.2.1 Aircraft noise

Aircraft noise emissions constitute "a very serious threat" towards the local population inhabiting the surroundings of airports. (Knipschild, 1977, p. 203) Noise is considered to negatively affect the natural well-being and to cause mental disorders, somatic symptoms, and diseases with humans. Moreover, there is evidence that aircraft noise adversely influences animals to a certain degree (e.g., fertility rates). (Pepper *et al.*, 2003)

As a result, the number of airports that have implemented operational restrictions due to aircraft noise (e.g., night curfews, noise abatement procedures, noise charges) has continuously increased since the 1970s. (Boeing Commercial Airplanes, 2011) In addition, the Committee on Aviation Environmental Protection (CAEP)[1] has been constantly working on

---

[1] The CAEP is "a technical committee of the ICAO Council established in 1983. CAEP assists the Council in formulating new policies and adopting new Standards and Recommended Practices related to aircraft noise and emissions, and more generally to aviation environmental impact." (CAEP (2015))

lowering the maximum allowable noise levels of aircraft, forcing aircraft manufacturers to consider increasingly stringent noise requirements when developing new aircraft types. (Dickson, 2013)

1.2.2 Aircraft exhaust gas emissions

When jet fuel is burned inside the combustion chamber of the gas turbine of a modern aircraft engine, the chemical reaction processes occurring during combustion lead to the production of various gases as well as liquid and solid matter. In case of a complete combustion,[2] two gaseous substances are produced, CO_2 and water vapor. In reality, other substances are produced additionally (FAA, 2005, p. 2; Lister *et al.*, 2003, p. 21):

- Nitrogen oxides (NO_x) are built when air passes through areas of high temperature and high pressure inside the combustion chamber, and the nitrogen and oxygen being present in the air combine to form NO_x.
- Unburned hydrocarbons (UHC) leave the gas turbine due to an incomplete combustion process of jet fuel.
- Carbon monoxides (CO) are produced due to an incomplete combustion of the carbon contained in jet fuel.
- Sulfur oxides (SO_x) are formed when small amounts of sulfur[3] combine with oxygen present in the air during combustion.
- Particulate matter/soot (PM) is a result of incomplete combustion.
- Ozone (O_3) is not produced directly by the gas turbine, but formed due to the reaction of UHC and NO_x in the presence of heat and sunlight. It is therefore considered an indirect emission substance of an aircraft engine.

Exhaust gas emissions at the local level. Although noise represents the primary adverse impact that aviation has on the local environment, exhaust gas emissions of aircraft engines also have harmful effects locally. The four chemical substances that contribute most to local air quality deterioration are NO_x, CO, UHC, and PM. (Waitz *et al.*, 2004, p. 15) They all have diverse negative effects on both the human body (e.g., lung irritation, aggravation of respiratory and cardiovascular diseases) and the environment (e.g., crop damage, generation of acid rain). (EPA, 2014)

Over the last decades, the efficiency of aircraft engines, and hence their fuel-consumption performance, have been improved significantly through technological measures (predominantly by raising the engine overall pressure ratio and turbine-entry temperature). This statement is equally true for most of the exhaust gas emission substances, with NO_x representing one particular exception though. (Koff, 2004, p. 587) In fact, controlling and mitigating NO_x emissions are difficult technological challenges, as they tend to increase with increasing pressure ratios and turbine-entry temperatures. (Chandrasekaran and Guha, 2012, p. 171) As a result, most of today's active aircraft types being equipped with modern engines ironically feature less favorable NO_x emission characteristics than their older predecessors. (Faber *et al.*, 2008, p. 122)

Exhaust gas emissions at the global level. The global impact of aviation exhaust gas emissions on the world climate is usually quantified using the radiative forcing (RF) metric, as there is evidence that "there is an approximately linear relationship between a change in global

---

[2] This is the case when a perfect mixture of fuel and air is prevalent in the combustion chamber called the stoichiometric fuel-to-air ratio. It is approximately 0.068 according to Bräunling (2009, p. 974).

[3] Sulfur is contained in practically all hydrocarbon fuels according to Bräunling (2009, p. 979).

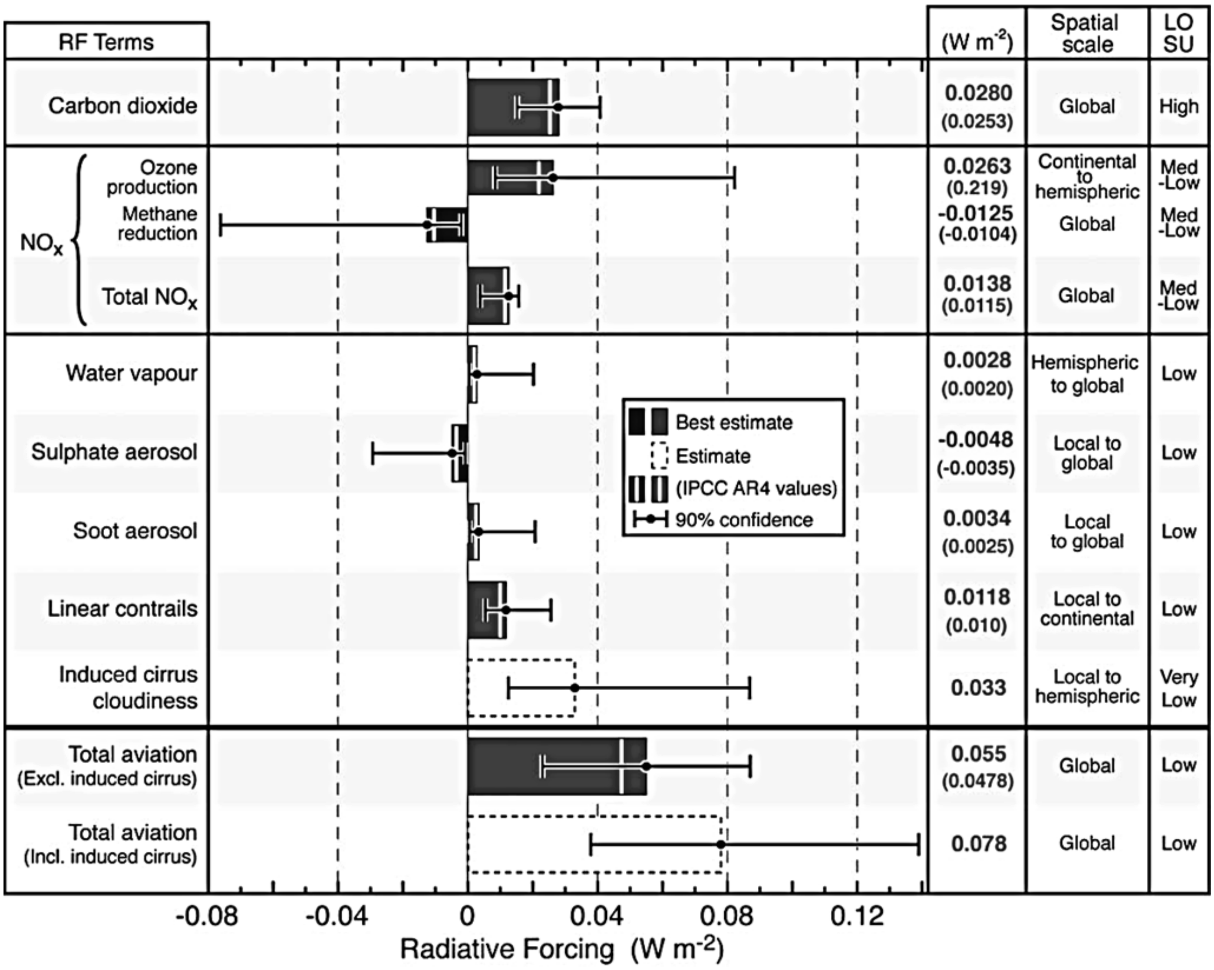


Figure 1-4 **Radiative forcing components from global aviation**
Image adapted from Lee et al. (2009, p. 3526)

mean radiative forcing and a change in global mean surface temperature.” (Lee *et al.*, 2010, p. 4679) The radiative forcing metric was first introduced by the Intergovernmental Panel on Climate Change (IPCC)[4] to “denote an externally imposed perturbation in the radiative energy budget of the Earth’s climate system.” (Ramaswamy *et al.*, 2001, p. 353)

More precisely, radiative forcing is defined “as the change in net downward radiative flux at the tropopause […] and constitutes the radiative heating of the surface-troposphere system.” (Bretherton *et al.*, 1990, p. 78) “It is usually expressed in Watts per square meter averaged over a particular period of time […] and provides a simple quantitative basis for comparing some aspects of the potential climate response to different imposed agents, […] and hence is widely used in the scientific community.” (Myhre *et al.*, 2013, p. 664)

By employing the radiative forcing metric, Figure 1-4 provides a quantified estimation of the world climate impact of aviation emissions from preindustrial times until 2005 according to the current level of scientific understanding (LOSU). The following major conclusions can be drawn from the figure (Lee *et al.*, 2010, p. 4680):

- CO_2 emissions lead to global warming (RF positive) and are highly likely to have the strongest impact on climate change among all aviation emission substances.
- NO_x emissions lead to global warming (overall RF positive), although their chemical interaction behavior with other substances contained in the atmosphere

---

[4] The IPCC is “a scientific body under the auspices of the United Nations (UN). It reviews and assesses the most recent scientific, technical, and socio-economic information produced worldwide relevant to the understanding of climate change.” (IPCC (2015))

is complex, resulting in a high degree of uncertainty and a low LOSU regarding their precise climate impact.

- Sulphate emissions originating from sulphur contained in jet fuel lead to global cooling (RF negative).
- PM/soot emissions lead to global warming.
- Contrails and cirrus clouds induced in the wake of aircraft flying at high altitudes during the cruise flight segment lead to global warming (overall RF positive). However, there is still a substantial degree of uncertainty attached to the estimation of the climate impact of contrails.
- In total, global aviation operations lead to global warming, but uncertainty still exists regarding the exact quantification of the overall climate impact.[5]

At present, the effects of CO_2 emissions on the global climate change are understood best among all aviation emission substances from a scientific point of view. As the quantity of CO_2 being emitted into the atmosphere is directly proportional to the amount of jet fuel burned,[6] the overall quantities of CO_2 produced by the global air transport fleet can be determined relatively easily for the past and the present. As a result, the milestones for reducing CO_2 emissions shown in Figure 1-2 equally stipulate goals that directly address an envisaged increase in global fuel efficiency.

Figure 1-5 shows the historical evolution of the total CO_2 emissions per year produced by the global air transport fleet according to data provided to the public by the US Energy Information Administration (EIA) and the International Civil Aviation Organization (ICAO). By 2010, the total quantity of CO_2 emissions reached almost 600 Mio. tons, which, according to ICAO (2013, p. 31), corresponded to an overall contribution of 2% to the global human-made CO_2 emissions inventory and 13% to the CO_2 emissions inventory of the global transportation sector.

In addition, Figure 1-5 portrays the evolution of the average amount of CO_2 produced by the global air transport fleet per available seat kilometer (ASK). It thereby indicates the speed of advancement in fuel efficiency that aviation achieved until 2010. From 2003 until 2010, referring to the numbers shown in the figure, aviation actually reached an efficiency improvement of almost 3% per year. In 2010, the global air transport fleet emitted approximately 93 grams of CO_2 per ASK, while in the eighties and nineties of the preceding century, values of roughly 130 grams of CO_2 per ASK were only reached.[7]

1.3 Research scope and goals of thesis

Given the highly challenging goals that the global air transport industry has defined regarding the mitigation of its adverse impact on the global climate (→Figure 1-2), the question of how these goals can potentially be reached has to be addressed adequately. In order to approach this question, three essential capabilities are required:

---

[5] With an RF of 55 $\frac{W}{m^2}$ (excluding cirrus cloud enhancement), aviation is estimated to contribute approximately 3.5% to the total human-made forcing of global warming. (Lee *et al.* (2009, p. 3525)

[6] A mean value for the CO_2 emission coefficient of 3,155 grams of CO_2 per 1 kilogram of jet fuel burned can be assumed according to Hadaller and Momenthy (1989).

[7] The numbers given in Figure 1-5 may not exactly reproduce reality, as they were derived from different sources of data that may thus use different definitions of the 'global air transport fleet.' To provide the reader with an orientation concerning real-life values, it can be stated that, according to Rowe (2010), a Boeing 747-400 (first flight in 1988) and an Airbus A380-800 (first flight in 2005) produce approximately 101 and 75 grams of CO_2 per ASK, respectively.

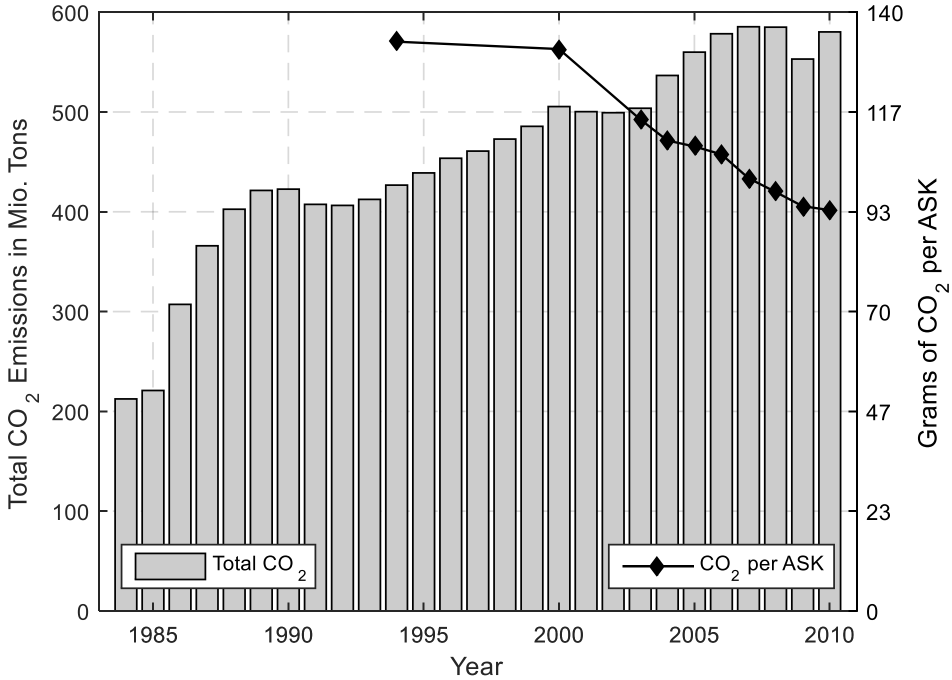


Figure 1-5 **Total CO_2 emissions produced by the global air transport fleet and CO_2 emissions per available seat kilometer**

Data sources: EIA (2015), ICAO (2014), author's calculations

Capability 1: The climate goals mentioned above refer to the global air transport industry. Consequently, estimations have to be made that stipulate the future economic development of the air transport industry as a whole and at a regional level.

Capability 2: The future evolution of the global air transport system in terms of size (i.e., number of active aircraft) and structure (e.g., network of air routes served, types of active aircraft, age distribution of active aircraft, and aircraft commissioning and retirement) has to be anticipated. This has to be made while taking into account the previously estimated economic development of the air transport industry.

Capability 3: The future performance characteristics of the global air transport fleet in terms of fuel burn and associated exhaust gas emissions production have to be quantified as a function of the evolution of the aircraft fleet.

In view of the three above issues, the paramount goal of this thesis is to quantitatively assess the effects of technological progress (i.e., the introduction of modern and potential future aircraft concepts and technologies) on the future performance of the global air transport fleet with emphasis on system-wide fuel burn and the associated production of exhaust gas emissions. Here, primary attention is paid to the estimation of the future production of CO_2 emissions and water vapor, while emission quantities of NO_x, CO, UHC, and PM are considered secondarily.

Accordingly, the thesis is intended to deliver an insight into the development perspectives of the global commercial air transport system for the upcoming decades and thereby supports a profound scientific discussion regarding the technological achievability of the climate goals shown in Figure 1-2.

For this, the thesis develops, portrays, and discusses a comprehensive methodological framework (referred to as the 'Aircraft Technology Assessment Framework,' abbreviated ATAF) that is capable of determining the development of the global air transport fleet as a function of time. A particular focus of ATAF is on modeling the introduction and propagation processes of new aircraft and aircraft technologies that join the world fleet at a predefined

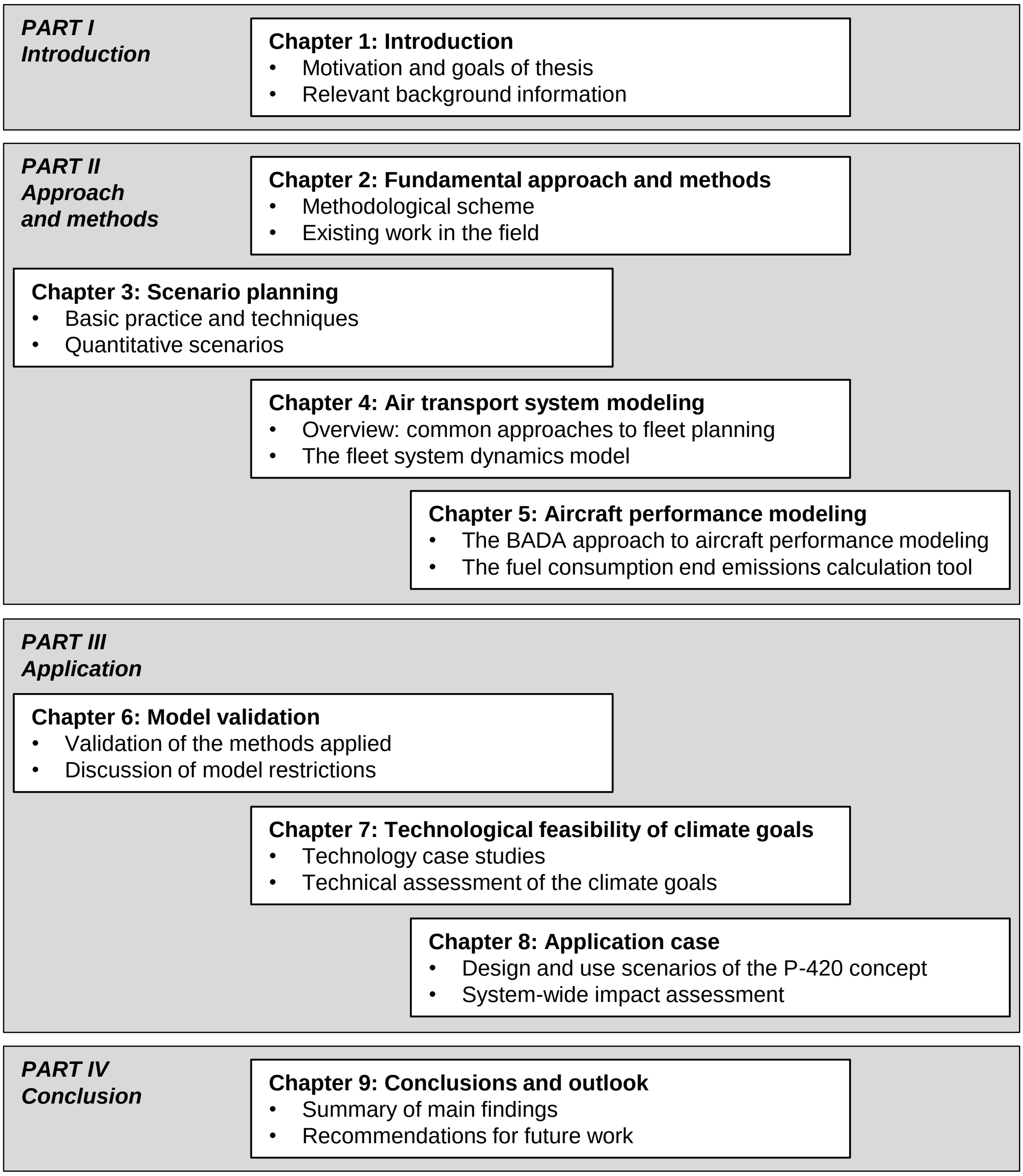


Figure 1-6 **Overview of the thesis structure**

moment in time. ATAF is built in a way to handle various input data, allowing comprehensive sensitivity studies on new aircraft and technologies and their impact on the global air transport system and its climate impact.

1.4 Structure of thesis

The thesis is essentially divided into four parts as shown by Figure 1-6.

The introductory part (→Chapter 1) depicts the motivation and goals of the thesis and additionally provides background information regarding aviation and its adverse impact on the environment, both at local and global levels.

Part II addresses the fundamental approach as well as all methods contained in ATAF to achieve the thesis goals as stated in Part I. After providing an overview of the paramount approach to the system-wide aircraft technology assessment developed here (→Chapter 2), the three essential methodological pillars of this thesis are subsequently portrayed in more detail. Hence, Chapter 3 reviews the basic practice and techniques of scenario planning, a methodology used to create multiple futures, representing the way used in this thesis to fulfill Capability 1 (i.e., stipulating the future economic development of the air transport industry, →Section 1.3). Chapter 4 then depicts the numerical model that was built to translate the data originating from the future scenarios into data related to the development of the global air transport fleet, which is intended to fulfill Capability 2 (i.e., anticipating the future evolution of the global air transport fleet in terms of size and structure). Finally, Chapter 5 presents the aircraft performance model developed and used here to quantify the scenario-related performance characteristics of the global air transport fleet in terms of fuel burn and associated exhaust gas emissions, aimed at fulfilling Capability 3.

Part III is dedicated to the validation and application of ATAF. In Chapter 6, the overall usability and functionality of ATAF are confirmed using data from other independent studies in the field. Moreover, model restrictions addressing simplification issues and limits of applicability are described in this chapter. With the support of ATAF, Chapter 7 then discusses and evaluates the fundamental achievability of the aviation climate goals (Figure 1-2) in terms of their technological feasibility by presenting multiple case studies that address alternative technological development scenarios. At last, Chapter 8 presents an application case of ATAF where a newly developed type of aircraft, the P-420 high-capacity transport concept, is evaluated with regard to its system-wide impact on fuel efficiency and exhaust gas emissions production. The chapter thus demonstrates how ATAF may be used as a support tool to anticipate the system-wide effects of an aircraft concept at its preliminary design stage.

Part IV (Chapter 9) of this thesis eventually summarizes the main findings and results of this thesis and briefly recaps the way they were achieved. It also provides various recommendations for future research activities that might follow the work presented here.

2. Fundamental approach and methods

ASSESSING future aircraft and aircraft technologies at a system-wide level (i.e., in consideration of the entire commercial air transport system and its future evolution) regarding their impact on total fuel burn and exhaust gas emissions production requires three basic capabilities: anticipating the future economic development of the air transport industry, correspondingly anticipating the development of the air transport system, and estimating the associated air transport fleet performance in terms of fuel burn and emissions production. This chapter gives an overview of the fundamental approach used in this thesis to provide these three capabilities as well as the methods involved. In addition, it describes what specific input data and infrastructure are needed for this approach to function properly. Finally, the chapter reviews the most relevant research work conducted by other institutions to approach goals similar to the ones of this thesis.

2.1 Overview and architecture

Figure 2-1 illustrates the methodological scheme that underlies the approach to system-wide aircraft technology assessment proposed in this thesis (ATAF). As shown by the figure, ATAF essentially follows a top-down scheme being composed of several modules that belong to the three basic capabilities of system-wide aircraft technology assessment (→Section 1.3). All modules are ultimately aimed at providing data required for determining the fuel and exhaust gas emissions-related performance of the global air transport fleet.

The initial step of ATAF is to specify the socio-economic and technological development of the *relevant environment* (→Glossary) that affects the air transport industry. As future is uncertain, multiple future scenarios, all of equal plausibility and probability, are built in order to cover a broad spectrum of possible futures with the intention of handling a certain minimum amount of imaginable future eventualities. Starting with an in-depth analysis and description of the status-quo situation, alternative development paths of the relevant environment are created that stipulate the socio-economic and technological situation in the target year of interest. This includes both qualitative and quantitative statements and data.

Evidently, the scenario building process is rather complex in nature, as it requires profound knowledge and extensive experience in social, political, economic, and technological matters and their interrelations with the global air transport industry and its development. Therefore, the process strongly relies on the expertise and contribution of a multidisciplinary team of experts and experienced professionals. As a result, the efficient and effective management of the scenario building process and the involved team is a challenging task that requires a highly systematic approach. In this context, *scenario planning* (→Glossary) provides a large number of techniques and best-practice guidelines that support the building of complex future scenarios. The scenario planning methodology is correspondingly employed within ATAF for the building of the scenarios. The theoretical foundations as well as some major best practices related to the building of scenarios are portrayed in more detail in Chapter 3.

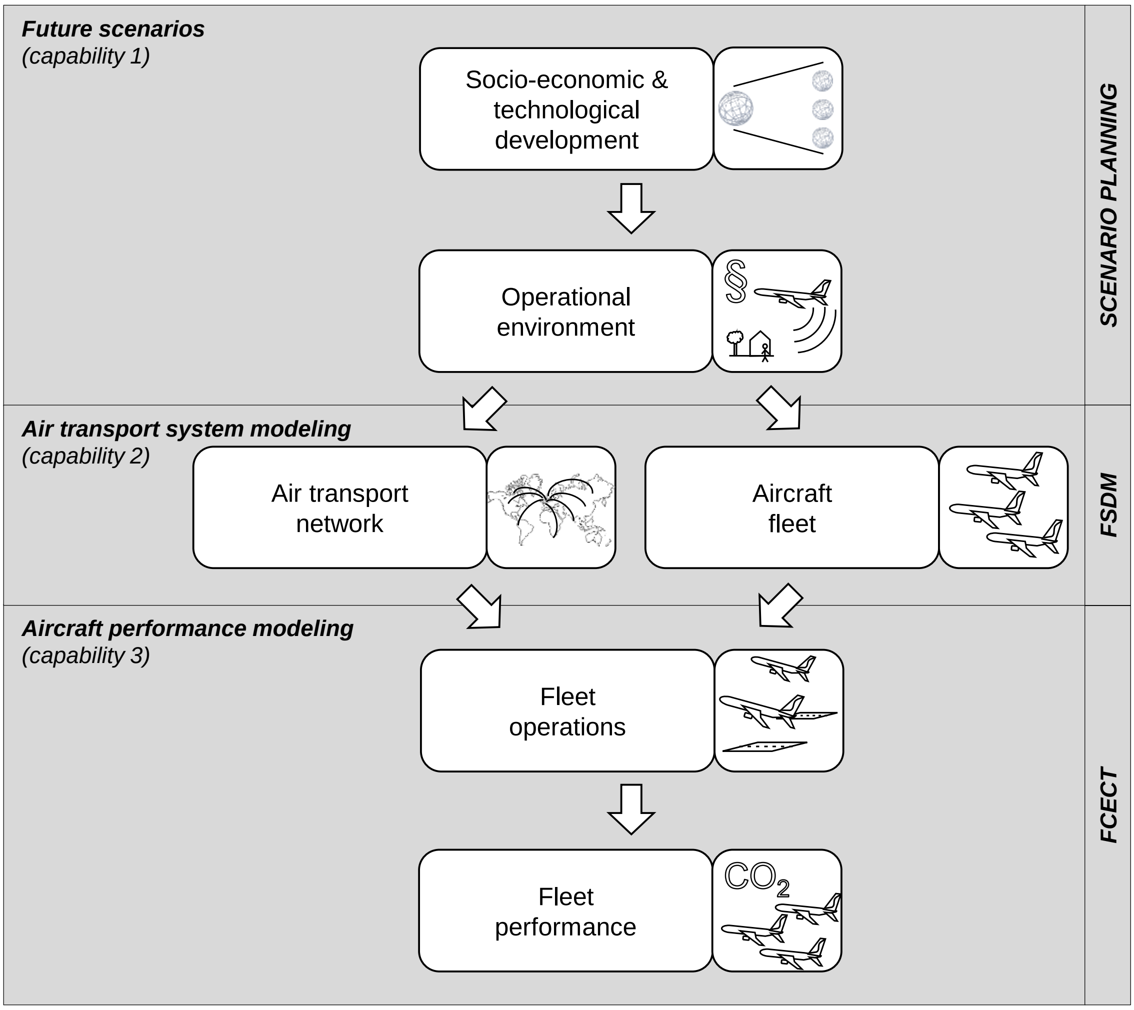


Figure 2-1 **Top-down approach to system-wide aircraft technology assessment: the Aircraft Technology Assessment Framework ATAF**

With the future scenarios available, the next step within ATAF is to derive the *operational environment* (→Glossary) in which the air transport system is going to operate and evolve. This particularly includes operational rules and regulations imposed by aviation authorities at both global and local levels in the different scenarios. It also comprises the physical environment in which aircraft move.[8]

Each scenario, and with it the relevant environment (of which the operational environment is a part), implicitly determines how the air transport industry will evolve into the future. Therefore, at the methodological center of ATAF, a model of the global air transport system consistently translates the scenario-related data into system-evolution data. An algorithm based on the principles of *System Dynamics* (→Glossary) was developed to accommodate the highly dynamic nature of this translation process on a year-by-year basis from the status-quo year until the target year of interest. This is achieved using a numerical fleet-simulation tool referred to as the 'Fleet System Dynamics Model (FSDM).'

The focus of the FSDM is on the simulation of two specific aspects of air transport system modeling, i.e., aircraft fleet modeling and air transport network modeling. The aircraft fleet module determines the size and structure of the global fleet of commercial transport aircraft for each year of simulation. Consequently, it must dynamically consider both the retirement

---

[8] For instance, consider a future scenario that may especially emphasize climate change leading to an increased occurrence of severe meteorological phenomena (storms, heavy rain, etc.), and hence negatively affecting aircraft operations on the ground and in the air.

of in-service aircraft as well as the commissioning of new types of aircraft (and technologies) as they become available at a certain moment in the simulated future. On the other hand, the air transport network module defines the physical characteristics (stage lengths in particular) of the air routes interconnecting local air traffic markets with each other to form the global network of air transport connections. The module additionally assigns the aircraft fleet determined by the fleet module to the network of air routes. In Chapter 4, the approach to fleet modeling with the FSDM is explained in more detail.

Finally, ATAF features the 'Fuel Consumption and Emissions Calculation Tool (FCECT),' which is an aircraft performance model being capable of simulating every flight operation performed by the aircraft fleet on the global air transport network as determined by the FSDM. Yet, the FCECT is a stand-alone tool and therefore does not require input data from the FSDM. In the stand-alone use case, various input parameters (e.g., flight distance, cruise altitude, payload carried) can be set by the user to simulate a particular flight mission with a particular type of aircraft. Likewise, the FCECT can be coupled to the FSDM to automatically determine fleet-wide performance characteristics such as fuel burn and exhaust gas emissions production.

The FCECT primarily relies on the BADA (Base of Aircraft Data) aircraft performance model that has been developed by Eurocontrol, the European air traffic management authority. Chapter 5 provides more details on aircraft performance modeling and BADA in particular.

2.2 Underlying philosophy of aircraft technology assessment

Given the modular architecture of ATAF (→Figure 2-1) that sets a particular focus on the numerical modeling of the dynamic evolution of the global air transport system as a function of distinct future scenarios, the philosophy of aircraft technology assessment underlying ATAF differs significantly from commonly applied approaches to aircraft and aircraft technology assessment. To better illustrate this issue, an example is given in the following.

Consider the Boeing 787-9 Dreamliner, a newly developed long-range airliner that made its first flight in 2013. Boeing assesses the Dreamliner in the following way:

> *"The Boeing 787-9 Dreamliner is the second member of the super-efficient 787 family. Both the 787-8 and 787-9 bring the economics of large jets to the middle of the market, with 20 percent less fuel use and 20 percent fewer emissions than similarly sized airplanes and passenger-pleasing features."*
>
> *(Boeing Commercial Airplanes, 2014b)*

Without qualifying or judging Boeing's assessment regarding the Dreamliner and its performance characteristics, one can still notice that the above text cannot be used to assess the impact of this aircraft type on the performance of the fleet of a particular airline. Neither is it possible to quantify the Dreamliner's impact on the global fleet performance (which is the goal of this thesis), as Boeing's assessment does not answer the following questions:

- Which type(s) of aircraft is the Dreamliner compared with?
- For what specific flight mission is the above assessment true? (Consider stage length, payload carried, altitude of cruise flight, meteorological conditions, etc.)
- What other (operational, physical, environmental, etc.) prerequisites have to be met in order to achieve the stated improvement in efficiency? (Consider restrictions imposed by air traffic management, airport infrastructure available, current traffic situation, etc.)

In other words, Boeing's assessment of the Dreamliner is only valid for one specific (yet unknown) flight mission under particular boundary conditions. It may help to get an initial estimate of the degree of technological progress and efficiency improvement of this aircraft relative to older types, but it does not support an understanding of the aircraft's behavior and effects under real-life conditions and operations at a fleet-wide level.

Hence, the decisive difference between the aircraft assessment methodology given in the example above and the methodology proposed in this thesis is the *perspective of assessment*. While in the Dreamliner example, the aircraft assessment is based on the exclusive consideration of one specific flight mission profile under predefined boundary conditions, the assessment methodology proposed in this thesis focusses more on the introduction and propagation processes of new aircraft (or technologies) and their effects at a fleet-wide level.

Once these effects are compared to predefined fleet-level goals such as the climate goals described in Section 1.1, quantitative assessment values can be assigned to the aircraft for each scenario under consideration. Eventually, these values will be more robust towards external variations, as they are based on a large variety of boundary conditions thanks to the consideration of the entire aircraft fleet, including a variety of flight mission and operation classes.

2.3 Input and infrastructure required

Each methodological part of ATAF requires specific pieces of input and infrastructure in order to deliver results that can actually help achieve the overall mission of this framework. In this section, these requirements are briefly presented and their characteristics discussed. This is done in an order that follows the methodological scheme of ATAF shown in Figure 2-1.

2.3.1 Future scenarios

As mentioned in Section 2.1, the creation of multiple scenarios that stipulate alternative development paths of the socio-economic and technological environment relevant to the global air transport system is accomplished through the scenario planning methodology. As will be shown in Chapter 3, this method relies on the knowledge and experience of those individuals that take part in actually building the scenarios, i.e., the scenario team members.

Therefore, the composition of the scenario team constitutes a critical input factor that strongly affects the quality and usefulness of the resulting scenarios, and the team members should be selected carefully. Chapter 3 discusses this issue in more detail.

In addition, as the team members should work on the scenarios together as a team and during a limited amount of time, the provision of adequate facilities (e.g., meeting and presentation rooms, computers, internet access, presentation materials, etc.) has to be ensured for this working process.

Finally, a moderator is needed who guides the team through the entire scenario building process while continuously examining its overall progress and effectiveness. He is equally responsible for ensuring that all requirements and boundary conditions are met to support a comfortable and non-disturbing working atmosphere.

2.3.2 Air transport system modeling

Air transport system modeling is accomplished in ATAF through the FSDM (→Section 2.1). As will be shown in detail in Chapter 4, the FSDM is a numerical model of the global fleet of commercial transport aircraft that is capable of dynamically simulating the evolution of the fleet on a predefined network of air routes based on the *System Dynamics* methodology (→Glossary).

An essential prerequisite for this model to function properly is the formulation of the initial conditions with which the model starts its dynamic calculation process. That is, an initial fleet and an initial routes network have to be defined a priori. Two particular databases are employed to provide the required data.

Official Airline Guide (OAG). OAG is a commercial database of scheduled flights provided by OAG Aviation Worldwide Limited. It contains extensive information for every scheduled commercial flight worldwide addressing its corresponding carrier name, flight number, name of origin and destination airport, great circle distance between the origin-destination (O-D) pair, local time of departure and arrival, period of effectiveness of the flight, number of flights offered within the period of effectiveness, type of operating aircraft, seat capacity offered, freight capacity offered, and some more data. The data provided by OAG can hence be used to determine the amount of ASKs and ATKs provided between a particular O-D pair within a specific period of time.[9] At the Institute of Aircraft Design of the Technical University of Munich (TUM LLS), OAG data is available for the period between November 2007 and October 2008. (OAG, 2008)

The data contained in OAG allow comprehensive statistical analyses of the transport performance of the air transport fleet at global and local market levels. However, caution must be exercised when doing so, as the database contains a non-negligible amount of duplicate entries that must be eliminated beforehand.[10] This is due to the fact that OAG has originally been designed for purposes of travel itinerary planning by airlines and travel agencies. Sutkus *et al.* (2001, pp. 12–15) distinguish three different categories of duplicate flights contained in OAG:

a) *Codeshare duplications*: OAG lists flights being simultaneously offered as codeshare flights by several airlines (i.e., cooperative flight sharing arrangements) individually under each airline's name. The actual (physical) flight is hence contained in OAG with an amount that is equal to the number of airlines partaking in the codeshare arrangement.
b) *Starburst duplications*: OAG lists certain flight segments of one-stop or multiple-stop flight itineraries individually, although in reality, the corresponding flights occur only once. This is true for those flight segments that airlines offer for the same physical flight using different flight numbers.[11]
c) *Effectivity duplications*: In certain cases, airlines sometimes change the flight number of a certain scheduled flight within its period of effectiveness (e.g., due to the sudden occurrence of single events such as a national holiday). OAG lists these flights separately. Counting these flights, however, would lead to a double-counting of the physical flight occurring in reality.

For all work presented in this thesis, only filtered OAG data were used that do not contain duplicate flights of the categories described above.

Aircraft Analytical System (ACAS). ACAS is a database of historical and present aircraft fleet information provided by Flightglobal, a subsidiary of Reed Business Information Limited. At TUM LLS, ACAS Version 2.5 with an update period until January 2008 is available. (Flightglobal, 2008) To access more updated fleet information, the freely available Excel spreadsheets provided by Verbrugge *et al.* (2013) are used as a complement in this thesis.

---

[9] Note that the OAG database does not provide information related to the payload factor of a particular flight, i.e., the ratio between the seats offered and seats actually sold (and freight tons offered and sold, respectively). Therefore, RPK and RTK information cannot be drawn from OAG.

[10] Duplicate flights refer to entries of scheduled flights contained in OAG that do not occur in reality. They should hence not be taken into account when conducting transport performance-related data analyses.

[11] This is especially the case for many long-haul flights carrying passengers with different origins but the same destination who have initially been carried to a central hub airport by feeder flights.

2.3.3 Aircraft performance modeling

In ATAF, aircraft performance modeling is accomplished through the FCECT.

Base of Aircraft Data (BADA). As mentioned in Section 2.1, the FCECT is based on the BADA aircraft performance model which is a reduced point-mass model based on a kinetic approach to performance modeling, the "Total Energy Model (TEM)." (Eurocontrol, 2015) Hence, BADA and its aircraft performance data files[12] represent an essential input for the FCECT and ATAF. The BADA approach to aircraft performance modeling as well as the FCECT will be presented in more detail in Chapter 5.

In its current revision number 3.12 (which is employed in this thesis), BADA supports the performance modeling of 166 different types of aircraft, including all major aircraft types of the currently operating commercial air transport fleet. In order to enable the consideration of future aircraft types that are currently not available in BADA (but required for the fleet-performance analyses of this thesis), the corresponding performance data files are derived from existing data of similar types.[13] For entirely new aircraft types such as the P-420 high-capacity transport concept (→Chapter 8), the related BADA performance data files are created using the Integrated Design Tool (IDT). IDT is a numerical tool developed at TUM LLS to support parameter variation studies for aircraft concepts at the preliminary design stage. (Kalwar, 2015; Kügler, 2014) More information about the IDT and its use is available in Chapter 8.

ICAO Aircraft Engine Emissions Databank. The BADA aircraft performance model merely supports the determination of fuel burn. Yet, within the scope of this thesis, quantities of aircraft exhaust gas emissions for each flight simulation are required as well. Therefore, the FCECT additionally employs data freely provided to the public through the ICAO Aircraft Engine Emissions Databank (ICAO EDB). This database contains the characteristics related to the production of exhaust gas emissions of all types of civil turbojet and turbofan engines that have been officially certified by ICAO.[14] (EASA, 2015)

FOI Database for Turboprop Engine Emissions. Since the ICAO EDB does not contain data related to civil turboprop engines, the FCECT employs a further databank in order to calculate emission quantities of turboprop aircraft, the Database for Turboprop Engine Emissions provided and maintained by the FOI (FOI EDB).[15] The data available in the FOI EDB are presented in the same format as in the ICAO EDB, but have not been officially endorsed by ICAO in a certification process. (FOI, 2015)

2.3.4 General computer and software infrastructure required

In general, ATAF has been designed in a way not to require extensive computational power and software infrastructure. While the methods covering capability 1 (→Figure 2-1) do not

---

[12] The FCECT requires only the 'Operations Performance File (OPF)' and the 'Airline Procedures File (APF)' of each type of aircraft. The 'Performance Table File (PTF)' and the 'Performance Table Data (PTD)' are not needed (→Chapter 5).

[13] For example, the performance model files of the Airbus A320neo with an entry into service in 2015 used in ATAF are derived from the existing files of the Airbus A320, taking into account the degree of efficiency improvement as declared by Airbus.

[14] The FCECT uses EDB data addressing the emission indices (i.e., values indicating the quantity of emissions per quantity of fuel burned) of NO_x, UHC, and CO to determine the corresponding emission quantities. To calculate PM emission quantities, the Smoke Number (SN) that is equally available in the EDB is employed (→Chapter 5).

[15] The FOI is the Swedish Defense Research Agency.

require the availability of specific software and computers at all, the FSDM and the FCECT do own more demanding requirements in this matter, though.

MATLAB®/Simulink®[16] is the primary software environment used for both tools, the FSDM and the FCECT. They were designed with the current release version of MATLAB® (R2014b), although they are likely to work properly with older releases of MATLAB® as well.

In addition, Microsoft® Excel® and Microsoft® Access® are employed to handle the databases described in the previous section.[17]

The development, debugging, application, and testing of all ATAF-related numerical tools were primarily accomplished on a Lenovo® ThinkPad® T520 machine featuring an Intel® Core™ i5-2430M processor with 4 Gigabytes of main memory and a hard drive of 500 Gigabytes.[18]

2.4 Existing work in the field

In this section, major research work of other institutions pursuing goals similar to the ones of this thesis is briefly reviewed with the purpose of providing an overview of the current trends and research activities within the scientific community.[19] In addition, the most important methodological differences of these studies by comparison with ATAF are summarized at the end of this section in order to reveal the scientific added value of ATAF as a framework to support the assessment of aircraft technologies at a system-wide level.

2.4.1 Background information and motivation

In view of the growth perspectives of the global air transport industry and the associated adverse impact of aviation on the environment examined by the 'Aviation and the Global Atmosphere' report of the IPCC published in 1999 (Penner *et al.*, 1999), the CAEP and the Framework Convention on Climate Change of the United Nations (UNFCCC) defined a series of environmental goals. This motivated numerous national and international research institutions to conduct extensive studies on the prediction of the future emission quantities of aviation (frequently referred to as 'aviation emissions inventories').

According to an analysis of these studies by Kim *et al.* (2007), among the most recognized ones have been the studies of NASA and Boeing (Baughcum *et al.*, 1996; Sutkus *et al.*, 2001, 2003), the 'Abatement of Nuisances Caused by Air Transport (ANCAT)/European Commission (EC) Group 2' report (Gardner, 1998), the reports of the Deutsches Zentrum für Luft- und Raumfahrt (DLR, German national aeronautics and space research center) (Schmitt and Brunner, 1997), and the 'Dutch Directorate-General of Civil Aviation's Aviation Emissions and Evaluation of Reduction Options Modeling System (AERO-MS)' report (Pulles, 2002).

However, Kim *et al.* (2007, p. 326) diagnose that the techniques and tools developed in these studies "were general unsuitable for long-term CAEP use as they fell short of one or more of the following: Non-proprietary data and methods that would provide the international aviation community with a clear understanding of how the model works (i.e., no

---

[16] MATLAB and Simulink are registered trademarks of The MathWorks, Inc., in the United States and/or other countries.

[17] Microsoft, Microsoft Excel, and Microsoft Access are registered trademarks of the Microsoft Corporation in the United States and/or other countries.

[18] Lenovo and ThinkPad are registered trademarks of Lenovo in the United States and/or other countries. Intel and Intel Core are registered trademarks or trademarks of the Intel Corporation in the United States and/or other countries.

[19] A more detailed overview and comparison of existing work in the field is provided for example in the publications of Olsen *et al.* (2013) and Schäfer (2006).

'black boxes'); a commitment by the developers to continue updating the data and methods used by the model, which are vital in the development of yearly inventories and tracking of temporal trends; and a dynamic and robust modeling environment that could be used to assess various scenarios." This circumstance led to the subsequent development of a 'second generation' of aviation emissions inventories of which the most important ones are reviewed in the following sections.

2.4.2 SAGE/AEDT

The System for Assessing Aviation's Global Emissions (SAGE) is a comprehensive computer model developed by the FAA in 2001 (and the following years) that focusses "on the development of yearly global inventories of commercial aircraft fuel burn and emissions of various pollutants to serve as the basis for scenario modeling." (Kim *et al.*, 2007, p. 325)

Its fundamental modeling unit is a single flight (i.e., the entire operational chain of a flight mission from gate to gate is taken into account). Hence, all information needed to describe the operations and performance values of an aircraft fleet (e.g., flight schedules, trajectories, aircraft performance parameters, and emission characteristics) is contained in SAGE in a way to support the simulations of single flights. Each simulation is conducted at a detailed level, featuring estimations of emission quantities for every individual segment of a flight (i.e., taxi operations, take-off, climbout, cruise, approach, and landing). This allows using the calculated data in a variety of different formats, including gridded plots of aviation emissions and their dispersion worldwide. (Kim *et al.*, 2007, p. 327; Kim *et al.*, 2005, p. 2)

The model is able to simulate all commercial flights worldwide for any day of a predefined year between 2000 and 2006. A forecasting module allows simulating the fleet development and operations based on future forecasting assumptions. (Kim *et al.*, 2007, pp. 327, 330–331)

Concluded at Version 1.5, SAGE has been "incorporated into the Aviation Environmental Design Tool (AEDT), which dynamically models aircraft performance in space and time to produce fuel burn, emissions, and noise." (FAA, 2010b) In this way, the AEDT has been developed as an extensive software tool that supports comprehensive studies "ranging from a single flight at an airport to scenarios at the regional, national, and global levels," replacing numerous older tools used by the FAA to assess the environmental effects of aviation. (Koopmann *et al.*, 2014, p. 1) A particular feature of the tool is the presence of a weather model that "allows for customization of weather conditions based on high-fidelity or airport-specific average weather data." (Koopmann *et al.*, 2014, p. 32) In this way, AEDT has become the primary tool used by ICAO to forecast the global environmental impact of aviation. (ICAO, 2013)

2.4.3 AERO2k

Within the 5th Framework Program project 'AERO2k' of the European Commission, a "new and improved global inventory of aviation fuel usage and emissions" was created by Eyers *et al.* (2004). AERO2k covers both civil and military flight operations. Emissions inventories are produced for two specific years, 2002 and 2025. For 2002, the "best available civil and military flight information" were employed, including radar-tracked flight data from movements over North America and Europe. This enhances "the knowledge of the actual global position at which aviation emissions actually occur." To forecast aviation emissions in 2025, "a scenario has been developed within AERO2k in which demand growth and technology improvements are based on estimates by Airbus and the UK DTI [Department of Trade and Industry of the United Kingdom]." (Eyers *et al.*, 2004, pp. 5–7)

The model is capable of simulating 40 representative types of aircraft using the PIANO aircraft performance tool.[20] Emission quantities are calculated based on flight altitude, current aircraft weight, and speed throughout all segments of an entire flight mission. The calculated emissions corresponding to each individual flight simulation are then summarized to form fleet-wide quantities that are eventually allocated to one of more than 3 million single cells on a 3D grid of the world globe. (Eyers *et al.*, 2004, p. 5)

2.4.4 Tetzloff and Crossley (2014)

In their work, Tetzloff and Crossley (2014) emphasize the fact that "the environmental and economic impact of a new aircraft is not solely a function of the aircraft's performance but also of how airlines use new aircraft along with other existing aircraft to satisfy the passenger demand for air transportation." (Tetzloff and Crossley, 2014, p. 1483) Hence, they have developed an optimization software that finds the optimal allocation of existing and future aircraft to the network of simulated air routes in terms of "minimizing fuel burn (and thus CO_2)," which represents the 'best-case' scenario concerning the environmental impact of the simulated fleet of aircraft. (Tetzloff and Crossley, 2014, p. 1486) The aircraft allocation problem is solved by employing the General Algebraic Modeling System (GAMS)[21] using the CPLEX[22] solver. (Tetzloff and Crossley, 2014, p. 1486)

The software can thus be used to assess the impact of new aircraft on the fleet-wide fuel-burn performance and equally evaluate the technical achievability of the climate goals related to global civil aviation (→Chapter 1). Therefore, with their work, Tetzloff and Crossley generally pursue goals very similar to the ones of this thesis.

They employ six different classes of aircraft (categorized according to their respective seat capacities) to represent the global air transport fleet, with each class featuring one specific representative-in-class, best-in-class, new-in-class, and future-in-class type of aircraft to address the technological evolution of the fleet. The Flight Optimization System (FLOPS)[23] is used to predict the costs, block hours, and fuel consumed for each simulated flight.

To reduce the complexity of the aircraft allocation problem underlying the approach of Tetzloff and Crossley, their numerical model does not capture the global network of air traffic routes, but utilizes the Worldwide LMI Network Queuing Model (WWLMINET)[24] that interconnects 257 airports in the United States and Europe, covering "65% of operations and

---

[20] The Project Interactive Analysis and Optimization (PIANO) tool is "an integrated tool for analyzing and comparing existing or projected commercial aircraft. It generates fast, accurate, industrial-quality evaluations […] covering geometry, mass, aerodynamics, flight performance, and other aspects." As such, it "can execute detailed flight performance calculations." (Lissys Ltd. (2015))

[21] GAMS "is a high-level modeling system for mathematical programming and optimization. It consists of a language compiler and a stable of integrated high-performance solvers. GAMS is tailored for complex, large scale modeling applications, and allows you to build large maintainable models that can be adapted quickly to new situations." (GAMS (2014))

[22] CPLEX is a "high-performance mathematical programming solver for linear programming, mixed integer programming, and quadratic programming." (IBM (2015))

[23] According to Case *et al.* (2007, p. 13), FLOPS is an open-source "software package that was developed at NASA for conceptual design and evaluation of aircraft. It allows a design space of up to 18 parameters and uses a combination of physical equations and empirical data fits to determine the best type of plane to perform a given mission."

[24] Schäfer (2006, p. 75) states that the WWLMINET is a derivative from a route network of commercial air traffic developed by the Logistics Management Institute (LMI), the LMINET. While the LMINET captures domestic en-route traffic and airport operations within the US, the WWLMINET covers 257 of the most frequented international airports with no coverage of en-route traffic.

80% of demand with an origin and/or destination in the United States." (Tetzloff and Crossley, 2014, p. 1485) The model is hence designed with a particular focus on the simulation of civil air traffic within and to/from the US.

Fleet performance simulations for 2005 and 2050 can be performed. Operational fleet statistics provided by the US Bureau of Transportation Statistics are used to determine the composition of the fleet size and structure in 2005. In order to calculate the fleet composition in 2050, the fleet forecast of the MITRE Corporation[25] is used as a means to provide a predicted breakdown of the aircraft fleet in terms of the six aircraft classes.

2.4.5 Jimenez, Pfaender, and Mavris (2012)

Jimenez *et al.* (2012) propose a numerical fleet-assessment model that is capable of dynamically simulating the evolution of the US commercial aircraft fleet, including a detailed modeling of aircraft retirement and replacement effects. Starting from the historical data baseline year (2006), future-year fleet compositions and operations are determined "by adjusting operations to reflect fleet retirements, replacements, and growth." The model formalizes fleet evolution "in terms of chronological order fleet generations, comparability of mission capabilities, and environmental performance improvements." (Jimenez *et al.*, 2012, pp. 1927–1928)

Jimenez *et al.* represent the base-year air transport fleet using six discrete aircraft categories. However, instead of utilizing a purely seat-capacity-based categorization frequently applied in other fleet models (→Section 2.4.4), their approach to aircraft grouping is capability-based, i.e., aircraft are grouped according to their chronological order of availability to the fleet (i.e., initial year of production), their specific mission capabilities (i.e., mission range and payload/seat capacity), and their environmental performance (i.e., fuel burn).

To simulate aircraft retirement, empirically derived survival curves provided by the FESG (2008a)[26] are employed that prescribe the percentage of aircraft that remain active within the fleet as a function of their age (see Chapter 4 for the related theoretical background information concerning aircraft retirement). By accessing the FESG retirement data, "retirements are modeled for each aircraft type as a percentage of operations of the 2006 reference set that it will no longer be assigned to in the out year." (Jimenez *et al.*, 2012, p. 1918)

In order to account for future aircraft types and technologies entering the fleet, a number of distinct new aircraft types being under development in the baseline year are considered for fleet introduction in a predefined entry-into-service year (e.g., Airbus A380-800, Airbus A350-900, Airbus A320neo, Boeing 787-8/9, Boeing 737max 7/8/9, Bombardier CS100/300).

Aircraft performance modeling is accomplished for current aircraft types through data provided by the AEDT performance model (→Section 2.4.2). Under-development aircraft types not being available in the AEDT datasets are modeled based on existing types of aircraft and by querying "publicly available information for approximate figures of fuel burn […], which are typically expressed relative to competitor aircraft or to aircraft targeted for replacement." (Jimenez *et al.*, 2012, p. 1923)

---

[25] According to MITRE (2015), the MITRE Corporation is a "not-for-profit organization that operates research and development centers sponsored by the federal government."

[26] The Forecast and Economic Analysis Support Group (FESG) is part of the CAEP. Following CAEP (2015), its "main role is to develop and maintain the databases necessary to provide the framework for performing economic analysis and forecasting fleet growth. It provides support to the other working groups within CAEP and works with them on data issues that concern more than one working group." (CAEP (2015))

2.4.6 Schäfer (2012)

Schäfer (2012) developed a comprehensive numerical model to quantify fuel burn and exhaust gas emissions of the global air transport system. The model employs a bottom-up approach for emissions calculation that is composed of a chain of software and database tools. The model essentially consists of three modules, an air-traffic-forecasting module, a route-network model, and an aircraft-performance module. In this sense, Schäfer pursues an approach to air transport system modeling similar to ATAF. His focus, however, is on determining future aviation emissions inventories instead of assessing the impact of new aircraft on fleet-wide performance metrics. Hence, his model can be coupled with DLR's in-house emissions inventory software FATE.[27]

Air traffic forecasting is accomplished in Schäfer's model through the utilization of air traffic growth data published in the Global Market Forecast (GMF) by Airbus S.A.S. (2011). The GMF is equally employed to predict the future size and composition of the global air transport fleet (→Section 2.4.8). In this context, a detailed "fleet rollover model" was developed to simulate the retirement of active aircraft and deliveries of new types. (Schäfer, 2012, p. 68) The model comprises four different categories of aircraft (turboprops, regional jets, narrow-body aircraft, and widebody aircraft), each containing particular types of current and future aircraft, as well as air freighters. For all types, specific delivery periods are defined.

The route-network module is based on global flight schedules data provided by OAG, covering monthly data of the years 2000, and from 2003 until 2010. The module converts the OAG data into a database of flight movements that is then supplemented by fleet data derived from the ASCEND fleet database (ASCEND Flightglobal Consultancy, 2011) as well as by load factor information from ICAO statistics. To account for inefficiencies regarding operational restrictions imposed by Air Traffic Management (ATM), various assumptions are made.

Similar to ATAF, aircraft performance characteristics and associated fuel burn quantities are determined using the BADA aircraft performance model. The ICAO EDB is employed to calculate exhaust gas emissions based on fuel burn. In addition, the model can be linked to the engine performance software 'VarCycle,' which is an in-house engine performance model developed by DLR. (Schäfer, 2012, p. 23)

2.4.7 Apffelstaedt (2009)

The work of Apffelstaedt (2009) aims at assessing the potential of new aircraft technologies and improved operations to increase the fuel efficiency (and hence reduce the CO_2 footprint) of individual aircraft types and the global air transport fleet. While the first part of his study discusses future options and effects of technological "key design variables" on the fuel consumption characteristics of aircraft in general, the second part elaborates on a concise future forecast of the global fleet that is then used to determine quantities of CO_2 in three different technology-driven scenarios ("pessimistic," "optimistic," and "trend").

Apffelstaedt (2009) does not rely on socio-economic forecasting data to derive growth rates of the future air transport system as in the case of ATAF. Instead, he directly utilizes fleet growth data of FESG (2008b) that he adjusts according to the global economic crises that prevailed in the years around 2009. He equally uses FESG (2008b) to predict the degree of utilization of aircraft over time as well as aircraft retirement functions ("Survival Curves," →Section 4.2.5). Data that he gathered through a comprehensive examination of aircraft order

---

[27] According to DLR (2009), the' Four-dimensional Calculation of Aircraft Trajectories and Emissions (FATE)' tool is a software developed by the Institute of Air Transport and Airport Research of DLR to create 4D emissions inventories of the global air transport system.

books and further relevant literature help him determine the future market shares of individual aircraft types and technologies within the global fleet. In this way, he is eventually capable of suggesting a forecast of the global fleet in terms of size and composition from 2009 until 2036.

In order to calculate fuel consumption (and related CO_2 emission quantities), Apffelstaedt (2009) does without an independent aircraft performance model but employs a statistical approach that is based again on a literature research. For each aircraft type being considered in his study, the average amount of fuel burned per block hour is determined at first. Then, this type-specific metric is multiplied with the average daily utilization of the relevant type. All obtained type-specific products are finally added up and thereby approximate the global fuel burn. A "specific carbon dioxide emission" factor is applied to calculate the corresponding CO_2 emission quantity.

Future aircraft types are modeled in terms of fuel burn per block hour through literature-based assumptions (i.e., fuel efficiency gains relative to reference types) and in terms of average utilization following FESG (2008b).

2.4.8 Fleet forecasts of commercial organizations

There is a plethora of aviation forecasts available, publicized by various commercial aviation stakeholders. In particular, the manufacturers of commercial transport aircraft publish aircraft fleet forecasts on a regular basis in order to update their shareholders and the interested community with information regarding the future sales potential of their aircraft portfolio. Hence, the intent of these reports is decisively not to determine future emissions inventories of aviation or to assess the environmental impact of future aircraft types and technologies.

The two most recognized commercial fleet-forecast reports are published by Airbus and Boeing once a year, each one featuring a twenty-year forecasting horizon. The underlying forecasting methodologies of these reports are depicted in the following, taking into account the relevant information given in the reports. It should be noted, however, that both Airbus and Boeing do not describe their forecasting methodologies in a precise and clear manner required for a profound understanding thereof.

Airbus Global Market Forecast (GMF). (Airbus S.A.S., 2014a) The methodological forecasting procedure employed in the GMF fundamentally distinguishes between the passenger aircraft forecast and the air freighter forecast. The former "consists of three main steps: the traffic forecast giving the overall shape of traffic evolution, the network forecast identifying the future evolution of the airlines networks, and the demand forecast estimating the number of aircraft required to accommodate the traffic growth." (Airbus S.A.S., 2014a, p. 173) The resulting data is then employed by the air freighter forecast to determine the future demand of freighter units, taking into account the cargo volume that is already transported by passenger aircraft (belly cargo).

To forecast global air traffic, the world market is divided into 19 traffic regions, resulting in more than 200 traffic flows within and between the regions. Then, using historical traffic volumes and both historical and forecast socio-economic data from "external data providers," "econometric equations" are fed to identify the one set or combination of variables that explains best the historical traffic evolution. With the best fit of equations and input variables, economic forecast data is used to derive the future traffic volume. (Airbus S.A.S., 2014a, p. 172)

The simulation of the airline-networks evolution aims at selecting "a subset of reasonable candidates […] for each airline" among a large set of potential new routes, based on an airline's current network structure and the growth potential and size of new markets. Around 800 different airlines and their subsidiaries are considered here. The set of new routes is then used as input for a "'Quality of Service Index'-based model, which determines for each new route the traffic potential and the point in time when it could be opened." (Airbus S.A.S., 2014a, p. 172)

Finally, the demand forecast aims at determining the number of aircraft needed by the airlines according to the forecast traffic development and route evolution. The new aircraft demand is expressed in seat categories, which "allows a view of future demand unconstrained by the product supply" (i.e., manufacturer production capacities are not taken into account), representing a best-match situation where airlines receive exactly the types and number of aircraft they require. (Airbus S.A.S., 2014a, p. 174)

Boeing Current Market Outlook (CMO). (Boeing Commercial Airplanes, 2014a) The CMO examines the travel demand of 63 intra- and interregional traffic flows. Relevant influencing factors are, among others, the global and regional development of the Gross Domestic Product (GDP), population, labor force composition, international trade, emerging technologies, business model innovation, and travel attractiveness. Each traffic flow is driven by different factors, and may hence experience a different evolution. (Boeing Commercial Airplanes, 2014a, p. 14)

Boeing emphasizes the difficulties in quantifying the effects of some factors on travel demand (e.g., market liberalization). "Where such factors are present, forecasting demand requires greater judgment than when the same factors are absent." (Boeing Commercial Airplanes, 2014a, p. 14)

2.4.9 Synopsis and comparison with ATAF

Table 2-1 provides a concise synopsis of the work and methods for the prediction of aviation emissions inventories and fleet forecasts presented in the above sections. In this way, the table enables a brief comparison with the ATAF methodology.

Table 2-1 Main features of ATAF and the work of other institutions

	Research goal	General future forecasting methodology	Fleet forecasting methodology	Aircraft performance modeling
ATAF	o Assessing the environmental impact of new aircraft concepts and technologies at fleet level (focus on global air transport system)	o Scenario planning is used to create global scenarios addressing the socio-economic and technological development	o Dynamic fleet model capable of simulating retirement, replacement, and introduction of new aircraft types	o Based on the BADA aircraft performance model o New aircraft types can be modeled using the IDT
SAGE/AEDT	o Creating global aviation emissions inventory (including aircraft noise emissions) o Analyzing distinct technology scenarios	o No independent forecasting module available o Future forecasting data required from external sources	o No independent fleet model available o Fleet data must be provided as input variables by external sources	o Based on the BADA aircraft performance model o Additional performance data from other sources are available as well

(Table continued on next page)

Table 2-1 (continued)

AERO2k	○ Creating global aviation emissions inventories for 2002 and 2025	○ No independent forecasting module available ○ One future scenario provided by Airbus and the UK DTI	○ No independent fleet model available ○ Fleet data must be provided as input variables by external sources	○ Use of the PIANO aircraft performance model
Tetzloff and Crossley	○ Assessing the environmental impact of new aircraft concepts and technologies at fleet level (focus on the WWLMINET)	○ No independent forecasting module available ○ Future forecasting data required from external sources	○ Use of the MITRE fleet forecast to determine the future fleet composition ○ Solving an aircraft allocation problem with the objective function of minimizing the total fuel burn	○ Use of FLOPS
Jimenez et al.	○ Assessing the environmental impact of new aircraft concepts and technologies at fleet level (focus on the US)	○ No independent forecasting module available ○ Primary use of the FAA Aerospace Forecast (FAA, 2010a)	○ Dynamic fleet model capable of simulating retirement, replacement, and introduction of new aircraft types	○ Use of performance data provided by the AEDT
Schäfer	○ Creating global aviation emissions inventories from 2011 until 2030	○ No independent forecasting module available ○ Use of the GMF	○ Dynamic fleet model capable of simulating retirement, replacement, and introduction of new aircraft types	○ Based on the BADA aircraft performance model
Apffelstaedt	○ Assessing the potential of new technologies and operations to mitigate CO_2 emissions of individual aircraft and global aviation from 2009 until 2036	○ No independent forecasting module available ○ Use of FESG data ○ Study focusses on three alternative technology scenarios	○ Fleet growth and retirement are simulated using forecast data provided by FESG (2008b) ○ A “market share” that is calculated with data available in relevant order books determines how quickly new aircraft types spread within the fleet	○ No independent aircraft performance model ○ Fuel burn and CO_2 emissions of each simulated aircraft type are calculated by using averaged fuel burn per block hour ratios; all ratios were determined through a comprehensive literature research
GMF/CMO	○ Determining the global sales potential of new aircraft	○ Use of historical data and extrapolation of long-term trends ○ Consideration of influencing factors and their impact on air traffic growth	○ Dynamic fleet model capable of simulating retirement, replacement, and introduction of new aircraft types for individual airlines	○ No fuel burn/emissions information available ○ No aircraft performance model available

3. Scenario planning

FUTURE is uncertain. To cope with future uncertainty, scenario planning is used in this thesis to generate 'alternative futures' addressing a broad range of potential paths of the socio-economic and technological evolution of the environment relevant to the global air transport system. The chapter focusses on actual experiences and application practices that originate from past scenario projects conducted at TUM LLS. It also discusses how to create and use quantitative and quantified scenarios, i.e., scenarios containing quantitative statements about the future. Background information as well as the major historical aspects of scenario planning are presented in Appendix A.

3.1 Scenario building using intuitive logics

In this section, a specific approach to the development of multiple scenarios is depicted that has been applied successfully in several future forecasting projects held at TUM LLS under the direction of the author of this thesis and his predecessors at the institute (e.g., → Phleps and Hornung (2013) and Strohmayer (2001)). In view of the positive execution and quality of the results obtained through this approach in each project, it has actually proven to be well working in practical application cases of the scenario planning methodology.

Note that the approach to scenario building applied at TUM LLS is depicted here in a generalized way, i.e., without referring to an actual research project of TUM LLS. Emphasis is also put on the fact that the TUM LLS approach is neither entirely new nor unique, but has been developed by consulting the relevant literature and adapting the principles declared there according to the specific needs and boundary conditions of the research projects at TUM LLS. The approach has been designed to follow the philosophy of the "approach to scenario planning" proposed by O'Brien (2004) and O'Brien *et al.* (2007). Therefore, as formulated by O'Brien *et al.* (2007, p. 217), the TUM LLS approach is a "qualitative, deductive approach, […] where the scenarios are constructed from a set of key uncertainties that shape the future of an organization's external environment." Note that the term 'key uncertainties' will be explained in the subsequent text.

The TUM LLS approach to scenario building consists of six methodological steps:

1. Defining the problem
2. Identifying the relevant environmental factors
3. Determining the key factors
4. Analyzing consistencies
5. Selecting raw scenarios
6. Elaborating scenario storylines

In the initial problem definition phase, the project leaders stipulate the thematic scope and goals of the scenario project. Furthermore, a multidisciplinary project team is compiled that usually comprises both selected industry professionals and researchers, as well as university students. As depicted in Appendix A, setting up the project team is a major preparatory task in order to ensure the later success of the overall project. Finally, the literature relevant to the

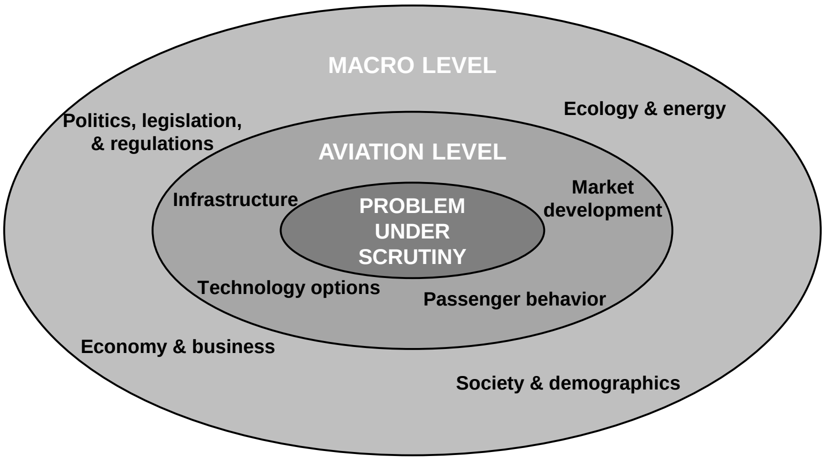


Figure 3-1 **The three-layer model of the scenario environment**
Source: author's creation based on Randt and Wolf (2014)

scope of problem and statistical data are scanned and prepared in a way to enable the project team to quickly access all information needed for the various upcoming project tasks.

Next, in order to identify all environmental factors relevant to the scope of problem, the project team conducts an in-depth analysis of the environment by utilizing a STEEP framework (→Appendix A). Usually, a list that contains the environmental factors used in preceding scenario projects is initially handed to the team to facilitate the search for factors and provide them with an idea of potential types of factors.

In order to take account of both paramount environmental factors at the macro level as well as factors specific to the aviation sector (that is considered in practically every scenario project at the institute) and the problem under scrutiny, a model of the environment is used that defines three different layers of detail (→Figure 3-1). The three-layer model supports the consideration and inclusion of a broad range of environmental factors by visualizing a large spectrum of aspects of the environment towards the project team. This project step ends with a typical number of fifteen to twenty-five environmental factors that the project team has identified.

Given the big amount of environmental factors determined, the complexity of the environment, and hence the number of the environmental factors, has to be reduced. Therefore, in the next step, the project team identifies the "key factors" (Gausemeier *et al.*, 1998, p. 116) by positioning all environmental factors relative to each other in a "driving force ranking space." (van der Heijden, 2005, p. 249) During this task, the team intuitively evaluates all factors in terms of their strength of impact on the problem considered as well as their degree of uncertainty concerning the way they may develop in the future.

As shown in Figure 3-2, the key factors are those environmental factors that are located in the upper right area of the driving force ranking space, thus featuring high uncertainty and high impact. That is why they are also referred to as "critical uncertainties." (van der Heijden, 2005, p. 122) Trends or premises are those factors that feature high impact, but simultaneously allow a relatively clear understanding of their future development. Finally, secondary factors show only a reduced impact on the problem, regardless of their estimated degree of uncertainty.

At the end of this project step, between six and nine key factors are typically found, with a maximum number of 10 factors. (A higher amount of key factors does not reduce the complexity of the environment, but unnecessarily complicates the entire scenario project.)

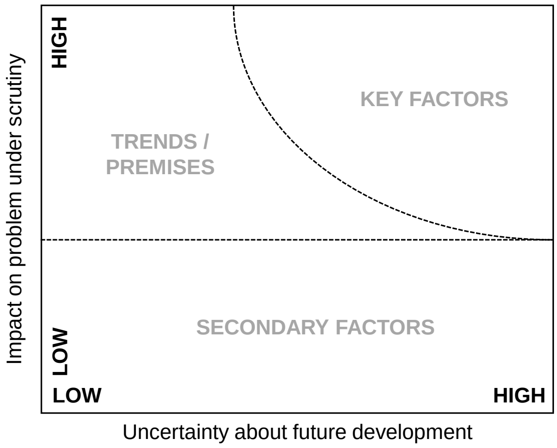


Figure 3-2 **Schematic display of the driving force ranking space**
Source: author's creation based on van der Heijden (2005, p. 249)

Subsequently, in the consistency analysis phase, the project team first describes several hypothetical future states of all key factors with the goal to address the range of their potential (and uncertain) directions of future development (→Appendix A). Here, between two and four future states per key factor are usually defined. While for some key factors, a linear scale for the description of future states may be appropriate (e.g., 'low,' 'moderate,' and 'high'), distinct future states may be defined for other key factors (→Figure 3-3).

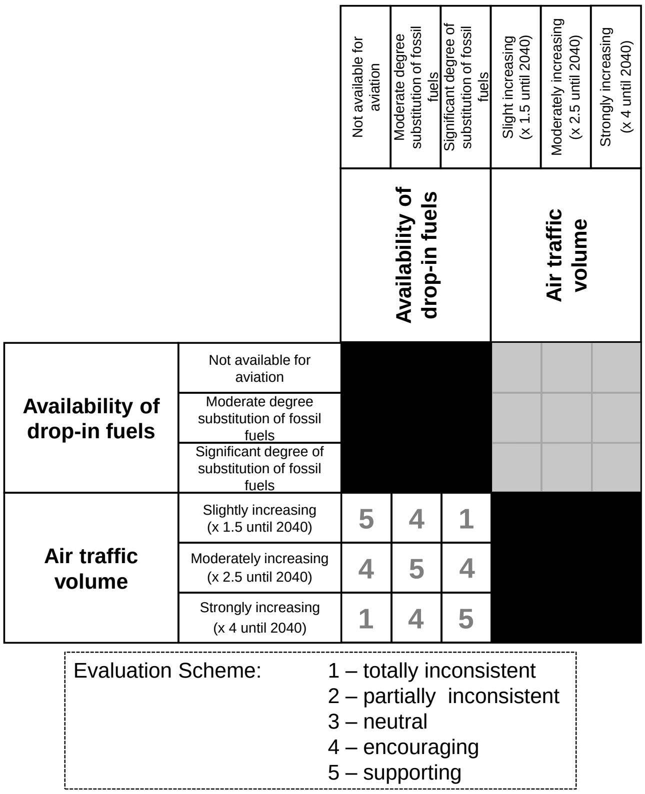
Then, after defining the future states of all key factors, all future states are mutually assessed on a pair-by-pair basis with respect to their consistency. That is, the compatibility of coexistence of all pairs in any imaginable future scenario is examined and evaluated. The question that has to be answered for every assessment is 'How high would the degree of compatibility be between future state X of key factor A and future state Y of key factor B if they coexisted in the future?'

To accomplish this task, the project team is provided with a "consistency matrix" in which all key factors and their previously defined future states are presented in the rows and columns of the matrix. As indicated by Figure 3-3, a quantitative five-step evaluation of the degree of consistency is conducted for all pairs of future states. Since the evaluation is always executed in a bidirectional way (i.e., directions of influence are not considered), only the lower half of the consistency matrix is completed. (Gausemeier *et al.*, 1998, pp. 121–122)

Note that like in the preceding steps of the scenario project, the team completes the consistency matrix solely based on their knowledge, experience, and intuition. This again underlines the importance of the team, its composition, and inherent expertise within the scenario project.

In the next step, a distinct number of combinations of future states of the key factors (i.e., raw scenarios, →Appendix A) is selected among the masses of mathematically possible key factor combinations. For example, consider the case shown in Figure 3-3 where two key factors are given, each featuring three different future states. From a purely mathematical perspective (i.e., ignoring the consistency assessment values), nine different raw scenarios ($3^2 = 9$) can be generated. Because of the exponential law underlying this topic, a huge number of raw scenarios is mathematically possible once the number of key factors and respective future states is increased (e.g., nine key factors with three future states per key factor lead to a number of $3^9 = 19{,}683$ possible raw scenarios).

It goes without saying that the handling of hundreds or even thousands of raw scenarios is impossible in any kind of scenario project. Therefore, the number of raw scenarios has to be reduced. This is accomplished through use of the previously generated consistency matrix: by



		Availability of drop-in fuels			**Air traffic volume**		
		Not available for aviation	Moderate degree substitution of fossil fuels	Significant degree of substitution of fossil fuels	Slight increasing (x 1.5 until 2040)	Moderately increasing (x 2.5 until 2040)	Strongly increasing (x 4 until 2040)
Availability of drop-in fuels	Not available for aviation	■	■	■	▨	▨	▨
	Moderate degree substitution of fossil fuels	■	■	■	▨	▨	▨
	Significant degree of substitution of fossil fuels	■	■	■	▨	▨	▨
Air traffic volume	Slightly increasing (x 1.5 until 2040)	5	4	1	■	■	■
	Moderately increasing (x 2.5 until 2040)	4	5	4	■	■	■
	Strongly increasing (x 4 until 2040)	1	4	5	■	■	■

Evaluation Scheme:
1 – totally inconsistent
2 – partially inconsistent
3 – neutral
4 – encouraging
5 – supporting

Figure 3-3 **Exemplary excerpt of a consistency matrix**
Source: author's creation based on Gausemeier et al. (1998, p. 122)

identifying those raw scenarios with the highest degrees of consistency, a greatly reduced amount of raw scenarios can be considered in the scenario project. Usually, a "scenario software" supports the project leaders in finding the most consistent raw scenarios among the many mathematically possible scenarios. (Gausemeier *et al.*, 1998, p. 121)

At TUM LLS, the scenario software package RAHS ("Risk Assessment and Horizon Scanning") is employed to numerically assist the selection of raw scenarios. RAHS is a "web-based foresight platform" developed to "facilitate systematic horizon scanning and long-term analysis of the strategic environment." The development of this software is a current research project at the strategy department of the German Federal Armed Forces. (Brockmann, 2012, pp. 6–7)

Besides the degree of consistency that serves as the most important criterion for selecting raw scenarios, further criteria may also support the selection process:

- The *degree of uniqueness* of one scenario among all others: according to the philosophy of the Intuitive Logics School (→Appendix A), multiple, equally plausible, and yet clearly distinguishable scenarios should be selected (see the 'scenario cone' displayed in Figure A-2).
- The *degree of surprise* of a scenario: a raw scenario that features a combination of future states of the key factors that appear implausible at first sight may actually become a highly interesting or challenging scenario once a deeper analysis of this scenario is undertaken.

Considering the above selection criteria, it is obvious that selecting raw scenarios cannot be automatized, but must remain a key task of the project leaders.

In the literature, there has been a continuous debate about how many scenarios should be created (Schnaars and Ziamou, 2001, p. 26), and "there is no precise response to the question as how many future scenarios are optimal." (Amer *et al.*, 2013, p. 31) Schnaars (1987, p. 108) claims that "there seems to be a consensus in the literature that three scenarios are best." Other authors recommend similar numbers. (Bradfield *et al.*, 2005, p. 808; Linneman and Klein, 1983; Durance and Godet, 2010, p. 1489)

At TUM LLS, most experience has been made in working with three scenarios (see Randt *et al.* (2015) for a recent example), although in some particular projects, a higher amount of scenarios was created. The final choice certainly depends on the particular needs and characteristics of the scenario project (e.g., project time available, team size and expertise, data available, and purpose of use of the scenarios).

The final step of the scenario building process deals with firstly integrating the remaining environmental factors (other than the key factors) to the raw scenarios, which is accomplished by intuitively defining future states of these factors that 'fit' each scenario, and secondly by elaborating the scenario storylines. Here, the goal is to create "stories or narratives that provide a vivid image of what some future end-state will look like." As such, the scenario storylines need to follow "a sequence of plausible, interrelated, connected events that make [the storylines] persuasive and believable." (Schnaars and Ziamou, 2001, p. 25) Well-written scenario storylines actually help their readers "identify themes that are strategically relevant" within the topical scope of the scenario project. (Schoemaker, 1995, p. 29) In other words, they point their readers to the important issues that the future environment may bring.

Writing scenario storylines apparently demands a certain degree of creativity from the project team, as the simplistic raw scenarios have to be transferred into conceivable images of alternative futures – especially targeted at those individuals who have not been involved in the scenario building process.

According to the experience of the author of this thesis, elaborating effective scenario storylines and communicating them to individuals outside the project team represent the most difficult tasks within the entire scenario project, as no best-practice guideline exists that could clearly define or suggest how to accomplish this task. Yet, good experience has been made with the practice that the project team produces contents specific to each scenario including

- a descriptive narrative of the scenario environment according to the three-layer model (→Figure 3-1),
- the formulation of five key messages of the scenario,
- a collage of pictures that illustrates the major aspects and statements of the scenario,
- and a timeline that describes how the future has evolved from the status quo into the future scenario by indicating some major evolution milestones or key events.

3.2 Scenarios and quantitative data

3.2.1 Necessity, benefits, and drawbacks

The approach to aircraft technology assessment proposed in this thesis utilizes future scenarios to stipulate the socio-economic and technological development of the relevant environment (→Figure 2-1). As such, the environment affects the global air transport system and controls the direction into which this system will evolve. The numerical model of the air transport fleet elaborated in this thesis (the FSDM) then translates the scenario data into data addressing the scenario-related fleet size and structure.

To be able to do so, the model requires quantitative input information provided by the scenarios (e.g., growth rates of regional air traffic markets and payload factor data, availability periods of aircraft types considered in the model, etc.; →Chapter 4). That is, purely qualitative scenario narratives (e.g., 'Air traffic will grow strongly in region A, while region B will suffer from a decline.') are not sufficient here. (For a more general view on this topic, see the work of Kirby and Mavris (1999, p. 2) and Chen *et al.* (1981, p. 28).)

Usually, quantitative data are hardly integrated into future scenarios. In fact, quantifying qualitative scenarios constitutes a highly challenging task that appears to be "rarely implemented in corporate foresight" and "there are few traces in the literature of numeric long-term models that include uncertainty that are applied in the corporate world of long-term planning." (Hirsch *et al.*, 2013, p. 366)

A reason for the predominant creation of qualitative scenarios is that most scenario projects are conducted with the goal to support strategic decision-making. (Varum and Melo, 2010, p. 364) Hence, quantitative scenario data is not needed here, as the scenarios are merely aimed at influencing decision-making "by way of the mind-set of executives." (Hirsch *et al.*, 2013, p. 366) Another reason is that the creation of quantified scenarios may require extensive numerical modeling that is able to project the complex interrelations among the considered environmental factors into the future. (Hirsch *et al.*, 2013, p. 365)

According to the experience of the author of this thesis, there are two fundamental drawbacks to quantitative scenarios in terms of their practical applicability.

- Quantitative scenarios are much more difficult to build (→next section). As the quantitative output data are strictly required to match the qualitative narratives of the scenarios, an in-depth understanding of the environmental factors and their interdependencies is vital but rarely available in scenario teams. If the data and narratives do not match, the scenarios will lack consistency, which will eventually result in some individuals ignoring the scenarios, or, in the worst case, questioning the methods and results of the overall scenario building process. This issue aggravates with a broader topical scope of the problem considered, as an increased amount of environmental factors has to be taken into account, eventually leading to a more complex network of interrelations and interdependencies between the environmental factors.
- Quantitative scenarios are much more easily contestable compared to purely qualitative scenarios because the quantitative data make hard and unambiguous statements, leaving no room for interpretation (which is either a positive condition or not, depending on the intended use of the scenarios). As a result, quantitative scenarios may be confused with forecasts or prognoses. When presenting quantitative scenarios, experience was made that some individuals (especially those who were not familiar with the scenario planning methodology) tend to focus purely on the quantitative aspects of the scenarios and neglect the 'softer' scenario narratives. Hence, these individuals tend to overestimate the validity and relevance of the quantitative data within the scenarios, misinterpret the scenarios and confuse them with forecasts, and thus may not grasp the key idea of scenario planning, which is to build and reflect on multiple futures.

On the other hand, working with scenarios that contain quantitative data features two major advantages, though.

- Quantitative scenarios require much less effort to be understood quickly and compared one to another. This constitutes a benefit in particular for those individuals who have not participated in the scenario building process, but who have to reflect on and work with the scenarios during subsequent project stages. If scenarios include quantitative statements about the future environment involving commonly known metrics (e.g., GDP development, oil price, tax rates, and inflation), they can be presented to a broad audience without the necessity of adapting or modifying them previously in order to make them more comprehensible.

- If scenarios are used to support corporate decision-making, quantitative scenarios provide a more solid basis for a decision to be taken and are thus more likely to lead to immediate action in a company – an observation that is confirmed by Hirsch *et al.* (2013).

3.2.2 Quantified scenarios vs. quantitative scenarios

If, for some reason, scenarios are required to contain quantitative data (as is the case in the context of this thesis), a fundamental methodological decision has to be made in terms of *when* quantitative data is inserted into the scenarios (i.e., at which point in time, either during the scenario building process or afterwards; →Chen and Kung (1984)).[28]

3.2.2.1 A-posteriori quantification of qualitative scenarios

The first option is to quantify qualitative scenarios in order to create *quantified scenarios* after the completion of the scenario building process, i.e., utilizing preexisting qualitative scenarios and identifying evidence contained in these scenarios that leads to the derivation of well matching quantitative data. There are two essential ways of how this task may be accomplished.

Consulting external expertise. A team of experts (who have not necessarily been a part of the scenario-building team) *interprets* the qualitative scenario storylines together with the scenario-project managers, and adds to these narratives the required quantitative information in a way to ensure consistency among the qualitative and quantitative scenario statements. In-depth knowledge of the socio-economic and technological environment described in the scenarios is required for this approach, hence the necessity to consult and integrate experts and professionals with profound experience in the relevant fields.

This technique is apparently of a rather intuitive nature, i.e., it neither features a systematic approach nor includes supportive tools (e.g., numerical models). The inherent consequence is that with an identical set of qualitative scenarios, two different teams of experts are very likely to produce two entirely different sets of quantitative data because their work substantially depends on the interpretation of the scenario narratives from the perspective of every individual expert. Even worse, an identical team of experts may produce two entirely different sets of quantitative data for an identical set of scenarios, depending on the prevalent boundary conditions and the moment in time when this task is accomplished.[29] In other words, consulting experts for the quantitative interpretation of scenario narratives will necessarily lead to the creation of highly ambiguous quantified scenarios.

Systematically deriving quantified data. Kuhlmann *et al.* (2009, p. 2) define the quantification of qualitative scenarios “as an elaboration of [scenario-related] results in higher detail and granularity by means of key values and calculations that are consistently derived from qualitative scenario conditions.” They propose a systematic approach to the quantification of qualitative scenarios. This approach essentially refers to the methodological approach to creating simulation models developed by Rabe *et al.* (2008, p. 5) and Wenzel *et al.* (2008, p. 6). Five steps are suggested (→Phleps (2011, pp. 72–73)).

---

[28] Parts of the information given in the subsequent sections are based on Steinmüller (2013).

[29] For example, in a period of global economic crisis, the expert team may derive rather conservative numbers while in a period of economic upswing, they may produce very positive numbers.

1. *Defining the scenario aspects to be quantified:* This step defines which aspects (i.e., environmental factors and their respective projections in each scenario) are supposed to be quantified assuming that not the entire range of factors is required to be quantified.
2. *Analyzing the system:* Each scenario (and with it the system of associated environmental factors) now has to be scanned for evidence regarding the key influencing areas within the scenario that can help derive the quantitative scenario data.
3. *Creating an (analytical) model:* The schemes of interrelation and interaction behavior between the previously identified key influencing areas then need to be described by creating an (analytical) model that is aimed at capturing the reaction behavior of a factor that is to be quantified as a function of the behavior of the key influencing areas modeled.
4. *Defining key indicators:* According to Phleps (2011, p. 73), there are circumstances under which the mere quantification of environmental factors does not suffice to provide the quantitative data desired after completion of the post-processing of a scenario.[30] In this particular case, 'key indicators' need to be defined in addition to the already existing environmental factors that help stipulate the quantitative data required. In this context, Kuhlmann *et al.* (2009, p. 2) propose several sources that support the quantification process.[31]
5. *Analyzing and defining the status quo:* This step refers to the initialization of the model developed during step 3, which is aimed at ensuring that the 'order of magnitude' or the 'range' of each indicator remains within plausible limits. (Phleps, 2011, p. 73)

Phleps (2011, p. 74) underlines that this approach is apt to increase the overall workload of a scenario project to a significant level, particularly due to the highly likely unavailability of information needed for the status-quo analysis (step 5). In addition, he points out that the creation of the analytical model and the definition of the key indicators (steps 3 and 4) represent very complex tasks.

3.2.2.2 Building quantitative scenarios

Scapolo (2005, p. 1059) emphasizes that "the level of participation [in a scenario project] is crucial for gathering knowledge in foresight and for the transfer of insights into decision-making." [cited after Hirsch *et al.* (2013, p. 367)] Moreover, Hirsch *et al.* (2013, p. 367) particularly underline that "a transparent and open scenario process facilitates acceptance and encourages participation." In consequence, the a-posteriori quantification of qualitative scenarios described in the previous section must be considered as a technique that highly discourages acceptance and participation, as the quantification process usually inhibits the scenario team members from contributing their knowledge.

Therefore, the second option available for the insertion of quantitative data into scenarios is established by the creation of *quantitative scenarios* right from the beginning of the scenario building process, which actively includes the scenario team and thereby explicitly encourages

---

[30] For example, the quantification of the change p.a. of the global GDP in a particular scenario does not stipulate per se the growth rate of the global air transport market in this scenario that may actually be required at the end of the scenario quantification process.

[31] Here, Kuhlmann *et al.* (2009, p. 2) distinguish between "preset conditions" (scenario-unspecific premises, scenario-specific premises), "resulting conditions from scenarios" (direct factors and indicators, indirect factors and indicators), and "assumed conditions of factors and indicators not covered by the scenario process."

participation and acceptance. This is the option selected in the context of this thesis. Here again, two fundamental approaches can be differentiated.

Parallel numerical modeling. In the face of the above-described findings, Hirsch *et al.* (2013, pp. 367–371) propose an approach to the creation of quantitative scenarios that prescribes a systemic numerical modeling of the scenarios parallel to the creation of the qualitative scenario parts. In particular, the authors recommend using *System Dynamics* (→Glossary) as a means to produce the scenario model, as its visual depiction "closely resembles an interaction diagram emerging from causal analysis," which will therefore correlate the qualitative and quantitative parts on the scenario model and help easily refine both in parallel.

The main principle of this approach is to translate the environmental key factors identified in the scenario project (→Figure 3-2) into "exogenous parameters at the border crossings of the system boundaries." Monte Carlo simulations (Liu and Chen, 1998) may be conducted to analyze the inherent sensitivities of the model. The approach essentially comprises five steps.

1. *Defining the model purpose and boundaries:* The desired output of the model is defined here. This is to ensure minimal efforts and complexity when creating the model. The authors especially note that the "aim should never be to assume to reach a higher precision through numbers, but to clarify the dynamic relations between influencing factors."
2. *Analyzing the key factors:* The goal of this step is to allocate "parameters to all key factors that allow for a numeric indicator with sufficient validity." Mathematical relations between the key factors are established that provide "a good first estimate on the impact of each interaction."
3. *Developing key factor projections.* In this step, specific projections of the key factors are developed. Here, "the quantification needs to identify concrete dynamics that point towards alternative futures."[32] The relations that have been created within the model "may already serve to estimate ranges of projections or the speed of change […] and can be underpinned with conventional regression or correlation analysis." The authors additionally recommend linking "the ranges of projections both to the statistical analysis as well as to assumptions on projections that might leave the trajectory as suggested by statistics."
4. *Modeling of consistent raw scenarios:* Now, the projections of the key factors are combined to "fit with each other to constitute draft scenarios."[33] Regarding the quantitative part of the scenario building process, the actual mathematical model is developed in detail, i.e., the interrelations among the key factors "are formalized with equations."
5. *Communicating the scenarios:* In this final step, the output data produced by the model are used to underpin "the main characteristics [of each scenario] with numbers to form a concrete future space." In this context, the authors underline, however, that "several facets of futures cannot be put into numbers."

Hirsch *et al.* (2013, p. 373) conclude that their approach "can be one tool to improve how scenarios are used more directly for actual, present-day decision-making – while at the same time improving the quality of the scenario project's results." Yet, the amount of workload required for creating the System Dynamics model should not be underestimated.

A similar approach is suggested by Pfaender and Mavris (2006), based on the research work of Pfaender (2006). In view of ever changing, unpredictable market needs and customer

---

[32] That is, the questions of 'How much?' and 'When?' need to be addressed properly for every projection.

[33] The terms 'draft scenario' and 'raw scenario' are used synonymously here.

requirements that prevail particularly in the aviation industry, they present "a high-level, System Dynamics model that captures the dynamics of a commercial transport aircraft market." (Pfaender and Mavris, 2006, p. 4) By means of a comprehensive set of key actors and variables that are interconnected through functional relations, the model determines the individual market attractiveness of competing aircraft types. It can hence identify their market shares under different scenarios, which may help designers of transport aircraft evaluate various (i.e., including revolutionary) concept ideas already at a very early stage of development ("Inverse Design," →Pfaender (2006, pp. 169–172)).

Pfaender and Mavris (2006) validate their System Dynamics market model with a real-life case study of two competing aircraft types and can therefore prove its fundamental functionality. Yet, Pfaender (2006, p. 189) explicitly underlines that "much care has to be taken to impose strict limits on the ranges of the […] variables [of the System Dynamics market model]." He generally sees that "a large number of System Dynamics models can exhibit very unstable behavior due to rapid changes in key process rates, which means that they have to be extensively calibrated and mechanically checked for stability and consistency of behavior at extreme settings."

The System Dynamics market model comprises an extensive number of variables. Therefore, with regard to the usability of the model, Pfaender (2006, p. 192) concludes that there is "a practical problem due to the effort that has to be undertaken in controlling and managing the appropriate ranges for such large amounts of data. Furthermore, there exists also a computational limitation due to this."

These statements give again an indication of the workload required to develop and interpret a properly functioning System Dynamics model for the purpose of quantitative scenario analyses. On the other hand, the work of Hirsch *et al.* (2013) and Pfaender and Mavris (2006) clearly demonstrate that System Dynamics can be used effectively for the creation of complex quantitative scenarios.

Intuitive modeling. To generate its long-term forecast, Eurocontrol (2010, pp. 29–32) employs a method that "uses a model of economic and industry developments to grow the baseline airport-pair traffic and produce a view of future flight movements."

This model is not depicted in detail here, as it is actually not intended for use within the methodological framework of scenario planning. Yet, the underlying philosophy of establishing and modeling the interrelations between the environmental factors makes the model very appealing in terms of practical applicability and complexity.[34] In fact, it has already been applied successfully in several scenario projects at TUM LLS and is hence employed in the context of developing quantitative scenario data within ATAF.

The approach to the quantitative modeling of the interrelations between the environmental factors can be referred to as an 'intuitive modeling' approach. It is furthermore aimed at quantifying the impact of a set of environmental factors on a desired output factor. Figure 3-4 schematically illustrates the approach.[35] Three steps are conducted to determine the required output data.

1. *Stipulating quantitative factor projections:* The first step requires that the projections of the environmental factors have already been defined in a qualitative way and that a number of consistent raw scenarios have been selected (see steps 4 and 5 of

---

[34] The reader's attention is especially drawn to Figure 24 in Eurocontrol (2010, p. 31).

[35] The figure exemplarily shows the hypothetical impact of five different environmental factors on the change p.a. of the global RPKs.

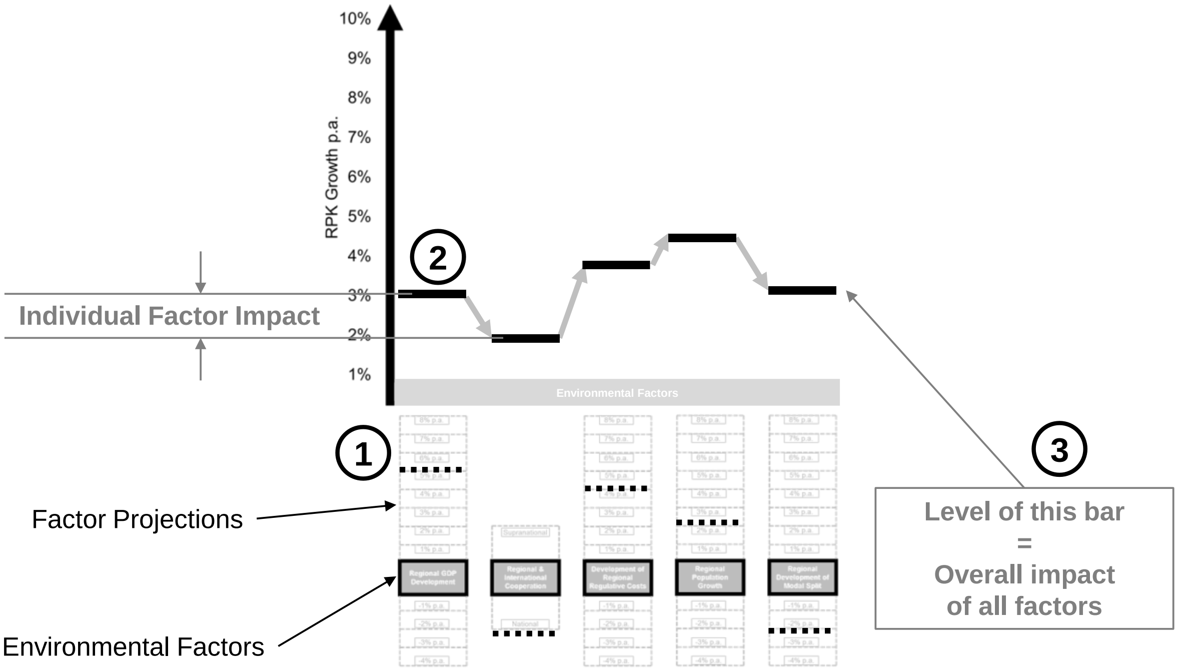


Figure 3-4 **Systematic intuitive-modeling approach to the quantification of environmental factor interrelations**
Source: author's creation based on Eurocontrol (2010, p. 31)

the TUM LLS approach to scenario building depicted in Section 3.1). Now, the scenario team stipulates the factor projections more precisely for each raw scenario by defining appropriate numbers.[36] The team may accomplish this task by accessing its own knowledge and experience, through intense discussions, and by consulting the relevant literature and statistical databases.[37] External experts may contribute to this task as well, provided they act as task supporters (i.e., not as task owners).

2. *Estimating the individual factor impact:* Once a quantitative projection has been defined for each environmental factor in every raw scenario, the individual impact of the factor on the desired output is examined separately.[38] This task again requires detailed knowledge in the relevant fields that can be gained by accessing the relevant literature, statistics, and external expertise. However, more important than identifying the scientifically correct impact of a specific factor (which may not even be possible in certain cases) is to ensure that the scenario team reaches a consensus about the quantitative impact, which will foster the overall acceptance of the scenario among the team members.
3. *Estimating the overall impact of all factors:* The last step is to sum up the individual impacts of all environmental factors to obtain a final number. This number will

---

[36] For example, the scenario team may have initially defined the projections of the environmental factor 'Global GDP growth' as 'low,' 'medium,' and 'high.' In the next step, the team is supposed to define a specific number in terms of a percentage of change p.a. for each projection.

[37] Adequate resources must be prepared, presented, and provided by the scenario-project managers beforehand.

[38] In the example case shown in Figure 3-4, the impact of each factor is determined by proceeding from the left to the right side within the diagram. Here, the level of the bars indicating the RPK growth p.a. take into account the effects of both the current and the preceding environmental factors. Therefore, the difference in height between one bar and its successor indicates the individual impact of an individual factor.

eventually reflect the total impact of the entire system of factors on the output factor.[39]

Of course, this approach induces a significant workload for the scenario team.[40] Here, a thorough preparation of supportive materials (e.g., relevant literature, databases, introductory presentations given by external experts) by the scenario-project managers can greatly facilitate the tasks involved, though. After all, the decisive advantage of the approach is that the entire scenario team takes part in the quantification process of the scenarios so that numbers are generated that establish a 'common ground' among all team members.

---

[39] In the example case shown in Figure 3-4, the bar at the very right position of the diagram indicates the total impact of all factors.

[40] However, the workload is certainly not higher compared to the other approaches to scenario quantification presented in the previous sections.

4. Air transport system modeling

THE socio-economic and technological environment stipulated by the future scenarios (→Chapter 3) impacts on the development of the future air transport system (→Figure 2-1). This chapter depicts the technique employed in this thesis to consistently translate this impact into quantitative data that captures the shape and characteristics of the air transport system. The chapter starts with a brief definition of the term 'air transport system' used in this thesis. It then reviews the fundamentals of aircraft fleet planning in general, as the relevant methods thereof constitute the foundations for the modeling of the air transport system. Finally, the Fleet System Dynamics Model (FSDM) is portrayed, which is a numerical model of the air transport system representing the 'methodological heart' of the Aircraft Technology Assessment Framework developed in this thesis.

4.1 The global air transport system: A definition

There are various definitions of the 'global air transport system' proposed and discussed in the literature. According to Mensen (2007, p. IX), the air transport system comprises three essential functional areas, which take responsibility for transporting passengers, freight, and post by air:

- *Airlines and other commercial aircraft operators* generating the actual transport performance within the air transport system through aircraft operations
- *Airports* providing the infrastructure required for the handling and processing of air passengers, freight, and post
- *Air traffic management (ATM) authorities* ensuring the safe, conflict-free, and economic execution of all aircraft operations

Mensen (2007, p. XI) additionally mentions the regulatory authorities that set the legal framework for aircraft operations at regional, national, and global levels.

Within the scope of this thesis, the *air transport system* is defined in a more narrow way, though. As shown in Figure 2-1, the air transport system is considered here as a system of aircraft (referred to as an *aircraft fleet*) that operates on a specific *network of air routes*.[41] Airports are explicitly not included in this definition. ATM authorities are only accounted for indirectly by considering their influence on the way aircraft are legally allowed to be operated. Table 4-1 provides an overview of those characteristics and metrics that are employed in this thesis to describe the two components of the air transport system relevant in this thesis.

Considering the above definition, it is also vital to define what particular aircraft categories and types are considered as part of the air transport system. In this thesis, the definition applied is given according to the OAG database of scheduled flights (OAG, 2008) described in Section 2.3.2.

---

[41] The *global* air transport system is hence a system that extends globally, i.e., throughout the entire world globe.

Table 4-1 **Characteristics and metrics of the global air transport fleet**

Air transport system	
Aircraft fleet	**Air routes network**
Size (number of operating aircraft)	Number of air routes
Composition (types of operating aircraft)	Length of air routes
Age distribution (age of individual aircraft units)	Geographical position of air routes
Capacity (seats, freight volume, range capabilities)	
Performance (fuel burn, emission quantities, flight speed)	

Here, the OAG aircraft categories 'Narrow-body Jet (JN),' 'Widebody Jet (JW),' and 'Turboprop (T)' are considered.[42] Table C-1 in Appendix C displays all types of aircraft considered. This definition implies that General Aviation aircraft, helicopters, and military aircraft are not taken into account.

4.2 Aspects and methods of airline fleet planning

4.2.1 Definitions and global objectives

Clark (2007) proposes the following definition of 'fleet planning.'

> *"Fleet planning is the process by which an airline acquires and manages appropriate aircraft capacity in order to serve anticipated markets over a variety of defined periods of time with a view to maximizing corporate wealth."*
>
> *(Clark, 2007, p. 1)*

Hence, fleet planning provides an airline with the methodological framework to be able to handle questions in their strategic planning like

- which types of aircraft to acquire,
- how many units of a specific aircraft to acquire,
- at which moment in time to acquire a new aircraft, and
- at which moment in time to retire aircraft currently in service.

Fleet planning represents one of the three essential strategic planning tasks of an airline with the other two tasks referring to the route planning ("where to fly the aircraft profitably, subject to fleet availability constraints") and the schedule development ("how frequently and at what times on each route should flights be operated, subject to operational and aircraft limitations"). (Belobaba, 2009, p. 153)

With the ultimate goal to maximize yield (or profit) within a certain period, airlines seek to plan their fleet according to "three basic attributes." (Clark, 2007, pp. 29–36) A 'good' fleet plan firstly fosters adaptability, i.e., the ability of the fleet to adapt smoothly to a dynamic variation of customer demand. This, however, does not only include a changing demand for transport capacity, but also a varying demand for a certain minimum level of travel comfort desired by the airline customers, which necessitates adaptable aircraft cabin configurations. Technical (i.e., range capabilities, flight speed capabilities, etc.) and economic capabilities of the fleet determine its adaptability as well.

Then, the second important attribute of a good fleet plan is to support flexibility of the fleet. This addresses the ability of the fleet to serve a large spectrum of different routes in a volatile network with an adequate degree of versatility in terms of transport capacity, which obviously requires a trade-off between fleet flexibility and fleet costs. Moreover, the fleet plan

---

[42] New or future types aircraft of equal categories not being listed in OAG (2008) are also considered part of the air transport system (e.g., Airbus A350, Boeing 777-X).

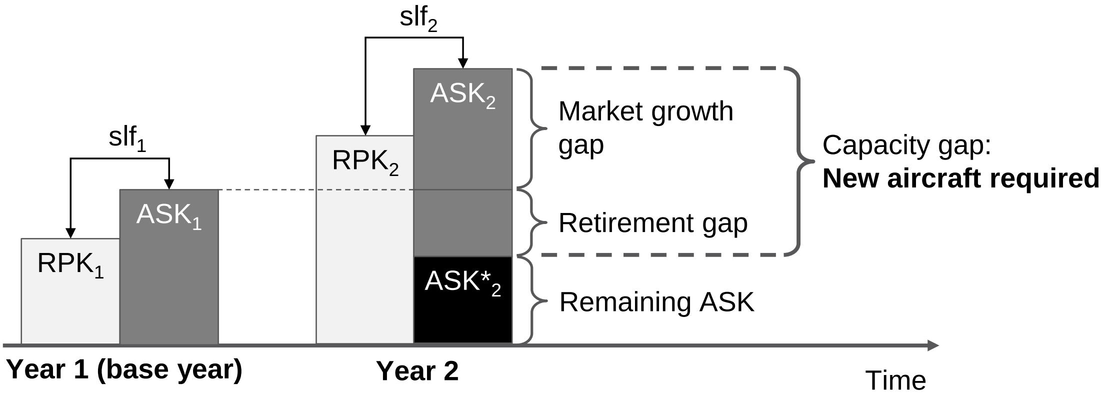


Figure 4-1 **Methodological scheme of the macro approach to fleet planning**
Source: author's creation based on McDonnell Douglas Aircraft Company (1981), cited after Belobaba (2009, p. 161)

should allow for easy phasing-in and –out of in-service aircraft units depending on the current situation of demand.

Finally, the fleet plan should properly address continuity. That is, the fleet and its technical and economic characteristics should not vary substantially over time, as in the opposite case, the airline would be required to reorganize its fleet-support strategy (e.g., aircraft maintenance, passenger handling) too frequently, which would result in high administrative expenses.

Given the paramount goal of an airline to maximize yield, tradeoffs are required to achieve this goal alongside with the three attributes of a good fleet plan. Therefore, airlines usually employ large-scale optimization models that have played "a significant role in shaping today's airline industry." (Jacobs *et al.*, 2012, p. 35) More generally speaking, two fundamental approaches to fleet planning have evolved over the last decades. These two approaches are described in the following sections.

4.2.2 The macro approach to fleet planning

The "macro approach" to fleet planning (Clark, 2007, pp. 50–55), also referred to as "top-down approach" (Belobaba, 2009, pp. 160–162), is utilized at a relatively high level of aggregation, i.e., considering the entire network of an airline or, at minimum, a number of smaller sub-networks. In this sense, the macro approach "is an excellent starting-point to get a grip on the magnitude of the capacity needs" of an airline. (Clark, 2007, p. 55) As the approach requires neither extensive data input nor complex analytical models, a macro fleet plan can be created rather quickly, which allows conducting a large number of sensitivity analyses (considering a variation of the input data required for the approach) with little expenditure of time.

The underlying principle of the macro approach is to determine the "capacity gap" (Belobaba, 2009, p. 161) from one year of interest to the subsequent one. The capacity gap is the mere result of the change in *transport supply* from year to year offered by the airline (based on an anticipated change in *transport demand* requested by the airline customers) as well as a *loss* in transport supply due to the necessary *retirement* of in-service aircraft units. Figure 4-1 schematically illustrates the capacity gap.

As shown in Figure 4-1, the airline determines the transport demand (and its market share in case adequate data of competing airlines are available) according to equation (4-1), given in Revenue Seat Kilometers of the base year of calculation (RPK_1).

$$\boldsymbol{RPK_1 = \sum_k p_k \cdot d_k} \tag{4-1}$$

$\boldsymbol{RPK_1}$ … *Transport demand (passengers) of the base year*

$\boldsymbol{k}$ … *addressing one flight performed by the airline*

$\boldsymbol{p}$ … *number of passengers transported*

$\boldsymbol{d}$ … *great circle distance between origin-destination pair of flight k*

In order to provide sufficient supply to accommodate the transport demand RPK_1 and to avoid an unnecessarily high value of demand spill,[43] the airline offers a number of seats to the market in the base year higher than the number of passengers who could be transported (ASK_1). The seat load factor (SLF) then represents the ratio of seat kilometers offered and seat kilometers sold.

$$\boldsymbol{slf_1 = \frac{RPK_1}{ASK_1} \cdot 100} \tag{4-2}$$

$\boldsymbol{slf_1}$ … *Seat load factor in the base year (in percent)*

$\boldsymbol{ASK_1}$ … *Transport supply (passenger seats) within the base year*

Now, the step in fleet planning from the base year to the subsequent year (year '2' in Figure 4-1) is accomplished by initially anticipating the rate of market growth (and the associated market share of the airline) between the two years (equation (4-3)). In the case shown in Figure 4-1, the growth rate is positive, although negative rates of growth can certainly occur as well. Next, the airline has to define a target seat load factor (slf_2) that it intends to achieve in year 2. It thereby determines the amount of ASKs that it must supply to the market (ASK_2).[44]

$$\boldsymbol{RPK_2 = RPK_1 \cdot \left(1 + \frac{pgr_1}{100}\right)} \tag{4-3}$$

$$\boldsymbol{ASK_2 = \frac{RPK_2}{slf_2} \cdot 100} \tag{4-4}$$

$\boldsymbol{pgr_1}$ … *Anticipated rate of growth in passenger transport demand from year 1 to year 2 (in percent)*

$\boldsymbol{slf_2}$ … *Target seat load factor in year 2 (in percent)*

Assuming that the airline owns a fleet of aircraft with a heterogeneous age distribution, it will retire aircraft from year 1 to year 2, which consequently induces a loss in transport capacity.[45] That is, the airline will not be able to supply the ASKs of year 1 in year 2. To refill this 'retirement gap,' it must acquire new aircraft units. In addition, it must equally fill the gap that exists between the transport supply in year 1 and 2, the 'market growth gap.'[46] Hence, the capacity gap is the sum of the retirement gap and the market growth gap.

The question of how many new aircraft units are to be acquired to fill the capacity gap can be addressed with equation (4-5). The equation generally defines the ASK metric.

$$\boldsymbol{ASK_{i,j} = \sum_{i,j} n_i \cdot f_{i,j} \cdot d_{i,j} \cdot s_{i,j}} \tag{4-5}$$

---

[43] Spill emerges due to the inability of an airline to accommodate transport demand for certain flights because of an insufficient provision of seat capacity. The topic of planning demand spill is exposed and discussed in detail by Clark (2007, pp. 56–69).

[44] Planning load factors is a task of the airline-planning department featuring a highly strategic character. Therefore, airlines usually do not disclose their load-factor planning policies.

[45] Airlines may also retire aircraft due to reasons other than aircraft age (e.g., full depreciation of an aircraft due to an accident).

[46] The market growth gap only emerges in the case of positive rates of market growth.

$\boldsymbol{i}$ *… Addressing one particular route of the airline's routes network*

$\boldsymbol{j}$ *… Addressing one particular aircraft unit of the airline's fleet*

$\boldsymbol{n_i}$ *… Number of aircraft operating on route i*

$\boldsymbol{f_{i,j}}$ *… Number of frequencies with which aircraft j operates on route i*

$\boldsymbol{d_{i,j}}$ *… Great circle distance flown by aircraft j on route i*

$\boldsymbol{s_{i,j}}$ *… Number of seats transported by aircraft j on route i*

Following equation (4-5), an airline can take one or several of the following measures in order to increase (or decrease) the amount of ASKs:

- *Increasing (or reducing) the number of frequencies with which an aircraft operates on a specific route ($f_{i,j}$):* In reality, this option is available with restrictions only. In case the airline intends to increase $f_{i,j}$, it simultaneously increases the utilization hours of the aircraft (→Section 4.2.4). It may do so only until the maximum utilization hours of the aircraft are reached. Here, the limiting factors are the flying speed of the aircraft, the maintenance hours mandatory to keep the aircraft under airworthy conditions, and the turn-around time required to prepare the aircraft for the next flight after it has completed a flight mission. On the other hand, $f_{i,j}$ should only be lowered to a certain minimum level. Below this minimum, the aircraft does not cover its costs of ownership and hence lowers the airline's total profit (i.e., the income generated by operating the aircraft is lower than the sum of the direct operating costs of this aircraft). The airline should therefore consider retiring the aircraft rather than keeping it in its fleet in this case.
- *Increasing (or decreasing) the distance between the origin-destination pair of a specific route ($d_{i,j}$):* This option is only available from a mathematical point of view. In reality, the distance between an O-D pair cannot be changed of course.
- *Increasing (or decreasing) the number of seats transported by the aircraft on a specific route ($s_{i,j}$):* Similar to $f_{i,j}$, restrictions in adaptability apply in reality. The maximum amount of seats is limited by the cabin design of an individual aircraft type and/or by the aircraft maximum take-off weight. Typically, the airline has to work out an adequate compromise between the range capability and the seat capacity of an aircraft while considering the estimated passenger demand and routes network on which the aircraft is planned to operate.
- *Increasing (or decreasing) the number of aircraft units operating on a specific route (n_i):* With this measure, the airline stipulates how many aircraft units are employed on a specific route to accommodate the transport demand. To reduce n_i, the airline can either shift aircraft from one route to another (with higher transport demand) within its network, or, more extremely, retire aircraft. In reality, aircraft are retired for several reasons, the most prominent one occurring once an individual aircraft has reached its economic end of life (→Section 4.2.5). To acquire new aircraft, the airline usually orders the required amount with an aircraft manufacturer. Here, the bottleneck is the production capacity of the manufacturer, i.e., the rate with which the manufacturer is capable of producing and delivering new aircraft units (→Section 4.2.6).

In the face of the four above-described measures of ASK adaptation available to an airline, the macro approach to fleet planning essentially relies on a trade-off between frequency and aircraft size. A priori, there is no generally applicable optimum solution. Every airline has to find its optimum trade-off, taking into account the specific boundary conditions and restrictions that affect the problem.[47]

With regard to the reliability of the results achieved through the macro approach to fleet planning, Clark (2007, p. 55) emphasizes that “as with any planning activity, the results you get are only as good as the assumptions you work with.” Virtually every input parameter that is required for the proper functioning of the macro approach depends on the assumptions the airline makes about the future market development. The most critical input is certainly the rate of market growth assumed (pgr_1 in equation (4-3)). Other input data that should also be handled with care are the target load factor (plf_2 in equation (4-4)) and the estimated utilization hours used to determine the optimum frequency of flights ($f_{i,j}$ in equation (4-5)).

A final note is given regarding the planning of air freight. Here, the macro approach is equally applicable of course with the only difference being that instead of employing the transported seat as the main metric for determining transport demand and supply, the freight ton is utilized. Thus, equation (4-5) turns into equation (4-6). In addition, a freight load factor (flf) is used to determine the ratio between freight demand and supply, and a rate of growth in freight transport demand (fgr) must be anticipated for the planning of future freight supply.

$$\boldsymbol{ATK_{i,j}} = \sum_{i,j} \boldsymbol{n_i} \cdot \boldsymbol{f_{i,j}} \cdot \boldsymbol{d_{i,j}} \cdot \boldsymbol{t_{i,j}} \tag{4-6}$$

$\boldsymbol{t_{i,j}}$ … *Tons of freight capacity transported by aircraft j on route i*

4.2.3 The micro approach to fleet planning

The “micro approach to fleet planning” (Clark, 2007, pp. 55–56), also referred to as the “bottom-up approach” (Belobaba, 2009, pp. 160–162), relies on an analysis of data and calculations at a level of detail much higher than the macro approach described in the previous section. That is, while the macro approach focusses on an airline’s entire network, individual routes and flights are considered and modeled in the micro approach. Accordingly, it requires much more detailed assumptions addressing the future development of the subnetworks and routes under consideration (e.g., growth rates of specific O-D pairs within the airline’s network). On the other hand, the micro approach will generate much more detailed output data including individual aircraft tail assignments and operating statistics by route, flight, and aircraft tail number.

In particular, by using a market-share model, the airline has to estimate its share in total transport demand for every O-D pair under scrutiny. Forecasts of demand and revenues for each O-D market are then allocated to each flight within the airline’s schedule using a traffic allocation model. As a result, the micro approach to fleet planning provides the airline “with a complete representation of its network and operations under different fleet alternatives for a range of time periods into the future.” (Belobaba, 2009, p. 162)

Clark (2007, p. 56) mentions three important drawbacks of the micro approach in real-life application cases. Firstly, the demand-allocation models involved can only be employed for short-term forecasts. Secondly, the degree of complexity of the network models requires a large amount of accurate data, which is unlikely to be available. Thirdly, the micro approach is “resource-heavy,” i.e., it requires extensive knowledge, experience, modeling, and computation capabilities to function properly. Comparing the macro approach to the micro

---

[47] The question of frequency vs. size has been an intensely discussed topic in the transportation research-related literature since the 1970s (e.g., →Mohring (1976)). This topic is not discussed in this thesis, though. The work of Pai (2010), Wei and Hansen (2007), and Givoni and Rietveld (2006) is recommended to the interested reader.

approach, Belobaba (2009) therefore concludes that mainly because of its simplicity, the macro approach…

> *"…is more commonly used for fleet planning evaluations, given that detailed future scenarios over 10-15 years are highly speculative. Demand and costs estimates are quite likely to be inaccurate in face of changing market conditions, putting into question the value of the enormous effort required to develop the detailed scenarios for the bottom-up approach. And in many airline fleet decisions, political decisions can overrule even the 'best' analysis of options, making the bottom-up approach an ineffective use of effort and resources."*
>
> *(Belobaba, 2009, p. 162)*

4.2.4 Aircraft utilization modeling

The accurate modeling of aircraft utilization is a major prerequisite for all fleet planning-related tasks and modeling efforts. Hence, this issue is treated in more detail in this section.

Whenever an airline plans a particular flight to accommodate transport demand, it must also determine the total period of time that an aircraft requires for the execution of this flight. This period is referred to as the *Utilization Hours (UHs)*. That is, during this period, the airline considers the aircraft as 'being utilized.'[48] The UHs comprise three sub-categories. (Tetzloff and Crossley, 2009, p. 3)

a) The *Block Hours (BHs)* specify the amount of hours that the aircraft requires to accomplish one flight mission. They begin at the moment when the aircraft leaves the gate at the origin airport and end at the moment when it arrives at the gate of the destination airport. BHs are primarily a function of the great circle distance of the O-D pair served and the flying speed of the aircraft. Other factors like the traffic situation and the meteorological conditions affect the BHs on an individual basis as well.

b) The *Turn-around Hours (THs)* specify the amount of hours the aircraft requires to get prepared for the next flight mission. They begin at the moment when the aircraft arrives at the gate of the destination airport and end at the moment when it leaves the gate again to depart for the next flight. THs are primarily a function of the size of the aircraft and the aircraft handling facilities available at the airport.

c) The *Maintenance Hours (MHs)* specify the amount of hours the aircraft requires to maintain airworthiness. Usually, the MHs are a direct function of the BHs. That is, for every BH, a certain amount of MHs is needed to keep the aircraft airworthy.

Equation (4-7) summarizes the above to establish the UH metrics. Note that usually, the BHs, MHs, THs, and UHs are calculated to represent daily average values, taking into account an extended period of time (e.g., one year).

$$\boldsymbol{UH = BH + TH + MH = \left(1 + \frac{MH}{BH}\right) BH + TH} \tag{4-7}$$

$$\boldsymbol{UH = \alpha \cdot BH + TH} \tag{4-8}$$

$\boldsymbol{\alpha}$ … *MH/BH-ratio*

Boeing Commercial Airplanes (2013, pp. 4–5) has published data regarding the average utilization of a 777 long-range aircraft and a 737 short-/mid-range aircraft. With these figures, the MH/BH-ratio (α in equation (4-8)) can be determined with equation (4-9).

---

[48] As opposed to 'not being utilized.'

$$\alpha = 1 + \frac{Daily\ Check + A,C,\&D\ Checks}{Taxi\ Time + Flight\ Time} \tag{4-9}$$

When employing the values given in Boeing's publication, equation (4-9) yields MH/BH-ratios of 1.244 and 1.253 for the 777 and the 737, respectively.

The *Maximum Utilization Hours* (UH_{max}) represent the upper limit of aircraft utilization within a predefined period of time. If the UHs are calculated as average values on a daily basis, UH_{max} is 24 hours, as one day comprises 24 hours. However, a value of 24 for UH_{max} can only be assumed if operational restrictions such as night curfews do not apply. Therefore, in many cases, a lower value for UH_{max} must be employed. For the 777 and the 737 aircraft types, Boeing Commercial Airplanes (2013) suggests values for UH_{max} of approximately 20 and 15 hours, respectively.

For a given value of UH, the maximum number of flight frequencies per day achievable for a specific aircraft on a specific route ($f_{i,j,max}$) can be determined eventually as shown by equation (4-10).

$$f_{i,j,max} = \frac{UH_{max}}{UH} \tag{4-10}$$

A simple example shall clarify the above:

> *An airline assigns one Boeing 737 aircraft unit (index 'j') to a specific route (index 'i'). The aircraft requires two BHs to accomplish the corresponding flight mission once. In addition, one TH is required to prepare the aircraft for the next flight on the same route. With an α-value of 1.253 and an UH_{max}-value of 15, the maximum number of frequencies per day can be determined using equations (4-8) and (4-10). Equation (4-11) yields a value of 4.3. Thus, per one day, the aircraft can fly four mission legs on the route, which allows it to repeat this operational sequence on the following day. (An odd number would require two days to enable repetitive operations).*[49]

$$f_{i,j,max} = \frac{15}{1.253 \cdot 2 + 1} = 4.3 \tag{4-11}$$

4.2.5 Aircraft retirement modeling

One further essential task related to fleet planning (especially on long term) is the modeling of the retirement of current in-service aircraft. In the context of this thesis, an aircraft is considered as retired from active service, once the aircraft is no longer intended for a resumption of operations in the long term.[50]

The most common reason for a retirement of an old aircraft occurs at the moment when the costs for operating this aircraft are higher than the costs for acquiring and operating a new type.[51] (Belobaba, 2009, p. 158) Numerous factors influence this decision. Some of the most important ones are summarized in the following.

---

[49] In reality, frequency planning is much more complex than shown here, as instead of basing the planning on numbers averaged over one year, actual day-to-day operations and restrictions have to be considered (e.g., mandatory maintenance intervals, availability restrictions of the flight crew, night curfews on certain airports). In addition, airlines usually operate a specific aircraft unit on more than only one route within their networks.

[50] This implies that aircraft being taken out of service temporarily due to seasonal fluctuations of transport demand (i.e., parked or stored aircraft) are not considered as retired here. In the case of a passenger aircraft being converted into a freighter, the passenger aircraft is considered as retired.

[51] Provided that the old aircraft has been fully depreciated during its lifetime, the costs of ownership of this aircraft are close to zero.

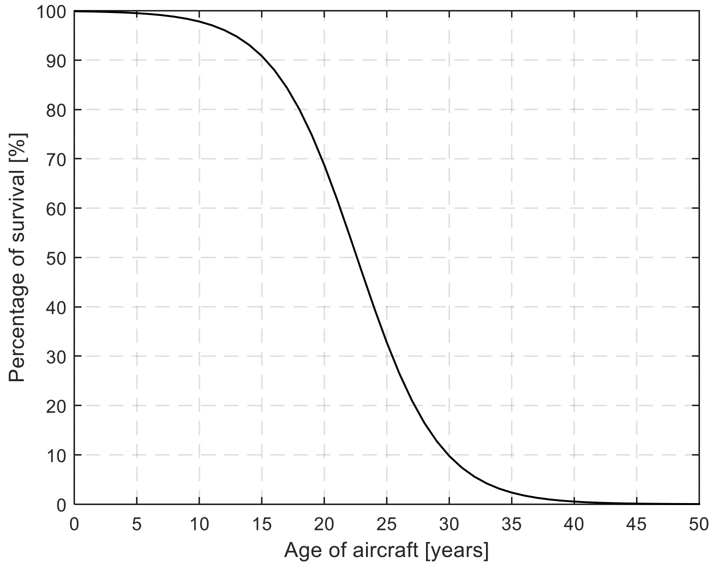


Figure 4-2 **Typical survival curve of a mid-range transport aircraft**
Data sources: Flightglobal (2008), Verbrugge et al. (2013)

- The operational performance of the aircraft has become unsatisfactory (e.g., fuel-burn performance).
- New regulations have become effective that prohibit the aircraft from being operated in certain regions (e.g., more stringent noise restrictions).
- The aircraft no longer fits into the airline's fleet requirements and operations philosophy (e.g., fleet commonality).
- The manufacturer of the aircraft has ceased maintenance support.

Hence, in the face of the above issues, the adequate approach to an accurate capturing of aircraft retirement-related decisions of airlines is to elaborate a model that approximates aircraft retirement through a function of aircraft age. (Morrell and Dray, 2009, p. 30) Here, the FESG (2008a, p. 33) proposes the utilization of "survival curves" that are employed in this thesis accordingly. Survival curves describe the percentage of aircraft that remain in the fleet depending on their respective age (equation (4-12): percentage of survival, POS). They can thus be interpreted as a mathematical description of the degree of probability with which an aircraft will remain active within an airline's fleet as the aircraft becomes older.

$$\boldsymbol{POS} = \frac{\boldsymbol{n_{active}(a)}}{\boldsymbol{n_{built}(a)}} \qquad \textbf{(4-12)}$$

$\boldsymbol{POS}$ … *percentage of survival*

$\boldsymbol{n_{active}}$ … *number of active aircraft*

$\boldsymbol{n_{built}}$ … *number of aircraft built*

$\boldsymbol{a}$ … *aircraft age (in years)*

To generate survival curves for a specific type of aircraft, historical data are required that reveal how airlines have retired this type in the past. This represents a decisive drawback of the survival curves concept of the FESG, as it requires extensive databanks that capture the historical retirement of aircraft. A further problem occurs for new or recent types for which no historical retirement data are available.

Morrell and Dray (2009, p. 30) suggest a "logistic (S-curve) function form" to mathematically formulate aircraft survival curves as shown by equation (4-13). Figure 4-2 illustrates the typical shape of a survival curve of a mid-range transport aircraft.

$$POS = \frac{1}{1+e^{-\beta_I-\beta_{II}\cdot a}} \tag{4-13}$$

β_I, β_{II} *… retirement coefficients specific for each type of aircraft*

The retirement coefficients β_I and β_{II} must be determined empirically and on an individual basis for each type or category of aircraft of interest by analyzing data of historical aircraft retirements. If such data are not available, existing retirement coefficients of similar aircraft should be employed as an approximation.

4.2.6 Aircraft production modeling

Provided that based on its fleet planning efforts, an airline has decided to acquire one or several new aircraft units, it must also take into account that these units will not be delivered by the aircraft manufacturer immediately after the order placement. Instead, depending on the actual situation regarding the total demand for new aircraft in the respective market, the airline may have to wait during a certain period of time until the manufacturer will eventually deliver the new aircraft units ordered.

Here, particular attention must be paid to the fact that especially newly developed aircraft types cannot be produced at high rates of production during the initial years of their availability, as the aircraft manufacturer first has to build up the necessary production facilities. Figure 4-3 and Figure 4-4 illustrate this circumstance by exemplarily referring to the historical evolution of annual delivery rates of the Airbus A320 narrow-body family and the Airbus widebody family including both the Airbus A300/A310 and the Airbus A330/A340.

The figures reveal that a linear increase in aircraft deliveries over time may be assumed when estimating the number of potentially available aircraft units of a new type or family of similar types.[52] Moreover, delivery rates of widebody aircraft types must be expected to grow much slower than those of narrow-body types.

To get an even better idea of the production capacities of the aircraft manufacturers, an airline should also examine the total amount of deliveries of the aircraft class or category of interest that can potentially be achieved by all relevant manufacturers in a certain future year. This will help the airline estimate more precisely how long it will have to wait for the delivery of the aircraft units ordered, and hence support the refinement of the fleet plan.

In this context, Engelke (2014, pp. 16–24) identified the historical evolution of the total sum of aircraft deliveries of the aircraft manufacturers Airbus, Boeing, and Embraer. In his study, he defined two fundamental aircraft categories, single-aisle types and twin-aisle types, and analyzed the historical delivery rates of the types of aircraft shown in Table 4-2. Then, in order to estimate the total production capacity of the three manufacturers in a certain year, he assumed that the production capacity was equal to the sum of aircraft units delivered in that year. In a year that showed a delivery number lower than the one of the preceding year, he assumed that the production capacity was not decreased in the same way but that it would maintain the level of the preceding year.

Figure 4-5 and Figure 4-6 show the results of this study. Like in the case of estimating the evolution of the individual production rate of a newly introduced aircraft type described above, here again, a linear approximation seems reasonable to anticipate the evolution of the

---

[52] The values of the coefficients of determination (R^2) of the two approximation equations given in Figure 4-3 and Figure 4-4 are 0.89 and 0.90, respectively.

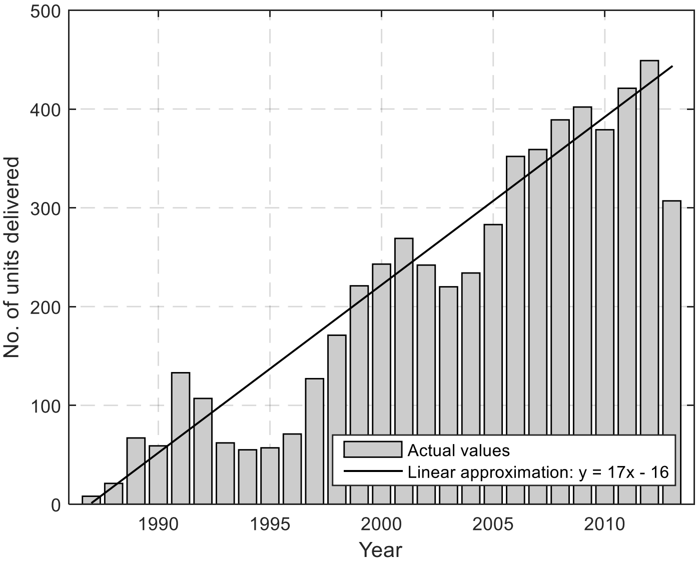


Figure 4-3 **Historical evolution of the total annual deliveries of the Airbus A320 narrow-body aircraft family**
Data sources: Flightglobal (2008), Airbus S.A.S. (2014b), and Verbrugge et al. (2013)

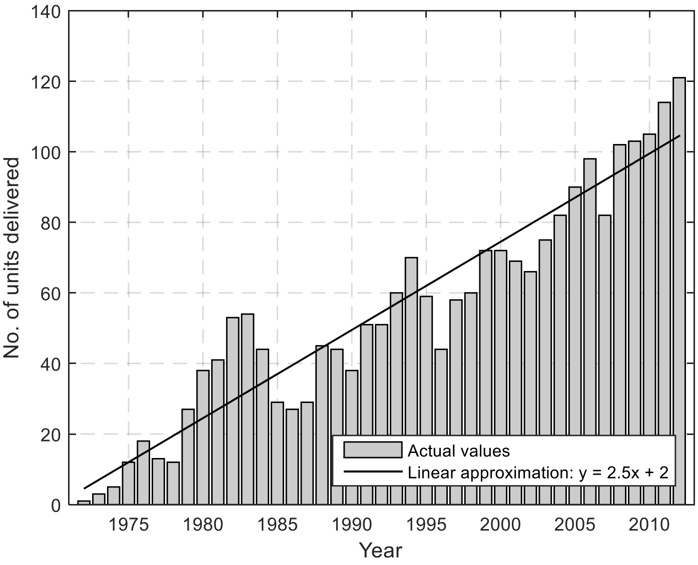


Figure 4-4 **Historical evolution of the total annual deliveries of the Airbus A300/A310 and A330/A340 widebody aircraft families**
Data sources: Flightglobal (2008), Airbus S.A.S. (2014b), and Verbrugge et al. (2013)

Table 4-2 **Aircraft types considered for the analysis of the total production capacities**
Source: Engelke (2014, p. 17)

Manufacturer	Aircraft types (single-aisle category)	Aircraft types (twin-aisle category)
Airbus	A318, A319, A320, A321	A300, A310, A330, A340, A380
Boeing	717, 737	747, 757, 767, 777, 787
Embraer	E135/145, E170/175, E190/195	

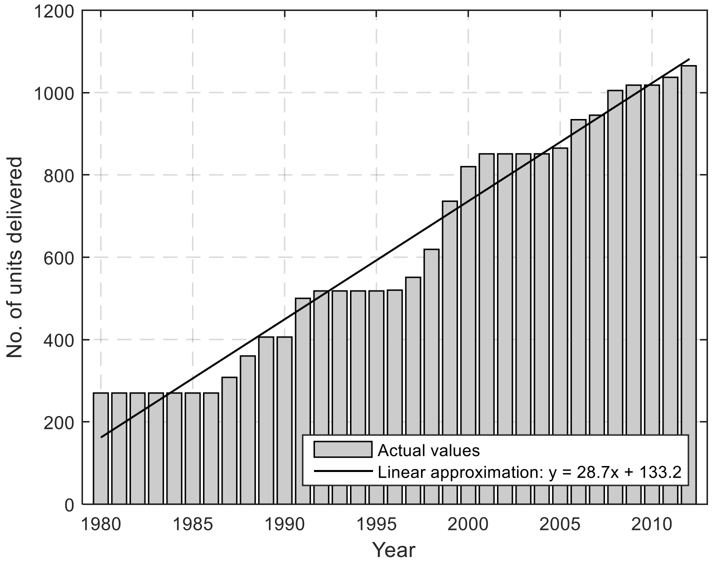


Figure 4-5 **Historical evolution of the total annual production capacity of single-aisle aircraft**
Image source: author's creation based on Engelke (2014, p. 19)
Data sources: Flightglobal (2008), Airbus S.A.S. (2014b), and Verbrugge et al. (2013)

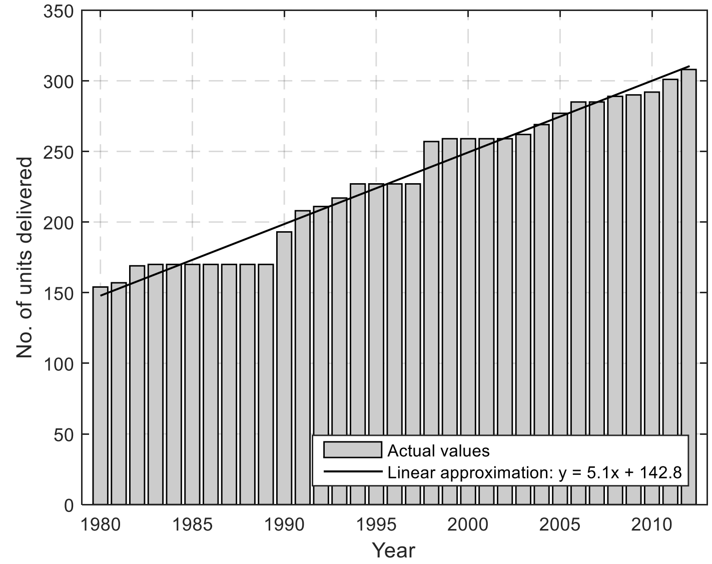


Figure 4-6 **Historical evolution of the total annual production capacity of twin-aisle aircraft**
Image source: author's creation based on Engelke (2014, p. 21)
Data sources: Flightglobal (2008), Airbus S.A.S. (2014b), and Verbrugge et al. (2013)

total production capacities of single-aisle and twin-aisle aircraft.[53] However, since the data shown in the figures only takes the production capacities of Airbus, Boeing, and Embraer into account, an adequate increase should be introduced for the assumption of future delivery rates in order to account for new aircraft manufacturers that are planning to enter the market in the near future (e.g., Bombardier, Comac, and Mitsubishi). This may be accomplished using time-dependent multiplication coefficients that artificially increase the anticipated production capacities by a certain level at predefined moments in the future.

---

[53] The value of the coefficients of determination (R^2) of the two approximation functions given in Figure 4-5 and Figure 4-6 is 0.97 for both.

4.2.7 Aircraft network allocation

Provided that an airline has completed the fleet planning and stipulated the network of routes that it intends to serve (i.e., the "route planning," →Belobaba (2009, pp. 162–173)), it must assign the fleet to the network and stipulate a detailed chronological schedule of the planned flights, including the aircraft rotation plan. This is done through the "schedule development." (Belobaba, 2009, pp. 173–180)

An essential part of the schedule development is the "Fleet Assignment Problem (FAP)" (Abara, 1989) that determines which type of aircraft of the airline's fleet and how many units of each type are supposed to operate on each flight leg, given a planned network of routes and a flight schedule. (Hane *et al.*, 1995, p. 212) Usually, the objective function of the FAP is to minimize the combined costs of spill (→Section 4.2.2) and fleet operating costs, or equivalently, maximize profit. The FAP is hence a mathematical optimization problem that many airlines handle using large-scale mathematical network optimization methods. (Belobaba, 2009, p. 179) Various constraints have to be taken into account when seeking the optimal fleet assignment solution, such as maximizing aircraft utilization (→Section 4.2.4), ensuring sufficient time available for aircraft maintenance, and considering operational restrictions (e.g., night curfews). (Bazargan, 2004, p. 44)[54]

4.2.8 Further aspects

Two additional facets are important in the airline fleet planning process that are briefly described in the following.

Aircraft storage. Under certain circumstances, an airline may decide to take one or several aircraft units of its fleet out of service for a limited period of time. Regular maintenance intervals or other technical issues do not belong to these circumstances usually. Instead, financially driven reasons are frequently the cause.

In times of volatile market demands, an airline may wish to maintain a certain level of flexibility to be able to quickly adapt its available transport capacity. In a situation of strong economic growth after a distinct period of decline, a high demand for additional aircraft units among airlines will make it more difficult (and increasingly expensive) for one particular airline to acquire the exact type and amount of aircraft that it wishes to operate. Moreover, in a situation of economic downturn, sales prices for used aircraft may fall more strongly than the prices for new aircraft (assuming a high market power of aircraft manufacturers in the aircraft sales market), which reduces the financial attractiveness for an airline to sell a part of its fleet compared to temporary aircraft storage.

Aircraft leasing. When operating a certain aircraft, an airline does not necessarily have to legally own this aircraft. In fact, getting rid of the costs of ownership of an aircraft may present a financially attractive option for an airline that comes with an increased flexibility in financial planning.[55] Leasing companies have been offering aircraft leasing contracts to airlines for several decades already. In fact, the share of leased aircraft among the world fleet has increased from 1.7% in 1980 to 37.7% in 2012. A share of >50% is expected by 2020. (KGAL Group, 2015; figures originating from the Boeing Capital Corporation).

From a system-wide point of view, a steadily increasing share of leased aircraft in the global fleet means that aircraft are more likely to be operated by several airlines during their

---

[54] For a more detailed overview of the methods and algorithms involved in handling the FAP, the work of Sherali *et al.* (2006) is recommended to the interested reader.

[55] A leased aircraft does not have to be depreciated over its period of use, which reduces an airline's capital commitment and increases its financial flexibility by improving the liquidity position.

lifetime. Moreover, leasing companies are financially motivated to keep their assets (i.e., the owned aircraft units) in operation with airlines as long as economically possible. This may then lead to the assumption that the usage characteristcs and average life expectancy of aircraft will change in comparison with what has happened to date. Aircraft storage is likely to play a more important role in the future as well.

4.3 The fleet system dynamics model

4.3.1 Methodological foundations

As shown in Figure 2-1, the Fleet System Dynamics Model (FSDM) is fundamentally divided into two model components: the aircraft fleet model and the air transport network model. The former dynamically determines the size and structure of the global fleet of commercial transport aircraft on a year-by-year basis. This implies that the smallest time interval considered by the model is one year. The latter defines the air routes that interconnect local air traffic markets with each other to form and represent the global network of air transport routes on which the aircraft fleet operates.

The FSDM essentially relies on the macro approach to fleet planning (→Section 4.2.2). This has two decisive consequences for the basic functioning of the model:

- For each year of simulation, the model requires *a target amount of ASKs and ATKs*, or alternatively, *a target amount of RPKs and RTKs along with load factor data* (seat/freight load factors), in order to determine the 'capacity gap,' which in turn stipulates the amount of new aircraft units to be added to the fleet (→Figure 4-1). In other words, for each year of simulation, the model determines the fleet that is required to deliver a certain transport performance predefined by the model user.
- The user must initialize the model by defining a *start year of simulation* along with an *initial fleet of aircraft* (in terms of size, composition, and age distribution) as well as the *initial transport performance* (given in ASKs/ATKs or RPKs/RTKs and corresponding load factor data) that the initial fleet has to deliver.

To capture the dynamic evolution of the global aircraft fleet, the FSDM uses the principles of *System Dynamics* (→Glossary).[56] In particular, interdependent *stocks* and *flows* are utilized to capture the dynamics of the fleet evolution as a function of time.

Figure 4-7 schematically illustrates the overall functioning of the model. The fleet (*stock*) is shaped by two *flows*, the 'Add aircraft'-inflow and the 'Retire aircraft'-outflow. The 'Add aircraft'-inflow is aimed at delivering new aircraft to the fleet, depending on the growth rates of air traffic defined by the user. In addition, it is constrained by both the availability of aircraft (in terms of whether or not a particular type of aircraft is still being produced in a specific year of simulation) and the capability of the aircraft manufacturers to deliver the amount of aircraft units required (→Section 4.2.6). The 'Retire aircraft'-outflow is essentially determined by the aircraft retirement modeling (→Section 4.2.5). That is, aircraft retirement is accomplished by accessing the aircraft-specific survival curves specified by the user. Given an initial age distribution of the fleet defined by the user, the model will apply the survival curves to the various types of aircraft incorporated in the model to determine the statistical amount of aircraft to be retired in each year of simulation.

---

[56] For a detailed introduction into System Dynamics, the work of Sterman (2000) is recommended to the interested reader.

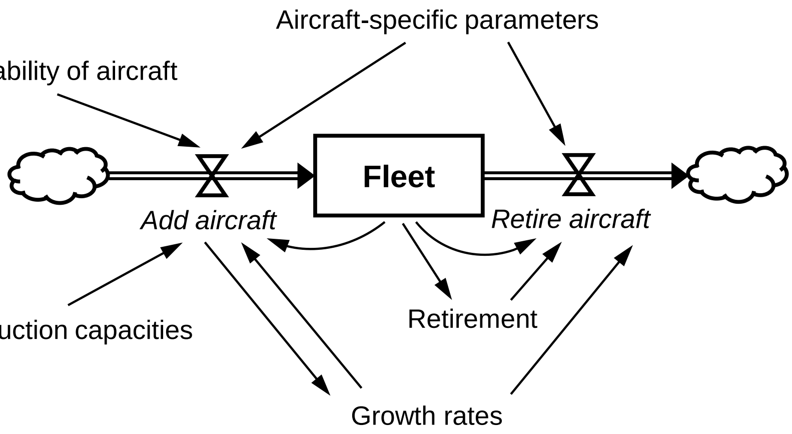


Figure 4-7 **System Dynamics-based functional scheme of the FSDM**
Source: author's creation based on Wache (2014, p. 22)

4.3.2 Model assumptions and limitations

Modeling the global air transport system (→Section 4.1) constitutes a challenging endeavor given the high degree of complexity of this system. Therefore, the FSDM relies on some decisive assumptions that were made to simplify the modeling efforts and reduce complexity. On the other hand, these assumptions naturally lead to a degradation in model accuracy.

4.3.2.1 Airline competition

Commercial aviation is an industry sector that is strongly characterized by competition among airlines courting passengers at a local, regional, and global level. However, the modeling of airline competition requires a profound economic understanding that was not available during the studies of this thesis. As a result, similar to the work of Tetzloff and Crossley (2009, p. 2), the model merely simulates "one benevolent, monopolistic airline" that exists to meet all passenger and freight transport demand.

This limitation implies that the various airline business models (e.g., "full-service carriers," "low-cost carriers," etc.[57]) are not implemented in the model. In consequence, the model does not simulate the influence of airline business models on fleet-planning decisions either. Yet, given the paramount goals of this thesis (→Section 1.3), this limitation is not considered to reduce the model quality by a substantial degree.

4.3.2.2 Fleet allocation

As described in Section 4.2.7, airlines will always try to assign their aircraft fleets to the routes network in a way to maximize profit. Profit maximization is then used as the objective function required for solving the FAP. Capturing this real-life behavior in a model, however, would require an in-depth understanding of the various airline business models as well as an incorporation of airline cost functions. As mentioned in the previous section, distinct airline business models are not considered in the FSDM, though. The model rather simulates one global airline. Models and functions of airline operating costs are not captured either, as this would exceed the topical scope of this thesis.

Instead of using profit-maximizing objective functions, fuel burn is employed to formulate the objective function for the FAP in the FSDM. That is, the FSDM will assign aircraft to the routes network in way to minimize the total fuel consumption of the global fleet in each year

---

[57] See Reichmuth *et al.* (2008) for a detailed overview of the various airline business models.

Table 4-3 Aircraft type-specific criteria used for the aircraft clustering

Clustering criteria	Data source	Name used in OAG database
Seat capacity available	OAG (2008)	SEATS
Freight capacity available	OAG (2008)	FREIGHTTONS
Overall payload capacity available	Own calculations[58]	n/a
Average flight distance flown	OAG (2008), own calculations	KM
Type of propulsion	Flightglobal (2008)	n/a

of simulation. Although this approach does not exactly reproduce reality, it has two distinct advantages.

- The implementation of airline business models and operating cost functions is not necessary, which results in a lower model complexity and lower requirements concerning input data.
- The effect of a new aircraft or technology on the overall performance of the global fleet in terms of fuel consumption can be examined more precisely, as the model will be able to generate and simulate fuel-optimal fleets with and without the new aircraft or technology to be assessed. That is, secondary factors affecting the fuel performance of the fleet in reality (due to the profit-maximization objective) have no influence on how new aircraft or technologies are integrated into the fleet. In other words, the FSDM simulates technological best-case scenarios in terms of fleet-wide fuel consumption.

4.3.2.3 Possible periods of time of simulation

As described in Section 2.3.2, essential input data addressing the transport performance (i.e., the OAG database of scheduled flights, OAG (2008)) and the fleet size and composition (i.e., the ACAS world fleet database, Flightglobal (2008)) are required for the FSDM to be initialized. These databases originate from 2008. Therefore, any simulation performed by the FSDM must begin in 2008. Although this reduces the flexibility of application of the model, two important advantages are induced by this restriction.

- Starting the simulation in 2008 allows a model validation in the period between 2008 and 2014, if real-life fleet data is available.
- Using data of 2008 to initialize the model excludes the effects of the global financial crisis of 2009 onwards that had a tremendous impact on commercial aviation and the global aircraft fleet.

Regarding the simulation of future years after 2014, the FSDM is able to simulate periods of time until 2050 and beyond. However, the functionality of the model has only been verified for simulation periods until 2050.

4.3.2.4 Representation of the global aircraft fleet

The OAG database of scheduled flights (OAG, 2008) lists almost 200 different types of aircraft that contribute to the total transport supply of the global aircraft fleet. Including all would lead to a very high degree of complexity of the FSDM. Therefore, in order to keep complexity within acceptable limits, the model defines a distinct number of aircraft categories to simulate the global fleet, with each aircraft category being represented by a specific type of aircraft.

---

[58] For one seat, 100 kg of equivalent payload mass were assumed here.

In many other studies, the seat capacity specific to each aircraft type is used to group aircraft (e.g., Tetzloff and Crossley (2014), Jimenez *et al.* (2012)). However, while this approach may very well lead to an adequate representation of the world fleet in terms of transport capacity supplied, it is not able to represent the fleet in terms of operational and technical characteristics and performance values. The technical representation of the global fleet is vital for the technology assessment objectives pursued in this thesis, though.

Therefore, aircraft categorization is accomplished here based on multiple type-specific criteria including transport performance-related, operational, and technical metrics (→Table 4-3). In this context, Arnold (2012) conducted detailed analysis and assessment studies of various clustering algorithms described in the literature. He identified the k-medoids algorithm as being most suitable for the purpose of aircraft categorization in the context of this thesis.[59] This algorithm is hence used here, which is why the term 'aircraft cluster' is the preferred expression to address a specific representative group or category of aircraft types.

Due to this multi-criteria approach, every FSDM aircraft cluster is intended to represent not only a specific seat category and range capability but also a distinct technology level that stipulates the technical performance of this cluster. This technology level is treated constant over time. That is, the moment in time when an aircraft of a certain cluster joins the simulated fleet does not improve or deteriorate its technical performance (including its specific fuel efficiency).

4.3.2.5 Representation of the global routes network

The OAG database of scheduled flights (OAG, 2008) lists more than 37,000 different O-D pairs that together form the global network of air routes. Like in the case of the representation of the global fleet described in the previous section, representing the entire set of O-D pairs in the FSDM would lead to a significant degree of complexity of the model that would make its handling very difficult.

To reduce complexity, the FSDM defines the six global regions shown in Figure 4-8. Twenty-one regional and interregional connections referred to as 'route groups' are then established to represent the global network. Note that the route groups do not account for directions. For example, no distinction is made between the route group from Europe (EU) to North America (NA) and the one from NA to EU (i.e., EUNA is identical to NAEU).

Stage lengths specific to each type or cluster of aircraft operating on a particular route group are employed to characterize each route group. To initialize the FSDM, statistical analyses of the OAG database are conducted to deliver a definition of the cluster- and route group-specific stage lengths (→Section 4.3.3.3). During the simulation of the subsequent years, the FSDM does not vary these stage lengths. That is, the stage lengths are considered constant over time in the simulation.

---

[59] For more information about the mathematical foundations of the k-medoids algorithm, the work of Kaufman and Rousseeuw (2005) is recommended to the interested reader.

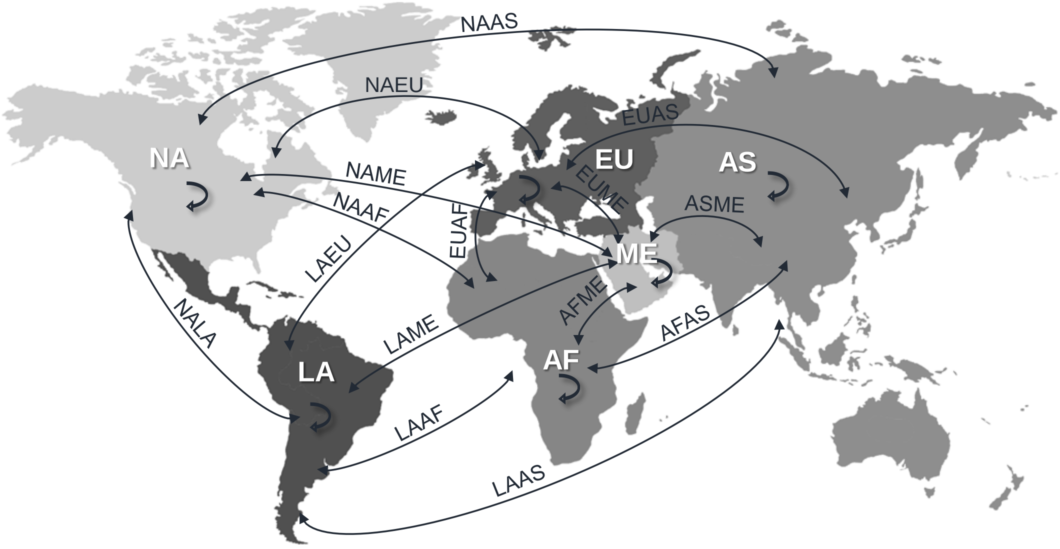


Figure 4-8 **Definition of the global regions and route groups used by the FSDM**
Image source: world map adapted from OAG (2008)

4.3.2.6 Further limitations

As will be shown through the validation of the FSDM in Chapter 6, in its current version, the model features four additional methodological limitations that decrease the model accuracy by a non-negligible degree.

- ***Dynamic aircraft utilization modeling.*** Once defined by the user, the utilization characteristics (i.e., the α- and UH_{max}-values specific for each type of aircraft being simulated; →Section 4.2.4) are treated as constants.
- ***Aircraft retirement.*** The FSDM always retires aircraft on a statistical basis as defined through the β-coefficients set by the user (→Section 4.2.5), regardless of the actual situation of aircraft demand.
- ***Aircraft storage.*** The FSDM does not support the simulation of temporary aircraft storage that airlines undertake in reality during short periods of economic decline in order to reduce their available transport capacities temporarily. Once retired, an aircraft will not resume service in the FSDM.
- ***Dynamic payload factor modeling.*** Like for the aircraft utilization characteristics, the seat and freight load factors are treated as constants.

On the one hand, integrating the above capabilities into the FSDM would certainly increase the overall model accuracy (and equally raise the model complexity by the same degree). On the other hand, the validation of the current version of the model (employed throughout this thesis) reveals that even without these capabilities, the FSDM is very well able to determine a realistic development of the global air transport fleet (→Chapter 6). In addition, a method is developed in this thesis that allows an a-posteriori modeling of a dynamic evolution of the aircraft utilization and load factor characteristics (→Appendix K).

4.3.3 Model initialization

Due to the macro approach to fleet planning (→Section 4.2.2) underlying the FSDM, the model requires an initialization to function properly (→Section 4.3.1). As described above, the FSDM is designed to begin all fleet simulations in 2008. The following sections depict how the data that are required for the initialization of the global fleet, routes network, and transport performance are derived.

Table 4-4 **FSDM initial fleet aircraft clusters and associated representative aircraft types**
Data source: OAG (2008)

Cluster ID	Cluster name[60] (SA/TA class)	Representative aircraft type (OAG name)	Approx. ASK/ATK-share within cluster[61]
1	Long-range combi (TA)	Boeing (Douglas) MD-11 Passenger	43%
2	Long-range heavy (TA)	Boeing 747-400 (Passenger)	77%
3	Mid-range freighter (n/a)	Boeing 767-300F Freighter[62]	25%
4	Jet commuter (SA)	Embraer 190[63]	9%
5	Long-range freighter (n/a)	Boeing 747-400F (Freighter)	47%
6	Turboprop commuter (SA)	ATR 72-500	100%
7	Mid-range (TA)	Boeing 767-300 Passenger	22%
8	Long-range (TA)	Boeing 777-200 Passenger	16%
9	Narrow-body (SA)	Airbus A320	23%

4.3.3.1 Initial fleet: size, composition, age

To determine the size and composition of the global commercial aircraft fleet in 2008, the OAG database (OAG, 2008) was initially consulted, revealing an amount of almost 200 different types of aircraft. Then, a selection was done by choosing all types listed in OAG that had a minimum individual share in the global production of ASKs and ATKs of at least 0.1% for passenger aircraft (ASK share) and 0.1% for air freighters (ATK share). Table C-1 in Appendix C shows these 86 aircraft types. Together, they contributed roughly 98% to the global ASKs and equally 98% to the global ATKs in 2008. Other types were not considered further.

The 86 aircraft types were then clustered using the k-medoids-based clustering tool developed by Arnold (2012) (→Section 4.3.2.4). Table 4-3 shows the aircraft-specific parameters that were used as clustering criteria. The table also indicates the data sources that were utilized to supply the corresponding data values for each aircraft type considered. In case of OAG-derived data, the name-identifiers employed by OAG are also displayed in the table.

By employing the cluster assessment module that is part of the clustering tool of Arnold (2012), an optimum number of aircraft clusters of nine could be identified. Table C-1 in Appendix C displays the allocation of the 86 OAG aircraft types to the nine clusters as

---

[60] The cluster names have been adapted from Assenheimer (2012).

[61] ATK shares are only indicated for clusters 3 and 5.

[62] The Boeing (Douglas) DC-10 (Freighter) was actually the largest contributor to the global ATKs within cluster 3 in 2008. However, from a technical and operational point of view, this type is not considered as representing the cluster 3 aircraft types well. Therefore, the Boeing 767-300F was chosen which was the second biggest contributor to the global ATKs within the cluster.

[63] The Canadair Regional Jet 700 was actually the largest contributor to ASKs within cluster 4 in 2008. However, like in the case of cluster 3, this type is not considered as a suitable representative of cluster 4. Therefore, the Embraer E190 was chosen which was the third biggest contributor to ASKs within the cluster after the Canadair Regional Jet 700 and the Embraer RJ 135/140/145 family.

suggested by the clustering tool. In order to identify the type per cluster that represents the cluster best, the one type with the highest share in ASKs for passenger aircraft and the highest share in ATKs for air freighters among all types contained in the respective cluster was chosen, unless indicated otherwise in Table 4-4. In case an OAG aircraft name defined a family of aircraft instead of a specific aircraft type (e.g., the 'Boeing 777 Passenger'), the particular type of this family with the highest individual ASK/ATK-rank was selected.

Table 4-4 indicates the nine clusters, their associated representative aircraft types, and the individual share in global ASKs/ATKs within each cluster. As depicted in Section 4.3.2.4, the technology levels of these clusters are assumed to be constant in the model. This means, for example, that a Cluster 9 aircraft being introduced into the fleet in 2010 features exactly the same technical performance (including fuel efficiency) as a Cluster 9 aircraft joining the fleet in 2020 or even in 2030.[64]

Next, the size and age distribution of the nine aircraft clusters were examined for 2008 using the ACAS fleet database (Flightglobal, 2008). Through this examination, an overall fleet size of 17,992 aircraft units could be identified. Table C-2 in Appendix C shows the size and age distribution of each cluster in detail.

4.3.3.2 Initial transport supply

In addition to the determination of the size, composition, and age distribution of the initial fleet presented in the previous section, a definition of the transport supply of this fleet in 2008 (measured in ASKs and ATKs) is necessary for the initialization of the FSDM. Table C-3 in Appendix C shows the overall transport supply for each of the 21 route groups (→Figure 4-8) according to data provided by OAG (2008).

4.3.3.3 Initial transport performance characteristics

To initialize the transport supply delivered by the initial fleet using the FSDM routes network shown in Figure 4-8, characteristic stage lengths were statistically derived using OAG data (OAG, 2008). This was accomplished by determining the median values of the frequency-weighted average stage lengths flown by each one of the nine aircraft clusters on each route group (where applicable). The values obtained are summarized in Table C-4 of Appendix C.

In addition, the characteristic seat and freight capacities supplied by each aircraft cluster on the respective route groups on each flight were determined in the same manner described above. The corresponding values are summarized in Table C-5 and Table C-6. Furthermore, the average sum of flight frequencies (i.e., the number of individual flights) per month was derived for each cluster and route group, which is also required to initialize the FSDM (→Section 4.3.4). The corresponding data are shown in Table C-7.

Finally, the initialization of the FSDM also requires defining an allocation of the initial aircraft fleet to the routes network.[65] This was achieved through a statistical approach that assigns a certain amount of aircraft units of a specific cluster to a route group as a function of this cluster's share in ASKs (or ATKs for freighter clusters) on this route group. Table C-8 displays the initial fleet allocation determined in this way.

---

[64] Note to the reader: This assumption is equally true for the 'next-generation aircraft types' depicted Section 6.2.1.

[65] An initial fleet allocation reduces the calculation period required for solving the FAP by a significant degree (→Section 4.3.4). However, this initial allocation is not required to define already the optimum allocation in terms of fleet-wide fuel consumption as described in Section 4.3.2.2.

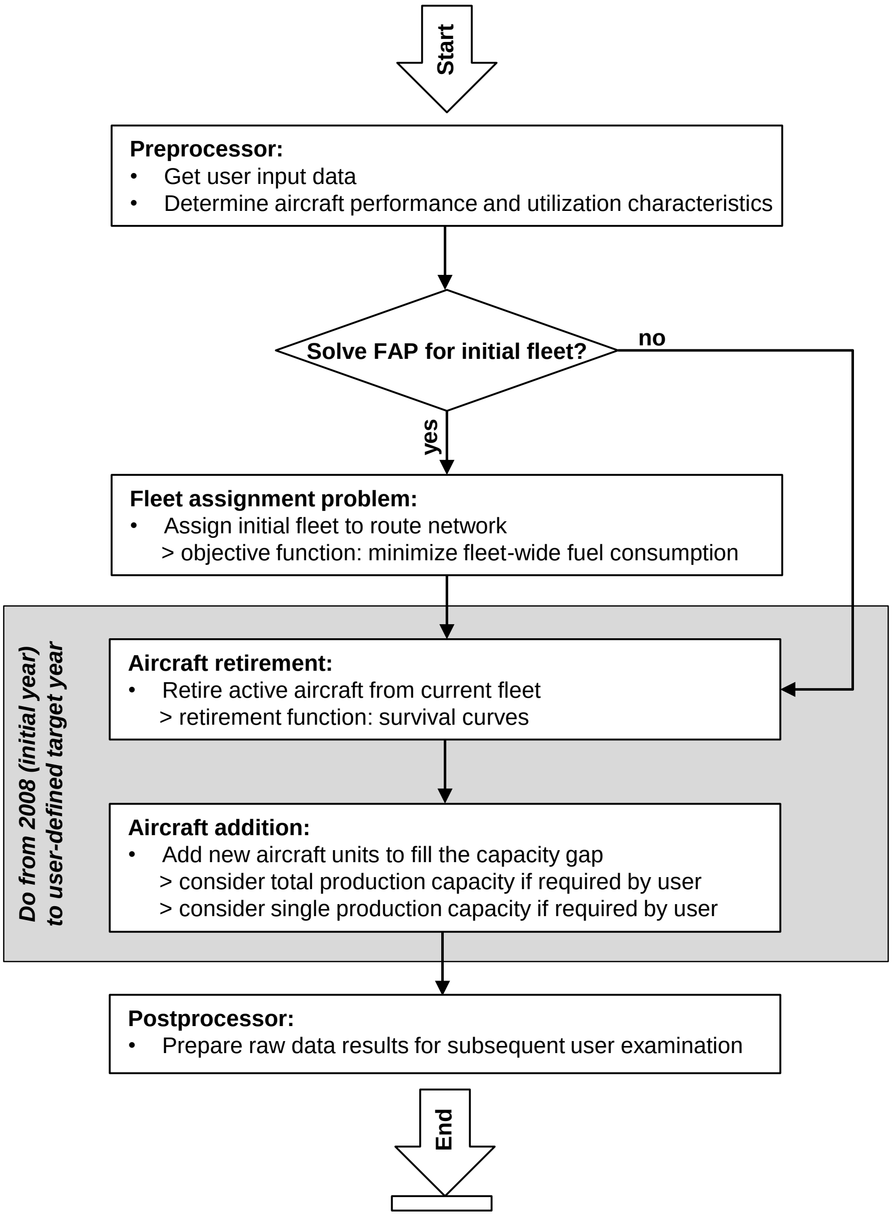


Figure 4-9 **Flow chart of the FSDM**

4.3.4 Software implementation

4.3.4.1 Overall program sequence

As mentioned in Section 2.3.4, the FSDM is implemented in a MATLAB® software environment. The dynamic nature of the evolution of the simulated fleet is captured through a Simulink® model that fundamentally relies on the principles of the *System Dynamics* methodology (Section 4.3.1). The overall program sequence is displayed in Figure 4-9 and will be depicted in the following.

The program sequence starts with a preprocessing of the input data and parameters provided by the user. The preprocessor also determines the performance and utilization characteristics of each individual type of aircraft simulated by the FSDM. This includes both the aircraft types of the initial fleet (→Table 4-4) as well as future types defined by the user that are available to the fleet from a user-defined future year of simulation. In Sections 4.3.4.2 and 4.3.4.3, more details regarding the user input and the preprocessor are available.

The FSDM then assigns the initial fleet of 2008 to the route groups by solving the FAP with the objective function of minimizing the total fuel consumption, provided that the user wants the model to do so. In the opposite case, the model will employ the statistical fleet assignment matrix (→Table C-8) to allocate the aircraft of the initial fleet to the routes network. More information in this regard is presented in Section 4.3.4.4.

Now, the FSDM enters a calculation loop that will terminate only after reaching the target year of simulation defined by the user. The loop essentially consists of two modules, the aircraft retirement module and the aircraft addition module. The former is employed to simulate aircraft retirements using cluster-specific survival curves (→Section 4.2.5). More information on this topic is presented in Section 4.3.4.5. The latter is applied to fill the capacity gap from the current year of simulation to the subsequent one by adding new aircraft units to the fleet (→Section 4.2.2). Here, depending on the preferences of the user, the model may limit the number of aircraft additions to predefined maximum aircraft production capacities. These limits can be set to capture the total production capacities of all aircraft manufacturers as a whole (→Figure 4-5, Figure 4-6) and/or the production capacity of one individual aircraft manufacturer who introduces a new aircraft type in a user-defined future year of simulation (→Figure 4-3, Figure 4-4). More information on the aircraft addition module is provided in Section 4.3.4.6 and in Appendix B.

Once the calculation loop reaches the target year of simulation, the FSDM exits the loop and starts the postprocessor that essentially prepares the raw results data in a way to enable the user to easily analyze and process the results further. A description of the postprocessor is available in Section 4.3.4.7.

4.3.4.2 User input data required

The FSDM requires a range of quantitative input parameters that the user has to supply in order to enable a proper functioning of the model. Table 4-5 summarizes these input parameters and contains additional explanations.

In principle, the information shown in the table can be derived from any source. For example, data available in Boeing's Current Market Outlook (Boeing Commercial Airplanes, 2014a) is used to validate the FSDM functionality in Chapter 6. However, as shown in Figure 2-1, ATAF is built to fundamentally rely on data provided through alternative future scenarios that must necessarily contain quantitative data (→Section 3.2).

To obtain these data, the *intuitive modeling* approach to scenario quantification is suggested (→Section 3.2.2.2). The outcome of this approach should at least comprise *the future year of interest* for the subsequent fleet simulation as well as *payload factor data* and *expected annual RPK/RTK growth rates* for each of the six global regions considered in the FSDM (→Figure 4-8).[66] Of course, a more detailed quantitative scenario may even provide data addressing the full range of route groups. If this is not the case, it is suggested to average the growth rates and load factors of two global regions to define the value corresponding to the route group that connects these two regions.

Nonetheless, it remains the responsibility of the FSDM user to supply adequate input data in order to ensure a consistent translation of a future scenario into fleet development information.

---

[66] See Randt (2014) for a suitable example of applying the intuitive modeling approach to generate quantitative input data for the FSDM.

Table 4-5 **User input required by the FSDM**

User input	Description and comments
Target year of simulation	…stipulates the final year of the fleet simulation.
Current aircraft production intervals	…define the time intervals during which the types of the initial fleet are produced.
Future aircraft data	…define which types of aircraft will enter the fleet in the future. The user must provide the full range of aircraft data including BADA performance files,[67] utilization data (α-factors, →Section 4.2.4), and survival curves (β-coefficients, →Section 4.2.5).
Future aircraft production intervals	…define the time intervals during which the future types are produced.
Production capacities	…define the total amount of aircraft that can potentially enter the fleet as well as the maximum amount of aircraft units of particular future aircraft types available to the fleet in each year of simulation (→Section 4.2.6).
Market growth factors	…define the year-on-year change of the RPKs and RTKs in each one of the 21 regional markets (i.e., route groups shown in Figure 4-8) between 2008 and the target year of simulation. The market growth factors should be drawn from previously elaborated quantitative scenarios (→Section 3.2.2.2).
Payload factors	…define the seat and freight load factors that the monopolistic airline simulated in the FSDM is expected to achieve in each one of the 21 regional markets. In the current version of the FSDM, all payload factors are considered constant over time. The payload factor data should be drawn from previously elaborated quantitative scenarios (→Section 3.2.2.2).

4.3.4.3 Preprocessor

The preprocessor fulfills two tasks (→Figure 4-10). Firstly, it loads all user input data (→Table 4-5) required to start the program sequence of the FSDM. Secondly, it determines the performance and utilization characteristics of each specific type of aircraft being simulated by the model (including all types that do not belong to the initial fleet) on each route group (→Figure 4-8) where it will be operated.

The latter is accomplished through the Fuel Consumption and Emissions Calculation Tool (FCECT) that incorporates an aircraft performance model, which is based on Eurocontrol's Base of Aircraft Data (→Chapter 5). The primary objective of the FCECT is to determine the aircraft type- and route group-specific performance in terms of fuel burn (and exhaust gas emissions) of all aircraft that together form the global aircraft fleet of the FSDM.[68] That is, for each year of simulation, the preprocessor determines a ranking list for every route group that captures all types of aircraft available in this year as defined by the user (including those aircraft types that are not a part of the initial fleet). This ranking list is created based on the specific fuel consumption (SFC) per ASK for passenger aircraft (sfc_{ask}) and the SFC per ATK (sfc_{atk}) for all aircraft including air freighters according to equations (4-14) and (4-15).

---

[67] The BADA aircraft performance model is presented in Chapter 5. A method how to model new aircraft types with BADA is depicted in Chapter 5 as well.

[68] As described in Section 4.3.2.2, the FSDM will always employ all aircraft in a way to minimize the total fuel burn.

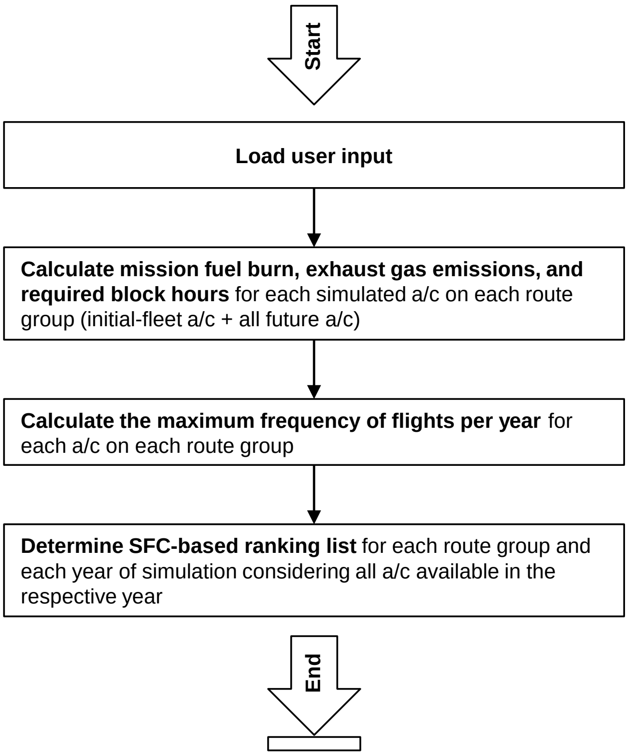


Figure 4-10 **Flow chart of the FSDM preprocessor**

$$sfc_{ask,i,j} = \frac{FB_{i,j}}{RD_{i,j} \cdot s_{i,j}} \tag{4-14}$$

$$sfc_{atk,i,j} = \frac{FB_{i,j}}{RD_{i,j} \cdot t_{i,j}} \tag{4-15}$$

sfc_{ask}	*… Specific fuel consumption (per ASK)*
sfc_{atk}	*… Specific fuel consumption (per ATK)*
FB	*… Mission fuel burn*
RD	*… Mission distance (great circle distance)*
s	*… Number of seats transported*
t	*… Freight tons transported*

In addition, based on the mission performance characteristics of each aircraft type on the route groups, the preprocessor determines the maximum number of flights for each year of simulation as a function of the Maximum Utilization Hours UH_{max} and α-factors stipulated by the user (→Section 4.2.4, equations (4-10) and (4-11)).

4.3.4.4 Fleet assignment problem

Once the preprocessor has accomplished all of its assigned tasks, the user is asked to decide whether he wants the FSDM to solve the FAP to assign the initial fleet to the routes network (→Figure 4-11). In the negative case, the FSDM will use the statistically determined fleet assignment shown in Table C-8 of Appendix C (→Section 4.3.3.3). In the positive case, the FSDM will solve the FAP for the initial fleet with the objective function of minimizing the fleet-wide fuel consumption in the initial simulation year.

The FSDM will not be capable of returning a valid solution of the FAP, if one or both of the following conditions are true:

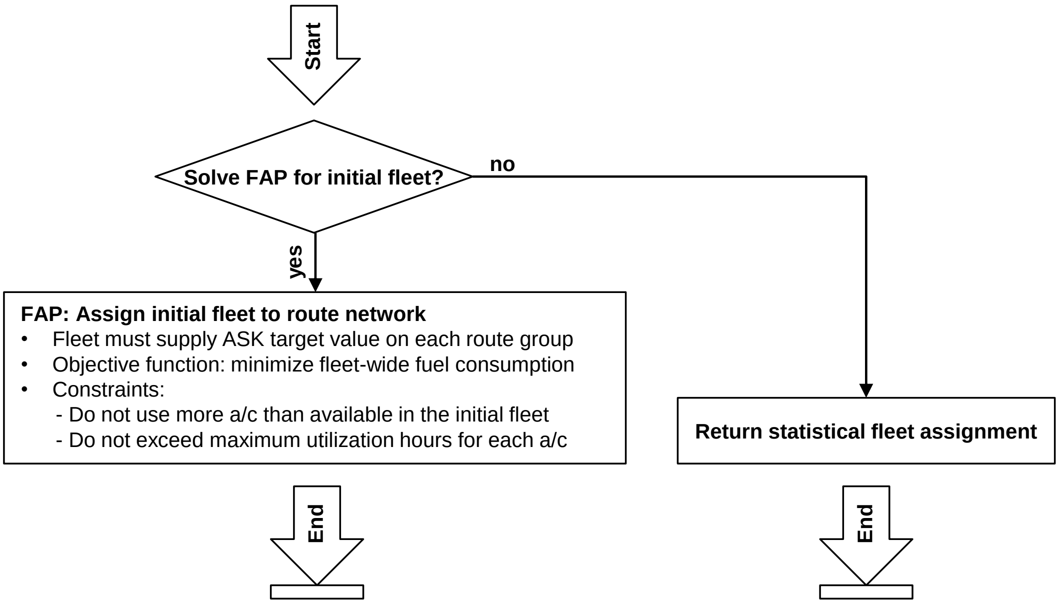


Figure 4-11 **Flow chart of the FSDM fleet-assignment sequence**

- The initial transport supply is too high to be delivered by the initial fleet (or, equivalently, the size of the initial fleet is too small to deliver the initial transport supply required).
- UH_{max} of one or several clusters or types of aircraft of the initial fleet is too low. Alternatively (or simultaneously), the respective α-factors are too high.

To identify the fleet-wide fuel-burn minimum and hence solve the FAP, the FSDM employs the *fmincon* function available in MATLAB® that "attempts to find a constrained minimum of a scalar function of several variables starting at an initial estimate. This is generally referred to as constrained nonlinear optimization or nonlinear programming." (Mathworks, 2014) To ensure the proper functioning of *fmincon*, various input parameters and options have to be provided by the user, including the above-mentioned 'initial estimate' regarding the fleet assignment solution. This is provided through the statistical fleet assignment shown in Table C-8.[69]

4.3.4.5 Aircraft retirement

Figure 4-12 shows that aircraft retirement is primarily accomplished by applying statistically determined aircraft type-dependent survival curves that stipulate the probability of survival (POS) of a certain simulated aircraft as a function of its individual age (→Section 4.2.5). The shape of a survival curve is determined by the two β-factors of equation (4-13) (→Figure 4-2). Because of this purely statistical approach, the FSDM retires aircraft in every year of simulation by determining their individual age-dependent POS, regardless of the current situation of aircraft demand expressed by the capacity gap (→Figure 4-1). That is, in a situation of significant growth with high demand for transport capacity (and thus high demand for additional aircraft units), the FSDM will retire aircraft in the exact same manner like in a situation of strong downturn. Note that in reality, airlines adapt their retirement strategies to the prevailing situation of transport demand.

Engelke (2014) conducted an extensive statistical analysis of the past retirement of all major commercial aircraft types. He thereby determined the β-factors of the nine aircraft clusters of the initial fleet (→Table 4-4). In this thesis, the β-factors have been slightly refined

---

[69] In his work, Zwenzner (2014) examined various numerical approaches to solving the FAP. Based on his finding, he recommends the *fmincon* function of MATLAB®, which is why *fmincon* is employed by the FSDM.

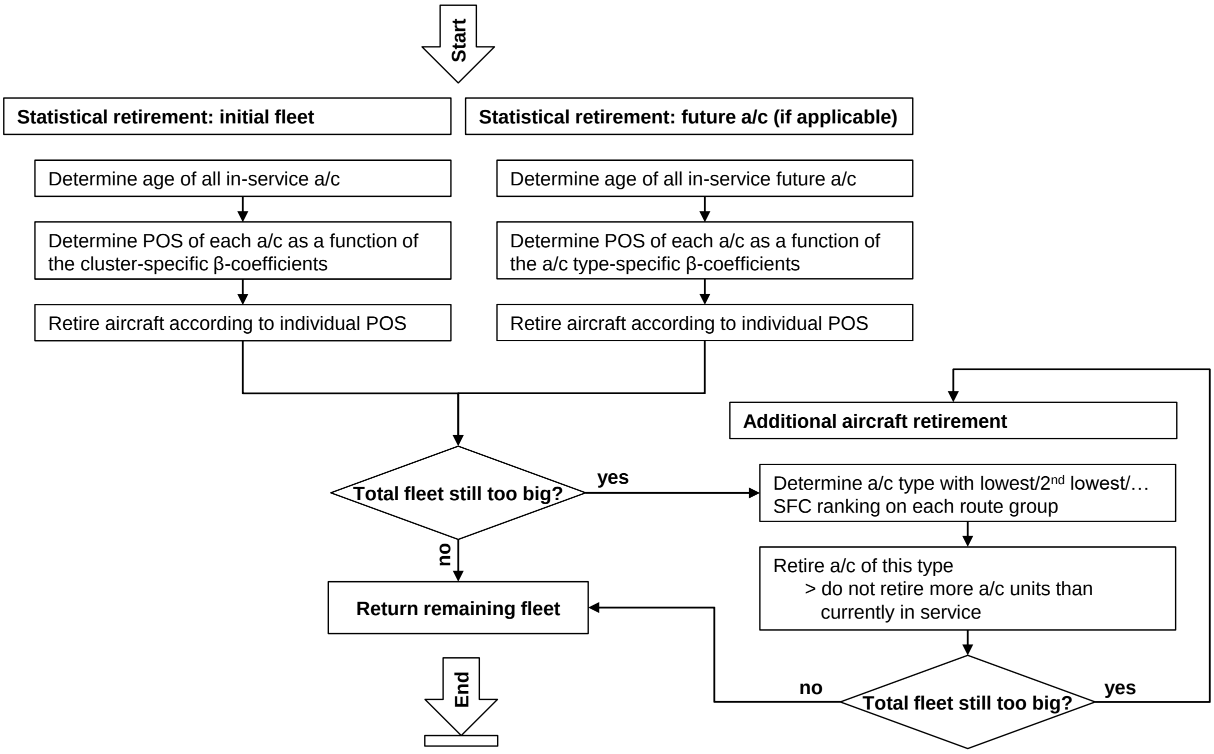


Figure 4-12 **Flow chart of the FSDM aircraft retirement sequence**

Table 4-6 **β-factors used for the statistical retirement modeling of the aircraft clusters 1 through 9 (initial-fleet aircraft)**

Data sources: Flightglobal (2008) and Verbrugge et al. (2013)

Cluster ID	β_I	β_{II}
1	2.4099	-0.1350
2	7.1835	-0.3366
3	5.8592	-0.1881
4	4.8128	-0.1942
5	6.0198	-0.2425
6	3.9517	-0.1684
7	6.9248	-0.2961
8	5.8329	-0.2556
9	6.8054	-0.3010

based on a further analysis of fleet data provided by Flightglobal (2008) and Verbrugge *et al.* (2013). These β-values (→Table 4-6) are used by the FSDM to simulate the retirement of aircraft belonging to the aircraft clusters 1 through 9. To capture the retirement of a future aircraft type, the user may either utilize the β-factors of one of the aircraft clusters 1 through 9 or define entirely new values for this type at his own discretion.

Under certain circumstances, the FSDM may be required to retire a number of aircraft that exceeds the number determined through the above-described statistical retirement approach. This case occurs once the capacity gap gets 'negative' due to highly negative RPK and RTK growth rates from one year to another. In this case, the statistical approach is by itself unable to reduce the overall fleet size by a sufficient extent, which would therefore result in an oversized fleet.

To cope with this topic, the FSDM features the additional capability of retiring an increased amount of aircraft that goes beyond the number of purely statistical aircraft retirements. If required, the FSDM will therefore retire in-service aircraft of those types of the fleet with the lowest SFC ranking number on each route group.[70] If the retirement of all of these aircraft still results in an oversized fleet (i.e., the capacity gap is still negative after this supplementary retirement process), the FSDM will continue retiring aircraft units of the type with the second lowest SFC ranking number and so forth. In doing so, the FSDM reveals again its fundamental modeling philosophy, which is to generate a fleet that develops towards an optimal fuel-burn performance (→Section 4.3.2.2).

4.3.4.6 Aircraft addition

After the FSDM has determined the number of aircraft to be retired in a particular year of simulation, it calculates the capacity gap to define the amount of aircraft to be added to the fleet in the subsequent year, following the macro approach to fleet planning (→Section 4.2.2).

Section 4.3.2.2 already pointed out that in each year of simulation, the FSDM allocates, operates, and adds aircraft in a way to minimize the total fuel consumption of the global fleet. The real-life airline behavior of profit maximization is not modeled. Therefore, in order to determine which type of aircraft is to be added to the fleet in a specific year of simulation, the FSDM accesses the SFC ranking list that has been created by the preprocessor of the FSDM (→Section 4.3.4.3). By default, the model will then select the number-one aircraft type of each route group and add an unconstrained number of aircraft units of this type to each route group's fleet.

This, however, will necessarily lead to an unrealistic future fleet composition being predicted by the model, as in reality, aircraft manufacturers are obviously not able to deliver an unconstrained amount of aircraft units of a specific type within a limited period of time. Especially when introducing a new aircraft type being available for purchase from a specific future year of simulation, unconstrained aircraft supply cannot be granted by the manufacturer, as he would at first need to build up the facilities required for the production of the new type (→Figure 4-3, Figure 4-4).

To address this topic and thereby enable a more realistic fleet simulation, the FSDM allows constraining the number of aircraft available for addition in each year of simulation. Here, the model distinguishes aircraft supply at two different levels:

1. The *total production capacity (TPC)* refers to the maximum number of aircraft units that can be supplied annually by all aircraft manufacturers together at the global level. Here, a fundamental differentiation is made between the single-aisle (SA) and twin-aisle (TA) aircraft classes (→Figure 4-5, Figure 4-6). For every type of aircraft being simulated by the FSDM, the user must therefore define to which class the type belongs.[71] Table 4-4 suggests an SA/TA-assignment of the aircraft types representing the initial-fleet clusters that is currently implemented in the FSDM.
2. The *single production capacity (SPC)* refers to the maximum number of aircraft units of a single aircraft type (i.e., *not* an aircraft cluster) that can be supplied annually by a specific aircraft manufacturer starting from a user-defined future year (→Figure 4-3, Figure 4-4).

The user can hence choose among four different cases in terms of constraining aircraft addition in the FSDM. These four cases are shown in Table 4-7. Furthermore, Figure 4-13

---

[70] Of course, it cannot retire more units of this type than currently in service, which would otherwise lead to a 'negative' fleet size.

[71] The FSDM does not support the assignment of air freighters to the SA and TA classes. As a result, the total annual supply of air freighters cannot be constrained.

Table 4-7 Use cases of the FSDM to constrain aircraft addition

		Constrain SPC?	
		YES	**NO**
Constrain TPC?	**YES**	**CASE 1** o Total aircraft addition numbers limited to SA/TA total production capacities →Table D-1 o Addition numbers of future aircraft types limited to single production capacities →Table D-2 o FSDM may ***not*** be able to fill the capacity gap entirely →FSDM will lower the target ASKs and ATKs if necessary	**CASE 2** o Total aircraft addition numbers limited to SA/TA total production capacities →Table D-1 o Addition numbers of future aircraft types ***unconstrained*** o FSDM may ***not*** be able to fill the capacity gap entirely →FSDM will lower the target ASKs and ATKs if necessary
	NO	**CASE 3** o Total aircraft addition numbers ***unconstrained*** o Addition numbers of future aircraft limited to single production capacities →Table D-2 o FSDM will ***always*** be able to fill the capacity gap entirely	**CASE 4** o Total aircraft addition numbers ***unconstrained*** o Addition numbers of future aircraft types ***unconstrained*** o FSDM will ***always*** be able to fill the capacity gap entirely

portrays the positions of the four cases within the overall aircraft-addition sequence. In the following, this sequence and its most important characteristics are described briefly. The numerical implementation of the four cases is rather complex and is explained in more detail in Appendix B.

In the Cases 1 and 2 shown in Table 4-7, the upper limit of the total annual number of aircraft addition is established by the SA and TA TPCs of the respective year. The TPC values used in this thesis are displayed in Table D-1 of Appendix D.[72]

Constraining the total aircraft addition numbers may lead to a situation where the capacity gap determined by the FSDM in a specific year of simulation requires a number of aircraft to be added that exceeds the TPC. In this case, the FSDM will add the maximum allowed number of SA and TA aircraft units to the fleet and then determine the amount of ASKs and ATKs that this fleet can actually supply. Next, the model recalculates all future ASK and ATK target values that have originally been determined by the FSDM preprocessor based on the market growth factors provided by the user (→Table 4-5).

If the FSDM intends to add more aircraft of either the SA or the TA class than the respective production capacity allows, the model will add the maximum possible number of aircraft units of the respective category to the fleet and then fill the remaining capacity gap with aircraft of the other class. It does so while referring to the SFC ranking list created by the preprocessor (→Section 4.3.4.3), ensuring that only the number-one types of each category in terms of fuel efficiency are added to the fleet.

---

[72] The numbers given in Table D-1 have been derived from the approximation equations shown in Figure 4-5 and Figure 4-6 for SA and TA aircraft, respectively, based on the statistical analyses conducted by Engelke (2014).

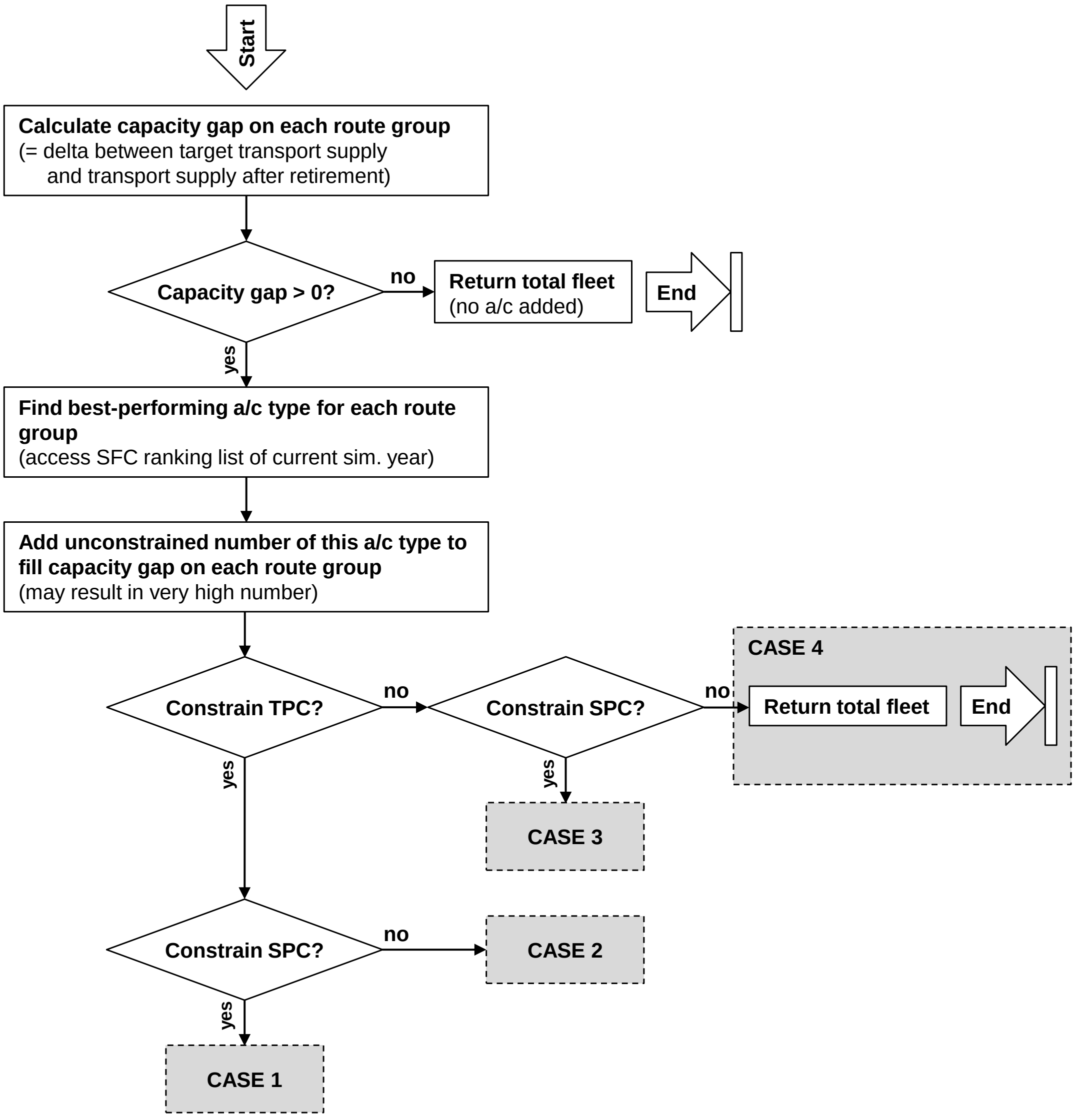


Figure 4-13 **Flow chart of the FSDM aircraft addition sequence**

The user may simultaneously choose to limit the annual number of addition of a specific future type of aircraft that is not represented by the aircraft clusters of the initial fleet.[73] This situation is covered by the Cases 1 and 3 shown in Table 4-7. Provided that due to the SFC ranking list, the FSDM intends to add this future aircraft type in a specific year of simulation, the model will limit the aircraft addition number of this type to the values displayed in Table D-2 of Appendix D.[74] If this number does not suffice to fill the capacity gap, the model will add the maximum possible number of aircraft units of this type to the fleet and then select the next best aircraft type according to the SFC ranking list. It repeats this sequence until the capacity gap is completely filled. In Case 1 (→Table 4-7), the model will additionally ensure that the overall number of aircraft additions does not exceed the SA and TA TPCs, which may lead to a necessary reduction of the total ASK and ATK target values as depicted above.

---

[73] An individual restriction of the aircraft addition number of an initial-fleet aircraft cluster is not supported by the FSDM, as all clusters of the initial fleet are considered as representing the status-quo technology reference in the base year 2008. Therefore, limiting the aircraft addition numbers of the clusters would be inappropriate for the fleet simulation purposes of the FSDM. The addition of these types can only be constrained by the SA and TA TPCs.

[74] The numbers given in Table D-2 have again been derived from the approximation equations shown in Figure 4-3 and Figure 4-4 for SA and TA aircraft, respectively, based on the statistical analyses conducted by Engelke (2014).

4.3.4.7 Postprocessor

The FSDM postprocessor is essentially aimed at preparing the raw results data created during the fleet simulation loops of the model for a subsequent user examination. The postprocessor thus generates various output data that the user can directly employ to analyze the simulation results with special emphasis on

- the fleet size and composition (i.e., the number and types of active aircraft in each year of simulation for each route group and in total),
- aircraft addition (i.e., the types and numbers of aircraft units added by the FSDM in each year of simulation),
- fleet age distribution (i.e., the age of each aircraft being part of the simulated fleet in each year of simulation),
- transport supply (i.e., the ASKs and ATKs actually supplied by the fleet on each route group in each year of simulation),[75] and
- fuel burn as well as related exhaust gas emission quantities on each route group in each year of simulation.

The postprocessor generates all results data within the MATLAB® software environment. Yet, the user can of course export the data to other file formats such as Microsoft® Excel® for further examination.

---

[75] As described in Section 4.3.4.6, the ASKs and ATKs actually supplied by the simulated fleet may be lower relative to the target values determined by the FSDM preprocessor due to production capacity constraints.

5. Aircraft performance modeling

AIRCRAFT performance modeling is an essential capability of the Aircraft Technology Assessment Framework (ATAF) developed in this thesis (→Figure 2-1). The aircraft performance model (APM) employed in ATAF is fundamentally based on the Base of Aircraft Data (BADA) that has been created and is now being maintained and distributed by Eurocontrol, the European Organisation for the Safety of Air Navigation (Air Traffic Management authority, ATM). Over the last years, BADA has become a widely utilized and recognized APM in the international scientific community. Today, it can certainly be considered as a standard tool for performance simulation purposes of civil aircraft (→Table 2-1).

This chapter is dedicated to providing a brief introduction into the methodological foundations of BADA including its performance simulation purposes and its limitations. In addition, the chapter presents the 'Fuel Consumption and Emissions Calculation Tool (FCECT),' which is employed by ATAF to predict the fuel consumption as well as the associated exhaust gas emissions of the global aircraft fleet determined by the FSDM (→Chapter 4).

5.1 The BADA aircraft performance model

BADA is essentially a collection of data files that specify the operational and performance characteristics of various current and historical aircraft types with emphasis on the currently operating commercial air transport fleet. BADA is primarily intended "for use in trajectory simulation and prediction algorithms within the domain of Air Traffic Management." (Nuic, 2014, p. 1) Hence, BADA is intended to capture the aircraft performance characteristics under ordinary flight conditions rather than simulate the operational limits of the flight envelope of an aircraft.[76] The model is therefore unlikely to deliver realistic performance data at the boundaries of an aircraft's performance limits.

5.1.1 The total-energy model

The aircraft performance model underlying BADA is "based on a mass-varying, kinetic approach [that] models an aircraft as a point and requires the modeling of underlying forces that cause aircraft motion." (Nuic *et al.*, 2010, p. 851) This approach is referred to as the 'Total-Energy Model (TEM).'

The TEM "relates to the geometrical, kinematic, and kinetic aspects of the aircraft motion, allowing the aircraft performances and trajectory to be calculated." (Nuic *et al.*, 2010, p. 851) It

---

[76] This statement is true for BADA Family 3, while BADA Family 4 features enhanced modeling capabilities. According to Suchkov *et al.* (2003, p. 7), the main assumption here is that "commercial flights are operated at relatively small flight path angles," which allows a significant simplification of the differential equations that govern the six-dimensional movement of an aircraft in the air.

Table 5-1 **Cases describing the flight dynamics of an aircraft in the Total-Energy Model**
Adapted from Nuic (2014, pp. 13–16)

Case	Thrust	Speed	ROCD	Remarks
1	Controlled	Controlled	Dependent variable	Case commonly applied to perform climbs or descents when the throttle is set to a fixed position and the speed is kept constant.
2	Controlled	Dependent variable	Controlled	Case commonly applied to accelerate or decelerate in level flight when ROCD is set to zero.
3	Dependent variable	Controlled	Controlled	Case commonly applied to maintain a constant speed and constant altitude, for example in cruise flight.

$$\boldsymbol{E_{total} = E_{pot} + E_{kin} = m\, g_0\, h + \frac{1}{2}\, m\, v_{TAS}{}^2} \tag{5-1}$$

$$\boldsymbol{(T - D)\, v_{TAS} = m\, g_0\, \frac{dh}{dt} + m\, v_{TAS}\, \frac{dv_{TAS}}{dt}} \tag{5-2}$$

$\boldsymbol{E_{total}}$	*… Total energy of aircraft*
$\boldsymbol{E_{pot}}$	*… Potential energy of aircraft*
$\boldsymbol{E_{kin}}$	*… Kinetic energy of aircraft*
$\boldsymbol{m}$	*… Aircraft mass*
$\boldsymbol{g_0}$	*… Gravitational acceleration*
$\boldsymbol{h}$	*… Geodetic altitude*
$\boldsymbol{v_{TAS}}$	*… True airspeed*
$\boldsymbol{T}$	*… Thrust*
$\boldsymbol{D}$	*… Drag*
$\boldsymbol{\frac{d}{dt}}$	*… Time derivative*

determines the forces that act on an aircraft by referring to the rate of change in kinetic and potential energy of the aircraft over time as shown by the equations (5-1) and (5-2).[77]

If aircraft devices such as spoilers, leading-edge slats, or trailing-edge flaps are ignored, two independent control inputs are available to determine the vertical trajectory of an aircraft: the throttle and the elevator. With these two parameters, two of the three important variables that describe the energy state of an aircraft (i.e., thrust, speed, and rate of climb or descent (ROCD)) can be controlled independently, while the third variable can be determined using equation (5-2). This results in the three different cases shown in Table 5-1.

5.1.2 BADA data files

In its revision 3.12, BADA covers 438 different types of aircraft, of which 166 types are supported directly through the provision of the corresponding BADA data files. The remaining types are modeled indirectly through a selection of one equivalent aircraft type out of the 166 directly supported types for each of these aircraft. (Nuic, 2014, p. 5)

For every directly supported aircraft type, BADA essentially provides four different data files in the ASCII format, i.e., the 'Operations Performance File (OPF),' the 'Airline Procedure

---

[77] A detailed introduction into the TEM is available in the work of Nuic (2014, pp. 13–16).

File (APF),' the 'Performance Table File (PTF),' and the 'Performance Data Table (PTD).' The latter two are generated automatically based on the BADA OPF and APF files and hence do not provide any further information to the user. (Nuic, 2014, p. 54) As will be shown in Section 5.2, the Fuel Consumption and Emissions Calculation Tool employed in this thesis requires only the OPF and APF files.

Nuic *et al.* (2010, p. 852) emphasize that besides the TEM-based APM described in the previous section, BADA also incorporates an 'Airline Procedure Model (ARPM).' The ARPM is aimed at providing "information on nominal aircraft operations to different simulation and modeling tools for various ATM applications."

The BADA OPF and APF files address this aspect in particular by capturing data of each directly supported aircraft such as a specific aircraft type and engine designation, aircraft masses, aerodynamic characteristics, engine performance and fuel burn data, and ground movements characteristics in case of the OPF file.[78] The APF file additionally defines "standard airline procedures" separately for the climb, cruise, and descent flight phases of each directly supported aircraft type. (Nuic, 2014, pp. 29–32)

5.2 The fuel consumption and emissions calculation tool

The fuel consumption and emissions calculation tool (FCECT) provides the third key capability within ATAF (→Figure 2-1), which is to determine the performance characteristics of all current and future aircraft types being part of the global aircraft fleet as simulated by the FSDM (Chapter 4). Following the motivation of this thesis (→Section 1.3), the major performance characteristics of interest within the scope of this thesis are

- the fleet-wide fuel consumption and
- the fleet-wide emission quantities of CO_2 and water vapor.

At a secondary level of interest are the calculation of the fleet-wide emission quantities of CO, UHC, NO_x, and PM/soot.

To achieve these objectives, the FCECT employs the BADA APM as the fundamental technique for simulating aircraft performance. Figure 5-1 shows the basic structure of the FCECT. In particular, the figure reveals that the FCECT is essentially split into an aircraft performance calculation module called the 'Fuel Consumption Calculation Tool (FCCT)' and an exhaust gas emissions calculation module referred to as the 'Emissions Calculation Tool (ECT),' with the FCCT feeding calculated flight simulation data into the ECT. The basic functioning of these two modules is depicted in the following sections. A model validation of the FCECT is presented afterwards.

5.2.1 Flight simulations and fuel consumption calculation

The foundations of the FCECT are established by the FCCT that essentially translates the theoretically described Total-Energy Model of the BADA APM into a MATLAB®-based flight simulation algorithm.[79] As shown by Figure 5-1, the FCCT provides flight simulation capabilities at both an individual flight mission level as well as at the global fleet level. The former is accomplished through the 'Single Mission Calculator (SMC),' the latter through the 'Global Fleet Mission Calculator (GFMC).'[80]

---

[78] In total, fifty different parameters are used in one OPF file to describe the performance characteristics of one directly supported aircraft type, as listed by Nuic (2014, pp. 27–28).

[79] Although the FCCT is generally capable of handling both BADA Families 3 and 4, the FCECT is set to employ Family 3 only (→Section 2.3.3).

[80] A detailed description of the FCCT and its sub-tools can be found in the work of Ittel (2014).

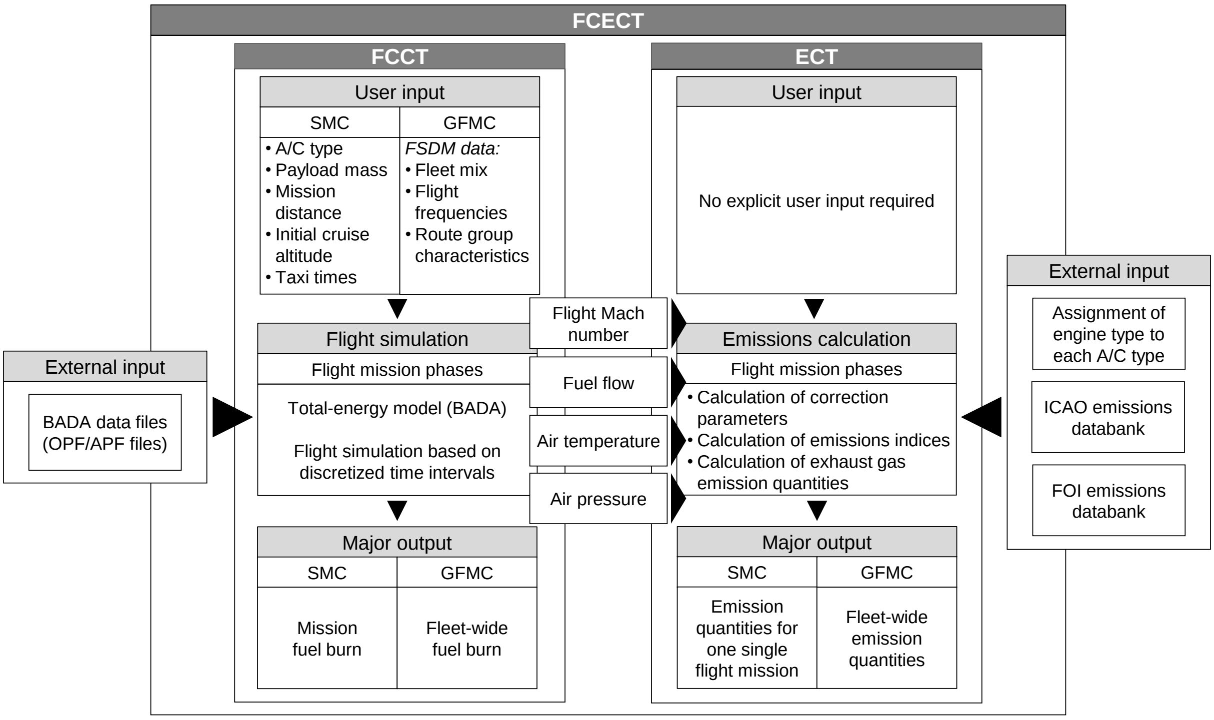


Figure 5-1 **Functioning scheme of the FCECT**
Scheme based on Engelke (2015, p. 47)

5.2.1.1 The single mission calculator

The SMC relies on input data provided by the user. These data include the selection of a specific type of aircraft of interest as well as a definition of the flight mission to be simulated (payload mass to be carried, mission distance, cruise altitude, and taxi time). Based on this input, the tool is capable of simulating a single flight mission (e.g., calculation of the required block time and the vertical flight profile) and especially of determining the fuel burn during this particular mission. Figure 5-2 depicts the fundamental program sequence of the SMC.

Whenever the SMC simulates an individual flight, particular attention is paid to determining the minimum initial mission mass of the aircraft, i.e., the sum of the operating empty mass of the aircraft, the payload mass defined by the user,[81] and the fuel mass required to accomplish the particular flight mission including reserve fuel.

At the beginning of the simulation process, the required fuel mass and thus the initial mission mass are unknown and must therefore be initialized through an estimation. After that, the tool determines the minimum initial mission mass (and hence the minimum possible fuel mass) through an iterative calculation process as shown by Figure 5-2.[82]

All flight missions simulated by the SMC feature simplified flight procedures and operations in comparison to their real-life counterparts. The most significant simplifications include the following aspects:

---

[81] In the current version of the FCCT, one passenger is considered equivalent to 90 kg of payload mass (including baggage).

[82] By default, the initial mission mass at the first iteration step is set to be equal to the maximum take-off weight (MTOW) of the aircraft given in the BADA OPF file. This reduces the overall computation speed of the FCCT algorithm by some degree, especially in the case of short-range flight simulations. It is hence suggested that an enhanced version of the FCCT may initially estimate the required fuel mission mass simply through application of the Breguet Range Equation (→Filippone (2006, pp. 216–218)).

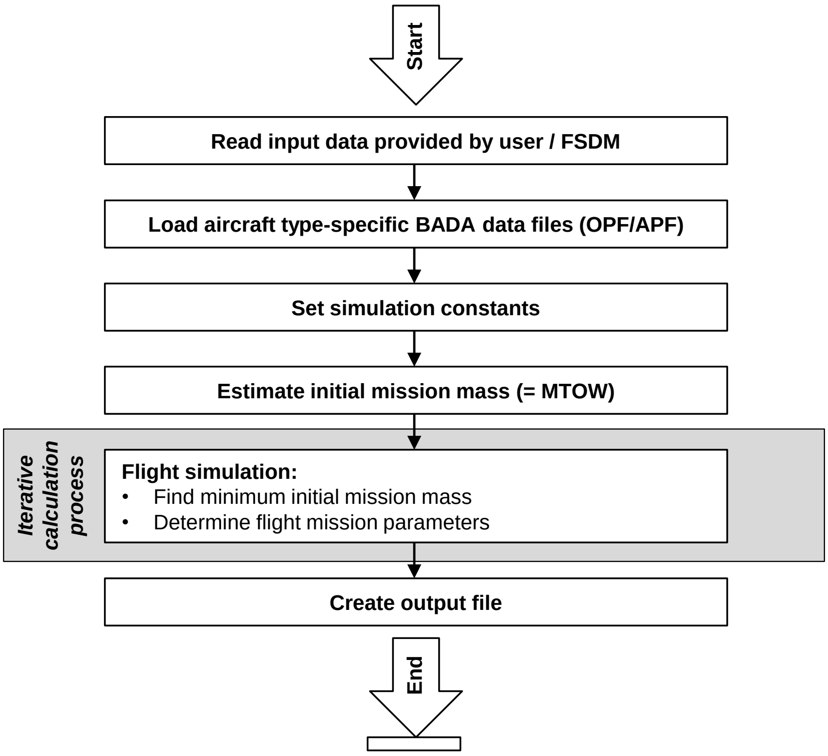


Figure 5-2 **Flow chart of the SMC**
Scheme based on Ittel (2014, p. 28)

- The flight mission distance set by the user simultaneously represents the actual flight distance flown by an aircraft (unless the mission distance is artificially increased by the Total Ground Track Extension Factor that is described later in this section). That is, route deviations due to ATM restrictions (e.g., airways, holding procedures) or meteorological conditions (e.g., route deviation to avoid a thunderstorm) are not considered.
- After take-off, all aircraft will continuously climb to the Initial Cruise Altitude (ICA) set by the user. That is, climb interruptions due to ATM restrictions or meteorological conditions are not considered. This is equally true for descent and approach procedures after the cruise flight phase.
- During cruise flight, all aircraft will maintain the predefined ICA until the descent phase begins (unless the user activates the step-climb option that is described later in this section).
- The simulated environment within which all aircraft are moving is solely defined through the International Standard Atmosphere (ISA). That is, wind and other unsteady meteorological conditions are not considered. In addition, all simulated aircraft depart and land at Mean Sea Level (MSL).

To enable more realistic flight simulations, the FCCT features two functions the user may optionally activate when desired, the first one addressing an artificial route extension to accommodate ATM and weather effects, and the second one allowing aircraft to conduct one or several step climbs during cruise flight under certain conditions.

Option 1: Route extension. If the user activates the route extension option, the SMC will extend the flight mission distance originally set by the user by a certain factor referred to as the 'Total Ground Track Extension Factor (TGTEF).' By analyzing the statistical data published by Reynolds (2009), Ittel (2014, p. 33) derived equation (5-4) to provide a logarithmic approximation function for the estimation of the TGTEF and hence account for real-life route extensions. Figure 5-3 illustrates this function.

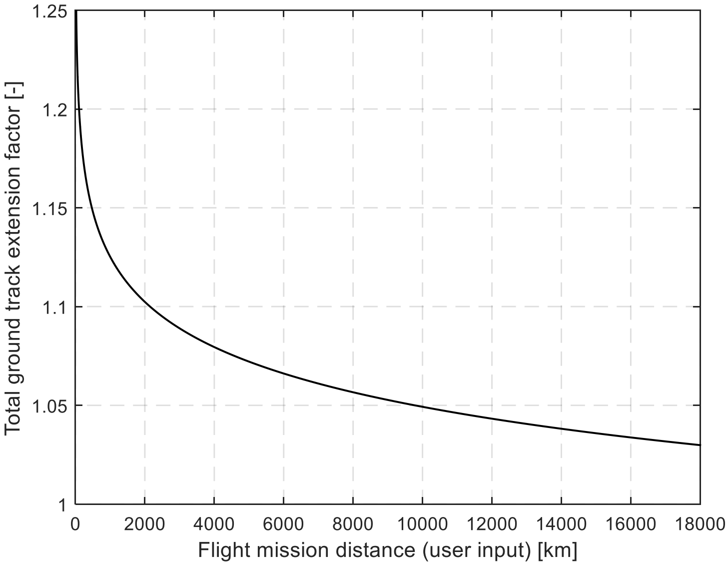


Figure 5-3 **Total ground track extension factor as a function of the flight mission distance**
Based on Ittel (2014, p. 33), data source: Reynolds (2009, p. 4)

$$\boldsymbol{TGTEF} = \frac{\boldsymbol{FMD_{ext}}}{\boldsymbol{FMD}} \tag{5-3}$$

$$\boldsymbol{TGTEF} = -\boldsymbol{0.033} \cdot \boldsymbol{ln(FMD)} + \boldsymbol{1.3532} \tag{5-4}$$

$\boldsymbol{TGTEF}$ … *Total ground track extension factor*

$\boldsymbol{FMD_{ext}}$ … *Extended flight mission distance*

$\boldsymbol{FMD}$ … *Flight mission distance predefined by the user*

Option 2: Step climb. The step-climb option provided by the SMC allows aircraft to conduct one or several step climbs during the cruise phase. Analyses of real-life flight data accomplished by Oezer (2013, pp. 38–40) have revealed that this option makes the simulation of long-haul flights more realistic in particular. Therefore, if activated by the user, the SMC will force a step climb during cruise flight under the following conditions (Ittel, 2014, p. 31):

- Step climbs will only occur every 3,000 km of distance flown.
- Every step climb will increase the current cruise altitude by 2,000 ft.
- An aircraft will only perform a step climb if the step climb results in a decrease in the current fuel flow of at least 2%.
- An aircraft will only perform a step climb if the currently remaining flight distance is at least twice as long as the distance currently required for a complete descent (i.e., from the current cruise altitude to MSL).

5.2.1.2 The global fleet mission calculator

The GFMC is implemented in a way to utilize fleet-related parameters provided by the FSDM (→Chapter 4) as main input data. With these data, the tool simulates all flights of the FSDM fleet one after the other and sums up the obtained results to form various fleet-level metrics such as the fleet-wide fuel burn in a specific year of simulation. In doing so, the GFMC calls the SMC for each simulation of a single flight.

5.2.2 Exhaust gas emissions calculation

As shown by Figure 5-1, the calculations of exhaust gas emissions within the FCECT are performed by the ECT.

Table 5-2 **Exhaust gas emission substances calculated by the ECT**
Adapted from Engelke (2015, p. 52)

	CO_2	Water vapor	CO	UHC	NO_x	PM/soot
Calculation method	Fuel flow multiples		Boeing fuel flow method 2[86]			Fraport method[87]
Area of applicability	Entire flight mission					LTO-cycle only
Remarks	Emission index applied: 3.156 kg/kg[88]	Emission index applied: 1.237 kg/kg[88]	ICAO EDB required (turbofan/turbojet engines) FOI EDB required (turboprop engines)			

The tool relies on flight simulation data provided by the FCCT as well as input data that address the exhaust gas emissions characteristics of the simulated aircraft engines during the LTO-cycle (Landing-and-Take-off cycle) provided by the ICAO and the FOI (→Section 2.3.3).[83] Accordingly, the user is required to provide an assignment of a specific type of engine to each simulated type of aircraft in order to ensure the proper functioning of the ECT.[84] Table 5-2 provides an overview of the exhaust gas emission substances calculated by the ECT as well as the underlying calculation methods.[85]

5.2.3 Validation

In this section, a brief validation of the FCECT is conducted to discuss the general functionality and provide the reader with an estimate about the degree of accuracy of the tool. Emphasis is put on the calculation of the fuel burn of selected individual flight missions that are intended to serve as exemplary validation cases.[89] The calculation of exhaust gas emission substances can only be validated for the CO_2 emissions production due to a lack of real-life flight data.[90]

Figure 5-4 through Figure 5-6 provide a brief comparison between the real-life and simulated flight distance, block time, and fuel burn data for all flight missions under consideration. Table E-1 in Appendix E contains a more comprehensive list of flight data produced by the simulations. The following observations can be made in terms of the simulation accuracy of the FCECT:

---

[83] See ICAO (2008, pp. III-2-2) for a definition of the LTO cycle. Note that the taxi times prescribed by the LTO-cycle are replaced here with the sum of the taxi times set by the user (→Figure 5-1).

[84] Table C-9 in Appendix C provides an overview of the engine type assignment to each type of aircraft of the initial fleet (→Section 4.3.3.1).

[85] A detailed description of the ECT can be found in the work of Engelke (2015).

[86] The Boeing fuel flow method 2 is described in detail in the work of DuBois and Paynter (2006).

[87] The method to calculate PM/soot emissions utilized by the ECT is based on the 'Fraport' method ('Variant B') that is described in detail in the work of iMA (2004, pp. 24–30). Further assumptions concerning the application of this method are described by Engelke (2015, pp. 37–39).

[88] Following Rachner (1998).

[89] A more comprehensive validation of the FCECT at fleet level is presented in Chapter 6.

[90] The real-life flight data used for the validation purposes of this section are classified data excerpts of the aircraft data acquisition system of a major European airline exclusively made available to TUM LLS. Hence, these data are not publicly available.

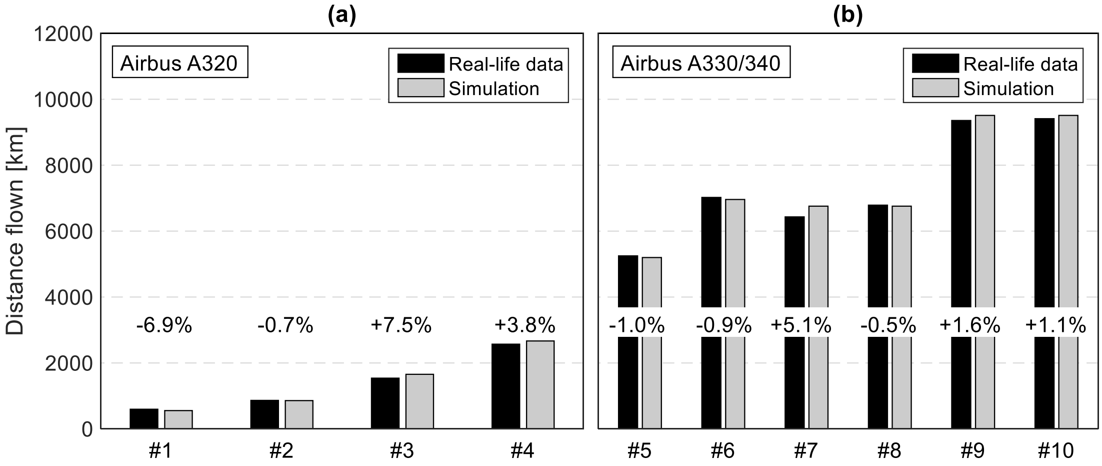


Figure 5-4 **Validation data for flight distance calculations: (a) Airbus A320 short- and mid-range operations, (b) Airbus A330/340 long-range operations**
Data sources: author's calculations, classified airline data

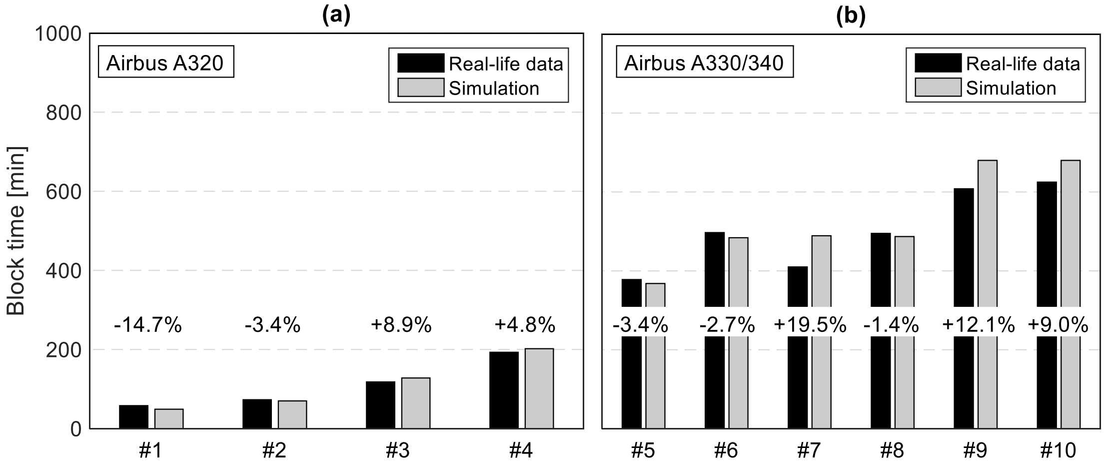


Figure 5-5 **Validation data for block time calculations: (a) Airbus A320 short- and mid-range operations, (b) Airbus A330/340 long-range operations**
Data sources: author's calculations, classified airline data

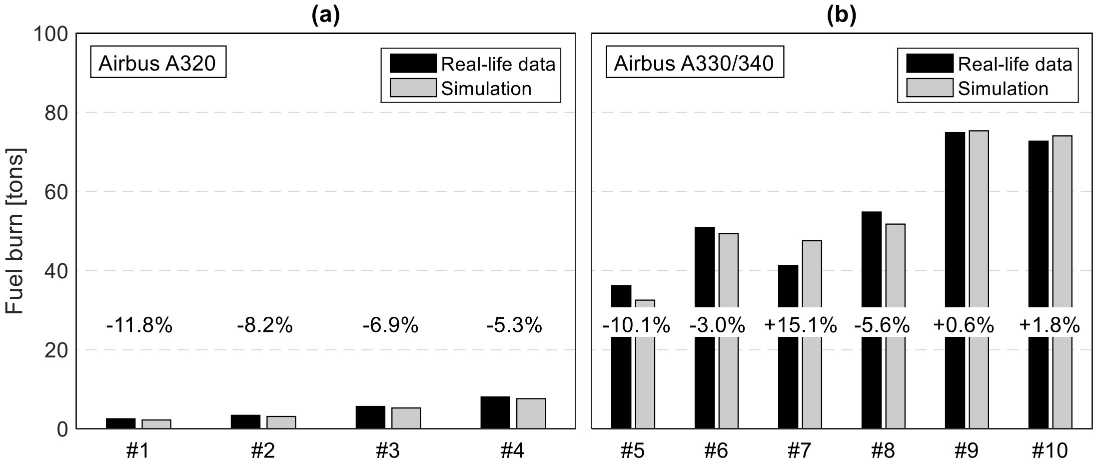


Figure 5-6 **Validation data for fuel burn calculations: (a) Airbus A320 short- and mid-range operations, (b) Airbus A330/340 long-range operations**
Data sources: author's calculations, classified airline data

- The FCECT simulations fundamentally reproduce the major characteristics of the real-life flight operations under scrutiny. That is, the relative differences between the simulation data and the real-life data of interest vary within an error range of below 20%. There is no clear evidence of a dependency of the simulation accuracy on the simulated mission type (short-, mid-, or long-range) or aircraft type.
- The flight distance appears to be reproduced very well through the application of the TGTEF model being utilized by the FCECT (→Section 5.2.1.1). Simulation errors constantly remain below 8% in this respect.
- The simulated block times remain within an error margin of below 10%. There is no clear evidence whether the duration of a long-range flight is simulated more accurately than the one of a short- or mid-range flight.
- In most cases, the FCECT underestimates the mission fuel burn within an error margin of below 15% in comparison to the real-life values. There seems to be a certain tendency of the FCECT to simulate long-range flights more accurately than short-haul flights in this respect.
- The initial mission mass determined by the FCECT matches the initial mission mass of the real-life flight very accurately (i.e., within an error margin of below 1%, →Table E-1).

From these observations, the following conclusions can be drawn:

- The calculation routine for the initial mission mass of the FCECT works very reliably.
- The route-extension routine is able to capture real-life flight route extensions well. This is especially true for long-haul flights.
- Weather phenomena (wind in particular) that cannot be captured by the FCECT appear to affect flight operations by a significant degree in reality. This is very well apparent for Flight #7 and Flight #8 that represent an eastbound and a westbound transatlantic O-D connection between Europe and North America, respectively. The strong winds prevailing over the North Atlantic Ocean strongly affect the block time and accordingly the fuel burn of these flights.

The above observations only consider ten distinct flights. Hence, more validation analyses should be undertaken in order to verify the FCECT functionality more thoroughly. To obtain an advanced understanding of the degree of simulation accuracy of the FCECT, Ittel (2014, pp. 42–74) conducted a comprehensive validation campaign. His major findings were as follows:

- Apart from certain exceptions, the tool can be considered as being capable of reproducing real-life flight operations reliably.
- Exceptions where the tool does not function accurately include flights that feature ‘extreme’ (i.e., abnormal) mission characteristics (e.g., ultra-long-range flights, flights carrying extraordinarily high or low payload masses, flights being affected by strong winds, or flights being affected by highly restrictive ATM measures like excessive holding patterns). Regarding ATM measures, Ittel (2014, p. 74) underlines that “these factors are poorly predictable.” That is, considering real-life ATM measures in the simulation of a single flight is only possible to a limited degree.
- The tool is particularly capable of accurately predicting the time-dependent fuel flow during a flight mission. Flight variables of secondary interest like the time-dependent engine thrust are not simulated very realistically. This is due to the underlying BADA model that has been designed with a clear focus on fuel burn estimations.

Therefore, when utilizing the FCECT for simulations of single flights, the obtained results should be interpreted carefully. The user should be constantly aware of the limitations of the tool and its underlying assumptions, and should primarily use it for simulating flights under 'ordinary' (i.e., non-extreme) conditions. Chapter 6 will show, however, that the FCECT can be used reliably and effectively for performance simulations at fleet level. At this level, flights occurring under extreme conditions usually have an insignificant share among all flights of the entire fleet.

5.2.4 Consideration and integration of future aircraft types

As mentioned above, in its revision 3.12, BADA supports the direct simulation of 166 aircraft types. While this range covers both modern aircraft types such as the Boeing 787-8 and older types such as the Boeing 707, aircraft types of the near future or types that are about to join the global air transport fleet are either represented by older types[91] or not included at all. However, given the goal of this thesis of predicting the global fleet development in a range of future scenarios, future aircraft types must be considered, as these types will decisively affect the future fleet composition and performance.

As a result, a method was developed that allows the integration of future aircraft types into the model by generating the corresponding BADA data files. Here, a fundamental distinction was made between entirely new aircraft concepts (such as the P-420 high-capacity transport concept depicted in Chapter 8) and aircraft types that essentially constitute advanced aircraft derivatives of currently operating aircraft types (such as the Airbus A320neo following the Airbus A320 and the Boeing 777-X succeeding the Boeing 777).

To capture completely new types, a software-based technique (the 'Integrated Design Tool') was developed for the derivation of the associated BADA data files. This tool is depicted in Chapter 8.

The data files of the advanced aircraft derivatives were generated in a rather simplistic way by modifying the BADA parameters given in the OPF and APF files of the respective aircraft predecessors (see Nuic (2014, p. 28)) for an overview of all coefficients employed by BADA).[92] In particular, the 'Fuel Consumption'-related coefficients (C_{f1} through C_{f4}) provided in the OPF files of the corresponding predecessor aircraft were adapted in a way to achieve the degree of *efficiency improvement in fuel consumption* published by the manufacturers of the aircraft derivatives relative to their predecessors.[93] In doing so, it was assumed that the published percentages of efficiency improvement applied for a characteristic flight mission profile as currently operated by the corresponding predecessor aircraft.[94] Figure F-1 in Appendix F displays the corresponding data for each type considered. The entry-into-service year was defined for each future type as well, as shown by Figure F-1.

---

[91] For example, the Airbus A350-900 is represented by the Boeing 777-200 in BADA v3.12.

[92] Table F-1 in Appendix F reveals which advanced aircraft derivatives were considered and from which type of aircraft present in the BADA databank they were derived.

[93] The 'Cruise Correction' coefficient (C_{fcr}) was left untouched.

[94] A typical mission, as it is considered here, is defined through the average stage length served, the average seat and freight capacities available, and generic seat and freight load factors. The corresponding values were identified through a statistical analysis of the data provided in OAG (2008). Table F-1 in Appendix F provides an overview of the mission definitions as well as the associated fuel burn of all aircraft derivatives under consideration.

6. Model validation

ATAF is a semi-numerical model of the global air transport system aimed at assessing the fleet-wide effects on fuel burn and exhaust gas emissions of new aircraft types and technologies under the consideration of alternative future scenarios. The high degree of complexity involved requires a thorough validation of the model in order to evaluate its overall functionality and limits of applicability.

There is obviously not much sense in validating the methodological part of ATAF related to the creation and quantification of alternative future scenarios (→Chapter 3).[95] Yet, the proper functioning of both the FSDM (→Chapter 4) and the FCECT (→Chapter 5) must be confirmed, as these two models form the basis for translating the quantitative scenario data into fleet development and performance data (→Figure 2-1).[96] This task is accomplished in this chapter.

The chapter starts with a validation of the status-quo modeling of the global air transport system considering the period from 2008 to 2013 with particular focus on fleet development and performance calculations. Here, the obtained data is compared to real-life data to evaluate the degree of model accuracy. Then, in order to evaluate the capability of the model of predicting the future fleet composition and related performance characteristics beyond the status quo, Boeing's Current Market Outlook (CMO) 2014-2033 (Boeing Commercial Airplanes, 2014a) is employed as a basis for an exemplary input scenario to calculate the associated future fleet data from the present until 2033. The obtained data is then compared to the figures published in Boeing's CMO. Finally, the chapter reviews the major validation results and discusses the limits of applicability of ATAF on this basis.

6.1 Validation of the modeling of the status quo

This section deals with the assessment of ATAF in terms of its ability to reproduce the real-life development of the world air transport fleet as well as the associated fuel consumption and production of exhaust gas emissions from 2008 to the present (i.e., 2013).[97] The real-life data that form the basis of this validation process are mainly derived from Boeing's CMO reports published annually between 2009 and 2014 (with some exceptions).[98] This is to ensure consistency among the data excerpts used here for the validation of the different years under scrutiny.[99] All relevant data being derived from Boeing's CMO reports and other relevant studies are summarized in Appendix G.

---

[95] The elaborated future scenarios cannot be validated by any means.

[96] A validation of the FCECT at the single-mission level is presented in Section 5.2.3.

[97] The reader is reminded that the FSDM has been designed to start all fleet simulations in 2008 (→Section 4.3.3). The year 2013 is considered as 'the present' here, as this is equally done in Boeing's CMO 2014-2033.

[98] All reports are freely accessible on the internet.

[99] During the analysis of the various published sources of aviation-related statistical data, it was found that these data sometimes vary substantially from one source to another.

6.1.1 Simulation input

To determine the fleet composition and performance data for the years from 2008 to 2013, the following input data were used for the FSDM fleet simulations:

- The route group-specific RPK and RTK growth factors shown in Table G-6 and Table G-7 were used, respectively.
- Payload factor data published by ICAO (2014): An average seat load factor of 77.8% and an average freight load factor of 47.7% were employed.[100] A differentiation among the different route groups (→Figure 4-8) was not made.
- Based on the data provided by Boeing Commercial Airplanes (2013), MH/BH-ratios of 1.57 (with UH_{max} = 20) and 2.07 (with UH_{max} = 15) were defined for long-range and short-range aircraft, respectively (→Section 4.2.4).
- The FAP was solved to assign the initial fleet to the routes network in a way to minimize the total fuel consumption (→Section 4.3.4.4).

All remaining input data required to initialize and start the simulation (→Table 4-5) were left unchanged relative to the data shown in Appendix C and Appendix D. Regarding the restriction of aircraft additions (i.e., the maximum possible delivery rates of aircraft per year), Case 1 (→Table 4-7, Appendix B) was selected for the simulation.

6.1.2 Simulation results and assessment

Figure 6-1 through Figure 6-5 show the simulation results and compare them to the real-life data published in the Boeing CMO reports.[101] The figures reveal that the simulation generally reproduces the real-life data well in terms of the modeling of the global transport supply, fleet development, and fuel performance. However, some deviations are apparent that are discussed in the following.[102]

Figure 6-1 (a) shows the data related to the transport supply of the global air transport fleet. In the initial year 2008, approximately 4.6 trillions of RPKs were generated in reality, which is reproduced well by the simulation. The corresponding supply of ASKs shows some deviation, though. Apparently, the assumed seat load factor of almost 78% was assumed too high in the simulation compared to reality, which results in a slightly lower amount of simulated ASKs supplied in 2008.

Moreover, the deviations between the simulated transport supply and the real-life data further increase from 2009 to 2013. The explanation for this observation can be identified when referring to Figure 6-1 (b). While the simulation can achieve the negative growth rate of almost -2% from 2008 to 2009 without any problem, it is unable to reach the strongly positive growth rates prevalent in the subsequent years. Two reasons for this model behavior must be emphasized in this context:

- The TPC restriction of the simulation does not permit to add the number of aircraft that would actually be required to fill the capacity gap and hence achieve the intended growth rates.

---

[100] The reader is reminded that in its current version, the FSDM is unable to support dynamically varying load factors (→Section 4.3.4.2).

[101] The associated raw results data are available in Appendix G.

[102] In this chapter, all aircraft types are generally categorized following Boeing's aircraft categorization. For that, the FSDM aircraft clusters are assigned to the Boeing aircraft categories in the same way as suggested by the CMO reports.

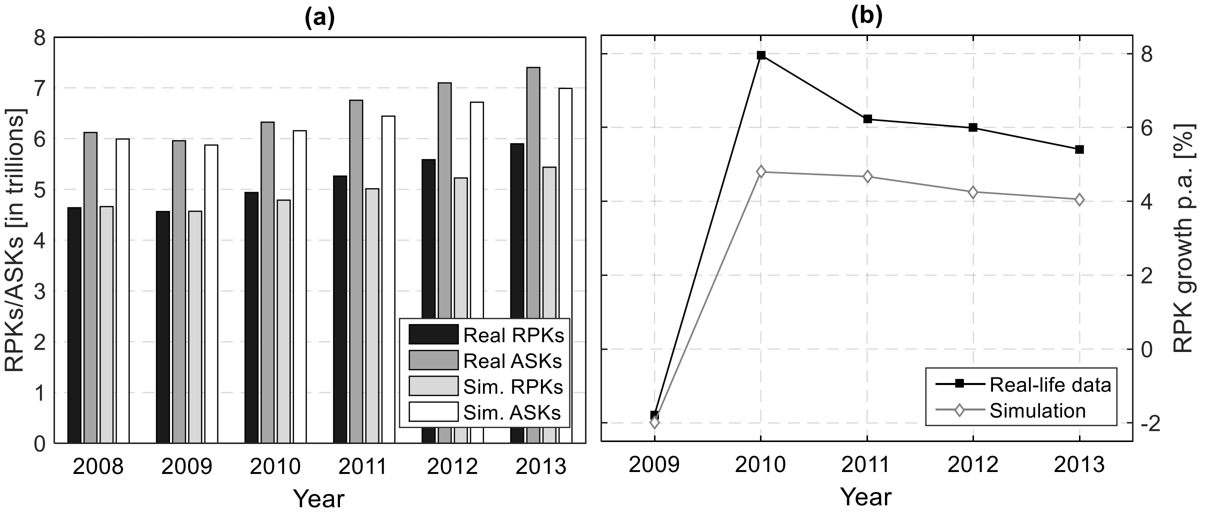


Figure 6-1 **Real-life and simulated development of global RPKs and ASKs: (a) absolute values p.a., (b) growth relative to preceding year**
Data sources: Boeing CMO 2014, author's calculations

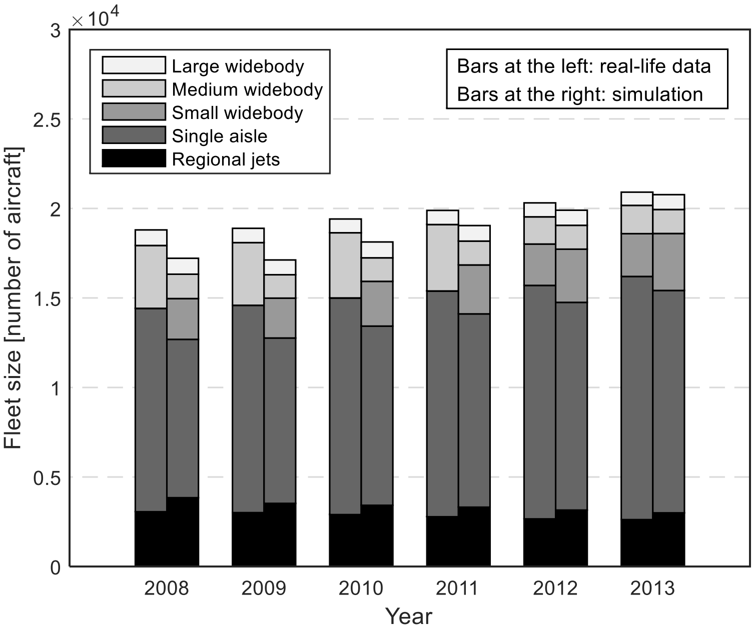


Figure 6-2 **Real-life and simulated development of the global fleet size and composition**
Data sources: Boeing CMO 2014, author's calculations[103]

- The fact that the model is unable to store aircraft temporarily (and later reactivate and reassign them to the simulated routes network) makes the demand for new aircraft units raise even more strongly in the years succeeding the economic recession after 2008. That is, the model can only achieve growth by adding new aircraft units. This particular model limitation therefore aggravates the above topic.

Referring to Figure 6-2 and Figure 6-3, a certain difference concerning the global fleet size and composition between the simulation and the real-life data is obvious as well.[103] This difference is most prominent in the initial year 2008, which reveals that the ACAS-based fleet

---

[103] *Important note:* Unlike in the more recent CMO reports, Boeing did not differentiate between the aircraft categories 'Small widebody' and 'Medium widebody' in the reports published in 2009, 2010, 2011, and 2012. Instead, Boeing treated these two categories as one single aircraft category. Therefore, where applicable, the 'Small widebody' and 'Medium widebody' categories are together referred to as 'Medium widebody' in the respective bar charts shown in this chapter.

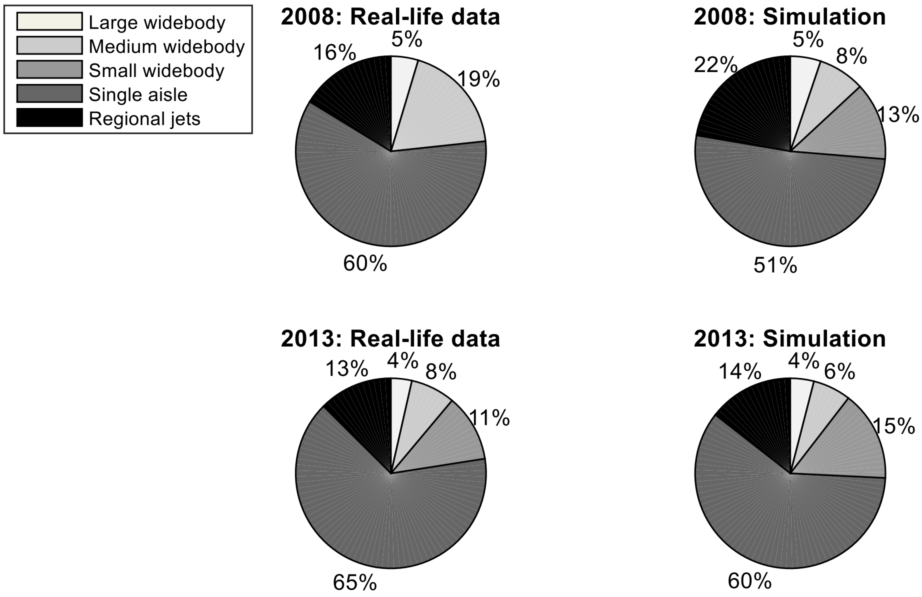


Figure 6-3 **Real-life and simulated fleet composition in 2008 and 2013**
Data sources: Boeing CMO 2009 and 2014, author's calculations[103]

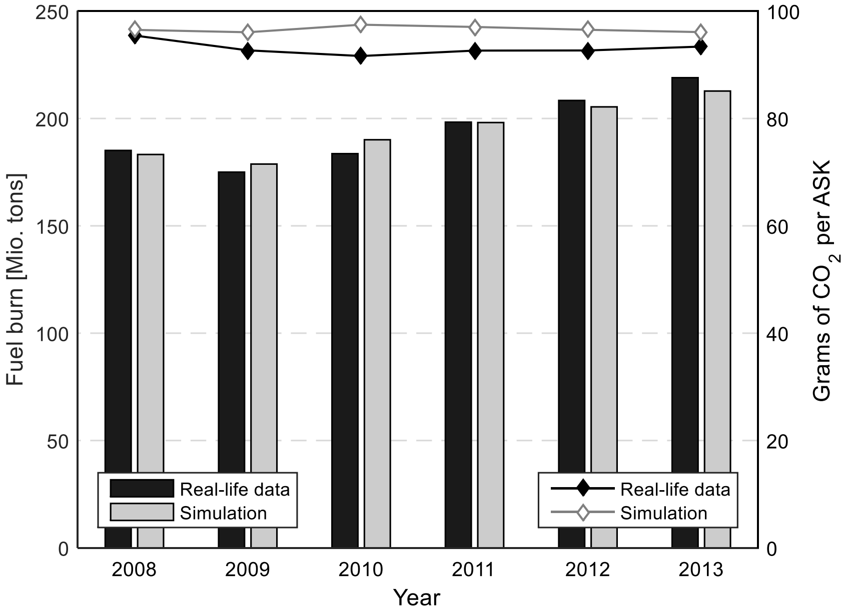


Figure 6-4 **Real-life and simulated development of the fuel consumption and CO_2 performance of the global air transport fleet**
Data sources: Boeing CMO 2014, EIA (2015), Schäfer (2012, p. 222), author's calculations

data used to initialize the simulation (Flightglobal, 2008) do not match well the data provided in the CMO reports. This may especially be justified with the handling of those aircraft being marked as 'parked' and 'temporarily stored' in the ACAS databank. During the preparation of the initial-fleet statistics (→Table C-2), these aircraft were not considered part of the active air transport fleet and hence ignored in the subsequent statistical analyses.

Figure 6-4 indicates the simulated fuel consumption and CO_2 performance (measured in grams of CO_2 produced per ASK on average) of the global fleet relative to the real-life data. The figure reveals a good coincidence of the simulated data with reality. In particular, the CO_2 performance in the initial simulation year 2008 is almost exactly reproduced. That means that the simulated fleet requires an identical amount of fuel (and thus produces the same amount of CO_2) to supply a certain number of ASKs as the real fleet, independent of the absolute fleet

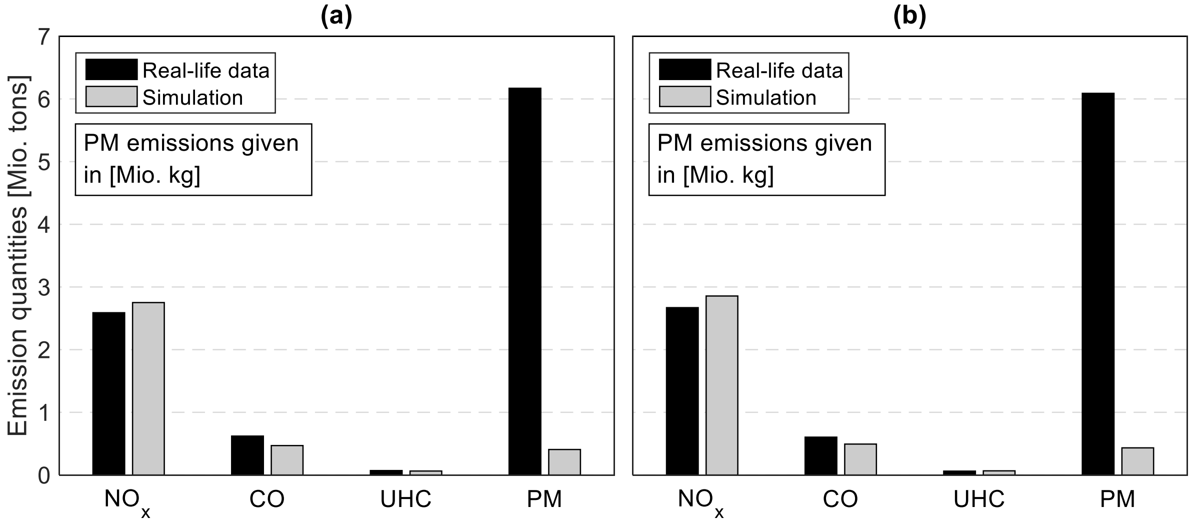


Figure 6-5 **Real-life and simulated exhaust gas emission quantities at the global level for (a) 2008 and (b) 2010**
Data sources: Schäfer (2012, p. 222), author's calculations

size and transport supply. This finding is essential in assessing the quality of the fleet model within the scope of this thesis, as it fundamentally proves an adequate functioning of the approach of ATAF to reproduce the fleet-wide fuel and CO_2 performance.

For the subsequent years, the simulated and real-life fuel consumption and CO_2 performance differ slightly. This, again, must be explained with the inability of the model to simulate temporary aircraft storage. In reality, one can assume that in 2009 (a year of economic recession), airlines grounded less efficient aircraft with higher priority than more efficient modern types when reducing the transport supply. This resulted in a non-negligible increase in the fleet-wide CO_2 performance that is observable well in Figure 6-4.

In contrast, the simulation anticipates a small decrease of the CO_2 performance from 2009 to 2010.This is because of the TPC restriction of the simulation. In order to achieve the very high growth rate required between these two years (8% are required), the model has to add suboptimal aircraft types to the routes network apart from the best-performing types, as the constrained TPC limits the addition of the best types (→Sections 4.2.6 and 4.2.7, Appendix B).

Therefore, the reason for the worsening of the global CO_2 performance of the simulated fleet is the suboptimal (but inevitable) assignment of the fleet to the network. The model is unable to allocate the optimal aircraft type to each route group. Instead, it has no choice but employ other types to produce the required transport supply. If the model were able to reactivate aircraft that were parked in 2008, it would require less new aircraft to be added to the fleet, which would again diminish the negative effect of the suboptimal fleet assignment. This observation thus demonstrates that besides the purely *technical characteristics of the fleet*, the question *of how this fleet is assigned to the network* also plays a vital role when evaluating its actual fuel and CO_2 performance.

Finally, Figure 6-5 displays the total quantities of exhaust gas emissions produced by the global fleet in the years 2008 and 2010.[104] The figure reveals again a good coincidence of the simulation results with the real-life data with one substantial exception. The estimation of the PM emissions strongly differs, as the FCECT supports the calculation of this emission substance for the ICAO LTO-cycle only (→Section 5.2.2).

---

[104] Data addressing the exhaust gas emissions of more recent years were not available.

6.1.3 Case study 1: Unconstrained aircraft addition

The simulation results presented in the previous section reveal a significant influence of the question whether or not restrictions apply regarding the addition of new aircraft to fill the capacity gap. In Case 1 (→Table 4-7) that underlies the simulation presented above, both the TPC and the SPC were intentionally constrained to avoid unrealistically high aircraft addition numbers. On the other hand, this leads to the inability of the model to fill the capacity gap completely for the years after the economic recession of 2009.

In this section, the simulation presented above is depicted again. However, this time, aircraft additions are not constrained (i.e., Case 4 shown Table 4-7 is applied), which allows a more thorough investigation of the influence of restricting aircraft additions on the fleet modeling. Figure 6-6 through Figure 6-10 show the simulation results.[105] Figure 6-6 confirms that without restricting the aircraft addition numbers, the model is capable of achieving the predefined rates of growth. The constant load-factor modeling explains why the simulated total ASKs tend to exceed their real-life counterparts by some degree (according to ICAO (2014), the average seat load factor has increased from 76% in 2008 to almost 80% within recent years). The slight deviations of the RPK growth rates visible in Figure 6-6 (b) can be explained with the input data related to RPK growth taken from Boeing's CMO reports. These figures do not exactly match the total RPKs given in the reports.[106]

Figure 6-7 reveals that based on the predefined initial fleet of 2008, the model determines a fleet development that differs clearly from reality. In 2013, the total fleet size is calculated to be much larger in the simulation than in reality (25,416 units in the simulation vs. 20,910 in reality, which is equal to a difference of +21.5%). Figure 6-8 reveals the reason of this deviation: the simulated world fleet of 2013 consists of much more low-capacity aircraft units (i.e., single-aisle aircraft plus regional jets) than it was the case in reality (84% vs. 78%). The model obviously prefers adding single-aisle aircraft types to the fleet rather than larger types due to their better SFC performance. It hence requires more aircraft units to fill the capacity gap.[107] Because in this simulation case, the model is permitted to add any number of any type of aircraft available in the respective year of simulation, it radically selects the best performing type on each route without considering aircraft addition constrains.

The corresponding positive effect on the fleet-wide CO_2 performance is visible in Figure 6-9. Compared to the restricted-aircraft-addition case presented in the previous section, the global aircraft fleet is now capable of reducing the amount of CO_2 produced per ASK more quickly and even matches the value of the real-life fleet in 2013. Unconstrained additions of next-generation aircraft types (e.g., Boeing 787) additionally support this effect.

Yet, the total gain in CO_2 performance within the 5 years of simulation remains relatively small due to two reasons. (1) The initial fleet of 2008 features almost the same technical characteristics than the fleet in 2013 (i.e., only very few new-generation aircraft types like the Boeing 787 have joined the fleet until 2013. The vast majority of added aircraft belongs to the

---

[105] The associated raw results data are available in Appendix G.

[106] Note that Boeing provides both very detailed numbers of RPK growth concerning the different world regions and numbers at a more aggregated level (e.g., see the CMO report of 2014, pp. 34 and 40). These numbers are not always consistent within one report. In addition, Boeing defines a traffic flow named 'CIS Region—International' that cannot be allocated to the FSDM routes network model (→Figure 4-8) and that is hence ignored here.

[107] The reader is reminded that the model selects aircraft to add to the fleet based on their individual SFC performance determined by the preprocessor (→Sections 4.3.4.3 and 4.3.4.6).

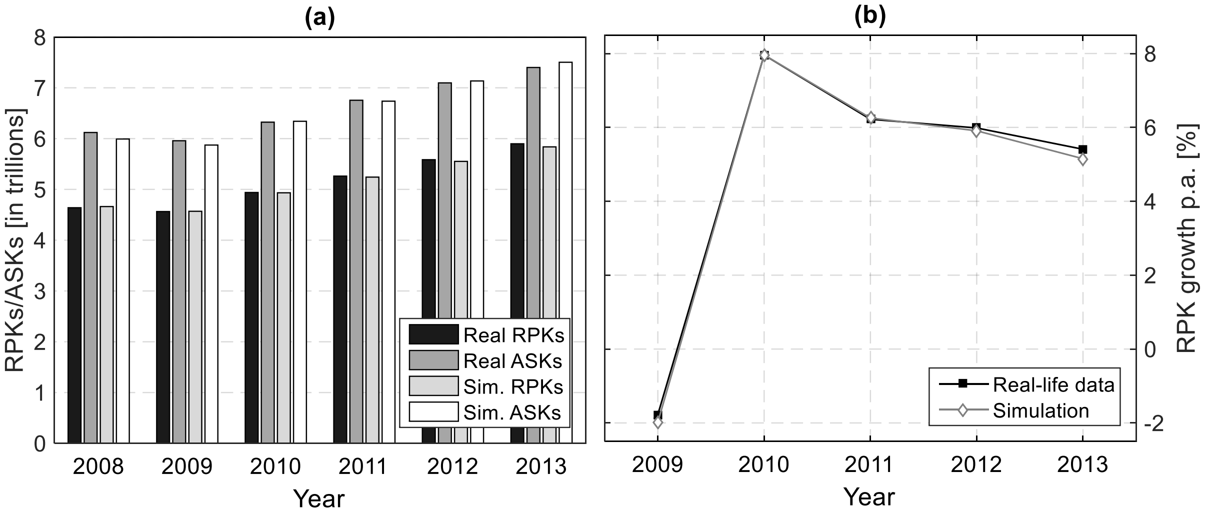


Figure 6-6 **Case study 1 (unconstrained aircraft addition): Real-life and simulated development of global RPKs and ASKs: (a) absolute values p.a., (b) growth relative to preceding year**
Data sources: Boeing CMO 2014, author's calculations

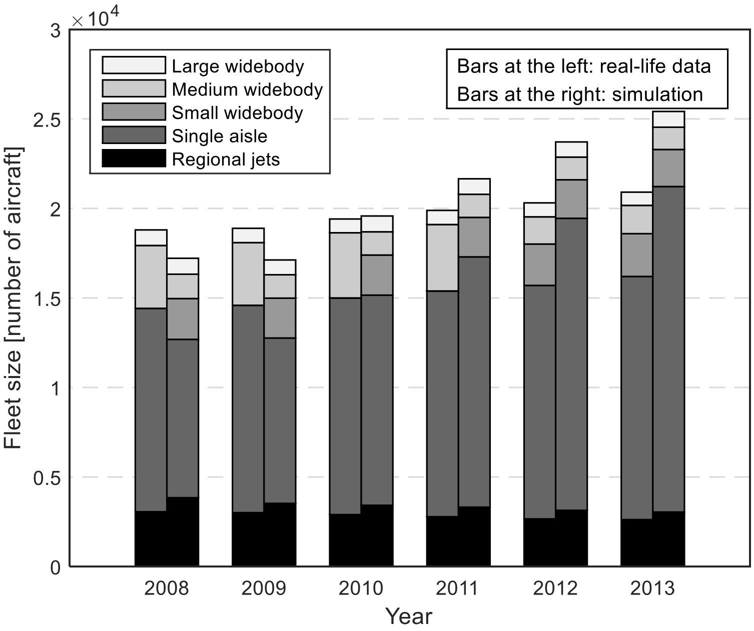


Figure 6-7 **Case study 1 (unconstrained aircraft addition): Real-life and simulated development of the global fleet size and composition**
Data sources: Boeing CMO 2014, author's calculations

clusters 1 through 9[108]). (2) The initial fleet of 2008 operates optimally on the routes network due to the FAP that was solved for this fleet. Hence, an improvement of the fleet assignment can only be achieved slowly through a retirement of less efficient aircraft types (e.g., Cluster 1: MD-11) and the commissioning of more efficient types (e.g., Cluster 8: Boeing 777-200).

Finally, Figure 6-10 shows a slightly higher amount of emissions substances produced in 2013 in the unconstrained case compared to the constrained case (Figure 6-5). However, this increase is not as high as the increase in ASKs produced by the fleet in the unconstrained case. In other words, the more efficient fleet of the unconstrained case features a better ratio of emission substances produced per ASK supplied, which underlines the above-described

---

[108] The reader is reminded that the moment in time when an aircraft of a certain type or cluster joins the simulated fleet does not affect its technical performance (including its specific fuel efficiency). (→Section 4.3.2.4).

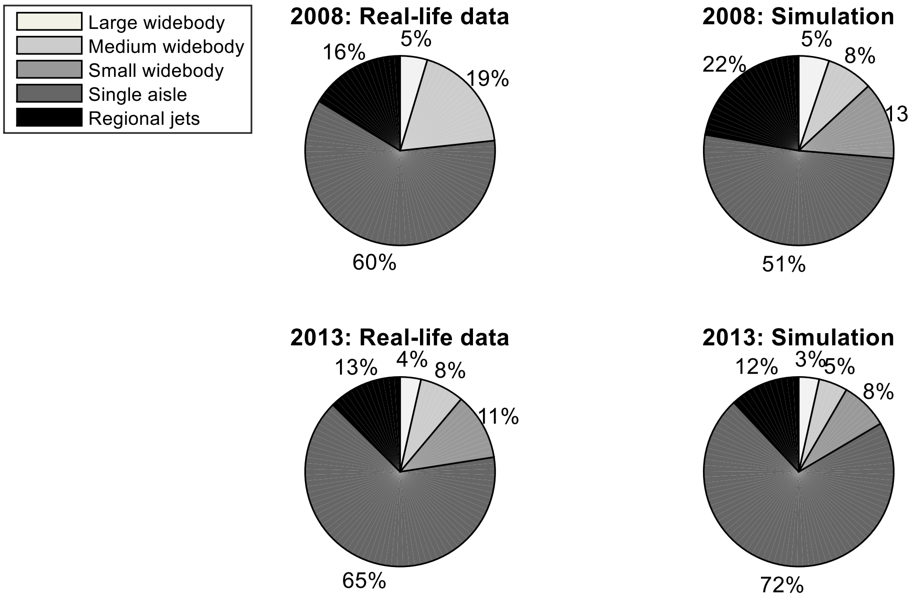


Figure 6-8 **Case study 1 (unconstrained aircraft addition): Real-life and simulated fleet composition in 2008 and 2013**
Data sources: Boeing CMO 2009 and 2014, author's calculations

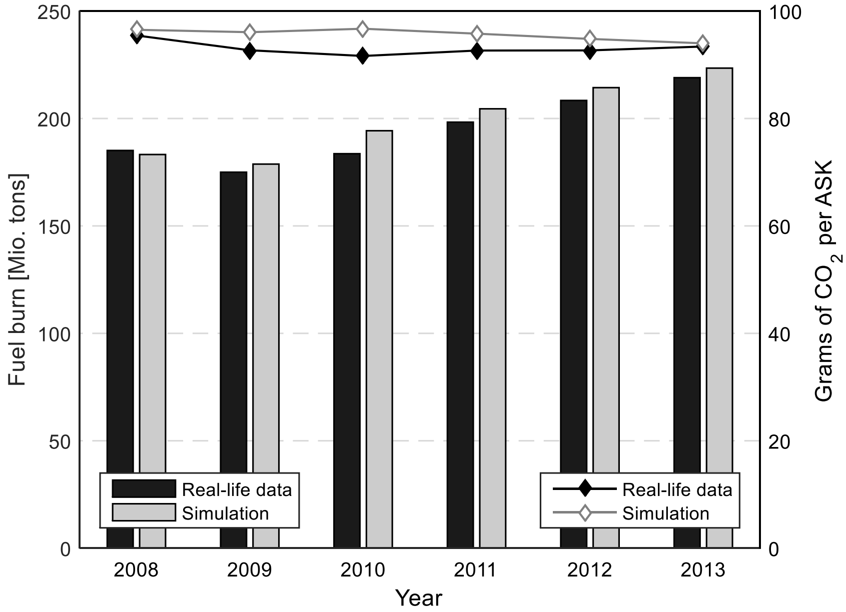


Figure 6-9 **Case study 1 (unconstrained aircraft addition): Real-life and simulated development of the fuel consumption and CO_2 performance of the global air transport fleet**
Data sources: Boeing CMO 2014, EIA (2015), Schäfer (2012, p. 222), author's calculations

effects of restricting the aircraft addition numbers on the fleet-wide fuel efficiency simulated by the model.

The conclusion of these observations actually reveals a specific *dilemma* of ATAF due to

- the underlying modeling philosophy (especially the philosophy to strictly determine an optimum fleet in terms of total fuel consumption for all years of simulation) and
- the fact that the model is set to start all fleet simulations in 2008 – a year that is followed by a severe economic decline, leading to a necessary reduction of the global fleet size and temporary aircraft storages that cannot be captured by ATAF.

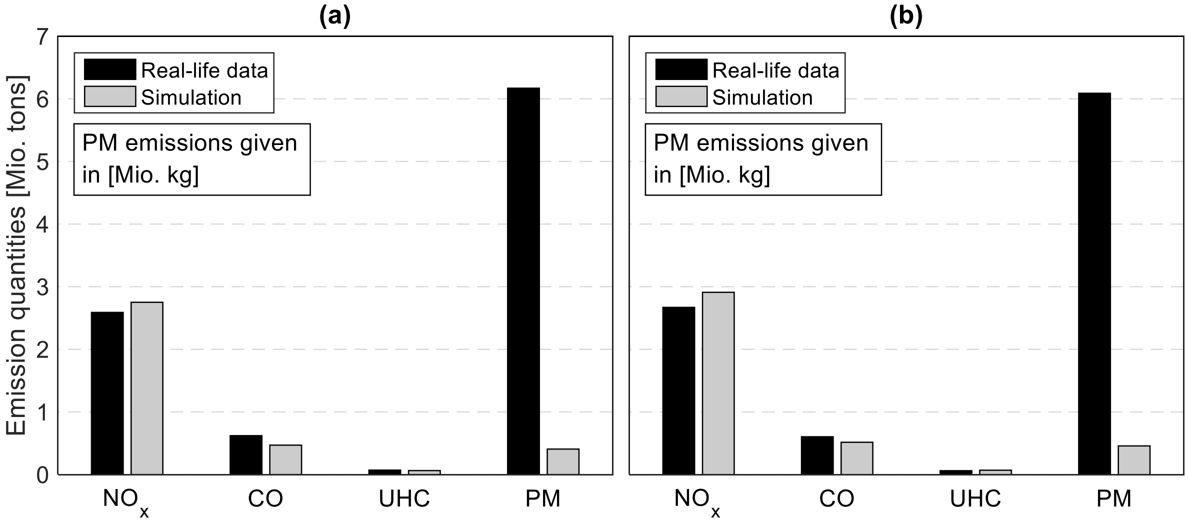


Figure 6-10 **Case study 1 (unconstrained aircraft addition): Real-life and simulated exhaust gas emission quantities at the global level for (a) 2008 and (b) 2010**
Data sources: Schäfer (2012, p. 222), author's calculations

As a result, the user must fundamentally select between two options. Either the model is set to simulate a fleet that meets the predefined transport demand in each year of simulation, regardless of the number of aircraft additions required to fill the capacity gap, or, alternatively, the user makes the model simulate a more realistic aircraft-addition behavior to the detriment of the modeling of the RPK growth. The essential problem underlying this dilemma is the inability of the current version of the model to simulate temporary aircraft storage paired with a purely fuel-consumption-optimizing assignment of the fleet to the routes network. A future version of the model should therefore consider aircraft capacity distribution as a second optimization parameter.

6.1.4 Case study 2: Average growth rates

The simulation results presented in the previous two sections revealed that for moderate rates of RPK growth (i.e., rates at approximately 4.0% p.a. or lower), the model is likely to meet the required transport demand even if the total aircraft addition numbers are constrained. Therefore, the model is tested again in terms of its ability to reproduce the real-life fleet development while restricting the aircraft production capacities again. In this case study, however, the rates of growth of RPKs and RTKs for each route group are averaged throughout the simulation period under scrutiny leading to moderate values (the corresponding values are shown in Table G-1 and Table G-2 of Appendix G). In particular, aircraft storage can be avoided in this case. Figure 6-11 through Figure 6-15 summarize the major simulation results obtained for this case study.[109]

Figure 6-11 (a) shows that similar to the reference simulation case depicted in Section 6.1.2, the model is again unable to meet the required growth of RPKs from 2008 to 2013 entirely due to the restrictions of aircraft additions. However, the total fleet size in 2013 is about 4% bigger now than the one of the reference case (21,570 units vs. 20,770 units). This observation underlines again the relevance of aircraft storages and their significant impact on the modeling of the fleet development.

In addition, Figure 6-11 (b) displays that the model is unable to maintain the RPK growth rate at a constant level either, although this has been prescribed by the input data of this case study. The conclusion from this observation is that the number of in-service aircraft that

---

[109] The associated raw results data are available in Appendix G.

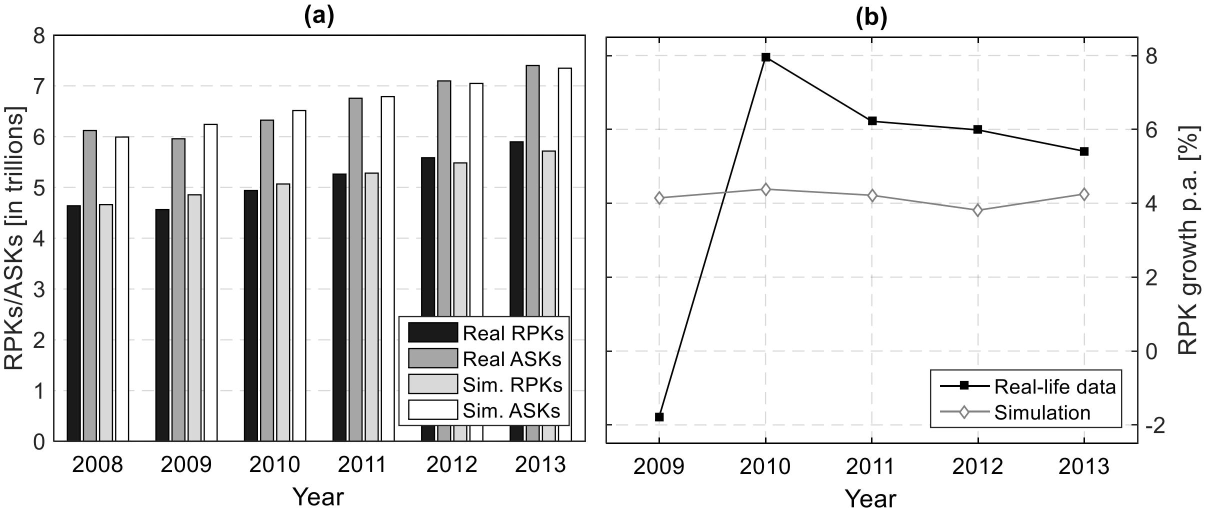


Figure 6-11 **Case study 2 (average growth rates): Real-life and simulated development of global RPKs and ASKs: (a) absolute values p.a., (b) growth relative to preceding year**
Data sources: Boeing CMO 2014, author's calculations

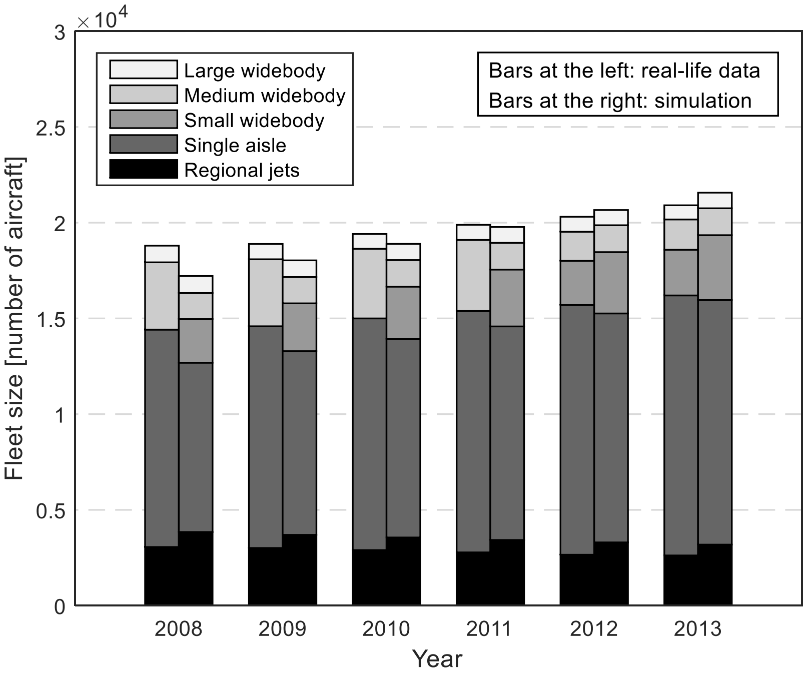


Figure 6-12 **Case study 2 (average growth rates): Real-life and simulated development of the global fleet size and composition**
Data sources: Boeing CMO 2014, author's calculations

underlie statistical retirement varies from year to year, resulting in a varying size of the capacity gap. In years with a large capacity gap, the production capacity limits are reached where the model cannot meet the originally prescribed rates of growth. Hence, it has to decrease the total amount of RPKs being supplied by the simulated fleet.[110]

The remaining figures show that the simulation data match the real-life data well. As the fleet of the reference case is smaller and supplies less RPKs, the total fuel consumption is consequently lower compared to the fuel consumption of the case presented in this section (→Figure 6-4, Figure 6-15).

---

[110] As can be seen well in Figure 6-11 (b), this is especially true for the year 2012.

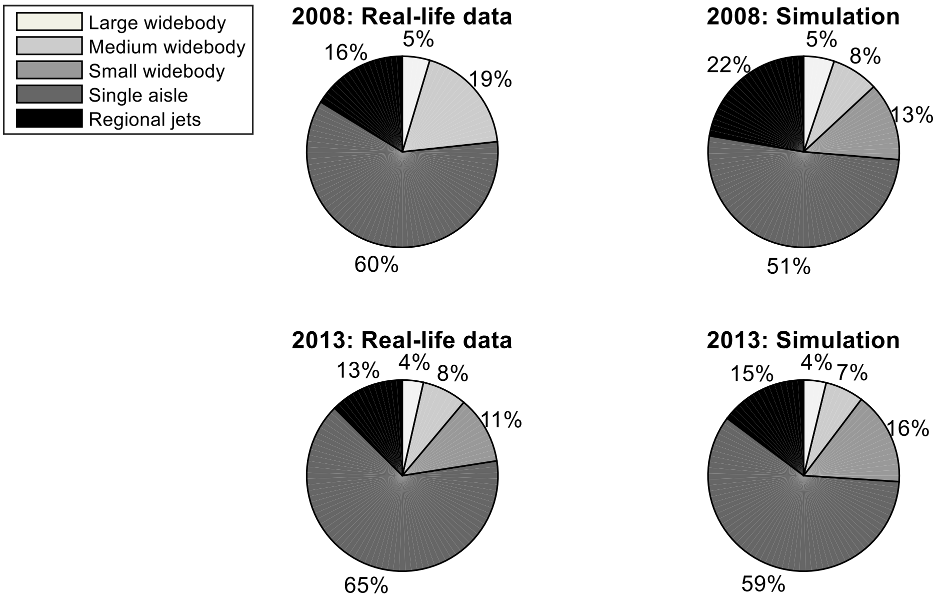


Figure 6-13 **Case study 2 (average growth rates): Real-life and simulated fleet composition in 2008 and 2013**

Data sources: Boeing CMO 2009 and 2014, author's calculations

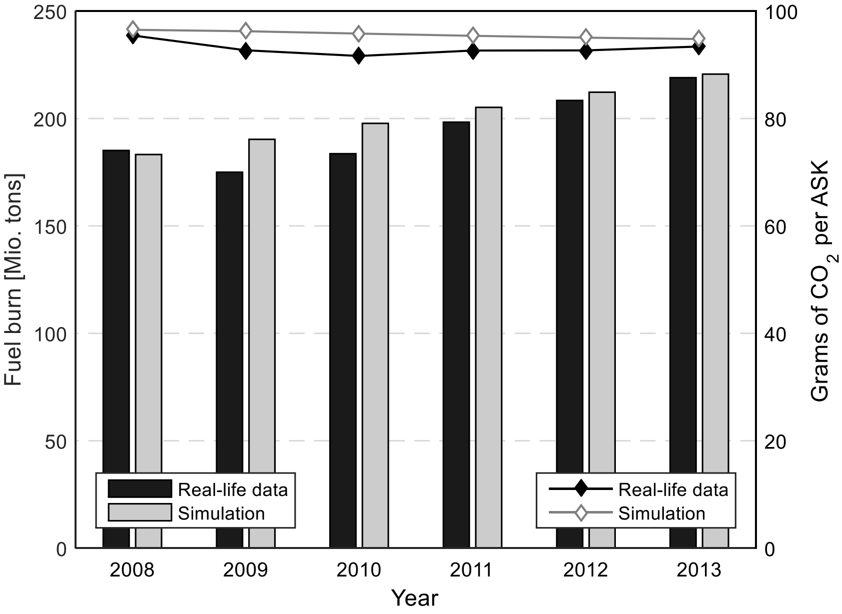


Figure 6-14 **Case study 2 (average growth rates): Real-life and simulated development of the fuel consumption and CO₂ performance of the global air transport fleet**

Data sources: Boeing CMO 2014, EIA (2015), Schäfer (2012, p. 222), author's calculations

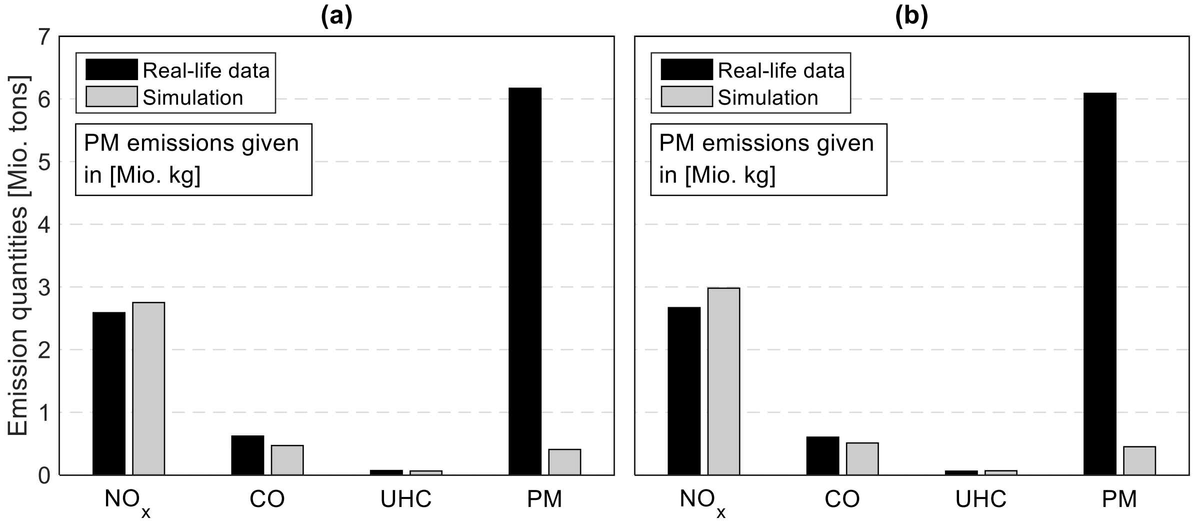


Figure 6-15 **Case study 2 (average growth rates): Real-life and simulated exhaust gas emission quantities at the global level for (a) 2008 and (b) 2010**
Data sources: Schäfer (2012, p. 222), author's calculations

6.2 Validation of the modeling of the future fleet development

In this section, ATAF is assessed regarding its ability to calculate the future development of the global air transport fleet and its related fuel-burn and emissions performance. This task involves the consideration of the uncertain future, which is why real-life validation data is not available obviously. Therefore, data from other future forecasting reports are employed as a basis for data comparison and validation purposes.

In the case study presented in this section, Boeing's CMO 2014-2033 (Boeing Commercial Airplanes, 2014a) is utilized as input scenario for the estimation of the future fleet size, composition, and performance.[111] Hence, a future horizon of 2033 is considered here. However, as Boeing does not disclose details of its future-forecasting methodology that underlies the CMO, the overall functionality of ATAF can only be assessed to a limited degree. As a result, this section is mainly intended to provide information regarding the numerical simulation data produced by ATAF relative to Boeing's future fleet estimations.

6.2.1 Next-generation aircraft types

When estimating the global fleet development, the consideration of next-generation aircraft types that are not captured by the initial fleet of the FSDM (→Table 4-4) is mandatory in order to simulate the future fleet composition and performance in a realistic manner. To accomplish this task, an analysis was conducted of those types of aircraft that are currently under development or shortly before entering the global fleet (i.e., after 2008), including estimations of their respective entry-into-service (EIS) year and their most likely increase in fuel efficiency. The results of this analysis are summarized in Appendix F.

Figure F-1 displays which future aircraft types were identified during the analysis, as well as their expected EIS year and margin of fuel-efficiency improvement relative to their respective predecessor types. In order to simplify the approach of integrating these types into the fleet simulations and maintain the aircraft-clustering philosophy inherent in ATAF, only

---

[111] All input data derived from Boeing's CMO report and employed for the fleet simulation purposes presented in this section are summarized in Appendix H.

the one type with the first EIS year among all next-generation types within each aircraft cluster was considered further.[112] BADA data files were generated for these types in the way depicted in Section 5.2.4.[113]

In addition, the production rates of the next-generation aircraft were estimated in order to set the foundations of a realistic integration of these types into the dynamically evolving air transport fleet. This estimation was accomplished while taking into account

- the historical data and statistical approximation equations of the production rates of currently operating aircraft types displayed in Figure 4-3 and Figure 4-4 and
- the number of aircraft types produced by the different aircraft manufacturers that had been identified as next-generation aircraft within each cluster.

Table F-2 in Appendix F summarizes the estimated production rates of the next-generation aircraft being considered in ATAF. Note that here, no estimation is made regarding the end of production of these types due to a lack of information regarding the current efforts of the aircraft manufacturers related to the development of aircraft types in the long-term future.

Finally, for all next-generation types considered, characteristic seat and freight capacities were assumed based on the previously mentioned analysis. Unlike for the initial fleet, a route group-specific distinction was not undertaken here, as this would have required a precise knowledge of how airlines may be expected to operate the next-generation types in terms of their available seat and freight capacities. To define the flight mission on each route group, the characteristic stage lengths of the associated initial-fleet aircraft clusters were equally employed for the next-generation aircraft (→Table C-4 in Appendix C). Table F-3 provides an overview of all data used to define the operational profile of the next-generation aircraft considered.

6.2.2 Further simulation input

Besides the definition of the future aircraft types to be considered for the simulation of the future fleet development, the following input data were utilized:

- The route group-specific RPK and RTK growth factors published in Boeing's CMO 2014-2033 were employed (see Table H-1 and Table H-2 for a summary of the corresponding values).
- Between the initial year of simulation 2008 and 2013, the RPK and RTK growth rates were averaged in order to avoid unrealistically high aircraft retirement rates in the years of economic recession (→Section 6.1.4).
- Based on the data published by ICAO (2014), an average seat load factor of 84% and an average freight load factor of 51% were assumed; a distinction among the different route groups (→Figure 4-8) was not made.
- Based on the aircraft utilization data provided by Boeing Commercial Airplanes (2013), MH/BH-ratios of 1.57 (with $UH_{max} = 20$) and 2.07 (with $UH_{max} = 15$) were defined for long-range and short-range aircraft, respectively.
- The FAP was solved to assign the initial fleet to the routes network in a way to minimize the total fuel consumption (→Section 4.3.4.4).

---

[112] For example, the Airbus A320neo was treated as the type of aircraft representing all next-generation aircraft types within Cluster 9. The Boeing 737max and/or other types were not modeled.

[113] Note that for the Boeing 747-8, the Boeing 747-8F, the Boeing 787-8, and the Boeing 787-8F, the corresponding BADA data files were already available in BADA version 3.12 and were thus not created manually. To model freighter derivatives of the corresponding passenger aircraft (e.g., Boeing 747-8/747-8F), solely the aircraft masses were adapted in the BADA OPF files according to official data published by the aircraft manufacturers.

All remaining input data required to initialize and start the simulation (→Table 4-5) were left unchanged relative to the data shown in Appendix C and Appendix D. Case 1 (→Table 4-7) was selected for the simulation to restrict the total number of aircraft additions in each year of simulation as well as the number of individual additions of the next-generation aircraft.

6.2.3 Simulation results and assessment

Based on the input data described in the previous sections (including the future input scenario described in the Boeing CMO), a comprehensive set of simulation data could be generated through the application of the FSDM and the FCECT. These data describe the anticipated development of the global air transport fleet and its associated fuel-burn and emissions performance at a high level of detail.[114] In this section, the most relevant results and data are summarized and compared to the figures published in the Boeing CMO.[115] The section is hence intended to provide the reader with a feeling of which data ATAF produces relative to Boeing's fleet-forecasting model given a similar future scenario and data input.[116]

Figure 6-16 displays the total amount of RPKs being produced per year by the simulated air transport fleet from 2013 to 2033 as well as the corresponding rates of growth year on year. The figure clearly reveals that the simulation is not able to meet the RPK growth requirements defined in Boeing's CMO. Obviously, the restrictions of aircraft addition do not allow growth rates that exceed approximately 4% p.a. This leads to the circumstance that the total RPKs produced by the simulated fleet only grow linearly, as the predefined production rates grow in a linear manner as well (see Figure 4-3 through Figure 4-6 and Table D-1 for more evidence).

Figure 6-17 displays the share in total RPKs production of the different route groups for 2013 and 2033 as determined by Boeing and through the FSDM.[117] It is obvious that, besides minor deviations, the FSDM is very well capable of reproducing the dynamic growth of the different route groups during the simulation of the global air transport system. This implies that the model is able to consistently translate the input data (i.e., the route group-specific growth factors stipulated by the CMO) into market development data.

Then, Figure 6-18 portrays the development of the global air transport fleet as determined by the FSDM. The figure clearly reveals the linear nature of the global fleet development due to the preset restrictions of the single-aisle and twin-aisle production capacities. The figure additionally compares the simulated data to the fleet development-related figures provided by Boeing for 2013 and 2033. While the total fleet sizes predicted by Boeing and the FSDM match well in these years, the anticipated fleet compositions differ by some degree.

These differences become more apparent in Figure 6-19. The FSDM appears to prefer widebody and regional aircraft to single-aisle types. As will be shown later in this section, this, however, is mainly a result of the assumed production rates of the next-generation aircraft

---

[114] As neither the ICAO EDB nor the FOI EDB contain emissions data of those engine types that are utilized by the simulated next-generation aircraft types (e.g., the Pratt & Whitney PW1100-JM or the CFM LEAP-1A powering the Airbus A320neo), the FCECT is unable to determine the exhaust gas emission quantities of the next-generation types. Consequently, only emissions of CO_2 and water vapor can be quantified (→Table 5-2).

[115] The associated raw results data are available in Appendix H.

[116] The reader is reminded that it must be assumed that not all input data used by Boeing to produce the CMO report are published in the report. Therefore, a mutual comparison of the simulation results must be made very carefully.

[117] Note that in its CMO 2014 report, Boeing specifies 43 different route groups of which the route groups labeled 'CIS Regional – International' and 'Rest of the World' cannot be allocated to one of the 21 route groups used in the FSDM (→Figure 4-8). Furthermore, the CMO lacks traffic data addressing the regions 'Latin America – Asia (LAAS),' 'Latin America – Middle East (LAME),' and 'Latin America – Africa (LAAF),' which is why in Figure 6-17, a number of only 18 route groups is shown in each pie chart.

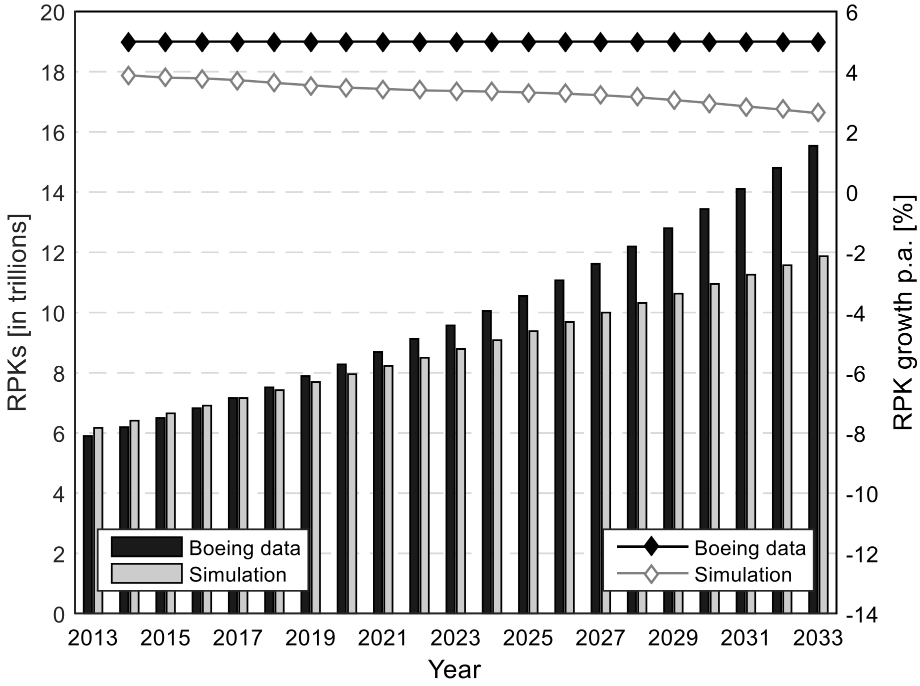


Figure 6-16 **Global RPKs produced per year and associated RPK growth from 2013 to 2033: Boeing data vs. simulation**

Data sources: Boeing CMO 2014, author's calculations

types (→Table F-2). The FSDM reaches the single-aisle production capacities in all years of simulation and therefore falls back inevitably on the widebody types in order to meet the prescribed RPK and RTK growth rates.

A fundamental question must be raised when looking at both Figure 6-16 and Figure 6-18. Although the total fleet sizes predicted by Boeing and the FSDM match very well in 2033 (the delta is about 1% only), the FSDM fleet can only produce an amount of RPKs that is roughly 24% lower than the one supplied by the Boeing fleet.[118]

Figure 6-20 reveals how this can be possible: while Boeing obviously assumes that within the upcoming twenty years, every aircraft unit being part of the global fleet will be capable of producing a gradually raising amount of RPKs per year, the FSDM estimates an almost constant value in this respect. Equation (6-1) generally describes the amount of RPKs that can be supplied by one aircraft unit within a limited period of time.

$$\boldsymbol{RPK = \sum_i d_i \cdot s_i \cdot f_i \cdot slf_i} \qquad \textbf{(6-1)}$$

---

[118] The share of small aircraft (i.e., regional and single-aisle types) and large aircraft (i.e., all wide-bodies) is approximately equal in the Boeing and FSDM fleets (Boeing 2033: large aircraft/small aircraft-ratio 24/76 = 0.32, FSDM 2033: large aircraft/small aircraft-ratio: 26/74 = 0.35; →Figure 6-19). The same is true when freighter aircraft are excluded from this consideration (a large aircraft/small aircraft-ratio of 21/79 = 0.27 is then obtained in both cases). Hence, using the total fleet size as a means to compare the fleet-wide RPK performance is justified here, as the composition of the two fleets are apparently very similar.

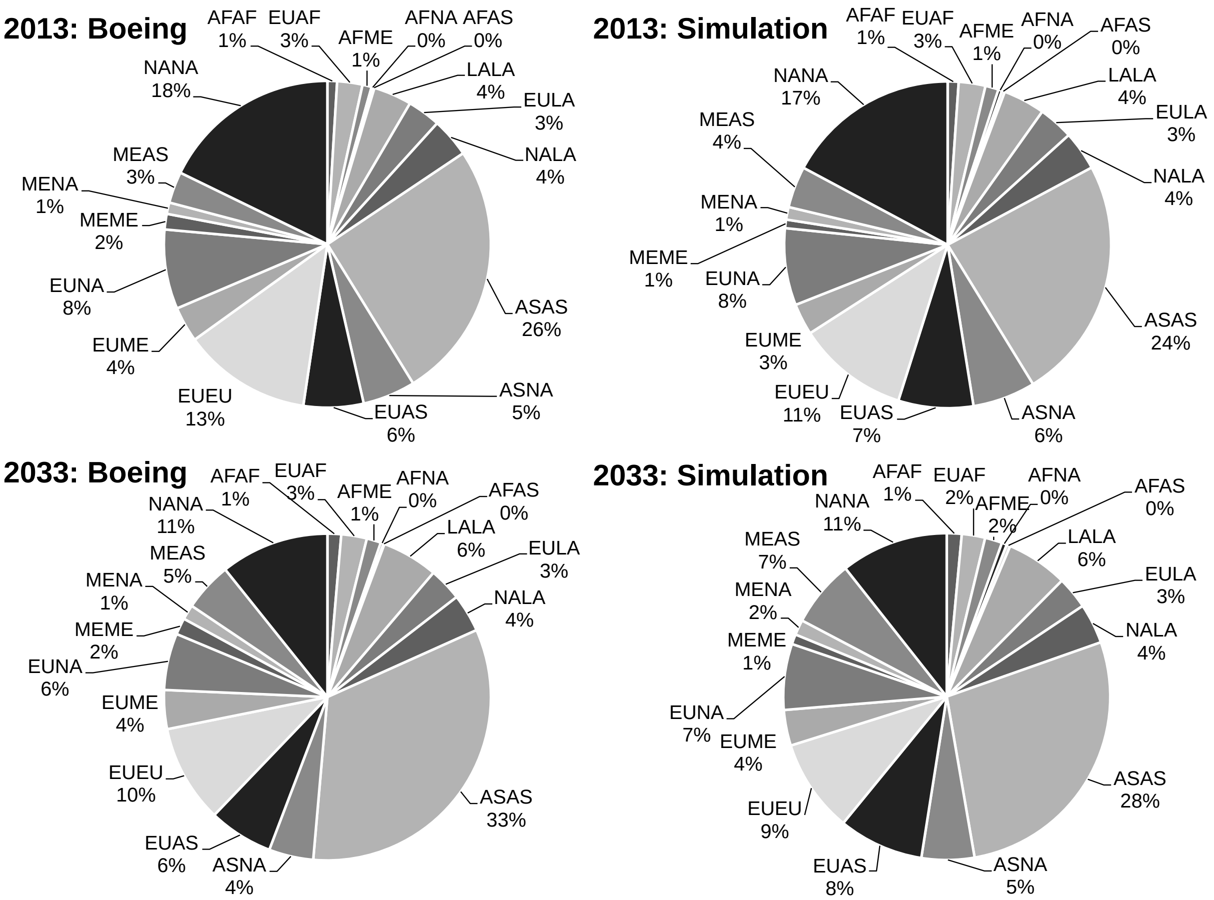


Figure 6-17 **Route group-specific share in global RPKs in 2013 and 2033: Boeing data vs. simulation**
Data sources: Boeing CMO 2014, author's calculations

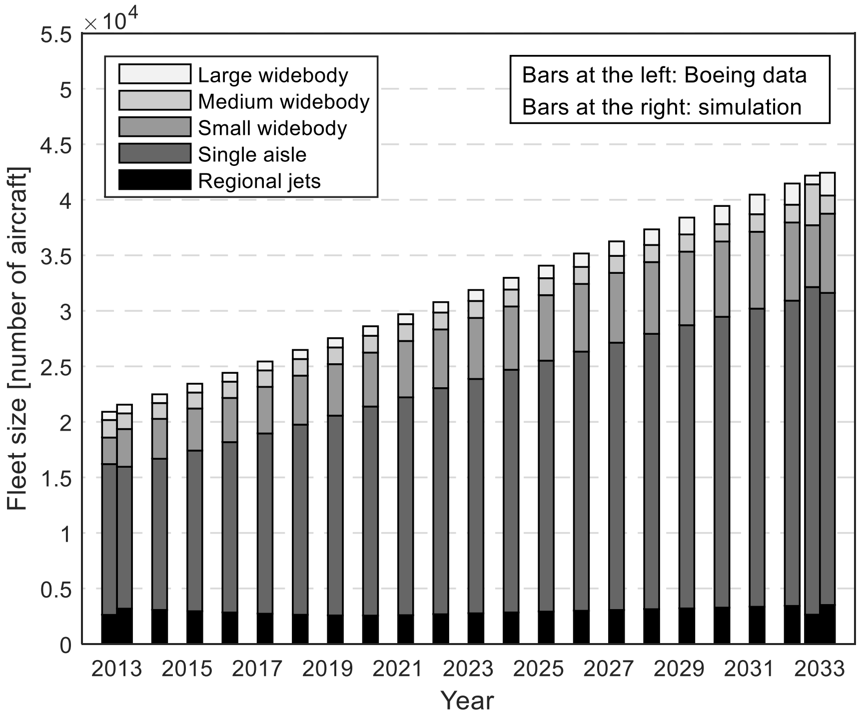


Figure 6-18 **Development of the global fleet size and composition: Boeing data (for 2013 and 2033 only) vs. simulation**
Data sources: Boeing CMO 2014, author's calculations

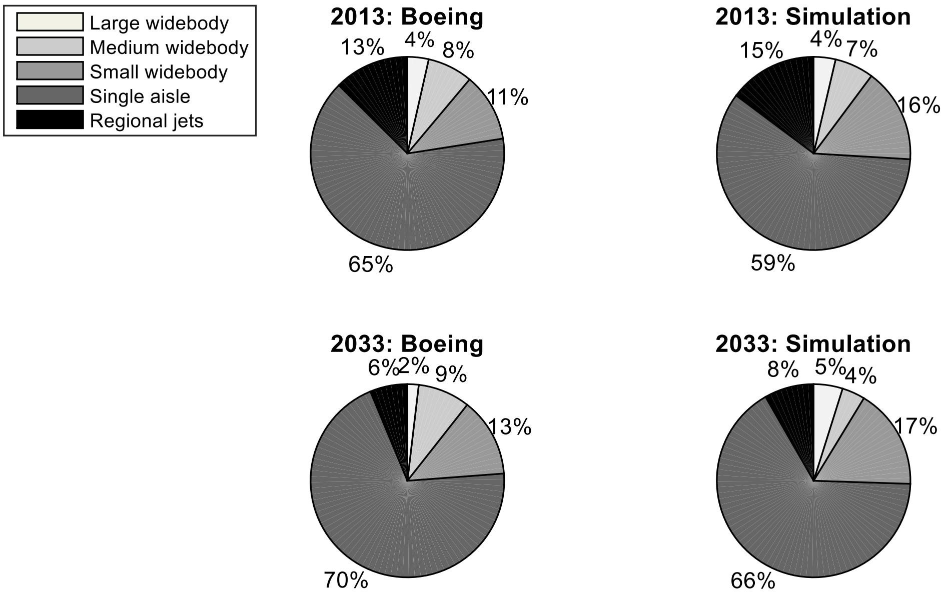


Figure 6-19 **Fleet composition in 2013 and 2033: Boeing data vs. simulation**
Data sources: Boeing CMO 2014, author's calculations

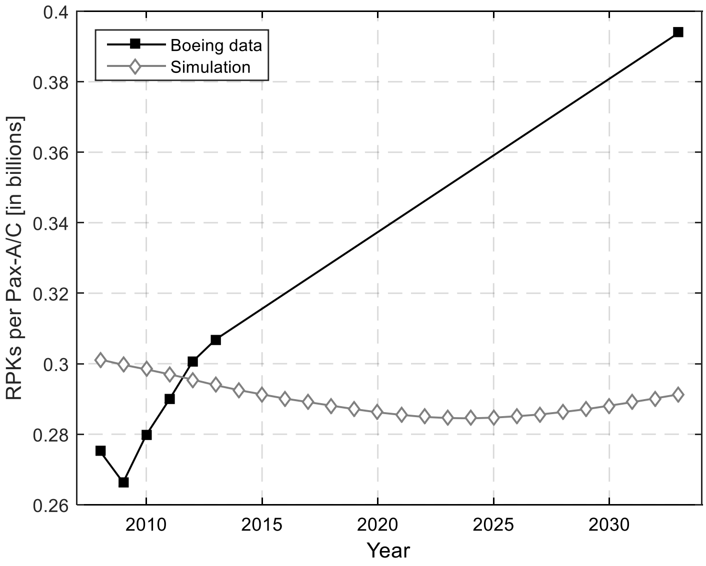


Figure 6-20 **Development of the average amount of RPKs produced per passenger aircraft p.a.: Boeing data vs. simulation**
Data sources: Boeing CMO 2014, author's calculations

Based on equation (6-1), one aircraft unit may thus raise its RPK production within a certain period either by

- serving longer O-D pairs,
- and/or transporting more seats (i.e., operating larger aircraft),
- and/or flying more frequently within this period,
- and/or increasing the seat load factor.

While, from the viewpoint of an airline, the first two items represent rather unpractical or expensive options of increasing an airplane's RPK supply, the latter two are actually very desirable. Raising an airplane's frequency of flights within a certain period is equal to increasing its degree of utilization, which is again equal to lowering its specific α-factor, BHs, and THs, and/or increasing its UH_{max} (→Section 4.2.4). Furthermore, if the airline somehow

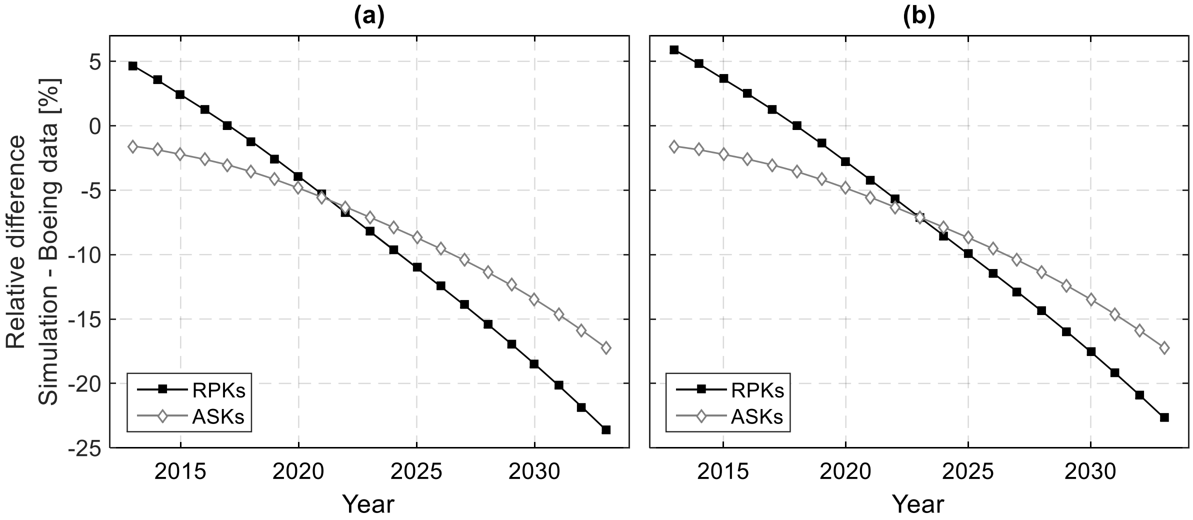


Figure 6-21 **Development of the relative difference of the transport performance (RPKs and ASKs) of the Boeing fleet (reference) and the FSDM fleet for different seat load factors: (a) 84%, (b) 85%**
Data sources: Boeing CMO 2014, author's calculations

manages to increase the airplane's seat load factor by selling more seats, it will equally generate more revenue and hence increase profit.

The consequence of the above considerations is that it can be assumed with high confidence that in its CMO, Boeing anticipates both an increasing seat load factor and an increasing aircraft utilization for the upcoming two decades.[119] Boeing may legitimately do so, as the historical trends in commercial air transport have shown exactly this development.[120] However, the question is whether these trends will persist within the next twenty years.[121]

In the context of validating the FSDM fleet-modeling functionality, it must be stated anyhow that, unlike the Boeing model, the FSDM is unable to simulate a dynamically evolving variation of the seat load factor and the aircraft utilization in its current version (→Section 4.3.2.6). The FSDM fleet of 2033 is therefore unable to supply the same amount of RPKs as the Boeing fleet.

This observation, however, is not entirely true when considering the total ASKs supplied. Assuming a steadily increasing seat load factor in the CMO from 79% in 2013 to 91% in 2033 (which is equivalent to an increase of 0.6% p.a.), the gap between the total RPKs and ASKs produced by the Boeing fleet constantly decreases. As shown in Figure 6-21 (a), this leads to the fact that for the years following 2021, the deviation of the difference between the ASKs produced by the Boeing fleet and by the FSDM fleet and the difference between the RPKs produced by the two fleets is gradually increasing, while from 2013 to 2021, this deviation decreases. In an ideal situation, the two curves shown in the figure should cross each other in 2023 (which is exactly in the middle of the considered simulation period from 2013 to 2033). If this were the case, the seat load factor of the FSDM would be equal to the average seat load

---

[119] The third option of increasing the average transport capacity of each aircraft by operating larger types is obviously not considered in the CMO by Boeing (refer again to Figure 6-19).

[120] See ICAO (2014) for an example that shows an increase of the average global seat load factor from 73.3% in 2004 to 79.0% in 2013, which is equal to an annual raise of about 0.6%.

[121] In the futurology community, many authors explicitly warn about simple trend extrapolations, especially in the context of long-term forecasting; see Taleb (2008) for a widely recognized example. Yet, it must be noted here that a trend extrapolation underlies the FSDM in the context of estimating the future aircraft production rates as well.

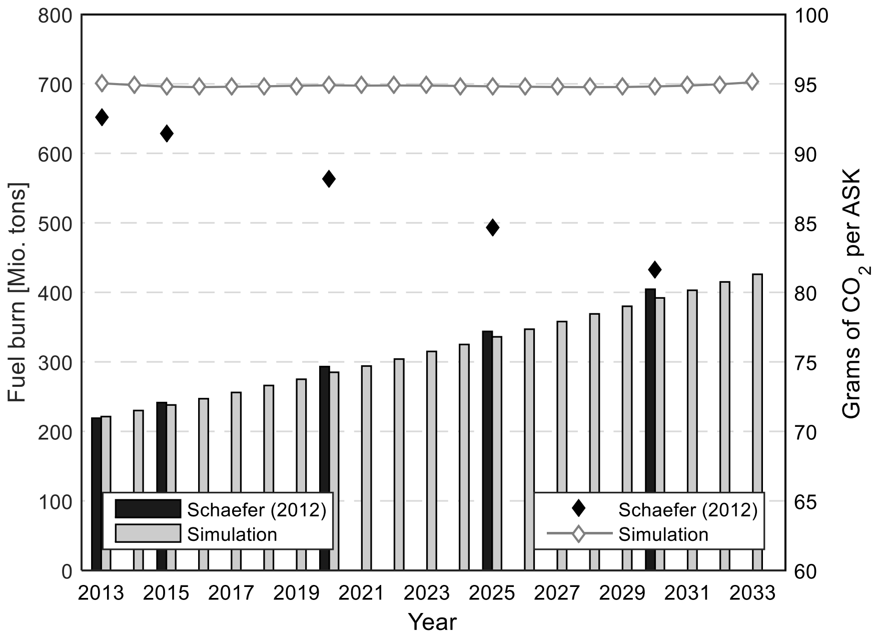


Figure 6-22 **Development of the fuel consumption and CO_2 performance of the global air transport fleet: Schäfer (2012) vs. simulation**
Data sources: Schäfer (2012), author's calculations

factor of the CMO within this period (i.e., 85% under the above-described assumptions). This exact situation is shown in Figure 6-21 (b).[122]

However, in the simulation, a seat load factor of only 84% was assumed (→Section 6.2.2). This consequently leads to the inability of the FSDM fleet to produce an amount of ASKs similar to the Boeing fleet. Yet, this also shows that the user should carefully select an appropriate load factor for the simulation. In general, the above considerations underline that the user should be constantly aware of the model capabilities when interpreting the simulation results.

Finally, the overall fuel consumption and the related CO_2 performance predicted by the FSDM are shown in Figure 6-22. However, the simulation data cannot be compared to the CMO here, as Boeing does not provide any data regarding the fleet-wide fuel burn or emissions production. Instead, data calculated by Schäfer (2012) is used as a basis for comparison in the figure.[123] The figure reveals a good coincidence of the simulated total fuel consumption with Schäfer's values.

Yet, a decisive difference is observable concerning the calculation of the fleet-wide CO_2 performance: it maintains an almost constant value of approximately 95 grams of CO_2 produced per ASK in the simulation but constantly decreases from about 93 grams in 2013 to 82 grams in 2030 according to Schäfer (which is equivalent to an efficiency improvement of 0.7% p.a.). This observation implies that although the FSDM adds next-generation aircraft with a better fuel efficiency relative to their predecessors to the fleet (see again Table F-1 and Table F-2), the fleet-wide fuel and CO_2 performance does not increase substantially (as in the case of Schäfer's work). The FSDM fleet simulation obviously requires further investigations in this respect. It is therefore analyzed further in the following section (case study 3).

---

[122] In order to generate the data displayed in Figure 6-21 (b), a new FSDM fleet simulation was conducted with all input data being equal to the data described in the previous section, with one exception being that the seat load factor was set to 85% and the freight load factor to 52%.

[123] Note that Schäfer's work is based on the Airbus Global Market Forecast 2011-2030, though.

6.2.4 Case study 3: Unconstrained addition of next-generation aircraft

In this case study, the fundamental ability of the FSDM to simulate the impact of the introduction of the next-generation aircraft (→Appendix F) on the fleet-wide fuel consumption and related CO_2 performance is investigated. The future scenario underlying this case study is again constituted by Boeing's CMO 2014 report that describes a rather optimistic development scenario from 2013 until 2033. All input parameters are left unchanged relative to the information given in Section 6.2.2 with one exception addressing the introduction and addition of the next-generation aircraft types. This case study thus consists of *two specific cases*:

- In the *reference case*, the next-generation aircraft are *not* introduced at all. That is, the FSDM can only fill the capacity gap by adding aircraft of the initial fleet (→Appendix C). The total number of aircraft additions per simulation year is constrained following the Cases 1 and 2 in Table 4-7.[124]
- In the *unconstrained-addition case*, the addition number of the next-generation aircraft is unconstrained, while the total number of aircraft additions remains constrained (Case 2 in Table 4-7).

Therefore, the two cases of this study constitute two extremes in terms of adding new-generation aircraft to the global fleet. The simulation data obtained in this case study is hence intended to support examining the reasons for the significant differences in the prediction of the fleet-wide CO_2 performance between Schäfer's results and the data obtained from the FSDM simulations depicted in the previous section (→Figure 6-22).[125]

Figure 6-23 displays the total amount of RPKs produced by the simulated fleet for both cases under scrutiny. It is clearly visible that the reference fleet cannot supply as many RPKs as the fleet in the unconstrained-addition case. When referring again to equation (6-1), the reason for this observation becomes apparent. The only varying parameter between the two fleets is the seat capacity, as all other parameters (i.e., distances between O-D pairs, aircraft utilization, and seat load factor) are identical in both cases.

One explanation for this simulation behavior is that the next-generation aircraft are generally capable of transporting a higher amount of seats than aircraft of the initial fleet. Therefore, they are able to produce more ASKs (and hence RPKs) per flight (compare Table C-5 with Table F-3).[126] This observation is underlined by the RPK growth rates of the unconstrained-addition fleet displayed in Figure 6-23 that increase suddenly once the first next-generation passenger aircraft units are introduced into the fleet in 2013.

In addition, Figure 6-24 reveals that the absolute fleet sizes determined in both cases only differ slightly. This observation is similar to the one depicted in the previous section where the Boeing fleet and the fleet determined by the FSDM were very similar in size, while the Boeing fleet was able to produce a substantially higher amount of RPKs due to a steadily increasing seat load factor and an improved aircraft utilization. Here, however, the only reason why the fleet of the reference case is not able to produce as many RPKs as the fleet of the unconstrained-addition case is due to a significant difference in aircraft type composition between the two fleets.

---

[124] Here, the Cases 1 and 2 are identical, as the next-generation aircraft are not introduced into the fleet. As a result, constraining their addition numbers would not have any meaning.

[125] The associated raw results data are available in Appendix H.

[126] The reader is reminded that while for the initial fleet, a statistically determined average seat capacity specific for each route group and aircraft cluster stipulates the number of transported seats, a route group-specific distinction of the seat capacity of the next-generation aircraft is not made (→Section 6.2.1).

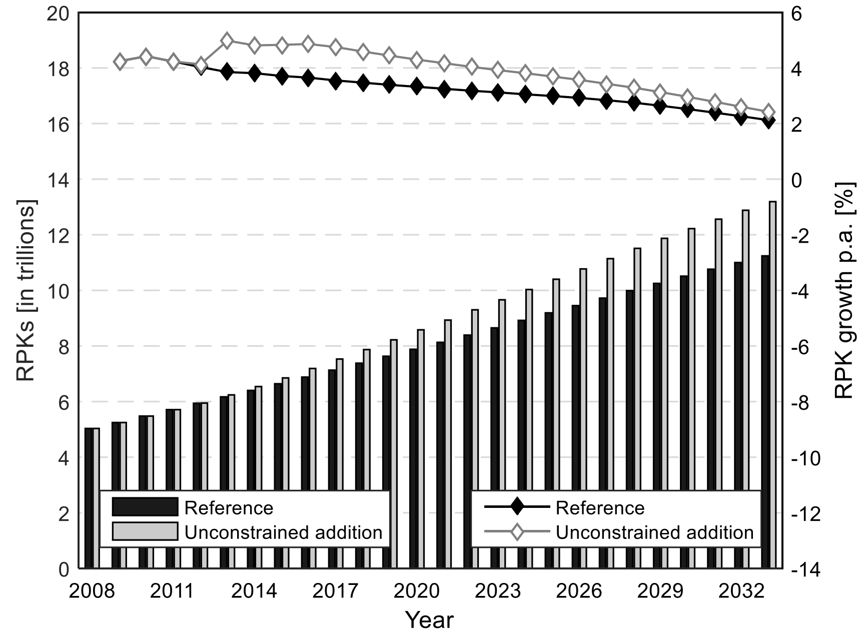


Figure 6-23 **Case study 3: Development of the global RPKs produced per year and associated RPK growth: reference case vs. unconstrained-addition case**

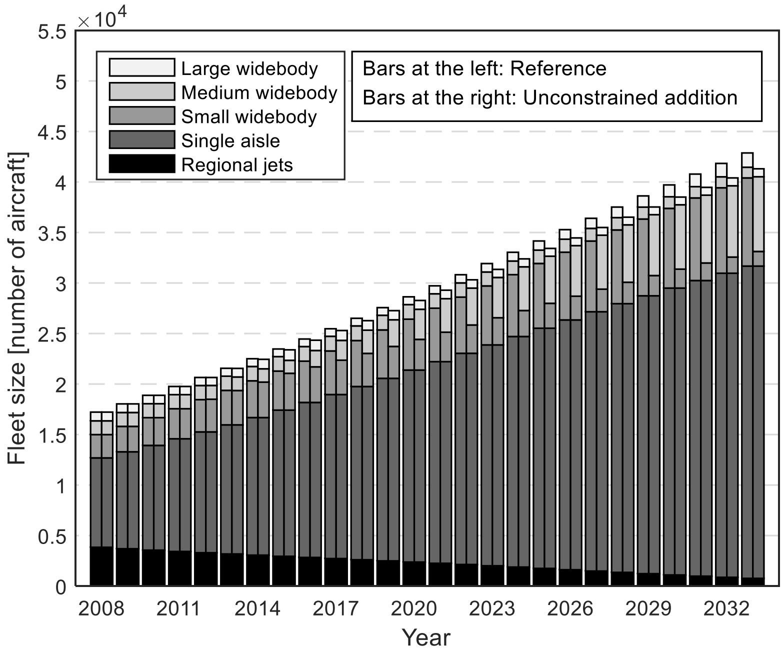


Figure 6-24 **Case study 3: Development of the global fleet size and composition: reference case vs. unconstrained-addition case**

Figure 6-25 clearly shows that in 2033, the reference fleet owns much less aircraft of the 'Medium widebody (MW)' category than the unconstrained-addition fleet (2% vs. 18%). Instead, more aircraft units of the 'Small widebody (SW)' category are part of the fleet (20% vs. 4%).[127] This implies that the unconstrained-addition fleet possesses more seats than the reference fleet in total, or, in other words, the number of large aircraft is lower for the reference fleet.

---

[127] Both of these categories are treated as belonging to the TA aircraft class, which is why the FSDM applies the TPC constraint of the TA class to both (→Table D-1).

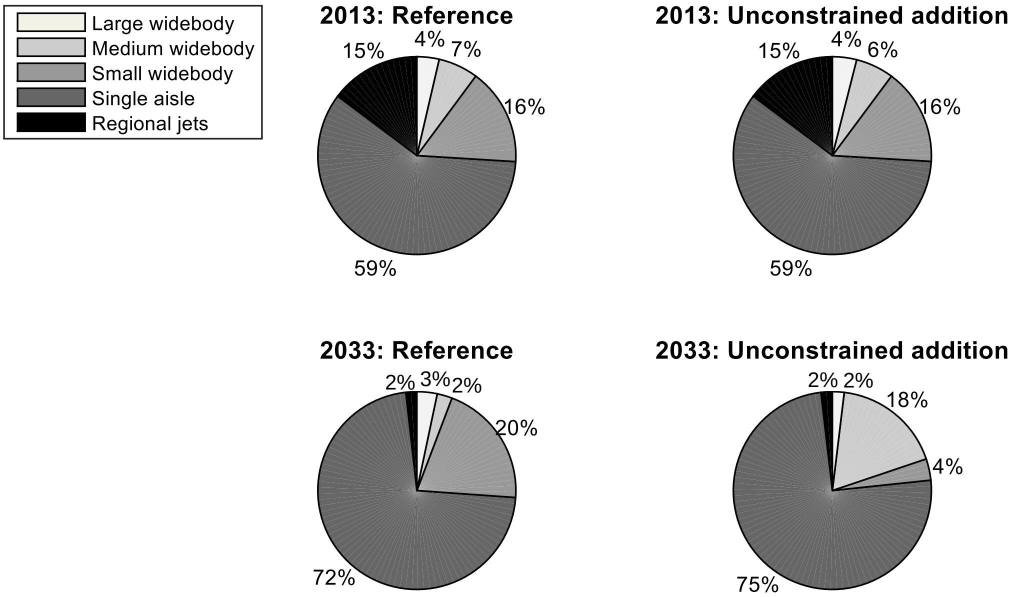


Figure 6-25 **Case study 3: Fleet composition in 2013 and 2033: reference case vs. unconstrained-addition case**

The reason for this can be found when considering the model algorithm again that determines which types of aircraft are selected to be added to the fleet in each year of simulation (→Sections 4.3.4.3 and 4.3.4.5, Appendix B). First, the reader is reminded that due to the model assumptions, the fuel performance of any aircraft type simulated by the model does not improve over the years (→Section 4.3.2.4). Now, in the reference case, the model is permitted to add aircraft types of the initial-fleet clusters only for every year of simulation. Because of their better fuel efficiency on long-range routes relative to the other available clusters, the model primarily selects Cluster 7 aircraft (represented by the Boeing 767-300) to fill the capacity gap.[128] In the unconstrained-addition case, however, the model is permitted to additionally select next-generation aircraft types besides aircraft of the initial fleet. Here, it decides to prioritize the addition of next-generation Cluster 8 aircraft (represented by the Airbus A350XWB, →Figure F-1) to fill the capacity gap on the long-range routes, as this specific aircraft features the best fuel efficiency among all aircraft clusters available.[129] Because an Airbus A350XWB can carry more seats than a Boeing 767-300, the total seat capacity of the unconstrained-addition fleet is higher than the one of the reference fleet. The unconstrained-addition fleet can therefore supply more ASKs and RPKs per year than the reference fleet, which is also observable in Figure 6-28.

Accordingly, as shown by Figure 6-26 (b), the average amount of RPKs produced per aircraft increases for the unconstrained-addition fleet, as more next-generation Cluster 8 aircraft enter the fleet (→Figure 6-26 (a)), while the RPK production per aircraft decreases slowly for the reference fleet. Here, the dominance of the smaller Cluster 7 aircraft is responsible for this effect.

---

[128] Cluster 7 aircraft are considered as ‘Small widebody’ aircraft according to the Boeing CMO.

[129] Next-generation Cluster 8 aircraft are considered as ‘Medium widebody’ aircraft according to the Boeing CMO.

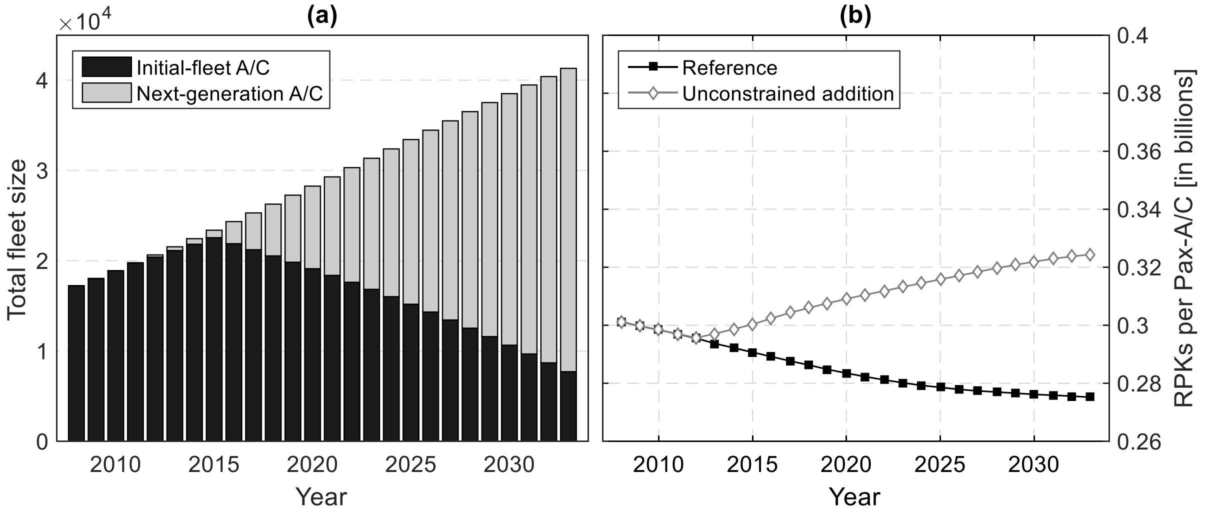


Figure 6-26 Case study 3: (a) Development of the absolute number of next-generation aircraft within the total fleet (unconstrained-addition case), (b) Development of the average amount of RPKs produced per passenger aircraft p.a.: reference case vs. unconstrained-addition case

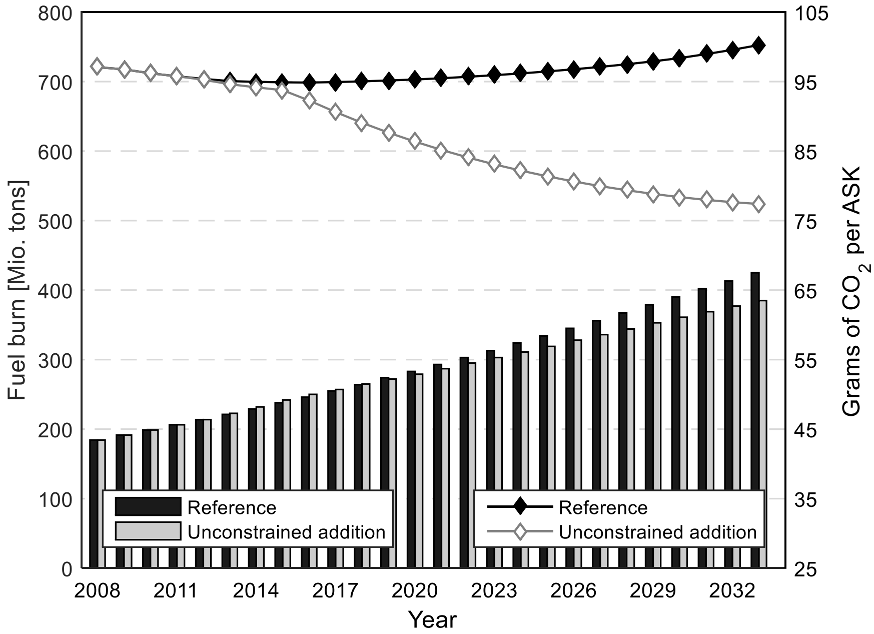


Figure 6-27 Case study 3: Development of the fuel consumption and CO₂ performance of the global air transport fleet: reference case vs. unconstrained-addition case

Eventually, Figure 6-27 displays the total fuel consumption and CO_2 performance of the global fleets of both cases under scrutiny. In particular, the figure clearly reveals the positive impact of the next-generation aircraft on the fleet-wide CO_2 performance in the unconstrained-addition case. Here, an increase in fuel and CO_2 efficiency of 19% from 2008 to 2033 is achieved, which is equivalent to an average efficiency improvement of 0.86% per year.

The reference fleet, however, is unable to improve its fuel efficiency on long term. On the contrary, after a short period of improvement between 2008 and 2016, the fuel efficiency diminishes again and ends up in 2033 at a value being 3.5% higher than in 2008. At first sight, this observation seems counter-intuitive and difficult to interpret. The simulation algorithm actually adds only the best aircraft types in terms of fuel efficiency to the fleet, independent of whether or not next-generation aircraft are available for addition. Therefore, this should

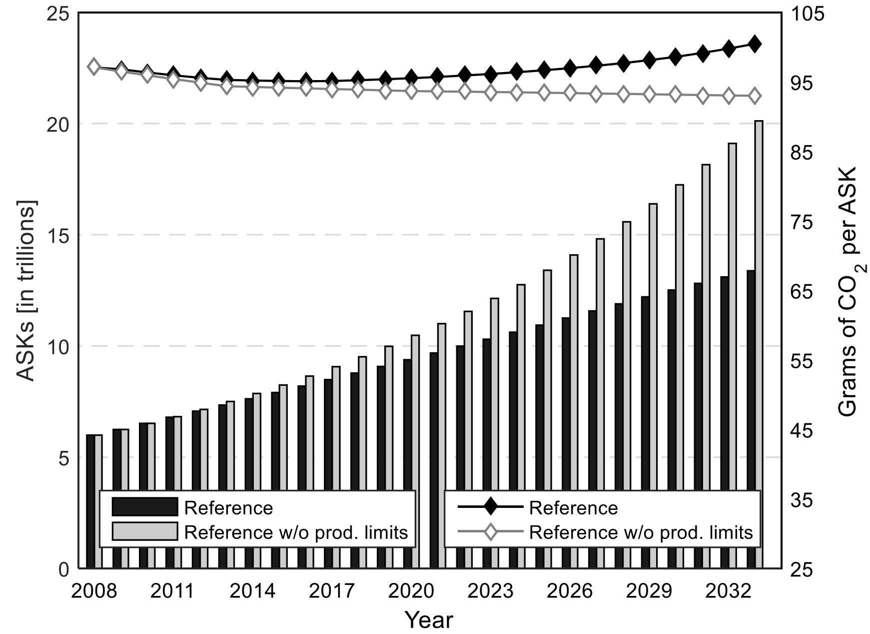


Figure 6-28 **Case study 3: Total ASKs production and CO_2 performance of the global air transport fleet: reference case vs. reference case without aircraft production limitations**

eventually lead to an overall improvement of the fleet-wide fuel efficiency rather than a worsening as observed in Figure 6-27.

There is no error in the algorithm, though. The long-term worsening of the fuel efficiency of the reference fleet shown by Figure 6-27 is an exclusive consequence of the restriction of the total aircraft production capacities. Figure 6-28 supports a better understanding of the simulation behavior in this respect. The figure reveals that a non-constrained fleet can actually improve its fuel efficiency, even without integrating next-generation aircraft types. This can be explained as follows:

Besides showing data of the original reference case again, Figure 6-28 indicates data of a further simulation, i.e., the reference case without production capacity constraints. During this specific simulation, the total production capacities of the SA and TA aircraft classes were not restricted.[130] This allowed the algorithm to add an unlimited amount of aircraft units of any cluster (i.e., Cluster 1 through 9), and thereby enabled an average growth of the total transport supply of 5% per year as prescribed by the CMO 2014 report.[131] On the other hand, the unconstrained aircraft addition of this simulation led to a total fleet size of about 88,000 aircraft units in 2033 (vs. 43,000 units for the original reference case). Here, the algorithm was actually able to add just those aircraft with the best fuel efficiency to the fleet without having to fall back on inferior types due to production capacity restrictions. This eventually caused an improvement in fuel efficiency of roughly 4% (i.e., 0.17% p.a.) from 2008 to 2033.

Restricting the aircraft production capacities in the simulation therefore has a substantial impact on the evolution of the fleet-wide fuel efficiency. The algorithm may be forced to select suboptimal aircraft types to fill the capacity gap once it reaches the production capacity limit of its most preferred type on each route group. The user should keep this in mind when setting up an FSDM fleet simulation.

---

[130] This corresponds to the Cases 3 and 4 of Table 4-7. Next-generation aircraft were not introduced again like in the original reference case.

[131] Note the exponential shape of the bar graph in Figure 6-28 corresponding to this case.

6.3 Summary and conclusions

In this section, the most important findings of the model validation presented in the previous sections of this chapter are briefly summarized. In this respect, concluding recommendations are additionally made that are intended to support an adequate usage of ATAF in the context of aircraft technology assessment as well as the correct interpretation of the data that the model generates.

6.3.1 Proven capabilities

- As with every other numerical model, the simulation results produced by ATAF strongly depend on the quality of the user input data (→Table 4-5).
- The model has proven capability of simulating the development of the global air transport fleet in terms of size and composition with a high degree of accuracy for short- and medium-term simulation periods while adequately considering the integration of new aircraft types. For long-term simulation periods, the limitations of the model affect the calculated total fleet size and composition by a non-negligible degree. The user should therefore be constantly aware of these limitations in order to avoid unexpected simulation behavior and results.
- The above is equally true for simulations of the development of the transport supply (measured in RPKs and ASKs) at the global level and at the level of the 21 route groups defined in the FSDM (→Figure 4-8). This capability allows investigating technology effects not only at the system-wide level but also at a more specific regional level.
- The model is capable of accurately simulating the fleet-wide fuel consumption and CO_2 emissions as a function of the development of the global air transport fleet. This capability particularly allows investigating the effects on fuel burn and CO_2 emissions of new aircraft concepts and/or aircraft technologies at a fleet-wide level.
- On condition that ATAF simulates a fleet being composed of only those aircraft types that utilize engines listed in either the ICAO EDB or the FOI EDB, the model is capable of estimating the quantities of the exhaust gas emission substances NO_x, CO, UHC, and PM of this fleet. The model is capable of accomplishing this task with a degree of accuracy that is similar to comparable fleet models described in the literature.

6.3.2 Major limitations

- The inability of ATAF to simulate temporary aircraft storage leads to the problem that for years of strong growth (i.e., ≥ 5%) following an economic downturn (that have previously led to a reduction of the total fleet size), the model is unable to fill the capacity gap if the total production capacity is constrained. This is because once retired, an aircraft of the simulated fleet cannot be put into service again to supply ASKs to the fleet. Furthermore, the model simulates aircraft retirements solely on a statistical basis, i.e., without considering the current situation of aircraft demand. Therefore, employing strongly varying rates of RPK/RTK-growth as input should be avoided. Instead, it is recommended using moderate rates of growth that change slowly over time.
- Restricting the total production capacities and/or the production capacities of the next-generation aircraft that enter the fleet after the initial year of simulation (i.e., 2008) has a strong impact on the simulated development of the fleet that the user should be aware of:

    - The model is very likely to be unable to fill the capacity gap with new aircraft for rates of RPK-growth exceeding approximately 4.5% per year for mid-term simulations (i.e., until 2020) and 3.0% per year for long-term simulations (i.e., until 2050).
    - The model is very likely not to select only the best-performing aircraft type in terms of fuel efficiency for each route group in a situation where the number of required aircraft additions exceeds the SA and TA TPCs, respectively, and/or the single production capacity limits (in the case of addition of next-generation aircraft). As a result, the simulated fleet will necessarily feature a suboptimal fuel efficiency relative to a fleet that would have been determined without restricting the production capacities.
    - In the above-described case, the resulting size and composition of the global fleet is affected as well. This will then lead to a positive or negative change of the fleet-wide average aircraft productivity (measured in RPKs per aircraft per year).
- The model is capable of varying the fleet-wide average productivity of each aircraft of the simulated fleet only through a change of the fleet composition (e.g., a fleet that is composed of a high number of large aircraft will feature an average aircraft productivity being higher than a fleet with primarily small aircraft). While in reality, the productivity of an aircraft can additionally be influenced by varying its payload factor and/or its degree of utilization, the model is unable to do so. Therefore, the model is unable to simulate conditions under which load factors and/or aircraft utilization parameters vary dynamically over time.

7. Technological feasibility of climate goals

COMMERCIAL aviation is facing challenging goals in terms of mitigating its adverse impact on the global environment and climate in the long term, as was described in Chapter 1 (→Figure 1-2). Four strategic pillars have been identified as supportive means to reach these goals. Among these pillars are advanced aircraft concepts and technologies. Quantifying their potential contribution to an environmentally friendly and sustainable development of commercial aviation, and thereby estimating the requirements for the remaining three strategic pillars, is the focus of this chapter.

In the face of the uncertainty inherent in the future development of the environment relevant to aviation, two alternative scenarios are utilized here: the optimistic 'Boeing' scenario described in Boeing's CMO report 2014-2033, and the rather pessimistic 'Rough Air' scenario defined by Randt *et al.* (2015). With these scenarios, ATAF is employed to determine the development of the global fleet and its fuel and emissions performance from the present until 2050. The results obtained here are eventually used to discuss the achievability of aviation's global climate goals from a technological point of view.

7.1 Future scenarios and further simulation input

In this chapter, two alternative future scenarios are used to handle the uncertain development of the global commercial air transport market. They primarily serve as data sources for the definition of the growth rates of RPKs and RTKs in each one of the 21 route groups of the FSDM (→Figure 4-8). In order to enable a consistent comparison of the simulation data produced by the FSDM in conjunction with the FCECT for the two scenarios, all remaining input data (→Table 4-5) are not varied from one scenario to another.

7.1.1 Boeing Current Market Outlook 2014-2033

The Boeing CMO describes an optimistic scenario for the upcoming two decades. For the purposes of fleet simulations in this section, the market growth-related figures defined by this report are extrapolated until 2050. Boeing has published the following summary of its market outlook:

> *"The aviation industry continually adapts to market forces. Key among these are fuel prices, economic growth and development, environmental regulations, infrastructure, market liberalization, airplane capabilities, other modes of transport, business models, and emerging markets. […] Our long-term forecast incorporates the effects of market forces on the development of the aviation industry. Economic growth […] is a primary contributor to aviation industry growth. GDP is forecast to rise 3.2 percent over the next 20 years, which will drive passenger traffic to grow 5.0 percent annually and cargo traffic […] to grow 4.7 percent annually."*
>
> *(Boeing Commercial Airplanes, 2014a, p. 3)*

Detailed data addressing the RPK and RTK development in the Boeing CMO report are available in Table H-1 and Table H-2 of Appendix H.

7.1.2 Rough Air scenario

In 2012, a comprehensive scenario project was conducted at TUM LLS using the scenario-building methodology described in Section 3.1. The results obtained there essentially consisted of three alternative scenarios, which were subsequently made available to a broader audience through a journal publication (→Randt *et al.* (2015)). Within the scope of this chapter, the Rough Air scenario that describes a rather pessimistic outlook on the future of commercial aviation is employed in order to consider a mediocre image of the industry's perspectives as opposed to the Boeing CMO scenario. A brief summary of the Rough Air scenario is given below:

> *"[…] political instabilities still have great influence on the world scenery and cause a non-homogeneous distribution of economic growth of the middle class and of wealth in general, which consequentially leads to new instabilities. […] Industrialized countries struggle with decreasing economic growth and saturated markets. The economic growth of the emerging countries (BRICS[132] and N-11[133] countries +4% p.a. on average) is slowing down due to concluded one-time effects, but still contributes to a global GDP growth at a moderate level. […] While within the industrialized countries, air traffic growth stagnates, there is still moderate growth within the BRICS and N-11 countries. This leads to a low but robust growth of world air traffic by 1.5% per year on average. […] The increasing number of extreme weather events and related flight cancellations force airlines to take out expensive insurance policies. Those costs in combination with other cost drivers (e.g., jet fuel prices) contribute to rising ticket prices. […] airlines especially focus on individually tailored products for sophisticated travelers in order to make a profit. The business model of the traditional low-cost carrier (LCC) gradually disappears in saturated markets such as the European Union and the USA due to stagnant growth, growing operating costs, and strong competition."*
>
> *(Randt* et al.*, 2015, pp. 11–13)*

Detailed data addressing the RPK and RTK development in the Rough Air scenario are available in Table I-1 and Table I-2 of Appendix I.

7.1.3 Simulation input parameters

Besides the two future scenarios that stipulate the development of the regional air traffic markets, the following input parameters were set for the simulations presented in this chapter:

- An average seat load factor of 86.0% and an average freight load factor of 53.0% were employed; a distinction among the different route groups was not made.
- Based on the data provided by Boeing Commercial Airplanes (2013), MH/BH-ratios of 1.57 (with UH_{max} = 20) and 2.07 (with UH_{max} = 15) were defined for long-range and short-range aircraft, respectively.
- The FAP was solved to assign the initial fleet to the routes network in a way to minimize the total fuel consumption.
- If not stated otherwise, all remaining input data required to initialize and start the simulation were left unchanged relative to the data shown in Appendix C and

---

[132] The "BRICS" countries are composed of Brazil, Russia, India, China, and South Africa (→O'Neill (2001)).

[133] The "N-11" or "Next-Eleven" countries are composed of Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, the Philippines, Turkey, South Korea, and Vietnam (→O'Neill (2005)).

Table 7-1 **Fleet simulations conducted for the evaluation of aviation's global climate goals**

Market development scenario	Simulation ID	Total production capacities	Integration of next-generation aircraft types
Boeing CMO 2014-2033	B_I	Constrained	Not integrated
	B_II (Reference)	Constrained	Single production capacities constrained by values given in Table F-2
	B_III	Constrained	Single production capacities constrained by values 15% above the values given in Table F-2
	B_IV	Constrained	Single production capacities only constrained by total production capacity limits
Rough Air scenario	R_I	Constrained	Not integrated
	R_II (Reference)	Constrained	Single production capacities constrained by values given in Table F-2
	R_III	Constrained	Single production capacities constrained by values 15% above the values given in Table F-2
	R_IV	Constrained	Single production capacities only constrained by total production capacity limits

Appendix D with one particular exception addressing the total production capacities of single-aisle and twin-aisle aircraft, though. These were increased by 25% each to capture the near-future market entries of new aircraft manufacturers like Comac, Irkut, Mitsubishi, and further potential players. This was done for all years of simulation after 2015 and 2019 for the total single-aisle and twin-aisle aircraft production rates, respectively. In addition, to simulate the entry of the next-generation aircraft types, the single production capacities shown in Table F-2 of Appendix F were taken into account.

7.2 Fleet simulation cases conducted

In order to achieve a broad evaluation basis of the technological feasibility of aviation's future global climate goals, a number of distinct fleet simulations were conducted, allowing an insight into the sensitivities inherent in the simulated air transport fleet and its fuel and CO_2 performance. The most relevant results are presented in this chapter. Table 7-1 provides an overview of the simulations conducted here.

In all fleet simulations, the total capacities of the single-aisle and twin-aisle aircraft productions were constrained as described in the previous section. This was supposed to enable fleet simulations with a realistic modeling of the future aircraft additions.

A variation from one simulation to another was achieved through a change in the productions rates of the next-generation aircraft. In the cases marked 'I,' the next-generation aircraft were not integrated into the global fleet at all, which therefore represent the *no-action* cases. In the subsequent simulations, the production rates of the next-generation aircraft were increased in three steps starting from the reference values given in Table F-2 ('II') through values increased by 15% relative to the values given in Table F-2 ('III'), and eventually ending with values that were solely constrained by the total production capacities ('IV').[134] This scheme was targeted at supporting an investigation of the technological impact of the next-generation aircraft on the fleet-wide fuel and CO_2 performance.

7.3 Evaluation of the simulation results

The fleet simulations of the eight cases depicted in Table 7-1 produced large amounts of results data addressing various parameters related to the structure and performance of the modeled fleet at both a regional level and the global level. The focus in this chapter is on the fuel and CO_2 performance of the future fleet at the global level and particularly on the impact of the next-generation aircraft on this performance within the two market scenarios described in the previous sections. At first, the results obtained for the Boeing CMO scenario are depicted that are then followed by the results belonging to the Rough Air scenario. Finally, all results are mutually compared and conclusions are drawn that address the maximum possible performance improvements that the global fleet may achieve until 2050.[135] Finally, these statements are compared to aviation's global climate goals in order to examine the feasibility of these goals from an aircraft technology-related point of view.

7.3.1 Simulation results for the Boeing CMO scenario

Figure 7-1 and Table I-6 in Appendix I summarize the most important fleet-level results obtained for the reference case of the Boeing CMO scenario (i.e., the 'B_II' simulation in Table 7-1).[136] The following four major findings can be drawn from there:

- From 2008 until both 2020 and 2050, the total fleet size grows more strongly than the transport supply delivered by this fleet. This indicates that the average transport supply delivered per one aircraft unit of the simulated fleet diminishes over time, or, in other words, the average aircraft size of the fleet decreases.[137] The simulation algorithm apparently prefers adding smaller aircraft to the fleet rather than larger types because of their more favorable specific fuel consumption on many FSDM route groups.
- Until 2020, the transport supply delivered by the global fleet grows with a higher rate than the associated fuel burn (+4.1% vs. +3.9%), while in the long term (until 2050), these two parameters grow identically. This indicates that despite the gradual integration of the more efficient next-generation aircraft types, the fleet-wide fuel performance does not improve. Responsible for this development is the restriction of both the total and single production capacities in this simulation that forces the FSDM to assign less efficient aircraft types to the routes network after the maximum number of additions of the most preferred aircraft types have been entirely exhausted. In other words, the algorithm can only partially fill the capacity gap with the most efficient aircraft types. The remaining gap is filled with inferior types. This particular simulation behavior and its effects are depicted in detail in Sections 6.2.3 and 6.2.4.

---

[134] The latter step was intended to simulate a situation where the aircraft manufacturers are able to immediately switch over to the production of the next-generation aircraft without being required to build up new production lines.

[135] Note that a potential aircraft generation that may follow the 'next-generation' aircraft types defined in this thesis is not considered here due to a current lack of adequate data.

[136] All relevant simulation data are available in Appendix I.

[137] The reader is reminded that neither the aircraft utilization characteristics nor the load factors vary over time in the simulation (→Section 6.3.2).

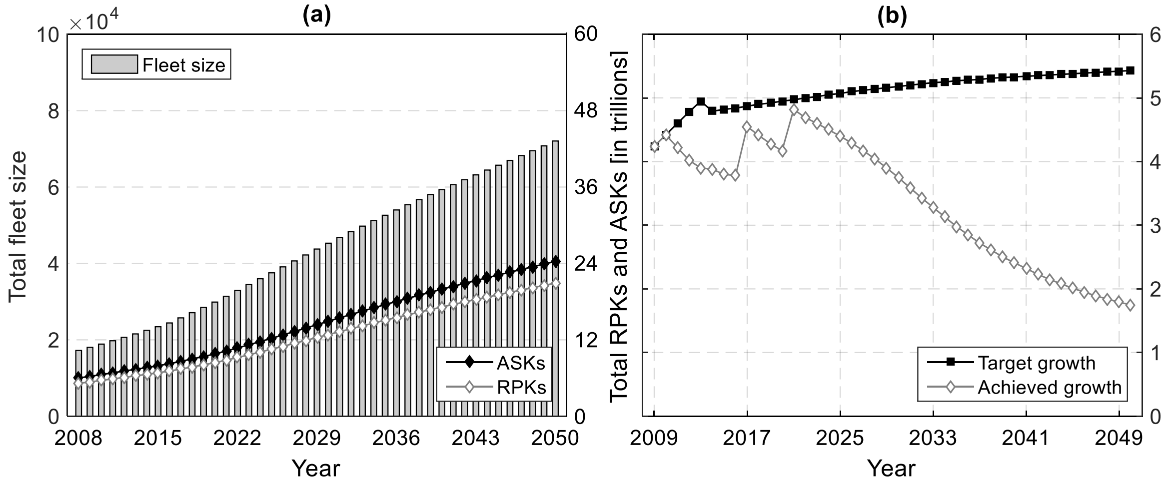


Figure 7-1 **Simulation data (B_II): (a) Development of the total fleet size, ASKs, and RPKs, (b) Target and achieved total RPK growth rates p.a.**

- While until 2020, the CO_2 performance decreases slightly, it remains almost stable until 2050 (-0.2% vs. +0.1%). Just like described above, the restrictions of the aircraft production capacities in the simulation are responsible for this development. The positive effect of the next-generation aircraft types on the fleet-wide CO_2 performance is negatively affected by the addition of less efficient types being required to fill the capacity gap.
- The simulated fleet in 2050 is unable to deliver the amount of RPKs required by the Boeing CMO scenario.[138] Two reasons cause this effect. (1) As depicted above, the average aircraft size decreases along the simulation years, which leads to a slowly diminishing amount of RPKs/ASKs supplied annually per aircraft unit of the simulated fleet. As shown by Figure 6-20 in Chapter 6, an increasing RPKs supply is assumed by Boeing, though. (2) The seat load factor of 86% remains constant over the entire simulation, which requires an even higher amount of ASKs to be produced by the simulated fleet and thus a higher number of aircraft units.

Based on these findings, it must be doubted that the simulation results can serve a realistic estimation of the long-term development of the global fleet. In particular, the model restrictions that inhibit a modeling of a dynamic development of the aircraft utilization and the evolution of the seat load factor do actually constrain a realistic prediction of the fleet-wide transport supply (especially the total ASKs) and thus the total fuel demand.

Therefore, in Appendix K, a method is introduced that enables an a-posteriori translation of the raw simulation results into data that capture a dynamic evolution of both the average aircraft utilization characteristics and the load factor. Through application of this method, the fleet-wide simulation results can be recalculated and yield the numbers shown in Table I-7 and Table I-8.

Figure 7-2 (a) and Table I-7 reveal that when taking a dynamic aircraft-utilization and seat-load-factor evolution into account, the fleet determined by the FSDM is actually able to supply a level of RPKs that yields an average total growth of 4.5% annually from 2008 to 2050. However, this growth is still below the value of 5.1% p.a. required by the Boeing CMO scenario. Apparently, the total single-aisle and twin-aisle aircraft production capacities assumed in the simulation (→Section 7.1.3 and Appendix D) do not suffice for a growth at this high level. The

---

[138] The Boeing CMO scenario requires an average global RPK growth of 5.1% annually from 2008 to 2050. In the B_II simulation, only 3.4% could be achieved on average.

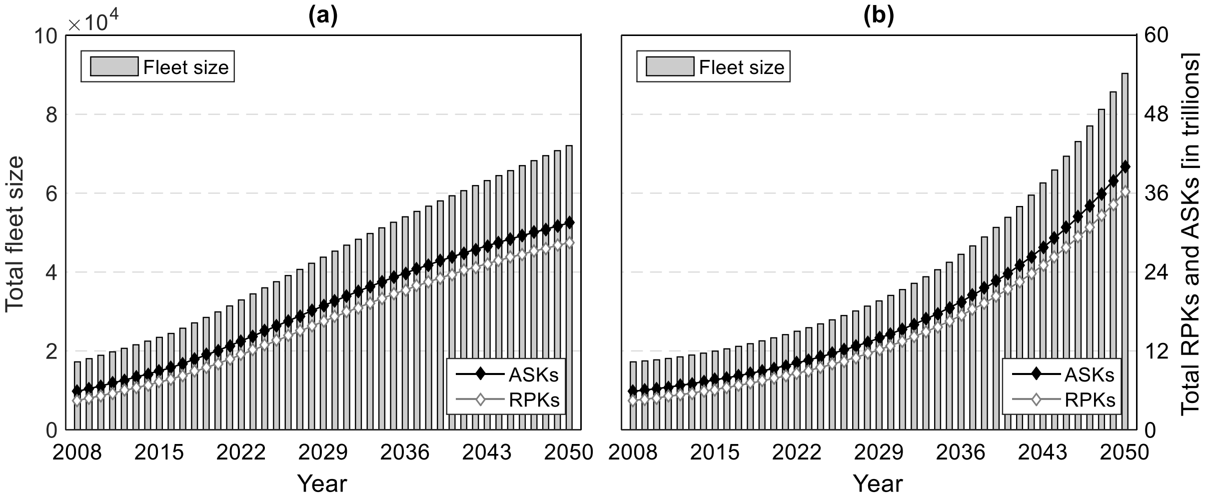


Figure 7-2 **Adapted simulation data (B_II, Variants 1 (a) and 2 (b)): Development of the total fleet size, ASKs, and RPKs**

total fuel demand necessary for this growth increases slightly slower with 4.1% p.a., which reveals the effect of the next-generation aircraft on the fleet-wide fuel consumption.

As shown by Figure 7-2 (b) and Table I-8, a total fleet size of around 90,000 aircraft would be required to enable an annual RPKs growth of 5.1% from 2008 to 2050. The necessary amount of new aircraft to be added to the fleet clearly exceeds the total aircraft production capacities.[139] Again, the effect of the next-generation aircraft on the fleet-wide fuel consumption is well observable when comparing the average growth rate of the total RPKs to the one of the total fuel demand (5.1% vs. 4.7% p.a.).

Finally, Figure 7-3 portrays the impact of the next-generation aircraft on the fleet-wide fuel consumption and CO_2 performance in more detail. The figure shows the simulation data adapted according to *Variant 2* (→Appendix K) that were obtained for all fleet simulations of the Boeing CMO scenario (→Table 7-1).[140] The figure thus enables an insight into the sensitivities of the fuel performance of the simulated fleet towards the speed and quantity of the integration of the next-generation aircraft types.

It is apparent in the figure that in general, the integration of the next-generation aircraft does actually have a positive impact on the fleet-wide fuel demand. In the reference case (i.e., simulation B_II), the next-generation aircraft reduce the total fuel burn needed for an annual growth of 5.1% from 2008 to 2050 by 12% relative to the no-action case (i.e., simulation B_I). In the case of a maximum introduction of the next-generation aircraft (i.e., simulation B_IV), a reduction of almost 29% in total fuel demand relative to the no-action case can be attained potentially.

However, the positive effect of the next-generation aircraft on the fleet-wide average CO_2 performance is only well apparent in the years from 2008 to 2020. Here, a maximum possible performance improvement of 1.0% p.a. is achievable. After 2020, the CO_2 performance worsens again in all simulations except for the B_IV simulation due the constrained single-aisle and twin-aisle production capacities. In B_IV simulation, the next-generation aircraft enable an annual performance improvement of 0.5% from 2008 to 2050.

---

[139] On the other hand, it is questionable whether an average growth of 5.1% p.a. from 2008 to 2050 is a reasonable assumption at all.

[140] As depicted in Appendix K, the adaptation method does not affect the fuel and CO_2 performance of the simulated fleet. Hence, the CO_2 performance values shown in Figure 7-3 are equally applicable for the original simulations and the simulation data adapted according to Variant 1.

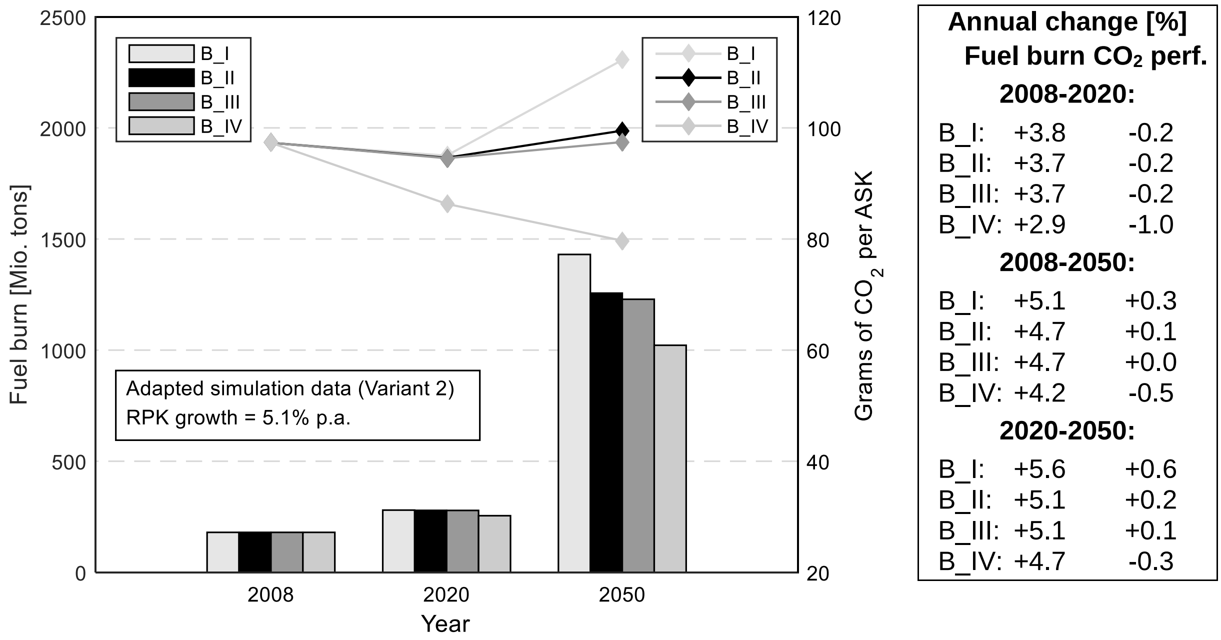


Figure 7-3 **Sensitivity analysis of the total fuel burn and CO_2 performance for all Boeing CMO simulations (B_I through B_IV), adapted simulation data shown (Variant 2)**

7.3.2 Simulation results for the Rough Air scenario

Like in the previous section, Figure 7-4 and Table I-18 depict again the most important fleet-level data obtained for the reference case of the Rough Air scenario (i.e., the 'R_II' simulation in Table 7-1).[141] The following important findings can be drawn from there:

- From 2008 until both 2020 and 2050, the total fleet size grows more strongly than the transport supply delivered by this fleet. The average aircraft size within the fleet hence decreases.
- The transport supply delivered by the global fleet grows with a higher rate than the associated fuel burn (+3.9% vs. +3.4% until 2020 and 3.0% vs. 2.5% until 2050). This indicates that the gradual integration of the more efficient next-generation aircraft types actually leads to an improvement of the fleet-wide fuel performance.
- The CO_2 performance decreases by an average value of 0.5% annually, which again confirms the positive impact of the next-generation aircraft on the fleet performance.
- The simulated fleet in 2050 is unable to deliver the amount of RPKs required by the Rough Air scenario, although the achieved growth rate comes very close to the target rate (3.0% vs. 3.1%).[142] Responsible for this finding is the Rough Air scenario itself that requires growth rates exceeding 3.0% p.a. from 2048 onwards (→Figure 7-4 (b)). The simulation is unable to attain these rates through the integration of an adequate number of new aircraft due to the constrained total production capacities set in the simulation.

---

[141] See Appendix I for a summary of all relevant simulation data.

[142] The Rough Air scenario requires an average global RPK growth of 3.1% annually from 2008 to 2050. In the R_II simulation, only 3.0% could be achieved.

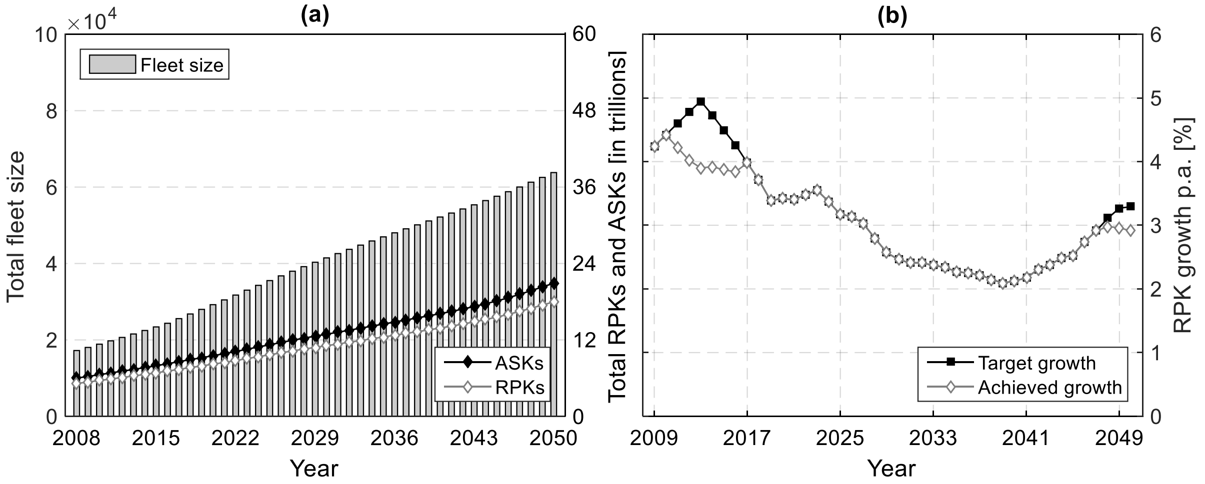


Figure 7-4 **Simulation data (R_II): (a) Development of the total fleet size, ASKs, and RPKs, (b) Target and achieved total RPK growth rates p.a.**

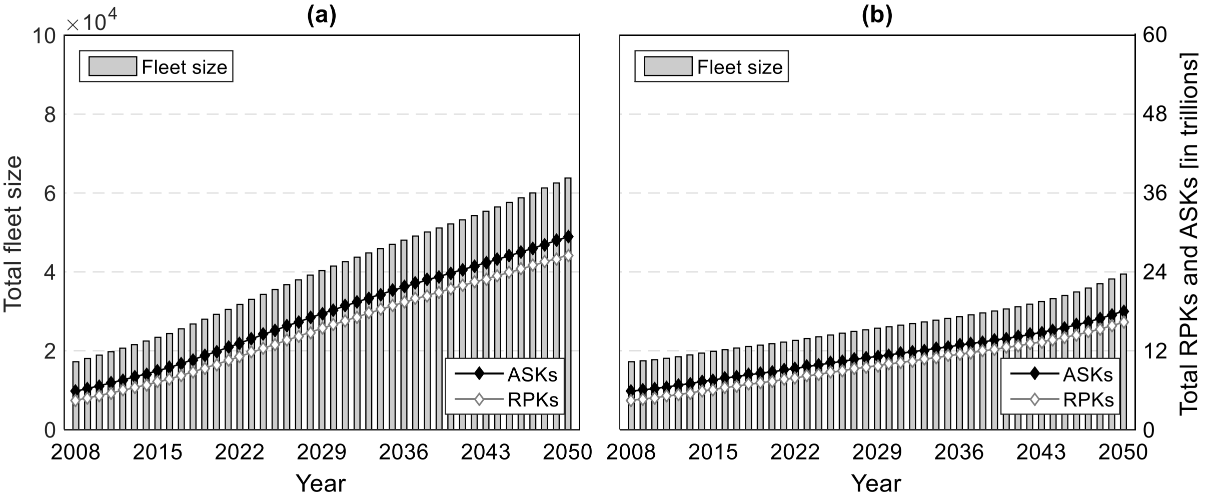
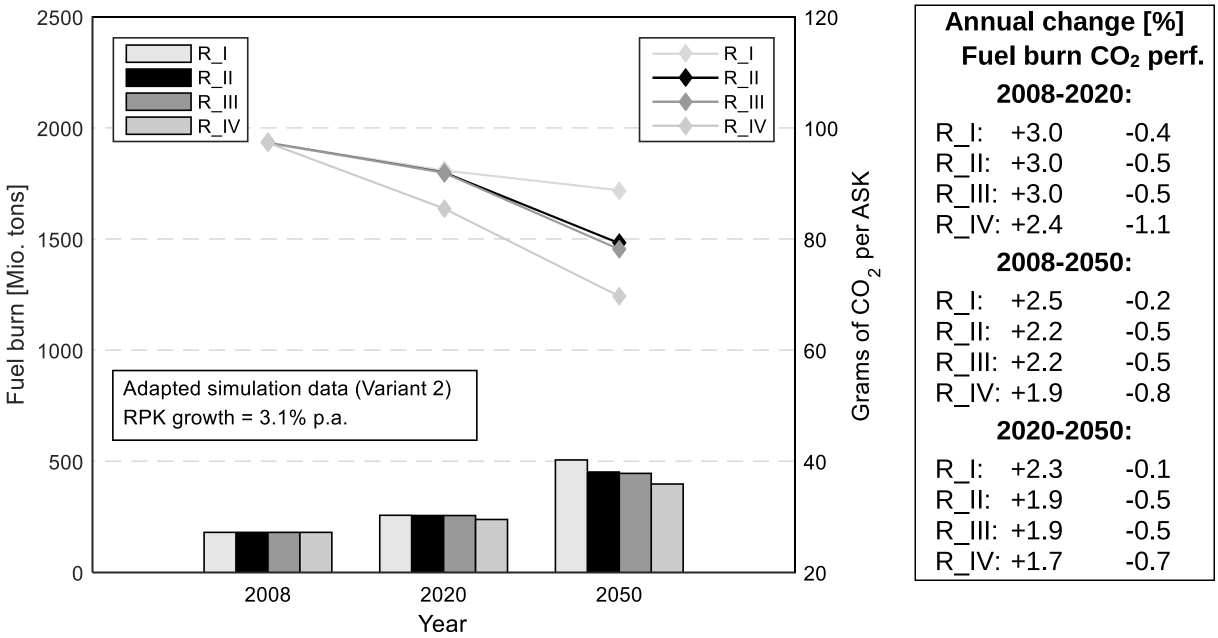


Figure 7-5 **Adapted simulation data (R_II, Variants 1 (a) and 2 (b)): Development of the total fleet size, ASKs, and RPKs**

Figure 7-5 (a) and Table I-19 reveal that once the dynamic aircraft-utilization and seat-load-factor functions are applied (→Appendix K), the fleet originally determined by the FSDM is actually able to supply a level of RPKs that yields an average total growth of 4.3% annually from 2008 to 2050. This growth rate clearly exceeds the value of 3.1% p.a. required by the Rough Air scenario. The total fuel demand necessary for this growth increases slower with only 3.4% p.a., showing again the effect of the next-generation aircraft types.

Figure 7-5 (b) and Table I-20 indicate that a fleet size of around 40,000 aircraft would actually be required to enable an annual RPKs growth of 3.1%, which is almost feasible for the FSDM simulation in spite of the restrictions of the total production capacities. Here again, the effect of the next-generation aircraft on the fleet-wide fuel demand is clearly noticeable when comparing the average growth rate of the total RPKs to the one of the total fuel demand (3.1% vs. 2.2% p.a.).

Figure 7-6 eventually portrays the adapted simulation data again. In comparison with the case of the Boeing CMO simulations depicted in the previous section (→Figure 7-3), the reduction potential of the total fuel demand is smaller between the no-action case (i.e., R_I) and the case that features the maximum insertion rates of the next-generation aircraft (i.e., R_IV). Here, a maximum reduction potential of around 21% can be attained in 2050. In the



Annual change [%]	Fuel burn	CO_2 perf.
2008-2020:		
R_I:	+3.0	-0.4
R_II:	+3.0	-0.5
R_III:	+3.0	-0.5
R_IV:	+2.4	-1.1
2008-2050:		
R_I:	+2.5	-0.2
R_II:	+2.2	-0.5
R_III:	+2.2	-0.5
R_IV:	+1.9	-0.8
2020-2050:		
R_I:	+2.3	-0.1
R_II:	+1.9	-0.5
R_III:	+1.9	-0.5
R_IV:	+1.7	-0.7

Figure 7-6 **Sensitivity analysis of the total fuel burn and CO_2 performance for all Rough Air simulations (R_I through R_IV), adapted simulation data shown (Variant 2)**

reference case (i.e., R_II), the next-generation aircraft can lower the total fuel consumption by 11%.

Figure 7-6 also reveals that unlike for the B_I fleet of the Boeing CMO scenario, the R_I fleet is able to deliver an RPKs growth rate of 3.1% p.a. while maintaining the associated growth in total fuel burn at a lower level of 2.3% only. This is possible due to the generally lower RPKs growth rates of the Rough Air scenario relative to the Boeing CMO, which allows the FSDM to accomplish a better fleet assignment to the simulated routes network in terms of fuel consumption, as the total production capacities are not reached permanently (as is the case in the Boeing CMO simulations).

The same is true regarding the fleet-wide CO_2 performance. Even without an introduction of the next-generation aircraft, a performance improvement of 0.2% p.a. is attained from 2008 to 2050. The maximum achievable improvement in this period is 0.8% annually in case of the R_IV simulation. A more realistic value of 0.5% can be determined when considering the R_II and R_III simulations. This improvement can be achieved under both a mid-term and long-term horizon.

7.3.3 Comparison of the simulation results with the global climate goals

This section examines the contribution of the fleet development, and particularly the next-generation aircraft, towards reaching aviation's global climate goals depicted in Section 1.1 (i.e., IATA goals 1 through 3). The simulation results obtained for both future scenarios (i.e., the Boeing CMO and the Rough Air scenario) are considered here. However, in order to reduce the amount of simulation data to be investigated, only the reference cases (i.e., B_II and R_II) and the cases capturing the maximum insertion rates of the next-generation aircraft (i.e., B_IV and R_IV) are taken into account (→Table 7-1). This will deliver an adequate estimation of the technological feasibility of the climate goals in terms of what can be achieved realistically and at maximum.

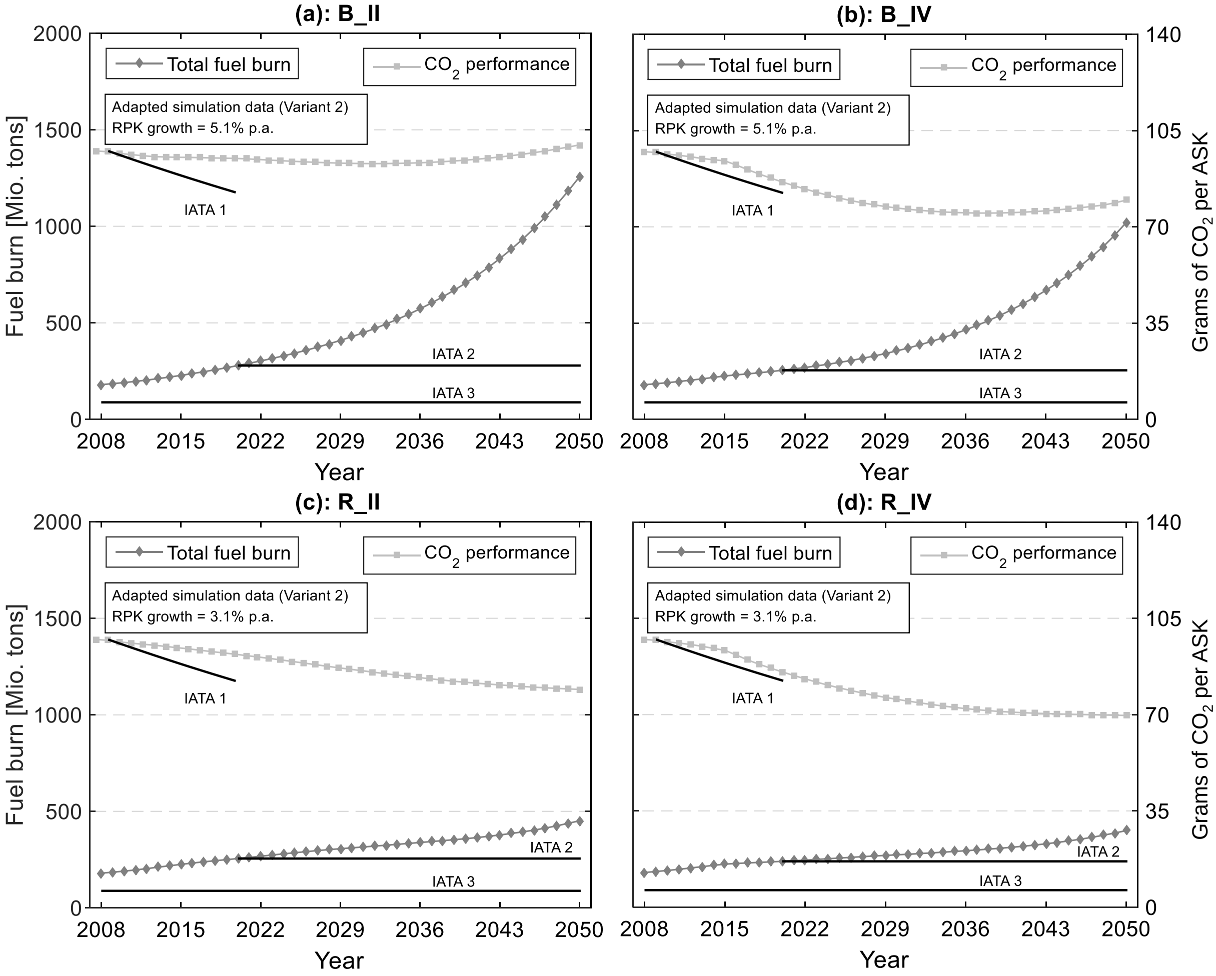


Figure 7-7 **IATA climate goals and fleet-wide fuel demand and CO₂ performance for simulations B_II (a), B_IV (b), R_II (c), and R_IV (d), adapted simulation data shown (Variant 2)**

Figure 7-7 summarizes the relevant simulation results and compares both the simulated total fuel demand and the fleet-wide CO₂ performance to the three IATA goals.[143] Note that unlike IATA goals 2 and 3, IATA goal 1 does not address an absolute target level of fuel consumption but an annual improvement in fuel efficiency. In this thesis, the *fuel efficiency* term is interpreted as a specific amount of fuel burned per ASK, which is equivalent to a specific quantity of CO₂ emitted per ASK. Consequently, IATA goal 1 is compared to the fleet-wide CO₂ performance in the figure.

Figure 7-7 clearly reveals that even in the best-case scenarios featuring a maximum insertion rate of the next-generation aircraft (i.e., simulations B_IV and R_IV), none of the three IATA goals can actually be reached. IATA goal 1 appears to be the best feasible goal from a purely technological point of view. IATA goal 2 may be achieved in the Rough Air scenario with an aircraft generation that features a performance improvement at a level similar to the current next-generation aircraft types (i.e., an improvement step of around 15-20%). IATA goal 3 seems infeasible under all conditions, though.

Table 7-2 portrays the gaps that remain between the fuel consumption and efficiency improvement achieved by the respective fleets of each simulation on the one hand and the three IATA climate goals on the other. The table confirms that among all IATA climate goals, goal 1 is the least challenging one to be reached. In the B_IV and R_IV simulations, an additional gain in fuel efficiency of only 0.4% per year would be required to reach this goal.

---

[143] The raw simulation data of this figure are available in Appendix I.

Table 7-2 **Fuel-consumption and efficiency gaps remaining to meet the IATA climate goals**

Goals	Simulations			
	B_II	B_IV	R_II	R_IV
IATA 1 *(1.5% improvement in fuel efficiency from 2009-2020)*	1.3% p.a.	0.5% p.a.	1.0% p.a.	0.4% p.a.
IATA 2 *(maintain total fuel-burn level of 2020)*	5.1% p.a.	4.7% p.a.	1.9% p.a.	1.7% p.a.
IATA 3 *(reduce total fuel burn by 50% rel. to 2005)*	6.6% p.a.	6.0% p.a.	4.0% p.a.	3.7% p.a.

Aids to interpretation of the numbers:

IATA 1: Shown is the annual increase in fuel efficiency (i.e., fuel consumption per ASK) additionally required to achieve an annual fuel-efficiency improvement of 1.5% from 2009 to 2020.

IATA 2: Shown is the annual decrease in total fuel consumption from 2020 to 2050 additionally required to maintain the total fuel-burn level of 2020.

IATA 3: Shown is the annual decrease in total fuel consumption from 2009 to 2050 additionally required to reduce the total fuel-burn level of 2050 by 50% relative to the level of 2005.

Furthermore, in the Rough Air scenario, IATA goal 2 also features mediocre requirements towards the fleet-wide fuel-efficiency improvements. However, reaching IATA goal 3 can still be considered highly challenging, if not infeasible.

7.3.4 Concluding remarks

The main objectives of this chapter were (1) to quantify the impact of the next-generation aircraft on the fleet-wide fuel burn and CO_2 performance and (2) to evaluate the feasibility of reaching the IATA climate goals from a purely technology-oriented perspective. Both objectives could be achieved.

It was found that unsurprisingly, the next-generation aircraft do have a positive impact on the development of the fleet-wide fuel burn and efficiency. However, the strength of this impact strongly depends on the question of how quickly aircraft manufacturers can switch over their production lines from building current aircraft types to the next-generation types. In addition, their overall capabilities of extending the total number of aircraft being produced within a certain period of time affect the fleet composition and associated fuel performance by a significant degree as well.

The simulation results of the Boeing CMO scenario, a scenario that describes a very strong market growth with the aircraft manufacturers reaching their production capacity limits, revealed that under these conditions, the full potential of the next-generation aircraft cannot be exploited entirely. To enable the high growth rates of this scenario, a huge air transport fleet would be necessary that would incorporate both next-generation aircraft and older types that would negatively affect the total fuel efficiency. More realistic in this respect seems the Rough Air scenario that shows rather moderate growth rates of the air transport sector in the long term. Here, the potential of the next-generation aircraft is much more important, as the overall fleet size is relatively smaller compared to the Boeing CMO scenario.

Moreover, the fleet simulations presented in this chapter revealed that the three global climate goals defined by IATA for the upcoming decades cannot be reached solely through an integration of the next-generation aircraft considered in this thesis. While IATA goal 1 appears to be feasible to a certain extent, IATA goals 2 and 3 seem highly challenging. Here, additional measures apart from the integration of new aircraft technologies must definitely be taken.

Among others, possible examples could be the further optimization of the global air traffic management system, the advancement of the air traffic infrastructure including airports, and the use of biofuels (that may not directly increase the fuel efficiency but help improve the fleet-wide CO_2 performance once their entire well-to-wake life cycle is taken into account). Not considered in this analysis was a future aircraft generation that may follow the next-generation aircraft types investigated here. These future types may enter the fleet from around 2030 to 2040. Their entry will of course affect the fleet-wide fuel efficiency positively and certainly help approach aviation's long-term climate goals. This chapter has introduced the requirements that define to what extent this future generation must beat today's best available aircraft technologies to ensure a sustainable development of commercial aviation in the long term.

8. Application case

The overall purpose of this thesis is to provide a comprehensive semi-numerical methodology not only for evaluating the technological feasibility of aviation's future global climate goals as presented in the preceding chapter, but also for assessing the potential impact of new aircraft concepts and technologies at the fleet level. This latter aspect is intended to help aircraft designers evaluate a new concept or technology in terms of its environmental impact already at the early stages of the design process.

This chapter is hence dedicated to demonstrating how the Aircraft Technology Assessment Framework ATAF may be used for the assessment of an exemplary aircraft concept in terms of its fleet-wide impact on fuel consumption and efficiency. The aircraft type portrayed here is the *Propcraft P-420*, a high-capacity transport aircraft designed for short-range operations on highly frequented routes. The P-420 has evolved out of an extended aircraft design project at TUM LLS since 2013. Three versions of the P-420 have been elaborated so far: a four-engined turboprop, a four-engined turbofan, and a twin-engined turbofan variant. All three variants are evaluated separately in this chapter to demonstrate the technology-assessment capabilities of ATAF.

At the beginning of this chapter, the three variants of the P-420 are portrayed briefly in terms of their major technical specifications and performance characteristics. Then, various assessment studies are presented that are intended to examine the system-wide impact of this aircraft on the fuel demand and performance. The chapter finally ends with a short review of the main findings of the aircraft assessment studies conducted.

8.1 The Propcraft P-420 high-capacity transport

In the face of the continuing growth of global air traffic together with an increasing congestion of all major hub airports worldwide, research is being conducted at TUM LLS that is aimed at finding, analyzing, and evaluating technical solutions for a sustainable long-term development of the commercial aviation industry. Among the many research projects being carried out at the institute, a particular project has been dealing with the conceptual and preliminary design of a large transport configuration that is targeted at serving strongly frequented short- and mid-haul routes much more efficiently than current competitor types.

Analyses of the current air traffic markets around the world conducted at the institute had revealed the outstanding role of the short- and mid-haul routes below 3,000 km (1,600 NM) within today's global air traffic network. (Iwanizki *et al.*, 2014, p. 2; Randt, 2014, pp. 1–2) Further analyses had revealed that at present, various airlines, especially in the Asian region, are operating large aircraft (e.g., Airbus A330, Boeing 777, or larger) on these routes to provide adequate transport capacities despite the fact that these aircraft were not designed for short-range missions. However, studies published by other institutions had already proven that large aircraft specifically designed for short-haul operations would have the potential of mitigating the environmental impact of aviation. (Kenway *et al.*, 2010)

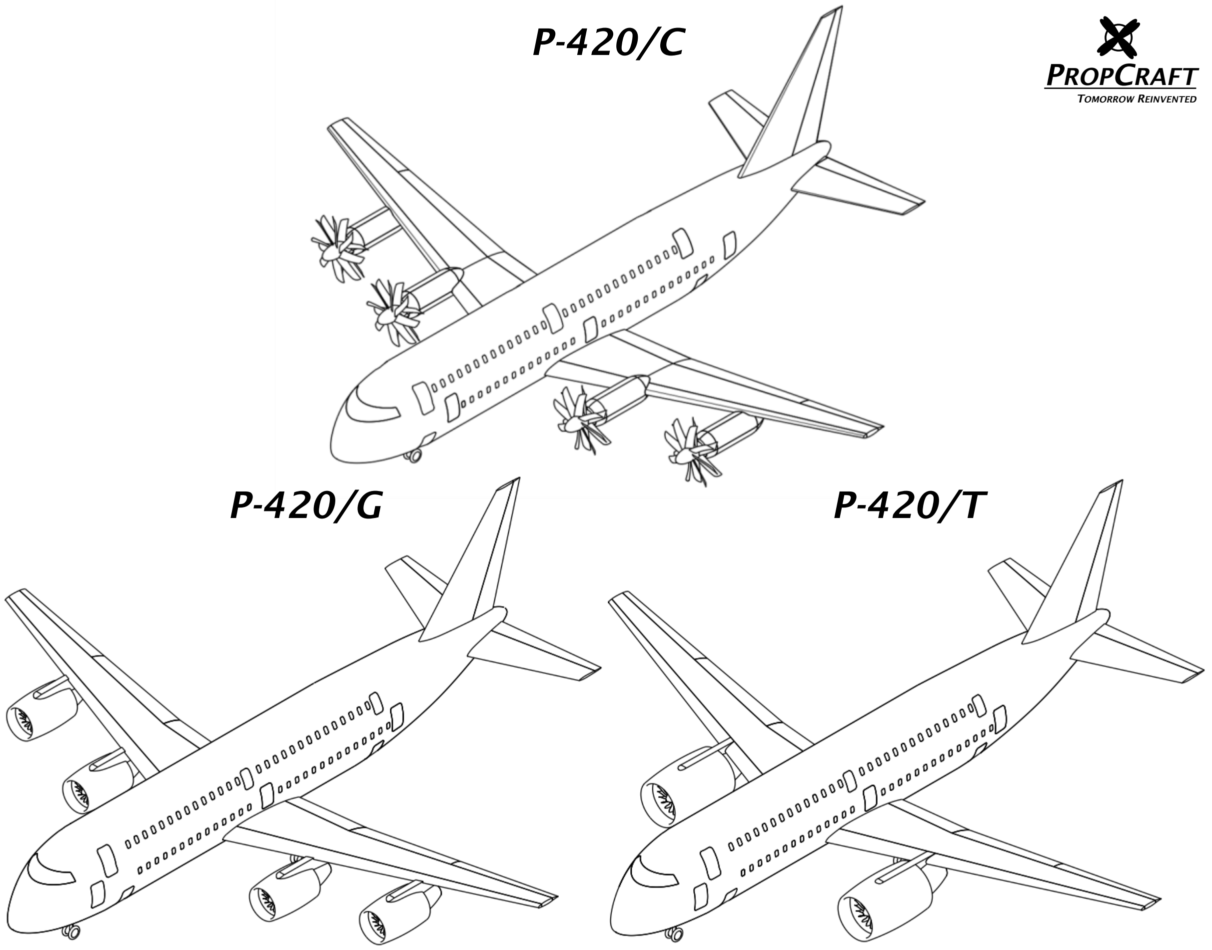


Figure 8-1 **Illustrations of the Propcraft P-420 variants /C (turboprop), /G (geared turbofan), and /T (high-bypass turbofan)**
Image sources: author's creation based on Iwanizki (2013) and Kalwar (2015)

With these aspects in mind, the *Propcraft P-420* aircraft design project was launched at TUM LLS in 2013 under the direction of the author of this thesis. Until today, the P-420 has seen continuous development iterations and regularly undergoes technical refinement. A major design requirement has been and still is that the aircraft shall only be equipped with components of the currently available technology level. This requirement is intended to produce aircraft concepts that can be employed as examples of demonstrating today's technological potential in terms of fuel efficiency.

The initial concept, the P-420/A, that came out of the first design iteration principally conducted by Iwanizki (2013), featured a classical tube-and-wing configuration with four turboprop engines. Each motor was planned to deliver almost 10 Megawatts of shaft power with a large counter-rotating propeller, a three-deck fuselage of which the upper two decks were designed as passenger cabins, and a conventional fuselage-mounted tail. However, during the initial design phase, a particular challenge became the modeling of the engine power and thrust characteristics as a function of the flight speed and altitude due to a substantial lack of reliable data of existing engines of a similar power class.[144] Therefore, further work at the institute focused especially on a refinement of the engine model, which

---

[144] Until today, the most powerful Western-built turboprop engine has been the TP400-D6 of European engine manufacturer Europrop International according to MTU (2014) that supplies a maximum shaft power of 8.2 Megawatts at sea level.

Table 8-1 **Technical specifications and performance characteristics of the P-420 variants /C, /G, and /T**
Data sources: Kalwar (2015), Iwanizki (2013), author's calculations

		P-420	
	/C	**/G**	**/T**
EXTERIOR DIMENSIONS			
Length [m]	47.7	47.7	47.7
Wing span [m]	51.7	51.7	51.7
Height [m]	17.3	17.3	17.3
Outer main gear wheel span [m]	10.9	10.9	10.9
Aerodrome reference code	4D	4D	4D
FAA airplane design group	IV	IV	IV
MASSES			
Operating empty mass [tons]	88.4	84.2	88.1
Maximum take-off mass [tons]	157.6	154.7	161.8
Maximum seat number (Economy class only):	420	420	420
Maximum freight load [tons]	10.	10.0	10.0
AERODYNAMICS			
Lift-to-drag ratio [-]	18.48	18.13	18.17
Zero-lift drag coefficient [-]	0.0218	0.0183	0.0182
PROPULSION			
Number and type of engine	4x turboprop	4x geared turbofan	2x high-bypass turbofan
Engine power / thrust at mean sea level	9.7 MW	120 kN	345 kN
Propeller / fan diameter [m]	5.0	2.1	2.8
Bypass ratio [-]	n/a	12.0	8.7
Specific fuel consumption at cruise flight	217 g/kWh	13.1 g/kNs	14.5 g/kNs
PERFORMANCE			
Maximum-payload range [km]	2,100	2,500	2,600
Ferry range [km]	11,100	11,900	10,400
Maximum operating Mach number [-]	0.77	0.85	0.85
Maximum operating altitude [ft]	35,000	38,000	45,000
Wake turbulence category	Heavy	Heavy	Heavy
FAR25 landing distance [m]	2,160	2,120	2,200
Balanced field length [m]	2,760	3,400	3,950
Typical mission fuel burn [kg] ***(3,000 km, 400 Seats, 41 tons of payload, 20 min taxi)***	16,450	15,910	17,960
CO_2 performance [gCO_2/ASK] ***(Typical mission)***	43.3	41.9	47.3

eventually led to the development of the /B (Kügler, 2014; Kügler and Randt, 2015) and later the /C (Kalwar, 2015).

Based on the /C, Kalwar then derived two additional variants of the P-420 essentially by replacing the existing turboprop engines with turbofans: the /G featuring four geared turbofans similar to the PW1127G engines of Pratt & Whitney, and the /T being propelled by two high-bypass turbofans equivalent to the GEnx-1B74 of General Electric. As shown by Figure 8-1, the overall configurational design of the P-420 was maintained, though.

Table 8-1 provides an overview of the major technical specifications and performance characteristics of the P-420 variants /C, /G, and /T that together represent the current state of progress of the P-420 project. As shown in the table, the /T generally features a less favorable performance in terms of fuel efficiency. Therefore, it will not be considered further in the aircraft assessment studies presented in the subsequent sections.

8.2 Integrated design tool

Within the scope of the P-420 project, Kügler (2014) developed the 'Integrated Design Tool (IDT),' which is a "parametric aircraft design tool that was created […] to support comprehensive analyses and design iterations of large turboprop aircraft." (Kügler and Randt, 2015, p. 1) Being implemented in a MATLAB® software environment, the IDT essentially relies on classical handbook methods commonly applied in aircraft conceptual design that have been published by recognized authors including Raymer (2012) and Torenbeek (1982). The tool facilitates parameter-variation studies, allowing the identification and investigation of the critical design parameters of the P-420 concept. Kalwar (2015) expanded the functionalities of the IDT in order to additionally enable design and trade studies for turbofan-powered configurations.

Besides its parameter-variation capabilities, the IDT is also able to create the OPF and APF data files of any P-420 variant under scrutiny, which enables a later integration of the respective variant into the BADA aircraft performance model and hence into the ATAF environment (→Chapter 5). In this way, OPF and APF data files were created for all variants of the P-420 concept.

8.3 System-wide impact assessment

The following sections deal with the assessment of the P-420 concept in terms of its potential impact on the fleet-level fuel burn and CO_2 performance. Before presenting and interpreting the results obtained through the application of ATAF, an overview of the simulations conducted here is provided and the relevant input parameters are presented.

8.3.1 Simulation cases conducted

Table 8-2 summarizes the simulations that were conducted in order to achieve a solid basis for the assessment of the P-420 concept. For all simulations, only the Rough Air market scenario was considered. Due to its moderate growth rates of global air traffic, this scenario was assumed to define a reasonable long-term development of aviation until 2050.[145] Of course, other published scenarios could be used as a basis for further P-420 assessment studies as well.

For the different simulations, the production rates of the next-generation aircraft and the P-420 were varied in order to isolate the impact of the P-420 from the effects of the remaining next-generation aircraft. In this sense, the two simulations marked '_R_IV' in Table 8-2 represent best-case scenarios as the numbers of next-generation aircraft that can potentially be added to the fleet are only constrained by the total single-aisle and twin-aisle production capacities.

8.3.2 Simulation input parameters

All input parameters required to initialize and carry out the simulations were set exactly equal to the simulations conduced in Chapter 7 (→Section 7.1.3). The P-420 was assigned to the routes network of the Cluster 9 aircraft types in order to simulate a possible situation of airlines operating their P-420s on a network equal to their current Airbus A320/Boeing 737 networks (i.e., a typical short- and medium-range network). In addition, the P-420 was set to provide a

---

[145] See Section 7.1.2. The market growth rates of this scenario are collected in Table I-1 and Table I-2 of Appendix I.

Table 8-2 Fleet simulations conducted for the P-420 concept assessment

Market development scenario	P-420 variant under scrutiny	Simulation ID	Total production capacities	Integration of next-generation aircraft types	Integration of P-420
Rough Air scenario	/C	P42C_R_I	Constrained	Not integrated	Production capacity constrained by values given in Table D-2 (twin-aisle aircraft class)
		P42C_R_II	Constrained	Single production capacities constrained by values given in Table F-2	Production capacity constrained by values given in Table D-2 (twin-aisle aircraft class)
		P42C_R_IV	Constrained	Single production capacities only constrained by total production capacities limits	Production capacity only constrained by total production capacities limits
	/G	P42G_R_I	Constrained	Not integrated	Production capacity constrained by values given in Table D-2 (twin-aisle aircraft class)
		P42G_R_II	Constrained	Single production capacities constrained by values given in Table F-2	Production capacity constrained by values given in Table D-2 (twin-aisle aircraft class)
		P42G_R_IV	Constrained	Single production capacities only constrained by total production capacities limits	Production capacity only constrained by total production capacities limits

payload capacity of 400 seats and 5 tons of cargo on all routes. Finally, for all simulations, the entry into service of the P-420 was assumed to take place in 2025.

8.3.3 Simulation results

This section presents the most important results obtained through the above-described simulations. The focus here is on the global fleet development as well as the fleet-wide fuel demand and CO_2 performance. At first, the results related to the P-420/C and the /G are presented separately. Then, at the end of this section, the two variants are mutually compared. All results shown were derived from the original simulation data through application of *Variant 2* (→Appendix K).

8.3.3.1 P-420/C assessment

Figure 8-2 shows the development of the simulated global fleet from 2025 to 2050 for the three simulations conducted.[146] In all simulations, the overall fleet size reaches a level of almost 40,000 units in 2050, since all fleets deliver a level of transport supply allowing an average growth in RPKs of 3.1% annually as prescribed by the Rough Air scenario.

---

[146] The raw data associated to the simulation results presented here and in the following sections are available in Appendix J.

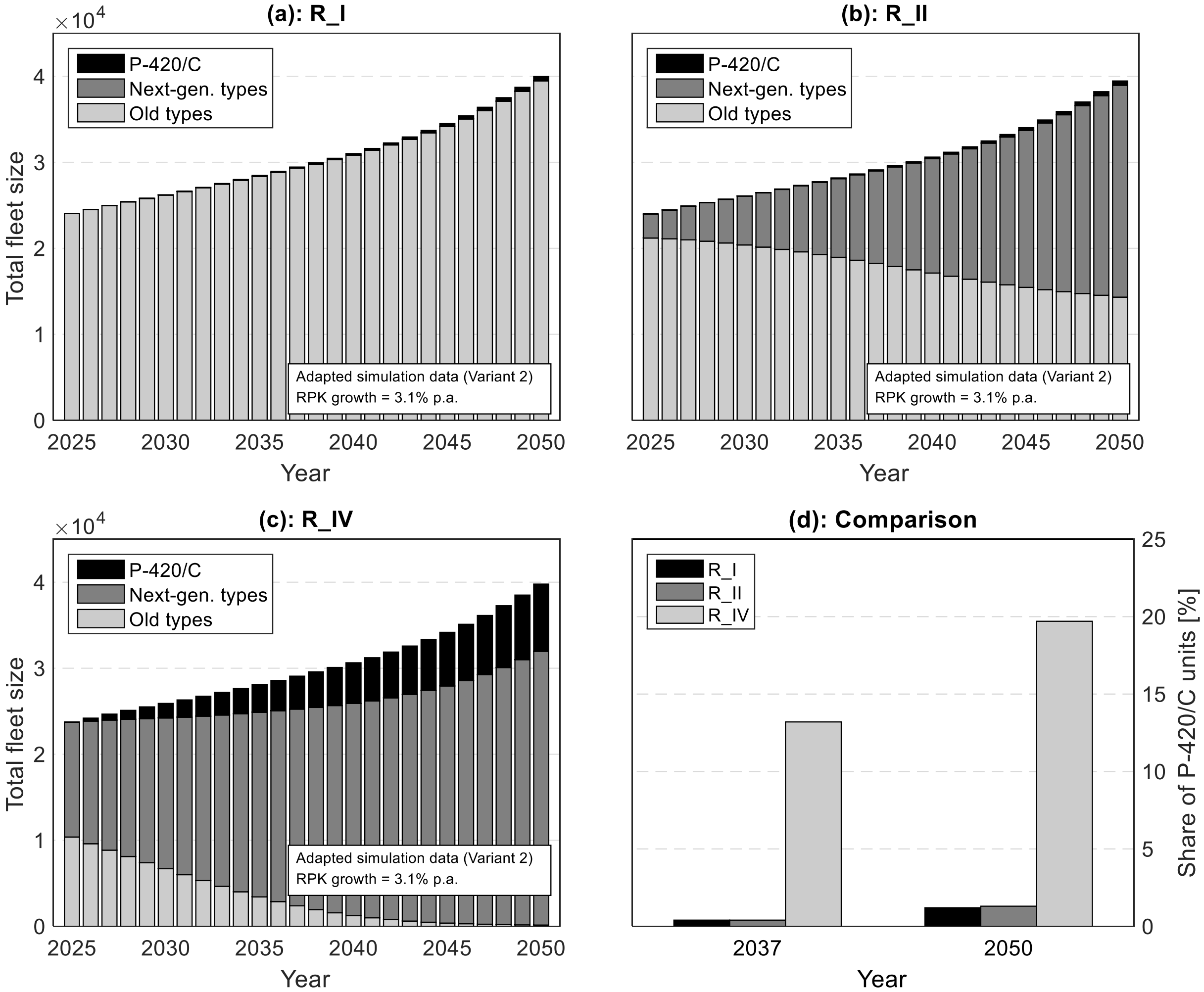


Figure 8-2 **Development of the total fleet size and share of P-420/C units in the total fleet**

The difference between the three fleets is fundamentally established by the share of the P-420/C units and the share of the next-generation aircraft types (in the R_II and R_IV simulations only). In the R_I and R_II simulations, the FSDM determined a very low share of a bit more than 1% for the P-420 in 2050. This corresponds to about 500 units in total.[147] In the R_IV simulation, however, where the numbers of additions of P-420s and next-generation aircraft were only constrained by the total single-aisle and twin-aisle production capacities, a share of the P-420 of almost 20% is reached (corresponding to a total number of about 7,800 units). The fact that in this simulation, the share of the P-420s increases strongly from 2025 onwards proves that the FSDM prefers selecting this type to fill the capacity gap. This again demonstrates that on many of the simulated traffic routes, the P-420 is capable of delivering transport supply more efficiently relative to its competitors.

---

[147] Five hundred units appear to be a very low number for a period of 25 years. In fact, the restriction of the P-420 production capacity allows a maximum delivery number of 869 aircraft units for a period of 25 year (→Table D-2, TA class). However, the a-posteriori adaptation of the simulation results according to Variant 2 (→Appendix K) decreases the absolute number of added P-420 units accordingly. Moreover, in 2050, the original number of P-420 deliveries is about 5% higher than the number of active units in this year. Some units have already been retired by the model between 2025 and 2050 due to the statistical-retirements approach of the FSDM (→Section 4.2.5). The production ramp-up function of large aircraft has been used here to predict the P-420 production development (→Figure 4-4). In reality, a manufacturer of the P-420 may build its production facilities much faster to produce more P-420 units than assumed here. Therefore, the R_IV simulation is presented in this section besides the R_I and R_II simulations to ignore production ramp-up effects.

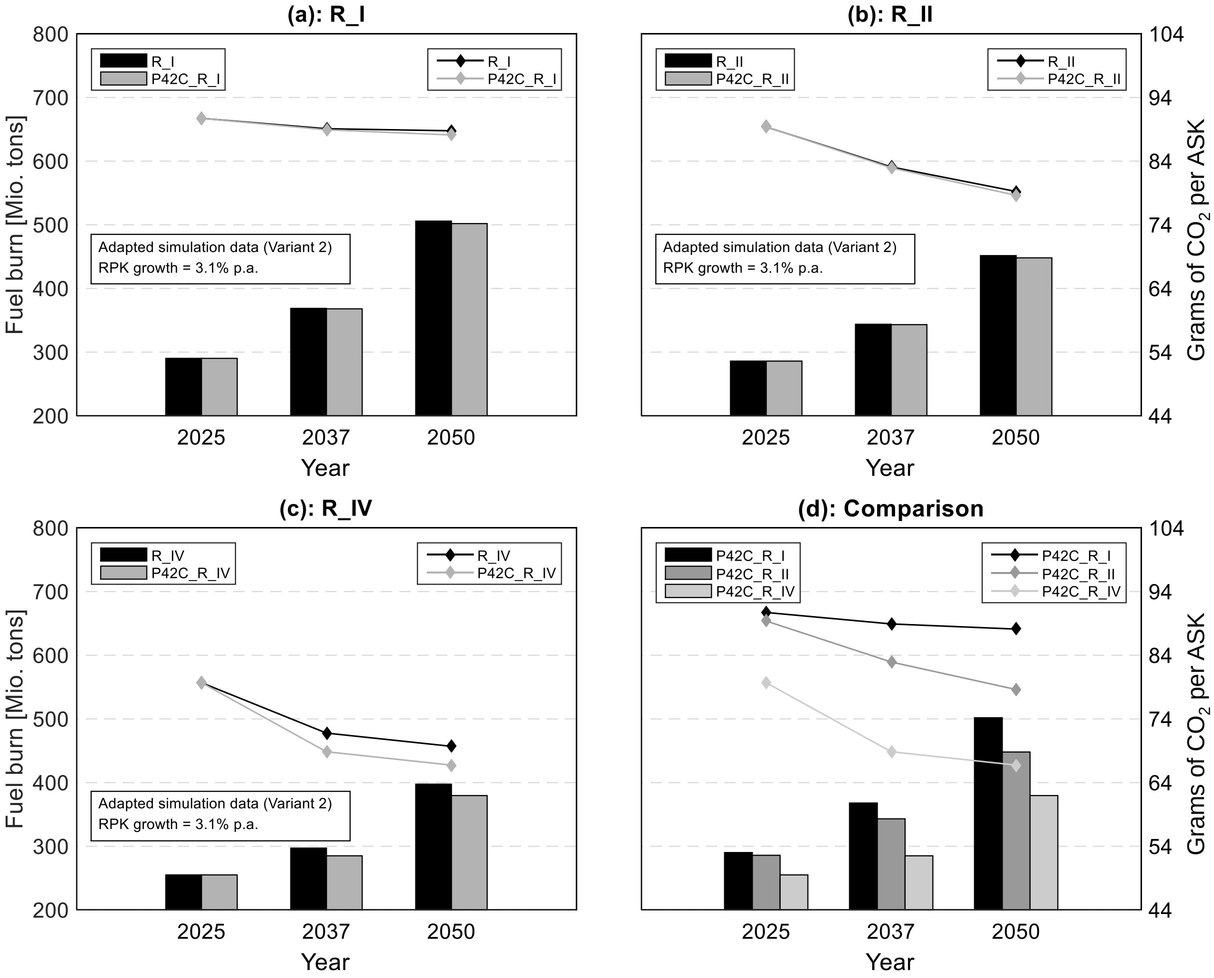


Figure 8-3 **Impact of the P-420/C on the fleet-wide fuel demand and CO_2 performance**

Accordingly, as shown by Figure 8-3, the impact of the P-420/C on the fleet-wide fuel demand and CO_2 performance is most significant in the R_IV simulation. Here, the P-420 can reduce the total amount of fuel burn by about 4.0% in 2037 relative to the fleet without this particular aircraft, and by 4.5% in 2050 (→Table 8-3). In the R_I and R_II simulations, however, the fleet-wide effects of this type on the fuel demand and CO_2 performance are barely noticeable (they remain below 1% in both simulations), while the total effect of all next-generation aircraft in sum can be observed very well.

8.3.3.2 P-420/G assessment

Figure 8-4 shows the results data related to the simulated fleet development for the case of the P-420/G being introduced into the fleet from 2025 onwards. Here, the major finding is that there is no important difference observable relative to the results obtained for the simulations with the P-420/C depicted in the previous section.

Not visible in the figure is that the higher cruising speed of the P-420/G relative to the /C leads to a slightly higher share in total ASK supplied by the global fleet because the /G requires less block hours when serving the simulated routes network and can thus fly more frequently. Here, the fleet-wide effect is very small though, as the routes network of the P-420 features many short-range routes where cruise-speed advantages are not very important due to short cruising segments.[148]

---

[148] For a specific airline, flight speed advantages may be very significant though, depending on its actual network characteristics.

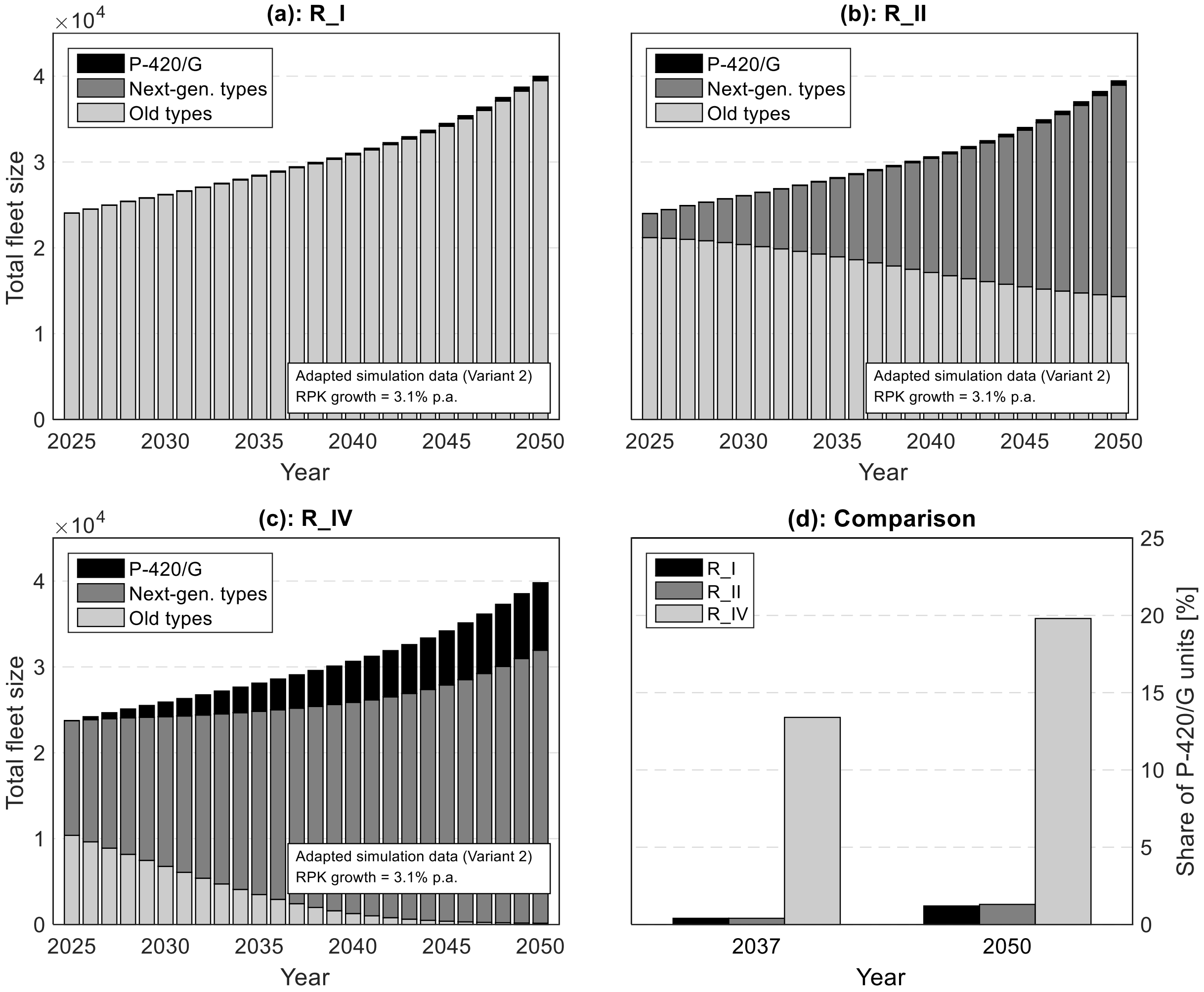


Figure 8-4 **Development of the total fleet size and share of P-420/G units in the total fleet**

There are no differences observable either when considering the simulations results related to the calculations of the total fuel demand and CO_2 performance portrayed in Figure 8-5. A closer look at the precise numbers reveals, however, that there are slight differences between the fleet-wide effects of the two P-420 variants. These differences are depicted in the following section.

8.3.3.3 Comparison of the P-420 variants /C and /G

Although the previous sections have revealed no substantial difference with regard to the fleet-wide impacts of the P-420 variants /C and /G, there are in fact minor distinctions observable. According to the performance values of the two variants given in Table 8-1, the /G is slightly superior compared to the /C. This finds particular expression in the fleet simulations data shown by Table 8-3 and Table 8-4.

The most significant difference between the /C and the /G is observable in the R_IV simulations where in 2050, the P-420/G can potentially lead to a saving in total fuel demand of up to 5.6% relative to a fleet without this aircraft, while the /C would lead to a fuel saving potential of around 4.7%. This makes almost 1% in difference. Other values associated to the two variants differ less significantly with minor advantages supporting the /G.

8.4 Summary of major assessment results

The fleet-simulation results presented in the previous section have generally confirmed the positive effects of the P-420 concept on the fleet-wide fuel demand and CO_2 performance in

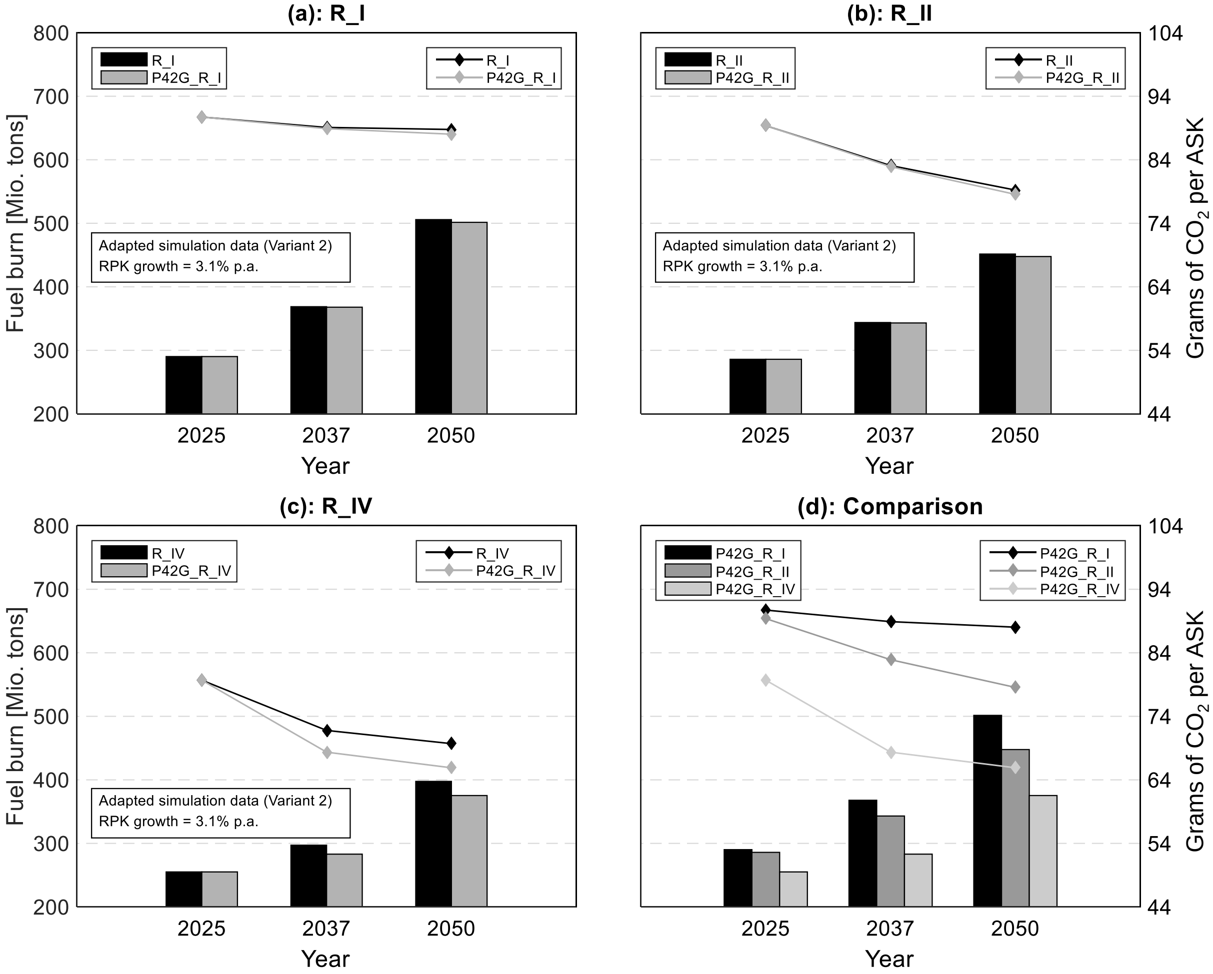


Figure 8-5 **Impact of the P-420/G on the fleet-wide fuel demand and CO2 performance**
Source: author's calculations

the long term (i.e., after 2025). More specifically, Table 8-4 reveals that both the P-420/C and /G can potentially mitigate the average yearly increase in total fuel demand by up to 0.4% between 2025 and 2037 and by up to 0.2% from 2025 until 2050 in a situation where the yearly production rates of the P-420 are only constrained by the total production capacities (R_IV simulations).

The P-420/G features slight advantages regarding the fuel and CO2 efficiency towards the /C. However, this advantage almost disappears when taking the impact on the overall fleet into account. Thus, from a purely efficiency-oriented point of view, neither variant of the P-420 is the preferred one.

Apart from the specific assessment results obtained for the P-420 aircraft concept, the simulations presented in this chapter have confirmed the applicability of ATAF for the assessment of new aircraft concepts in terms of their fleet-wide impact on fuel demand and efficiency in multiple future scenarios. Therefore, ATAF can be utilized effectively to replenish the toolbox that an aircraft designer possesses to evaluate new concept ideas.

Table 8-3 **Comparison of the fleet-wide effects of the P-420 variants /C and /G on fuel-burn**

Simulation	Parameter	2025	2037	2050
R_I	Reference fuel burn [Mio. tons] (w/o P-420)	290.2	368.7	505.8
P42C_R_I	Fuel burn [Mio. tons] w/ P-420/C (difference to ref.)	290.2	368.0 (-0.19%)	501.9 (-0.77%)
P42G_R_I	Fuel burn [Mio. tons] w/ P-420/G (difference to ref.)	290.2	367.9 (-0.22%)	501.5 (-0.85%)
R_II	Reference fuel burn [Mio. tons] (w/o P-420)	285.9	343.8	451.6
P42C_R_II	Fuel burn [Mio. tons] w/ P-420/C (difference to ref.)	285.9	343.2 (-0.17%)	448.1 (-0.78%)
P42G_R_II	Fuel burn [Mio. tons] w/ P-420/G (difference to ref.)	285.9	343.1 (-0.20%)	447.7 (-0.86%)
R_IV	Reference fuel burn [Mio. tons] (w/o P-420)	255.1	297.2	397.6
P42C_R_IV	Fuel burn [Mio. tons] w/ P-420/C (difference to ref.)	255.1	285.1 (-4.07%)	379.7 (-4.74%)
P42G_R_IV	Fuel burn [Mio. tons] w/ P-420/G (difference to ref.)	255.1	283.1 (-4.50%)	375.3 (-5.61%)

Table 8-4 **Comparison of the fleet-wide effects of the P-420 variants /C and /G on the annual increase in fuel demand**

Simulation	Parameter	Growth rate p.a. 2025-2037	Growth rate p.a. 2025-2050
R_I	Reference growth of total fuel burn (w/o P-420)	+2.02%	+2.25%
P42C_R_I	Growth of total fuel burn w/ P-420/C	+2.00%	+2.22%
P42G_R_I	Growth of total fuel burn w/ P-420/G	+2.00%	+2.21%
R_II	Reference growth of total fuel burn (w/o P-420)	+1.55%	+1.85%
P42C_R_II	Growth of total fuel burn w/ P-420/C	+1.53%	+1.81%
P42G_R_II	Growth of total fuel burn w/ P-420/G	+1.53%	+1.81%
R_IV	Reference growth of total fuel burn (w/o P-420)	+1.28%	+1.79%
P42C_R_IV	Growth of total fuel burn w/ P-420/C	+0.93%	+1.60%
P42G_R_IV	Growth of total fuel burn w/ P-420/G	+0.87%	+1.56%

9. Summary and outlook

IN this thesis, a comprehensive methodology for the assessment of the impact of future aircraft concepts and technologies on the fleet-wide fuel demand and related exhaust gas emissions has been elaborated, validated, and applied for the evaluation of a specific novel aircraft concept. This chapter briefly summarizes the most important findings of this work, gives some high-level conclusions in this regard, and eventually provides recommendations for work that may succeed the studies conducted here.

9.1 Summary of scope of thesis and underlying methodology

Many future-forecasting studies of major institutions associated with the commercial aviation industry predict a continuous increase in global demand for air travel. According to these studies, air traffic is expected to grow by around 3 to 5% annually within the upcoming two decades. While from an economic viewpoint, this development can be considered as very positive, the strong growth of the aviation sector will naturally lead to an adverse impact on the environment – both at a local level especially around airports and at the global level affecting climate change. The environmental impact of the growing aviation sector will therefore have negative consequences for humans and the natural environment if no countermeasures are taken.

In the face of the above-described area of tension between growth on the one hand and the negative consequences for the environment on the other, the global aviation industry has defined mid- and long-term goals defining the intended progress for a continuous reduction of its adverse environmental effects. Among others, goals have been defined that prescribe a decrease in the global quantities of exhaust gas emissions that are produced when burning jet fuel. Three key milestones have been introduced: (1) an annual increase in fuel efficiency by 1.5% from 2009 to 2020, (2) carbon-neutral growth from 2020, and (3) a decrease of the absolute amount of the CO_2 emissions produced by global aviation by 50% in 2050 relative to the level of 2005.

The question of how these milestones can actually be reached has only been addressed at a rather generic level so far. In this regard, the International Air Transport Association (IATA) has proposed a four-pillar strategy comprising the use of advanced technologies, an implementation of improved procedures and operations, the optimization of the aviation infrastructure, and an introduction of economic measures to incentivize environmental impact mitigation. No suggestions or estimations have been made yet that could predict the exact quantitative effects of each part of this strategy portfolio.

This thesis is therefore targeted at supplying a profound scientific contribution to the ongoing efforts in this area of research. In doing so, it focusses on the first aspect of the four-pillar strategy, the impact of advanced and new technologies. A methodology is introduced that aims at quantifying how novel aircraft and aircraft technologies may contribute towards achieving a more environmentally friendly air transport system in the future. This methodology has been named the 'Aircraft Technology Assessment Framework (ATAF).'

As the above-mentioned milestones have been formulated at a system-wide level addressing the entire commercial air transport fleet, ATAF is centered on a numerical model of this fleet that dynamically determines its future size, structure, and composition as a function of various input parameters provided by the user. Among others, these input parameters particularly include the future rates of growth of distinct regional air traffic markets that together form the global market of commercial air transport.

A key instrument of ATAF to handle the uncertainty about the future is the scenario planning methodology that the user may employ to create multiple alternative futures and in this way provide the necessary input parameters. The primary scenario-building technique of ATAF relies on the Intuitive Logics School of scenario planning, a philosophy of intuitively generating future scenarios in a knowledge-based way together with a multidisciplinary project team and without involving complex numerical tools. Of course, scenarios or other future-forecasting reports originating from third parties can be utilized as well, as long as the necessary input can be derived from them.

The ATAF fleet model, the 'Fleet System Dynamics Model (FSDM),' fundamentally works by means of a System Dynamics approach. The FSDM represents the simulated world fleet as a stock that is determined by in- and outflows of aircraft being added to the fleet and removed through retirement in each year of simulation. In this sense, the FSDM constitutes a numerical tool that consistently translates the scenario input data into data addressing the development of the global fleet. In this way, introduction and propagation effects of new aircraft entering the fleet at a specific moment in time can be predicted, which eventually enables the investigation of the impact of these aircraft on fleet-wide performance parameters such as the total fuel demand and the CO_2 performance (i.e., the quantity of CO_2 emitted per transport kilometer supplied).

Evidently, the FSDM requires an aircraft performance model (APM) that is capable of determining the performance values of all aircraft under scrutiny. In ATAF, this performance model is provided through an implementation of the BADA (Base of Aircraft Data) APM that is provided by Eurocontrol, the European Air Traffic Management authority. BADA enables the simulation of individual flights to determine mission parameters such as the block time and the amount of fuel burned. In ATAF, the BADA APM is replenished with several methods that enable the quantification of the most important exhaust gas emission substances including CO_2, NO_x, and soot provided that adequate input data is available. Together with the BADA APM, these methods form the 'Fuel Consumption and Emissions Calculation Tool (FCECT).' To capture not only currently operating aircraft but also next-generation types and novel concepts, several techniques have been developed to generate the data files necessary for an integration of these types into the FCECT.

In this thesis, a comprehensive validation of ATAF is conducted to demonstrate the overall functionality of this methodology. Here, a distinction is made between the modeling of the actual real-life development of the air transport system from 2008 until 2013 and the modeling of possible future development paths. The latter is achieved through the consideration of Boeing's Current Market Outlook 2014-2033. Here, the published forecasting data are compared to the data produced by ATAF under identical assumptions of the future.

The validation studies conducted here generally confirm the functionality of ATAF and particularly of the FSDM and the FCECT besides the limitations inherent in these tools. The inability of the FSDM to simulate temporary aircraft storage, to model a dynamic evolution of the aircraft utilization characteristics, and to flexibly adapt the simulated aircraft retirement process to the current situation of aircraft demand were identified as major model limitations. If simulations of the long-term future are conducted, these limitations may lead to distorted results with particular regard to the calculation of the overall fleet size and transport supply delivered. Accordingly, a work-around method has been elaborated that allows an a-posteriori adaptation of the raw simulation data in order to mitigate these distortion effects.

In this thesis, ATAF is applied in two ways. At first, the feasibility of the milestones for environmental impact mitigation of aviation is evaluated from a technological point of view. That is, assumptions are made regarding the introduction and performance of next-generation aircraft such as the Airbus A320neo and the Boeing 777-X in order to analyze the fleet performance under multiple future scenarios and to evaluate to share of contribution of these next-generation types towards reaching aviation's environmental goals. Secondly, ATAF is applied to assess the global impact of the Propcraft P-420 high-capacity transport, a newly developed aircraft concept that is intended for short-range operations.

9.2 Major findings and conclusions

In the context of the technological feasibility of the future environmental goals of aviation mentioned above, it was found that the next-generation aircraft considered in this thesis do actually have a positive impact on the development of the fleet-wide fuel burn and CO_2 performance. Relative to a hypothetical no-action scenario in which these aircraft are not integrated into the fleet, they may increase the gain in fleet-wide CO_2 performance from the present until 2050 by up to 0.8% annually and simultaneously mitigate the growth in total fuel consumption by the same value. These numbers can be found for an average global air traffic growth of 5% p.a. (Boeing CMO 2014) and when assuming that the world's most important aircraft manufacturers would switch over their production processes immediately to the production of next-generation aircraft while no longer producing current-state types.[149] In a more realistic aircraft-production scenario, the impact of the next-generation aircraft is lower and yields values between 0.3 and 0.4% p.a. Yet, an aircraft and technology generation succeeding the next-generation aircraft (not considered here) may very well lead to a further fuel efficiency improvement of the global fleet.

Nevertheless, the actual strength of this impact strongly depends on the question of how quickly aircraft manufacturers can switch over their production processes from building current aircraft types to the next-generation types and how intensely airlines will then operate the new types. Moreover, the studies conducted here revealed that the three environmental goals cannot be reached solely through an integration of the next-generation aircraft. While the first goal appears to be feasible to a certain extent, goals 2 and 3 seem highly challenging. Thus, further measures besides integrating new aircraft technologies must be taken under any circumstances.

Regarding the assessment of the P-420 concept, the corresponding assessment studies revealed a positive impact of this particular aircraft on the fleet-wide fuel and CO_2 performance characteristics. With an assumed entry into service in 2025, the P-420 can decrease the total fuel demand of the global fleet in 2050 by 0.8% with a maximum possible value of 5% when assuming the immediate-production-switch-over scenario mentioned above. In this scenario, the P-420 can reduce the annual increase in fuel demand of the world fleet from 2025 to 2050 by 0.2% p.a. at maximum. This shows the significant potentials that the P-

---

[149] Under this assumption, the production rates of the next-generation types are only constrained by the 'total production capacities.' In reality, aircraft manufacturers would produce both current-state and next-generation aircraft in parallel for a certain period of time, as they would require this period to build up and enlarge the production facilities for the next-generation types (→Sections 4.2.6 and 4.3.4.6).

420 possesses in terms of helping commercial aviation achieve its environmental goals in the long term.

9.3 Recommendations for future work

Building ATAF should be considered as a first step towards the development of a comprehensive methodology to assess the performance of the global air transport system and its adverse impact on the environment. Therefore, various aspects of ATAF should be improved and further capabilities added to increase the functionality and applicability of the model. In this respect, a selection of recommendations for future work is given in the following.

In general, highest potential of improvement can be found in the FSDM and FCECT of ATAF, while the scenario-building part relies on methods and techniques that have already been tested and advanced towards a level that appears sufficiently high for the use cases of ATAF. Here, a further advancement of the techniques related to the development of both quantitative and quantified scenarios appears most suitable, though.

Regarding the FSDM and especially its current modeling limitations, future work should definitely focus on reducing these limitations. A first step in this respect may concentrate on an integration of mathematical functions that help simulate a dynamic evolution of the aircraft utilization characteristics and load factors. As was shown in Chapters 7 and 8, the current limitations of the FSDM necessitate an a-posteriori adaptation of the raw simulation data in order to obtain results that are more realistic. Therefore, an improvement of the FSDM in this respect may quickly lead to much more accurate fleet simulations.

The same is true in terms of the current modeling of aircraft retirement that is purely based on a statistical approach. Hence, it cannot take into account a situation of a currently prevailing transport demand being at a high level where airlines would not retire an aircraft even if this aircraft was relatively old. Integrating more flexible retirement functions into the FSDM would allow simulating strong fluctuations in air traffic demand from one year to another with greater precision. More complicated but equally efficient would be an integration of the modeling of temporary aircraft storages that is not supported by the current version of the FSDM either.

Finally, introducing functions that could model a time-dependent technical improvement of all simulated aircraft types would further enhance the accuracy of the FSDM (e.g., modeling of winglet integration or integration of advanced engines for current-state aircraft types).

A more fundamental step towards improving the overall accuracy of the FSDM would be to integrate airline competition into the model. Simulating not only one global airline, as done currently, but considering multiple airlines with different business and profit models would allow investigations of the relationship between airline economics and the environmental impact of aviation. This indeed represents a very appealing area of research that has not been addressed sufficiently in the literature so far.

Finally, advancing the simulated air routes network and increasing the number of aircraft clusters that the FSDM can currently handle would of course increase its accuracy further. Yet, the amount of work required here must be considered rather high relative to the gain in accuracy achieved. In this respect, the validation of the model presented in Chapter 6 has already proven a sufficient degree of accuracy of the current model.

As far as the FCECT is concerned, primary focus of functionality improvements should be on the integration of next-generation aircraft and especially their engine types, as they cannot be modeled currently due to a lack of adequate emissions data. While in the current version of the FCECT, the fuel burn and the corresponding emissions of CO_2 and water vapor of the next-generation aircraft can be predicted already, other exhaust gas emissions like NO_x and soot cannot be determined. The BADA APM itself is considered not to require significant improvement efforts, though, as the validation studies conducted in this thesis already revealed a sufficiently high degree of modeling accuracy.

References

Abara, J. (1989), "Applying integer linear programming to the fleet assignment problem," *Interfaces*, Vol. 19 No. 4, pp. 20–28.

Airbus S.A.S. (2011), *Global market forecast 2011-2030: Delivering the future*, Blagnac, France.

Airbus S.A.S. (2014a), *Global market forecast 2014-2033: Flying on demand*, Blagnac, France.

Airbus S.A.S. (2014b), "Orders & deliveries viewer. Excel files," available at: http://www.airbus.com/company/market/orders-deliveries/ (accessed 13 May 2014).

Amer, M., Daim, T.U., and Jetter, A. (2013), "A review of scenario planning," *Futures*, Vol. 46, pp. 23–40.

Apffelstaedt, A. (2009), *Identifying CO2 reducing aircraft technologies and estimating their impact on global emissions*, Diploma Thesis, Department of Automotive Technology and Aircraft Construction, Hamburg University of Applied Sciences, Hamburg, Germany.

Arnold, C. (2012), *Clustering ziviler Flugzeuge: Bewertung möglicher Methoden und Anwendung [in German]*, Diploma Thesis (Report No. LS-DA 12/05), Institute of Aircraft Design, Technical University of Munich, Garching, Germany.

ASCEND Flightglobal Consultancy (2011), *ASCEND online fleets: Online database product obtained from 2008 to 2011*, Reed Business Information Ltd.

Assenheimer, C. (2012), *Entwicklung eines Evolutionsmodelles zur Beschreibung zukünftiger Flugzeugbetriebsarten und Entwicklungsmöglichkeiten von Flotten [in German]*, Diploma Thesis (Report No. LS-DA 12/09), Institute of Aircraft Design, Technical University of Munich, Garching, Germany.

ATAG (2011), *The right flightpath to reduce aviation emissions*, Air Transport Action Group, Durban, South Africa.

BAA (2003), *Airport water quality strategy 2003-2008*, Lickfield, East Susses, UK.

Baughcum, S.L., Tritz, Terrance, G., Henderson, Stephen, C., and Pickett, D.C. (1996), *Scheduled civil aircraft emission inventories for 1992: Database development and analysis*, NASA Contractor Report 4700, Langley Research Center, Hampton, Virginia, USA.

Bazargan, M. (2004), *Airline operations and scheduling*, Ashgate, Aldershot, Hants, UK, Burlington, Vermont, USA.

Belobaba, P. (2009), "The airline planning process," in Belobaba, P., Odoni, A.R., and Barnhart, C. (Eds.), *The global airline industry*, *Aerospace series*, Wiley, Chichester, UK, pp. 153–181.

Berghof, R., Schmitt, A., Middel, J., Eyers, C., Hancox, R., Gruebler, A., and Hepting, M. (2005), *Consave 2050 final technical report: Constrained scenarios on aviation and emissions*, Cologne, Germany.

Boeing Commercial Airplanes (2011), "Growth in airport noise restrictions," available at: http://www.boeing.com/assets/pdf/commercial/noise/restrictions.pdf (accessed 10 February 2015).

Boeing Commercial Airplanes (2013), *Enhancing airplane availability: Airline's most valuable asset, Aviation Week MRO Americas*, Atlanta, Georgia, USA, available at:

http://events.aviationweek.com/html/mro13/April%2016_B212_1100am_Ali.pdf (accessed 17 March 2015).

Boeing Commercial Airplanes (2014a), *Current market outlook 2014-2033*, Seattle, Washington, USA.

Boeing Commercial Airplanes (2014b), "Fact sheet. Boeing 787-9 Dreamliner," available at: http://www.boeing.com/farnborough2014/pdf/BCA/fct%20-787-9.pdf (accessed 4 March 2014).

Boeing Commercial Airplanes (2014c), *World air cargo forecast 2014-2015*, Seattle, Washington, USA.

Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., and Finnveden, G. (2006), "Scenario types and techniques: Towards a user's guide," *Futures*, Vol. 38 No. 7, pp. 723–739.

Bradfield, R., Wright, G., Burt, G., Cairns, G., and van der Heijden, K. (2005), "The origins and evolution of scenario techniques in long range business planning," *Futures*, Vol. 37 No. 8, pp. 795–812.

Bräunling, W. (2009), *Flugzeugtriebwerke: Grundlagen, Aero-Thermodynamik, ideale und reale Kreisprozesse, thermische Turbomaschinen, Komponenten, Emissionen und Systeme [in German]*, 3rd Edition, Springer, Berlin, Heidelberg, Germany.

Bretherton, F., Cattle, H., Houghton, J.T., Mitchell, J. F. B., Randall, D., Roeckner, E., Woods, J.D., and Yamanouchi, T. (1990), "Processes and modelling," in Houghton, J.T., Jenkins, G.J., and Ephraumes, J.J. (Eds.), *Climate change: The IPCC scientific assessment*, Cambridge University Press, Cambridge, UK.

Brockmann, K. (2012), "Futures analysis cooperation tool in the German armed forces," *Foreknowledge*, No. 4, pp. 6–7.

Bruce-Briggs, B. (2005), *Supergenius: The mega-worlds of Herman Kahn*, Lulu.com, Raleigh, North Carolina, USA.

CAEP (2015), "CAEP description," available at: http://www.icao.int/environmental-protection/pages/CAEP.aspx (accessed 9 March 2015).

Case, M., Haack, J., Kim, M., Kulkarni, M., Mohr, D., and Temimi, H. (2007), *High dimensional, nonlinear, non-convex optimization problems in the area of aircraft and vehicle design*, University of Minnesota, College of Science and Engineering, Institute for Mathematics and its Applications, Minneapolis, Minnesota, USA.

Chandrasekaran, N. and Guha, A. (2012), "Study of prediction methods for NOx emission from turbofan engines," *Journal of Propulsion and Power*, Vol. 28 No. 1, pp. 170–180.

Chen, K., Jarboe, K., and Wolfe, J. (1981), "Long-range scenario construction for technology assessment," *Technological Forecasting and Social Change*, Vol. 20 No. 1, pp. 27–40.

Chen, K. and Kung, S.-H. (1984), "Synthesis of qualitative and quantitative approaches to long-range forecasting," *Technological Forecasting and Social Change*, Vol. 26 No. 3, pp. 255–266.

Clark, P. (2007), *Buying the big jets: Fleet planning for airlines,* 2nd Edition, Ashgate Publishing, Aldershot, Hampshire, England, Burlington, Vermont, USA.

Cooke, R.M. (1991), *Experts in uncertainty: Opinion and subjective probability in science*, Oxford University Press, New York, USA.

Dickson, N. (2013), *ICAO noise standards, ICAO Symposium on Aviation and Climate Change ("Destination Green")*, Montreal, Quebec, Canada.

DLR (2009), "The 4D-calculation model FATE," available at: http://www.dlr.de/fw/en/Portaldata/42/Resources/dokumente/PDF/FATE-engl.pdf (accessed 10 March 2015).

DoD (2001), *Systems engineering fundamentals*, Defense Acquisition University Press, Fort Belvoir, Virginia, USA.

DuBois, D. and Paynter, G.C. (2006), “'Fuel Flow Method 2' for estimating aircraft emissions,” *SAE Technical Paper Series*, No. 2006-01-1987.

Durance, P. and Godet, M. (2010), “Scenario building: Uses and abuses,” *Technological Forecasting and Social Change*, Vol. 77 No. 9, pp. 1488–1492.

EASA (2015), “ICAO Aircraft engine emissions databank,” available at: http://easa.europa.eu/document-library/icao-aircraft-engine-emissions-databank (accessed 6 March 2015).

Egelhofer, R. (2008), “Aircraft design driven by climate change,” Department of Aerospace Engineering, Technical University of Munich, Munich, Germany, 2008.

EIA (2015), “International energy statistics,” available at: http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm (accessed 11 February 2015).

Engelke, C. (2014), *Flottenplanung und -einsatz: Untersuchungen zur Weiterentwicklung eines dynamischen Flottenmodells für Leistungsanalysen der Weltflotte [in German]*, Bachelor's Thesis (Report No. LS-BA 14/05), Institute of Aircraft Design, Technical University of Munich, Garching, Germany.

Engelke, C. (2015), *Erweiterung eines Programmes zur Flugleistungsrechnung für die emissionsbezogene Bewertung moderner Flugzeugkonzepte und -technologien [in German]*, Semester Thesis (Report No. LS-SA 15/02, confidential), Institute of Aircraft Design, Technical University of Munich, Garching, Germany.

EPA (2014), “Health effects of air pollution,” available at: http://www.epa.gov/region07/air/quality/health.htm (accessed 10 February 2015).

Eurocontrol (2010), *Eurocontrol long-term forecast: IFR flight movements 2010-2030*, Document Identifier CND/STATFOR Doc415, Eurocontrol Publication, Brussels, Belgium.

Eurocontrol (2015), “Base of aircraft data (BADA),” available at: https://www.eurocontrol.int/services/bada (accessed 6 March 2015).

European Union (2011), *Flightpath 2050 - Europe's vision for aviation: Maintaining global leadership and serving society's needs*, Report of the High Level Group on Aviation Research, Publications Office of the European Union, Luxembourg.

Eyers, C., Norman, P., Middel, J., Plohr, M., Michot, S., Atkinson, K., and Christou, R.A. (2004), *AERO2k global aviation emissions inventories for 2002 and 2025*, Report No. QINETIQ/04/01113, QinetiQ Ltd., Farnborough, Hampshire, UK.

FAA (2005), *Aviation and emissions: A primer*, Washington, DC, USA.

FAA (2010a), *FAA aerospace forecast: Fiscal year 2011-2031*, Washington, DC, USA.

FAA (2010b), “System for assessing aviation's global emissions (SAGE) incorporated into the aviation environmental design tool (AEDT),” available at: http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/sage/ (accessed 9 March 2015).

Faber, J., Greenwood, D., Lee, D., Mann, M., Mendes de Leon, Pablo, Nelissen, D., Owen, B., Ralph, M., Tilston, J., van Velzen, A., and van de Vreede, Gerdien (2008), *Lower NOx at higher altitudes: Policies to reduce the climate impact of aviation NOx emission*, CE Delft, Publication number 08.7536.32, Delft, The Netherlands.

FESG (2008a), *FESG CAEP/8 traffic and fleet forecasts*, Report No. CAEP-SG/20082-IP/02, ICAO Information Paper, Seattle, Washington, USA.

FESG (2008b), *FESG Forecast Task Group Progress Report*, Seattle 11-06-2008, Montreal, Canada.

Filippone, A. (2006), *Flight performance of fixed and rotary wing aircraft, Elsevier aerospace engineering series*, Butterworth-Heinemann, Oxford, UK.

Flightglobal (2008), *Aircraft Analytical System (ACAS) Version 2.5*, Reed Business Information Ltd.

FOI (2015), “FOI's confidential database for turboprop engine emissions,” available at: http://www.foi.se/en/Our-Knowledge/Aeronautics/FOIs-Confidential-database-for-Turboprop-Engine-Emissions/ (accessed 7 March 2015).

Foster, M. (1993), “Scenario planning for small businesses,” *Long Range Planning*, Vol. 26 No. 1, pp. 123–129.

Franco, L.A., Meadows, M., and Armstrong, S.J. (2013), “Exploring individual differences in scenario planning workshops: A cognitive style framework,” *Technological Forecasting and Social Change*, Vol. 80 No. 4, pp. 723–734.

GAMS (2014), “Welcome to the GAMS Home Page,” available at: http://www.gams.com/ (accessed 9 March 2015).

Gardner, R.M. (Ed.) (1998), *ANCAT/EC aircraft emissions inventory for 1991/92 and 2015*, Final Report EUR-18179, Defence Evaluation and Research Agency, Farnborough, UK.

Gausemeier, J., Fink, A., and Schlake, O. (1998), “Scenario management: An approach to develop future potentials,” *Technological Forecasting and Social Change*, Vol. 59 No. 2, pp. 111–130.

Georgantzas, N.C. and Acar, W. (1995), *Scenario-driven planning: Learning to manage strategic uncertainty*, Quorum Books, Westport, Connecticut, USA.

Givoni, M. and Rietveld, P. (2006), *Choice of aircraft size: Explanations and implications*, Tinbergen Institute Discussion Paper No. TI 2006-113/3, available at: http://papers.tinbergen.nl/06113.pdf (accessed 17 March 2015).

Go, K. and Carroll, J.M. (2004), “The blind men and the elephant: Views of scenario-based system design,” *interactions*, Vol. 11 No. 6, pp. 44–53.

Godet, M. (2000a), “Forefront: How to be rigorous with scenario planning,” *foresight*, Vol. 2 No. 1, pp. 5–9.

Godet, M. (2000b), “The art of scenarios and strategic planning,” *Technological Forecasting and Social Change*, Vol. 65 No. 1, pp. 3–22.

Godet, M. (2006), *Creating futures: Scenario planning as a strategic management tool,* 2nd Edition, Economica, London.

Gordon, T.J. (2003a), “Cross-impact Analysis,” in Glenn, J.C. and Gordon, T.J. (Eds.), *Futures research methodology (Version 2.0)*, American Council for the United Nations University, the Millennium Project, Washington, DC, USA.

Gordon, T.J. (2003b), “Trend impact analysis,” in Glenn, J.C. and Gordon, T.J. (Eds.), *Futures research methodology (Version 2.0)*, American Council for the United Nations University, the Millennium Project, Washington, DC, USA.

Hadaller, O.J. and Momenthy, A.M. (1989), *The characteristics of future fuels, Boeing publication D6-54940*, Seattle, Washington, USA.

Hane, C.A., Barnhart, C., Johnson, E.L., Marsten, R.E., Nemhauser, G.L., and Sigismondi, G. (1995), “The fleet assignment problem: Solving a large-scale integer program,” *Mathematical Programming*, Vol. 70 No. 1-3, pp. 211–232.

Haskins, C. (2006), *Systems engineering handbook: A guide for system life cycle processes and activities*, INCOSE-TP-2003-002-03, Version 3, International Council on Systems Engineering.

Hirsch, S., Burggraf, P., and Daheim, C. (2013), “Scenario planning with integrated quantification – managing uncertainty in corporate strategy building,” *foresight*, Vol. 15 No. 5, pp. 363–374.

Hull, E., Jackson, K., and Dick, J. (2011), *Requirements engineering,* 3rd Edition, Springer, London, UK.

Huss, W.R. and Honton, E.J. (1987a), “Alternative methods for developing business scenarios,” *Technological Forecasting and Social Change*, Vol. 31 No. 3, pp. 219–238.

Huss, W.R. and Honton, E.J. (1987b), "Scenario planning—What style should you use?," *Long Range Planning*, Vol. 20 No. 4, pp. 21–29.

IATA (2009), *A global approach to reducing aviation emissions: First stop: Carbon-neutral growth from 2020*, International Air Transport Association, Montreal, Canada.

IATA (2014), *Annual review 2014*, Montreal, Canada.

IBM (2015), "CPLEX optimizer," available at: http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/ (accessed 9 March 2015).

ICAO (2008), *Annex 16 to the convention on international civil aviation: Environmental protection*, Volume II - Aircraft engine emissions, 3rd Edition (July 2008), International Civil Aviation Organization, Montreal, Canada.

ICAO (2013), *Environmental report 2013: Aviation and climate change*, International Civil Aviation Organization, Montreal, Canada.

ICAO (2014), *Air transport yearly monitor 2013*, Montreal, Canada.

IEEE (1990), *IEEE Standard glossary of software engineering terminology* No. 610.12-1990, New York, USA.

IEEE (1996), *IEEE Guide for developing system requirements specifications* No. 1233-1996, New York, USA.

iMA (2004), *Ausbau Flughafen Frankfurt Main: Unterlagen zum Planfeststellungsverfahren*, Band B 11.18.1 Festlegung von flugzeugspezifischen Emissionsfaktoren [in German], iMA Consult GmbH, Wiesbaden, Germany.

IPCC (2015), "Organization," available at: http://www.ipcc.ch/organization/organization.shtml (accessed 9 March 2015).

Ittel, J. (2014), *Developing a software tool for comprehensive flight performance and mission analyses in the context of the assessment of a novel turboprop transport aircraft concept*, Master's Thesis (Report No. LS-MA 14/06, confidential), Institute of Aircraft Design, Technical University of Munich, Garching, Germany.

Iwanizki, M. (2013), *Vorentwurf einer schweren, Propellerturbinen-getriebenen Verkehrsflugzeugkonfiguration für den Einsatz auf hochfrequentierten Kurz- und Mittelstrecken [in German]*, Master's Thesis (Report No. LS-MA 13/02), Institute of Aircraft Design, Technical University of Munich, Garching, Germany.

Iwanizki, M., Randt, N.P., and Sartorius, S. (2014), "Preliminary design of a heavy short- and medium-haul turboprop-powered passenger aircraft," paper presented at the 52nd Aerospace Sciences Meeting, 13 - 17 January 2014, National Harbor, Maryland, USA.

Jacobs, T.L., Garrow, L.A., Lohatepanont, M., Koppelman, F.S., Coldren, G.M., and Purnomo, H. (2012), "Airline planning and schedule development," in Barnhart, C. and Smith, B. (Eds.), *Quantitative problem solving methods in the airline industry: A modeling methodology handbook*, Springer, New York, USA, pp. 35–99.

JADC (2014), *Worldwide market forecast 2014-2033*, Japan Aircraft Development Corporation, Tokyo, Japan.

Jimenez, H., Pfaender, H., and Mavris, D. (2012), "Fuel burn and CO2 system-wide assessment of environmentally responsible aviation technologies," *Journal of Aircraft*, Vol. 49 No. 6, pp. 1913–1930.

Jungermann, H. and Thuring, M. (1987), "The use of mental models for generating scenarios," in Wright, G. and Ayton, P. (Eds.), *Judgmental forecasting*, Wiley, Chichester, UK, New York, USA.

Kahn, H. and Wiener, A.J. (1967), *The year 2000: A framework for speculation on the next thirty-three years*, Macmillian, New York, USA.

Kalwar, D. (2015), *Integration of turbofan engines into the preliminary design of a high-capacity short- and medium-haul passenger aircraft and fuel efficiency analysis with a further developed* *parametric aircraft design software*, Master's Thesis (Report No. LS-MA 15/02), Institute of Aircraft Design, Technical University of Munich, Garching, Germany.

Kaufman, L. and Rousseeuw, P.J. (2005), *Finding groups in data: An introduction to cluster analysis*, Wiley, Hoboken, New Jersey, USA.

Kenway, G., Henderson, R., Hicken, J., Kuntawala, N., Zingg, D., Martins, J., and McKeand, R. (2010), "Reducing aviation's environmental impact through large aircraft for short ranges," paper presented at the 48th AIAA Aerospace Sciences Meeting, 04 - 07 January 2010, Orlando, Florida, USA.

KGAL Group (2015), *Aircraft leasing: A promising investment market for institutional investors*, Gruenwald, Germany.

Kim, B.Y., Fleming, G.G., Balasubramanian, S., Mahlwitz, A., Lee, J.J., Waitz, I.A., Klima, K., Locke, M., Holsclaw, C.A., Morales, A., McQueen, E., and Gillette, W. (2005), *System for assessing aviation's global emissions (SAGE), Version 1.5: Global aviation emissions inventories for 2000 through 2004*, FAA-EE-2005-02, Federal Aviation Administration, Office of Environment and Energy, Washington, DC, USA.

Kim, B.Y., Fleming, G.G., Lee, J.J., Waitz, I.A., Clarke, J.-P., Balasubramanian, S., Malwitz, A., Klima, K., Locke, M., Holsclaw, C.A., Maurice, L.Q., and Gupta, M.L. (2007), "System for assessing aviation's global emissions (SAGE). Part 1: Model description and inventory results," *Transportation Research Part D: Transport and Environment*, Vol. 12 No. 5, pp. 325–346.

Kirby, M. and Mavris, D. (1999), "Forecasting technology uncertainty in preliminary aircraft design," paper presented at the 4th World Aviation Congress and Exposition, 19 - 21 October 1999, San Francisco, California, USA, available at: https://smartech.gatech.edu/bitstream/handle/1853/6325/AIAA-99-01-5631.pdf (accessed 12 March 2015).

Knipschild, P. (1977), "Medical effects of aircraft noise: Review and literature," *International Archives of Occupational and Environmental Health*, Vol. 40 No. 3, pp. 201–204.

Koff, B.L. (2004), "Gas turbine technology evolution: a designer's perspective," *Journal of Propulsion and Power*, Vol. 20 No. 4, pp. 577–595.

Koopmann, J., Ahearn, M., Boeker, E., Hansen, A., Hwang, S., Mahlwitz, A., Senzig, D., Solman, G.B., Dinges, E., Yaworski, M., Hall, C., and Morre, J. (2014), *Aviation environmental design tool (AEDT): Technical manual*, Version 2a, Federal Aviation Administration, Office of Environment and Energy, Washington, DC, USA.

Kügler, M.E. (2014), *Development of a parametric aircraft design tool for design iterations of a high-capacity turboprop transport aircraft*, Master's Thesis (Report No. LS-MA 14/10), Institute of Aircraft Design, Technical University of Munich, Garching, Germany.

Kügler, M.E. and Randt, N.P. (2015), "Development and application of a parametric design tool for design iterations of large turboprop aircraft," paper presented at the 15th AIAA Aviation Technology, Integration, and Operations Conference, 22 - 26 June 2015, Dallas, Texas, USA.

Kuhlmann, A., Phleps, P., and Eelman, S. (2009), "An approach for quantification of qualitative scenarios applied to alternative aircraft fuels," paper presented at the CEAS 2009 Conference, 26 - 29 October 2009, Manchester, UK.

Lee, D., Fahey, D.W., Forster, P.M., Newton, P.J., Wit, R.C., Lim, L.L., Owen, B., and Sausen, R. (2009), "Aviation and global climate change in the 21st century," *Atmospheric Environment*, Vol. 43 No. 22-23, pp. 3520–3537.

Lee, D., Pitari, G., Grewe, V., Gierens, K., Penner, J., Petzold, A., Prather, M., Schumann, U., Bais, A., and Berntsen, T. (2010), "Transport impacts on atmosphere and climate: Aviation," *Atmospheric Environment*, Vol. 44 No. 37, pp. 4678–4734.

Linneman, R.E. and Klein, H.E. (1983), "The use of multiple scenarios by U.S. industrial companies: A comparison study, 1977–1981," *Long Range Planning*, Vol. 16 No. 6, pp. 94–101.

Lissys Ltd. (2015), "The things that Piano is used for," available at: http://www.piano.aero/ (accessed 9 March 2015).

Lister, D.H., Norman, D., Lecht, M., Park, K., Penanhoat, O., Plaisance, C., Renger, K., and Dunker, R. (2003), *Development of the technical basis for a new emissions parameter covering the whole aircraft operation: NEPAIR: Final technical report*, NEPAIR/WP4/WPR/01.

Liu, J.S. and Chen, R. (1998), "Sequential monte carlo methods for dynamics systems," *Journal of the American Statistical Association*, Vol. 93 No. 443, pp. 1032–1044.

Malaska, P., Malmivirta, M., Meristö, T., and Hansén, S.-O. (1984), "Scenarios in Europe - Who uses them and why?," *Long Range Planning*, Vol. 17 No. 5, pp. 45–49.

Marais, K. and Waitz, I.A. (2009), "Air transport and the environment," in Belobaba, P., Odoni, A.R., and Barnhart, C. (Eds.), *The global airline industry*, *Aerospace series*, Wiley, Chichester, UK.

Martelli, A. (2001), "Scenario building and scenario planning: state of the art and prospects of evolution," *Futures Research Quarterly*, Summer 2001.

Mathworks (2014), *MATLAB® Help (MATLAB® R2014b): fmincon*, The Mathworks, Inc., Natick, Massachusetts, USA.

McDonnell Douglas Aircraft Company (1981), *Airline fleet planning*, Unpublished Presentation, Long Beach, California, USA.

Mensen, H. (2007), *Planung, Anlage und Betrieb von Flugplätzen [in German]*, Springer, Berlin, Germany.

Millett, S.M. (2003), "The future of scenarios: challenges and opportunities," *Strategy & Leadership*, Vol. 31 No. 2, pp. 16–24.

MITRE (2015), "Corporate overview," available at: http://www.mitre.org/about/corporate-overview (accessed 9 March 2015).

Mohring, H. (1976), *Transportation economics*, Ballinger Publishing Company, Cambridge, Massachusetts, USA.

Morrell, P. and Dray, L. (2009), *Environmental aspects of fleet turnover, retirement and life cycle: Final report*, Omega, Cranfield, Cambridge, UK.

MTU (2014), "TP400-D6 turboprop engine. The innovative power," available at: http://www.mtu.de/fileadmin/DE/2_Triebwerke/2_Militaerische_Triebwerke/3_Transport_Aircraft/TP400-D6/TP400-D6_Leaflet.pdf (accessed 28 May 2015).

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and Zhang, H. (2013), "Anthropogenic and natural radiative forcing," in Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Naeuls, A., Xia, Y., Bex, V., and Midgley, P.M. (Eds.), *Climate change 2013: The physical basis: Contribution of Working Group I to the fifth assessment report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK.

Nuic, A. (2014), *User manual for the Base of Aircraft Data (BADA): Revision 3.12*, EEC Technical/Scientific Report No. 14/04/24-44, EUROCONTROL Experimental Center, Brétigny-sur-Orge, France.

Nuic, A., Poles, D., and Mouillet, V. (2010), "BADA: An advanced aircraft performance model for present and future ATM systems," *International Journal of Adaptive Control and Signal Processing*, Vol. 24 No. 10, pp. 850–866.

OAG (2008), *OAG (Official Airline Guide): Database of scheduled flights (November 2007 - October 2008)*, OAG Aviation Worldwide Limited.

O'Brien, F.A. (2004), "Scenario planning - lessons for practice from teaching and learning," *European Journal of Operational Research*, Vol. 152 No. 3, pp. 709–722.

O'Brien, F.A. and Meadows, M. (2013), "Scenario orientation and use to support strategy development," *Technological Forecasting and Social Change*, Vol. 80 No. 4, pp. 643–656.

O'Brien, F.A., Meadows, M., and Murtland, M. (2007), "Creating and using scenarios - Exploring alternative possible futures and their impact on strategic decisions," in O'Brien, F.A. and Dyson, R.G. (Eds.), *Supporting strategy: Frameworks, methods and models*, Wiley, Chichester, UK, Hoboken, New Jersey, USA.

Oezer, S. (2013), *Weiterentwicklung eines auf dem Total-Energy-Modell basierenden Programms für die Flugleistungs- und Missionsrechnung [in German]*, Semester Thesis (Report No. LS-SA 13/03, confidential), Institute of Aircraft Design, Technical University of Munich, Garching, Germany.

Olsen, S.C., Wuebbles, D.J., and Owen, B. (2013), "Comparison of global 3-D aviation emissions datasets," *Atmospheric Chemistry and Physics*, Vol. 13 No. 1, pp. 429–441.

O'Neill, J. (2001), "Building better global economic BRICs," *Goldman Sachs Economic Research Group Paper*, No. 66.

O'Neill, J. (2005), "How solid are the BRICs?," *Goldman Sachs Economic Research Group Paper*, No. 134.

Pai, V. (2010), "On the factors that affect airline flight frequency and aircraft size," *Journal of Air Transport Management*, Vol. 16 No. 4, pp. 169–177.

Penner, J., Lister, D.H., Griggs, D.J., Dokken, D.J., and McFarland, M. (Eds.) (1999), *Aviation and the global atmosphere: A special report of IPCC working groups I and III*, Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Pepper, C.B., Nascarella, M.A., and Kendall, R.J. (2003), "A review of the effects of aircraft noise on wildlife and humans, current control mechanisms, and the need for further study," *Environmental management*, Vol. 32 No. 4, pp. 418–432.

Pfaender, J.H. (2006), *Competitive assessment of aerospace systems using system dynamics*, Dissertation Thesis, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA.

Pfaender, J.H. and Mavris, D. (2006), "Scenario-based design competitiveness exploration with system dynamics," paper presented at the 25th Congress of the International Council of the Aeronautical Sciences, 3 - 8 September 2006, Hamburg, Germany.

Phleps, P. (2011), *Szenariobasierte Methode zur ökonomischen Lärm- und Emissionsbewertung zukünftiger Flugzeugkonzepte [in German]*, Dr. Hut, Munich, Germany.

Phleps, P. and Hornung, M. (2013), "Noise and emission targeted economic trade-off for next generation single-aisle aircraft," *Journal of Air Transport Management*, Vol. 26, pp. 14–19.

Pillkahn, U. (2008), *Using trends and scenarios as tools for strategy development: Shaping the future of your enterprise,* 1st Edition, Publicis Corporate Publishing, Erlangen, Germany.

Pulles, J. (2002), *AERO: Aviation emissions and evaluation of reduction options*, Main Report (Parts I and II), Directorate General for Civil Aviation, Ministry of Transport, Public Works and Watermanagement of the Kingdom of the Netherlands, The Hague, The Netherlands.

Rabe, M., Spiekermann, S., and Wenzel, S. (2008), *Verifikation und Validierung für die Simulation in Produktion und Logistik: Vorgehensmodelle und Techniken [in German]*, Springer, Berlin, Heidelberg, Germany.

Rachner, M. (1998), *Die Stoffeigenschaften von Kerosin Jet A-1 [in German]*, Research report no. 98-01, Institute of Propulsion Technology, Deutsches Zentrum für Luft- und Raumfahrt e.V. (German national aeronautics and space research center), Cologne, Germany.

Ramaswamy, V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajima, T., Shi, G.Y., and Solomon, S. (2001), "Radiative forcing of climate change," in Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C.A. (Eds.), *Climate change 2001: The scientific basis: Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK.

Randt, N.P. (2014), "Perspectives of turboprop aircraft: A stakeholder-oriented evaluation using scenario planning," paper presented at the 63. Deutscher Luft- und Raumfahrtkongress (63rd German Aerospace Congress), 16 - 18 September 2014, Augsburg, Germany.

Randt, N.P., Jeßberger, C., Plötner, K.O., and Becker, A. (2015), "Air traffic growth, energy, and the environment 2040. Drivers, challenges, and opportunities for aviation," *International Journal of Aviation Management*, Vol. 2 No. 3/4, pp. 144–166.

Randt, N.P. and Wolf, S. (2014), "Automation in future air transport: A scenario-based approach to the definitions of operational requirements," paper presented at the 29th Congress of the International Council of the Aeronautical Sciences (ICAS), 7 - 12 September 2014, St. Petersburg, Russia.

Raubitschek, R. (1988), "Multiple scenario analysis and business planning," in Lamb, R. and Shrivastava, P. (Eds.), *Advances in strategic management: Vol. 5*, JAI Press Inc., London, UK.

Raymer, D.P. (2012), *Aircraft design: A conceptual approach, AIAA education series,* 5th Edition, American Institute of Aeronautics and Astronautics, Reston, Virginia, USA.

Reibnitz, U.v. (1988), *Scenario techniques*, McGraw-Hill, Hamburg, Germany.

Reichmuth, J., Ehmer, H., Berster, P., Bischoff, G., Grimme, W., Grunewald, E., and Maertens, S. (2008), *Analyses of the European air transport market: Airline business models*, Topical Report, Release 1.01, Institute of Air Transport and Airport Research, Deutsches Zentrum für Luft- und Raumfahrt e.V. (German national aeronautics and space research center), Cologne, Germany.

Reynolds, T.G. (2009), "Development of flight inefficiency metrics for environmental performance assessment of ATM," paper presented at the 8th USA/Europe Air Traffic Management Research and Development Seminar, 29 June - 2 July 2009, Napa, California, USA, available at: http://www.atmseminar.org/seminarContent/seminar8/papers/p_122_EI.pdf (accessed 8 April 2015).

Rowe, M. (2010), "Boeing Dreamliner: the promise of greener flying," available at: http://www.telegraph.co.uk/travel/hubs/greentravel/7025139/Boeing-Dreamliner-the-promise-of-greener-flying.html (accessed 13 February 2015).

Saritas, O. and Nugroho, Y. (2012), "Mapping issues and envisaging futures: An evolutionary scenario approach," *Technological Forecasting and Social Change*, Vol. 79 No. 3, pp. 509–529.

Scapolo, F. (2005), "New horizons and challenges for future-oriented technology analysis. The 2004 EU-US seminar," *Technological Forecasting and Social Change*, Vol. 72 No. 9, pp. 1059–1063.

Schäfer, M. (2006), *Methodologies for aviation emission calculation: A comparison of alternative approaches towards 4D global inventories*, Diploma Thesis, Institute of Aeronautics and Astronautics, Technical University of Berlin, Berlin, Germany.

Schäfer, M. (2012), *Development of a forecast model for global air traffic emissions*, Research report no. 2012-08, Institute of Propulsion Technology, Deutsches Zentrum für Luft- und Raumfahrt e.V. (German national aeronautics and space research center), Cologne, Germany.

Schmitt, A. and Brunner, B. (1997), "Emissions from aviation and their development over time," DLR-Mitteilung 97-04, in Schumann, U., Chlond, A., Ebel, A., Kärcher, B., and Pak, H. (Eds.), *Pollutants from air traffic: Results of atmospheric research 1993-1997*, Deutsches Zentrum für Luft- und Raumfahrt e.V. (German national aeronautics and space research center), Köln-Porz, Germany.

Schnaars, S. and Ziamou, P. (2001), "The essentials of scenario writing," *Business Horizons*, Vol. 44 No. 4, pp. 25–31.

Schnaars, S.P. (1987), "How to develop and use scenarios," *Long Range Planning*, Vol. 20 No. 1, pp. 105–114.

Schoemaker, P. (1993), "Multiple scenario development: Its conceptual and behavioral foundation," *Strategic Management Journal*, Vol. 14 No. 3, pp. 193–213.

Schoemaker, P. (1995), "Scenario planning: a tool for strategic thinking," *Sloan Management Review*, Vol. 36 No. 2, pp. 25–40.

Seel, N.M. (Ed.) (2012), *Encyclopedia of the sciences of learning*, Springer, New York, USA.

Sherali, H.D., Bish, E.K., and Zhu, X. (2006), "Airline fleet assignment. Concepts, models, and algorithms," *European Journal of Operational Research*, Vol. 172 No. 1, pp. 1–30.

Steinmüller, K. (2013), *Personal communications at RAHS user meeting on 3 December 2013*, Berlin, Germany.

Sterman, J.D. (2000), *Business dynamics: Systems thinking and modeling for a complex world*, Irwin/McGraw-Hill, Boston, Massachusetts, USA.

Strohmayer, A. (2001), "Improving aircraft design robustness with scenario methods," *Acta Polytechnica*, Vol. 41 No. 4, pp. 68–73.

Suchkov, A., Swierstra, S., and Nuic, A. (2003), "Aircraft performance modeling for air traffic management applications," paper presented at the 5th USA/Europe Air Traffic Management Research and Development Seminar, 23 - 27 June 2003, Budapest, Hungary, available at: http://www.atmseminar.org/seminarContent/seminar5/papers/p_039_DS.pdf (accessed 7 April 2015).

Sutkus, D.J., Baughcum, S.L., and DuBois, D.P. (2001), *Scheduled civil aircraft emission inventories for 1999: Database development and analysis*, Report No. NASA/CR--2001-211216, Hanover, Maryland, USA.

Sutkus, D.J., Baughcum, S.L., and DuBois, D.P. (2003), *Scheduled aircraft emission scenario for 2020: Database development and analysis*, Report No. NASA/CR--2003-212331, Hanover, Maryland, USA.

Taleb, N.N. (2008), *The black swan: The impact of the highly improbable*, Penguin Books Ltd, London, UK.

Tetzloff, I. and Crossley, W. (2009), "An allocation approach to investigate new aircraft concepts and technologies on fleet-level metrics," paper presented at the 9th AIAA Aviation Technology, Integration, and Operations Conference, 21 - 23 September 2009, Hilton Head, South Carolina, USA.

Tetzloff, I.J. and Crossley, W.A. (2014), "Measuring systemwide impacts of new aircraft on the environment," *Journal of Aircraft*, Vol. 51 No. 5, pp. 1483–1489.

Torenbeek, E. (1982), *Synthesis of subsonic airplane design: An introduction to the preliminary design of subsonic general aviation and transport aircraft with emphasis on layout, aerodynamic design, propulsion, and performance*, Delft University Press, Delft, The Netherlands.

van der Heijden, K. (2005), *Scenarios: The art of strategic conversation*, 2nd Edition, Wiley, Chichester, UK, Hoboken, New Jersey, USA.

van Notten, P., Rotmans, J., van Asselt, M., and Rothman, D. (2003), "An updated scenario typology," *Futures*, Vol. 35 No. 5, pp. 423–443.

van Vught, F.A. (1987), "Pitfalls of forecasting. Fundamental problems for the methodology of forecasting from the philosophy of science," *Futures*, Vol. 19 No. 2, pp. 184–196.

Vanston, J.H., Frisbie, W., Lopreato, S.C., and Boston, D.L. (1977), "Alternate scenario planning," *Technological Forecasting and Social Change*, Vol. 10 No. 2, pp. 159–180.

Varum, C.A. and Melo, C. (2010), "Directions in scenario planning literature – A review of the past decades," *Futures*, Vol. 42 No. 4, pp. 355–369.

Verbrugge, S.C., Langevoort, A., and Fischdick, W. (2013), "Airlinerlist.com. Full production lists and histories of most major airliners," available at: http://www.airlinerlist.com/ (accessed Spring 2013).

Wache, L.H. (2014), *Szenariobasierte Modellierung der Weltflugzeugflotte unter Berücksichtigung dynamischer Einflussparameter [in German]*, Master's Thesis (Report No. LS-MA 14/15), Institute of Aircraft Design, Technical University of Munich, Garching, Germany.

Waitz, I.A., Townsend, J., Cutcher-Gershenfeld, J., Greitzer, E., and Kerrebrock, J. (2004), *Aviation and the environment: A national vision statement, framework for goals and recommended actions*, Cambridge, Massachusetts, USA.

Walsh, P.R. (2005), "Dealing with the uncertainties of environmental change by adding scenario planning to the strategy reformulation equation," *Management Decision*, Vol. 43 No. 1, pp. 113–122.

Wei, W. and Hansen, M. (2007), "Airlines' competition in aircraft size and service frequency in duopoly markets," *Transportation Research Part E: Logistics and Transportation Review*, Vol. 43 No. 4, pp. 409–424.

Wenzel, S., Weiß, M., Collisi-Böhmer, S., Pitsch, H., and Rose, O. (2008), *Qualitätskriterien für die Simulation in Produktion und Logistik: Planung und Durchführung von Simulationsstudien [in German]*, Springer, Berlin, Germany.

Woudenberg, F. (1991), "An evaluation of Delphi," *Technological Forecasting and Social Change*, Vol. 40 No. 2, pp. 131–150.

Wright, G., Bradfield, R., and Cairns, G. (2013), "Does the intuitive logics method – and its recent enhancements – produce "effective" scenarios?," *Technological Forecasting and Social Change*, Vol. 80 No. 4, pp. 631–642.

Zwenzner, S. (2014), *Potentialanalyse von Lösungsverfahren des Flottenzuweisungsproblems für die Anwendung in einem dynamischen Flottenmodell [in German]*, Semester Thesis (Report No. LS-SA 14/01), Institute of Aircraft Design, Technical University of Munich, Garching, Germany.

Appendix A Fundamentals of scenario planning

THE basis of practically every kind of decision that an individual or an organization has to make fundamentally relies on the development of the future. This is why there have been many different methods proposed, developed, applied, and discussed to handle the uncertainty about the future. In fact, after more than 50 years of evolution, *Scenario Planning* has become today one of the most popular methods to handle future uncertainty and is still being discussed intensely in the literature. (van Notten *et al.*, 2003, p. 423; Varum and Melo, 2010, p. 356)

Although 'scenarios' have been employed for a long time in human history (e.g., in the form of visions intended to proclaim a better future world), the modern approach of handling uncertainty through the development of multiple futures – which is what scenario planning is essentially aimed at – was first employed by German military strategists in the 19th century. (Reibnitz, 1988) This reveals the original purpose of scenarios, which is to support strategic decision-making by preparing an organization (and especially its leaders) for a broad range of future eventualities.

The actual beginning of the emergence of scenario planning was only in the 1960s when two "geographical centers," one in the USA and the other one in France, fostered the development and use of the scenario methodology. (Bradfield *et al.*, 2005, p. 797) The evolution of scenario planning at these two centers will be portrayed in the following sections.

A.1 The US center

In the aftermath of World War II, the US Department of Defense (DoD) was tasked with selecting industry projects for the development of new national defense and weapons systems that it would fund. Given the growing technical complexity of these systems, joined by the difficult political situation of that time (Raubitschek, 1988), two particular needs arose with the DoD. It required (1) a method to "capture the reliable consensus of opinion of a large and diverse group of experts" and (2) "simulation models of future environments which would permit various policy alternatives and their consequences to be investigated." (Bradfield *et al.*, 2005, p. 798)

In the 1950s, it was the RAND Corporation, a research group that had emerged out of a cooperation between the US Air Force and the Douglas Aircraft Company, that developed and delivered techniques to address the two needs of the DoD. (Cooke, 1991) The circumstances that the development of both computers and game theory was at its initial stages at those times, and that the US military required the capability of war game simulation models, actually formed the basis for the creation of scenario techniques at RAND. (Schoemaker, 1993, p. 195)

Initially, Herman Kahn, a leading researcher at RAND who focused on national defense and strategic planning, elaborated future scenarios for the US Air Defense System Missile Command, and, in doing so, actively contradicted the leading US military strategists who had

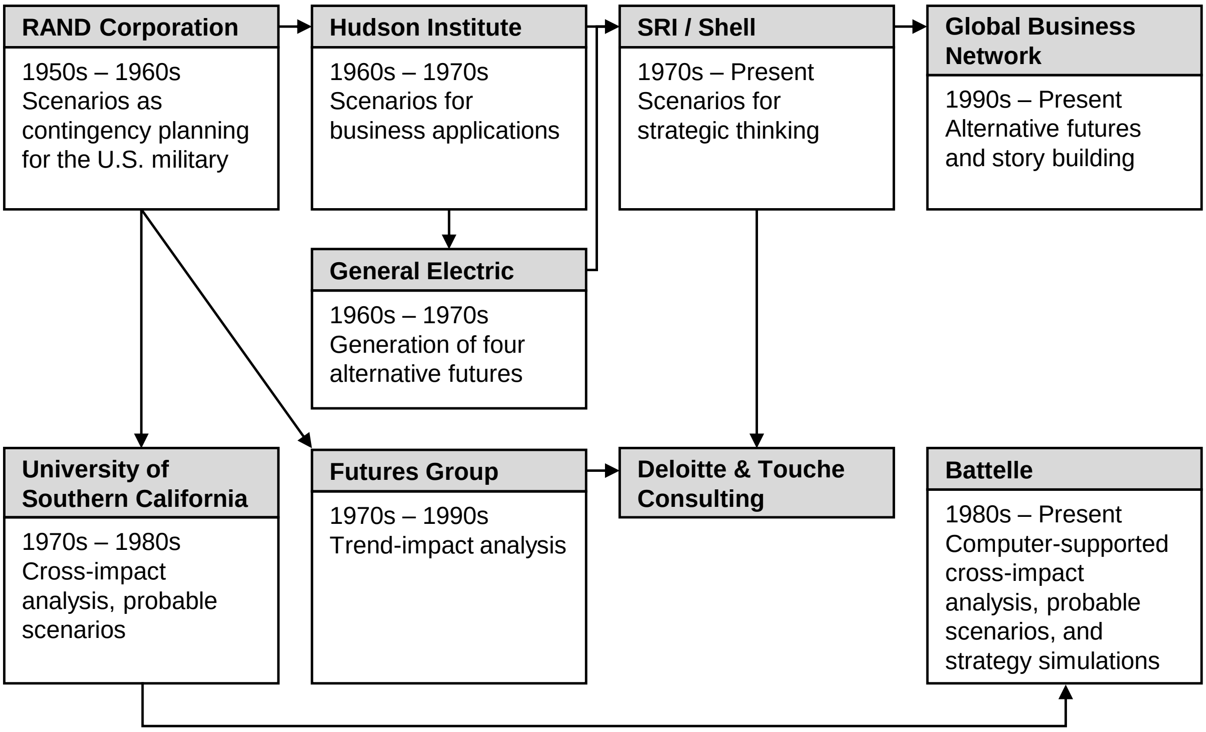


Figure A-1 **Historical evolution of scenario planning in the US**
Source: author's creation based on Millett (2003, p. 17)

a clearly different vision of the decades following World War II. (Bruce-Briggs, 2005) By forming the well-known phrase 'Thinking about the unthinkable,' he "demonstrated through a combination of facts and logic, that military planning tended to be based on wishful thinking rather than 'reasonable expectations.'" With his scenario-based approach, Kahn created a way of broadly exploring the future horizon, which is why scenarios that were created using Kahn's approach are sometimes referred to as "exploratory" (Godet, 2000b, p. 11) or "explorative" (Börjeson *et al.*, 2006, p. 727) (as opposed to "normative" scenarios (Godet, 2000b, p. 11), →section A.2). In this sense, Kahn employed the scenarios he had developed as a means to integrate the 'unthinkable' into the thinking of the leading military and political strategists, and thereby had "a major impact on the Pentagon's thinking in the 1950s and 1960s." (Bradfield *et al.*, 2005, p. 798)

When Kahn left RAND in 1961, he started developing scenarios for purposes of social forecasting and public policy support at his newly founded Hudson Institute (Figure A-1). During the subsequent years, together with Anthony Wiener, he coauthored 'The Year 2000: A framework for speculation on the next thirty-three years.' (Kahn and Wiener, 1967) This is a book today considered as a "landmark in the field of scenario planning," (Bradfield *et al.*, 2005, p. 799) as it introduced one of the earliest definitions of 'scenarios' into the strategy-planning literature. (Raubitschek, 1988) As a result, some authors of scenario-related literature have called Kahn the "father" of modern-day scenario planning. (Cooke, 1991)

Inspired by Kahn's and Wiener's work, the researchers Helmer, Gordon, and Dalkey (all of whom had been former staff of RAND – they are also known for their contributions to the development of the 'Delphi method,' another future forecasting technique (Woudenberg, 1991, p. 132)) worked on scenarios to support public policy planning. Based on their work, Pierre Wack, a strategy planner of the Royal Dutch Shell oil and gas company (Shell), introduced scenario planning in the corporate strategy development of the French branch of Shell in 1971. He did so with great success, as the elaborated scenarios "correctly identified an impending scarcity of oil and an ensuing pointed increase in oil prices." Henceforth, scenario planning was extended throughout the entire company. (Bradfield *et al.*, 2005, p. 800)

In this way, Shell had developed into one of the most distinguished corporate users of scenarios, and thereby set the "gold standard of corporate scenario generation." (Millett, 2003, p. 18) Shell's interpretation and application of scenarios eventually became an important milestone in the evolution of the scenario methodology in the context of strategic business planning. Helmer, Gordon, and Dalkey (along with the work of Peter Schwarz of the Stanford Research Institute (SRI)) had hence set up the foundations of what is today referred to as the "Intuitive Logics School" of scenario planning (Huss and Honton, 1987b) that will be depicted in more detail in section A.3.1.

Apart from the Intuitive Logics School, another school of scenario planning had emerged "almost in parallel" from the work of RAND. As this particular school was designed to involve the "probabilistic modification of extrapolated trends" by creating probable scenarios, some authors have named it the "Probabilistic Modified Trends School." However, it has not received as much attention in the literature as the Intuitive Logics School, which is why it is considered as less relevant in this thesis. As will be shown in section A.3.2, the Probabilistic Modified Trends School embraces two specific approaches to scenario building, the Trend-Impact Analysis and the Cross-Impact Analysis. (Bradfield *et al.*, 2005, p. 800)

Figure A-1 summarizes the principle evolution of scenario planning in the US and depicts the most important companies and institutions that have been using scenario planning.

A.2 The French center

In the 1950s, Gaston Berger, a French philosopher, founded the "Centre d'Etudes Prospectives" (French expression for 'Center of Future Studies') where he developed a scenario-based approach to long-term planning he called 'La Prospective' (French word for 'futurology'). (Bradfield *et al.*, 2005, p. 802) The key principle of this approach is to create 'normative scenarios' that define positive (i.e., desired) scenarios focusing on "certain future situations or objectives and how these could be realized." (Börjeson *et al.*, 2006, p. 728) Because of their "policy-oriented" nature (van Vught, 1987, p. 186), they were intended originally to "serve as a guiding vision to policy makers […] [by] providing a basis for action." (Bradfield *et al.*, 2005, p. 802) In fact, the Office for Regional Planning of the French Government (DATAR) first used normative scenarios based on the La Prospective methodology in the context of a regional future study in the mid-1960s. (Godet, 2006, p. 120)

In the 1960s and 1970s, Pierre Masse and Bertrand de Jouvenel continued Berger's work after he had died in 1960. In doing so, they were so successful as to be able to integrate their scenario approach into the economic planning of the French government, (Bradfield *et al.*, 2005, p. 802) making La Prospective – together with the Intuitive Logics approach – become one of "the most frequently adopted approaches" today. (Godet, 2000b, p. 11) Starting in the 1970s and continuing until today, Michel Godet, a French professor and economist, has enlarged La Prospective even further by "honing the tools" of this particular scenario methodology. (Godet, 2000a, p. 6)

A.3 The three schools of scenario planning

Following the suggestion of Bradfield *et al.* (2005, p. 805) that is based on the above-described historical origins and evolution of scenario planning, "three major categories of scenario 'schools'" are defined in this thesis. The respective key principles and approaches to scenario building are portrayed in the following sections with major emphasis on the Intuitive Logics

School, as this represents the scenario philosophy applied in this thesis. The final Section provides a table of comparison of the three scenario schools with regard to their main methodological aspects and differences.

A.3.1 The intuitive logics school

The key principle of the Intuitive Logics School of scenario planning is to develop between two and four scenarios, all being both "equally plausible" and probable (van der Heijden, 2005, p. 4), and explore with them the "limits of possibility" with regard to the way the future may evolve. (Wright *et al.*, 2013, p. 634) In this context, it is common to employ the image of a "scenario cone" (Pillkahn, 2008, p. 175) in order to illustrate the outcome of a scenario-building process of the Intuitive Logics School, which is an expanding horizon of alternative futures that is aimed at reflecting the increasing uncertainty about the future with longer time frames considered. Figure A-2 schematically illustrates the scenario cone.

Starting with a detailed analysis of the status-quo situation (including currently prevailing trends), the scenario building project is usually directed towards describing at least two paths that the future may potentially follow. (Schoemaker, 1993, p. 196) The more distant (in time) the future scenarios are relative to the status quo, the more difficult it gets to connect the present with the scenarios: the scenario cone becomes wider, as the uncertainty about the future grows.

In the Intuitive Logics School, the approach to the building of scenarios is rather "qualitative in nature," (Bradfield *et al.*, 2005, p. 806) and relies strongly on the "disciplined intuition" of those individuals that are involved in building the scenarios. (Jungermann and Thuring, 1987) As the scenarios usually comprise detailed descriptive narratives of a broad series of aspects of the future environment, a project team is required that unites a large range of multidisciplinary expertise and experience in the relevant fields. In consequence, the selection of the team members is a crucial determinant of the success and effectiveness of a scenario project and its results obtained. (Franco *et al.*, 2013, p. 730; van der Heijden, 2005, p. 220) Here, especially the presence of "remarkable people," i.e., those individuals who possess extensive knowledge and experience in the areas relevant to the scenario project, may help to "overcome the availability bias in scenario construction." (Wright *et al.*, 2013, p. 635)

A key task of a scenario project that is based on the Intuitive Logics School is the analysis of the uncertain future development of the "corporate environment" (Malaska *et al.*, 1984, p. 46) that appears relevant to the scope of the problem under scrutiny (refer again to the definition of the term 'environment' given in the Glossary). In this matter, a "STEEP" (Bradfield *et al.*, 2005, p. 807), "PEST" (O'Brien, 2004, p. 711), "SPECTRE" (O'Brien *et al.*, 2007, p. 219), or "PESTEL" (Wright *et al.*, 2013, p. 711) framework is often applied that has also been referred to as a "popular technique." (Walsh, 2005, p. 115) With this technique, the "external content" (Saritas and Nugroho, 2012, p. 512) of social, technological, economic, ecological, political, (and legal) factors is examined that establish the future environment and hence influence the problem under concern (i.e., in the case of this thesis, the development of the global air transport system).

In this sense, the environment is interpreted as a compilation of STEEP factors. These factors are usually referred to simply as "environmental factors" (Huss and Honton, 1987a, p. 237) or "driving forces" (van der Heijden, 2005, p. 120). Depending on the respective scenario, each environmental factor holds a certain future state, sometimes also called an "outcome," (Wright *et al.*, 2013, p. 634) or "projection" (Gausemeier *et al.*, 1998, p. 120). The future state of the factor is used to define how the factor will develop in the scenario. E.g., consider the

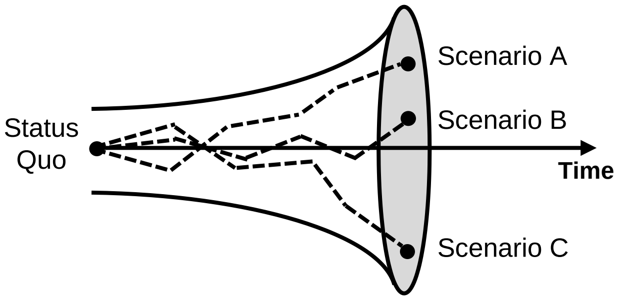


Figure A-2 **The scenario cone: alternative futures on an expanding horizon**
Source: author's creation based on Pillkahn (2008, p. 175)

environmental factor "Market growth rates." (Malaska *et al.*, 1984, p. 46) This factor may hold the future state 'high' in one scenario, while it is set to 'low' in another.

The complete set of environmental factors considered in a scenario project, with one specific future state per factor, is called a "raw scenario" (Amer *et al.*, 2013, p. 31) that represents the starting point for creating the associated scenario narrative.

Scenario building projects of the Intuitive Logics School may be composed of several methodical steps, starting by setting the topical agenda of the project, and terminating with verbalizing scenario narratives or "storylines" and analyzing implications if required. (Wright *et al.*, 2013, p. 634) In the literature, a recommended number of five (Foster, 1993, p. 125) to twelve (Vanston *et al.*, 1977, pp. 160–162) distinct steps can be found. Section 3.1 provides more details on the different steps of scenario building in the Intuitive Logics School.

The outcome of a scenario building project is a "set of logically linked scenarios in discursive narrative form […], often embellished with pictures, newspaper clippings, and vivid graphics for effect, most of which are contrived." (Bradfield *et al.*, 2005, p. 809) Note that many scenario planners avoid integrating numerical data into their scenarios (e.g., rates of market growth, interest or tax rates, and energy prices). (Hirsch *et al.*, 2013, p. 364) The challenges, advantages, and drawbacks of building quantitative scenarios will be discussed in Section 3.2.

A.3.2 The probabilistic modified trends school

As was mentioned above, the scenario work at RAND did not only result in the creation of the Intuitive Logics School of scenario planning, but also in a more probability-oriented approach, the Probabilistic Modified Trends School (PMTS). According to Bradfield *et al.* (2005, p. 800), the PMTS "incorporates two distinct methodologies, Trend-Impact Analysis and Cross-Impact Analysis."

Trend-Impact Analysis (TIA). The idea of TIA is to enhance traditional future forecasting methods (that usually rely on a simple extrapolation of historical data) by explicitly introducing "unprecedented future events" into the scenarios. (Gordon, 2003b, p. 3) Four fundamental steps are applied to build the scenarios (Bradfield *et al.*, 2005, p. 801):

At first, the historical data relevant to the scope of the scenario building project and topic are collected. Next, "'surprise-free' future trends" are determined by means of a mathematical extrapolation of these data, using numerical tools ('curve-fitting'). At the subsequent step, a list of critical events is elaborated that may potentially disturb the steady trend development in the future and hence the surprise-free scenarios. Finally, experts are asked to estimate the probability of occurrence of these events as a function of time. In addition, they are consulted on the impact of these events on the further development of the trends in order to adjust the extrapolated curves.

As a result, TIA-based scenarios are quantitative in nature on the one hand. Yet, they strongly rely on the availability and opinion of individual experts on the other (which may result in rather tedious scenarios).

Cross-Impact Analysis (CIA). The basic question that underlies the CIA principle is: "Can forecasting be based on perceptions about how future events may interact?" (Gordon, 2003a, p. 3) Again, similar to the TIA method, distinct future events and their respective probability of occurrence are considered that may disturb the simplistic extrapolation of historical data.

However, the difference between these two methods is that "rather than accepting the a priori probabilities attached to the future events by experts [as practiced by the TIA method], […] [the CIA method] attempts to determine the conditional or proportional probabilities of pairs of future events given that various events have of have not occurred, through cross impact calculations." (Bradfield *et al.*, 2005, p. 801) Therefore, the CIA method requires profound knowledge not only about the events, but also about the interdependencies between these events.

If this knowledge is available, the method will produce a range of well-thought-out alternative futures that do not simply rely on some experts' opinions. In this sense, the CIA method is able to create scenarios of higher quality compared to TIA.

A.3.3 The 'La Prospective' school

The La Prospective School is aimed at building normative scenarios (→section A.2). Based on the work of Michel Godet, La Prospective has become a "largely mathematical and computer-based probabilistic approach to scenario development." (Bradfield *et al.*, 2005, p. 802)

In comparison to the Intuitive Logics School, Bradfield *et al.* (2005, p. 803) state that La Prospective "is more elaborate, complex, and more mechanistic rather than an openly intuitive approach to scenario development, relying heavily on computer-based mathematical models which have their roots in TIA and CIA." Hence, La Prospective can be regarded as a "blending of the intuitive logics and probabilistic modified trend methodologies."

A.3.4 Synopsis

Considering all three schools of scenario planning presented in the previous sections, Table A-1 provides an overview of the major methodological aspects of each school and thereby allows a mutual comparison. Note that the table only displays information applicable to the majority of scenario use cases. In certain cases however, statements other than the ones shown in Table A-1 may be equally correct.

Table A-1 **Comparison of the methodological aspects of the three schools of scenario planning**
Source: author's creation based on Bradfield et al. (2005, pp. 807–808)

	Intuitive Logics School	PMTS	La Prospective School
Goal	Build multiple, equally plausible and probable scenarios that describe alternative futures (i.e., descriptive scenarios).	Build multiple scenarios with different probabilities of occurrence.	Build multiple scenarios that may define one or several desirable future states (i.e., normative scenarios).
Scope of the scenarios	Scenarios can range from a global, regional, country or industry focus to a distinct problem-specific focus.	Scenarios focus on the probability of occurrence and impact of specific events on historic trends.	Scenarios generally feature a narrow topical scope, but examine a broad range of factors within this scope.
Methodological orientation	Process-oriented, qualitative approach to scenario building that relies on the disciplined intuition of the project team.	Outcome-oriented, quantitative, and analytical approach to scenario building that involves computer-supported extrapolative forecasting and simulation models.	Outcome-oriented, quantitative, and analytical approach to scenario building that requires complex computer-supported analyses and mathematical modeling.
Project team	Team members usually come from within the organization and should together build up a broad range of expertise.	Expert external consultants undertake the scenario-building process.	Combination of some key individuals from within the organization who are led by an expert external consultant.
Role of external experts	Experts may support and facilitate one or several steps of the scenario building process and act as catalysts of new ideas.	Experts play a dominant role and strongly shape the scenario contents.	Experts play a dominant role by using a variety of proprietary tools to undertake comprehensive analyses and judgment to determine the scenarios.
Commonly used support tools	Intuition and knowledge of team members, STEEP analysis, consistency matrices, System Dynamics, stakeholder analysis	Trend-Impact Analysis, Cross-Impact Analysis, Monte Carlo Simulations, curve-fitting tools	Structural and actor analysis, morphological analysis, Delphi technique, sophisticated simulation models
Project output	Set of mostly qualitative scenarios in discursive narrative form supported by graphics and limited quantification of specific issues.	Quantitative scenarios including a baseline case plus upper and lower quartiles of adjusted time series forecasts. The scenarios may also contain short storylines.	Quantitative and qualitative scenarios of alternative futures that are supported by a comprehensive analysis of possible actions and their potential consequences.
Probability of occurrence	All scenarios must be equally probable.	Conditional probabilities attached to distinct future events	Probabilities attached to the evolution of variables under assumption sets of actors' behavior
Number of scenarios generated	Usually 2 – 4	Usually 3 – 6	Multiple
Quality attributes of the scenarios created	Coherence, comprehensiveness, internal consistency, novelty, plausibility	Scenarios must be plausible and verifiable in retrospect.	Coherence, comprehensiveness, internal consistency, scenarios must be verifiable in retrospect.

Appendix B FSDM aircraft addition cases

THIS appendix provides a description of the aircraft addition sequences implemented in the current version of the FSDM. Emphasis is on the four cases that address the different aircraft addition constraints (→Table 4-7 in Chapter 4). When activated by the user, these constraints actually have a strong impact on the simulation results produced by the FSDM. A good understanding of the four cases will therefore help interpret the simulation data.

Case 4 is the simplest one among the four cases, which is why it is depicted at first in this appendix. Then, the other cases are presented one after the other with Case 1 being explained at the end, as it is the most complex case among all.

B.1 Case 4

In Case 4, neither the TPC nor the SPC (→Section 4.3.4.6) are constrained, which allows the FSDM to add an unlimited number of aircraft units of any type being available in the respective year of simulation to the fleet of each route group (→Figure 4-13). Therefore, the model will always be able to fill every route group's capacity gap, no matter how big it gets. It will add the one aircraft type to each route group's fleet that features the best SFC performance (→Section 4.3.4.3) among all aircraft types available in the corresponding year of simulation.

As was discussed in Chapter 4, allowing unconstrained aircraft additions does not represent a suitable way of approaching real-life aircraft commissioning practices of airlines. Consequently, Case 4 should be used with care when conducting fleet simulations with the FSDM.

B.2 Case 3

Case 3 constrains the SPC while it leaves the TPC unconstrained. Like in Case 4, the unconstrained TPC enables the FSDM to fill every route group's capacity gap under any circumstance. The SPC restriction that does not apply to the addition of aircraft units of the initial-fleet clusters 1 through 9 (→Section 4.3.4.6, Footnote 73) is aimed at enabling a more realistic simulation of an aircraft manufacturer's production ramp-up once he introduces a new type of aircraft (→Figure 4-3, Figure 4-4).

As shown by Figure B-1, the aircraft addition sequence of Case 3 initially determines the total number of how many aircraft units of each type the FSDM intends to add to fill each route group's capacity gap (→Figure 4-13). The probability is very high that for a newly introduced aircraft type featuring a relatively low SPC number, the total number of added aircraft units will exceed the SPC of this type. This is due to the better SFC performance of this type relative to its predecessors, making the FSDM prefer this particular type to others (e.g., Airbus A350XWB vs. Boeing 777-200).

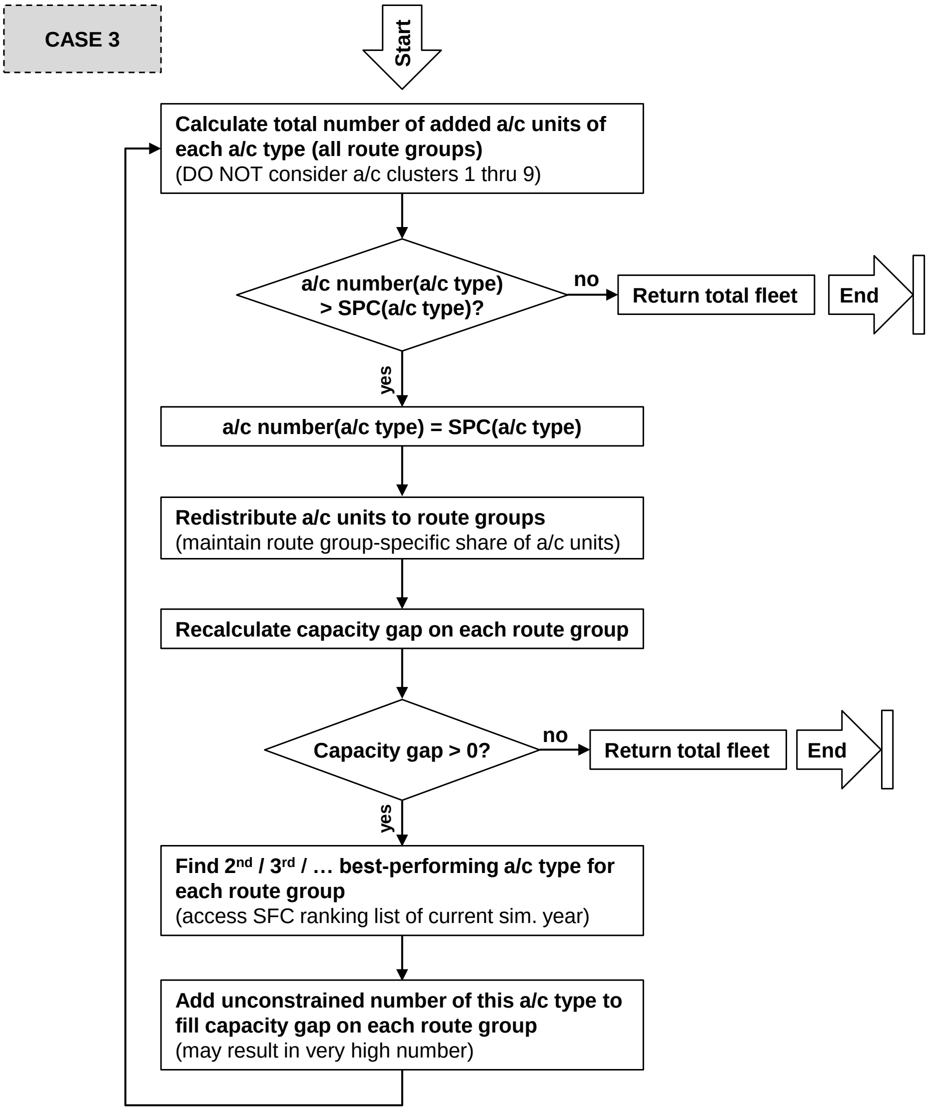


Figure B-1 **Case 3 aircraft addition sequence**

If the SPC of a certain aircraft type is exceeded, the algorithm will lower the total number of aircraft additions to the maximum possible number (which is equal to the SPC; a/c number(a/c type) = SPC(a/c type) →Figure B-1). It will then redistribute the reduced number of this type to those route groups where the FSDM originally intended to operate the aircraft type while keeping the original route group-specific share of aircraft units.[150]

Then, while considering the reduced number of aircraft additions, the algorithm recalculates the remaining capacity gap for each route group. It will then select the second best aircraft type available in the respective year of simulation on each route group and add an unlimited number of units of this type to fill the remaining capacity gap. Of course, this number may exceed again the SPC corresponding to the second best type. Hence, the algorithm restarts and reduces the number of additions of this type to the corresponding SPC level if necessary. The algorithm will repeat itself (selecting the third, fourth … best aircraft type available) until the capacity gap on each route group eventually gets zero (→Figure B-1).

---

[150] *Fictitious example:* The original aircraft addition number of a specific aircraft type was 120 in total, which exceeded the SPC by 30. Thus, the maximum possible aircraft addition number is 90. The original distribution of the 120 aircraft units was 80 units operating on route group A and 40 units on route group B. The new distribution of the 90 aircraft units will therefore be 60 units on route group A and 30 units on route group B.

As mentioned above, in Case 3, the capacity gap of each route group will always be filled entirely. This is possible because the SPC restriction only applies to aircraft types other than clusters 1 through 9. In other words, in a possible situation where the algorithm has exhausted the SPCs of all newly available (and hence better performing) aircraft types, it will inevitably fall back on aircraft types belonging to the clusters 1 through 9 to fill the remaining capacity gap.[151]

B.3 Case 2

Case 2 restricts the TPC that affects the overall amount of aircraft additions while not constraining the SPC that concerns additions of aircraft types other than clusters 1 through 9. Unlike in the Cases 3 and 4, here, the FSDM may not be able to fill the capacity on each route group entirely because of the TPC restriction.

Case 2 has been designed with the intention to simulate the ability of the aircraft manufacturers to deliver only a limited number of aircraft per year at the global level. Yet, the unconstrained SPC in Case 2 allows investigating the maximum possible effect of a newly introduced aircraft type on the fleet-wide fuel performance. Thus, the (unrealistic) assumption underlying Case 2 is that once a new aircraft type becomes available in a user-defined future year (e.g., the Airbus A320neo from 2015), the aircraft manufacturer would switch over his production processes immediately to the production of this new type. In other words, he would not require time for the production ramp-up of the new type (e.g., Airbus would cease the production of the A320classic in 2015 and use all of its available production facilities to build the A320neo from this year on). Figure B-2 illustrates how Case 2 is implemented in the FSDM.

The aircraft addition sequence of Case 2 initially determines the total number of how many aircraft units of the SA and TA classes the FSDM intends to add to fill each route group's capacity gap (→Figure 4-13). Next, it checks whether the TPC of the SA-class types has been exceeded. If this is the case, the algorithm will lower the total number of additions of SA-class aircraft to the maximum allowable number, which is the TPC (a/c number(SA class) = TPC(SA class) →Figure B-2). Similar to Case 2, the reduced number of aircraft will then be redistributed to their route groups while the route group-specific share of added aircraft units will be maintained (→Footnote 150).

The reduction of the total number of additions of SA-class aircraft has now caused the capacity gap to become greater than zero again. In this specific situation, the FSDM may refill this gap by adding TA-class aircraft only. Therefore, the algorithm checks whether the maximum number of additions of TA-class aircraft has already been reached (a/c number(TA class) = TPC(TA class)? →Figure B-2). If this is not true, there is a potential chance that the capacity gap can actually be filled with TA-class aircraft provided that the original number of additions of TA-class aircraft is lower than the TPC of the TA class.[152] Therefore, the algorithm determines the best TA-class aircraft type for each route group (by accessing the SFC ranking list, →Section 4.3.4.3) and adds an unconstrained number of aircraft of this type to each route group's fleet in order to fill the capacity gap, regardless of whether or not the TPC of the TA class has been exceeded previously.

---

[151] The reader is reminded that the FSDM does not differentiate in terms of performance between an aircraft of a specific type being added sooner or later in time relative to another aircraft of the same type (→Section 4.3.2.4).

[152] At this point, however, this particular condition is not checked on purpose because otherwise, the algorithm would fall into an infinite loop under certain conditions, →Figure B-2.

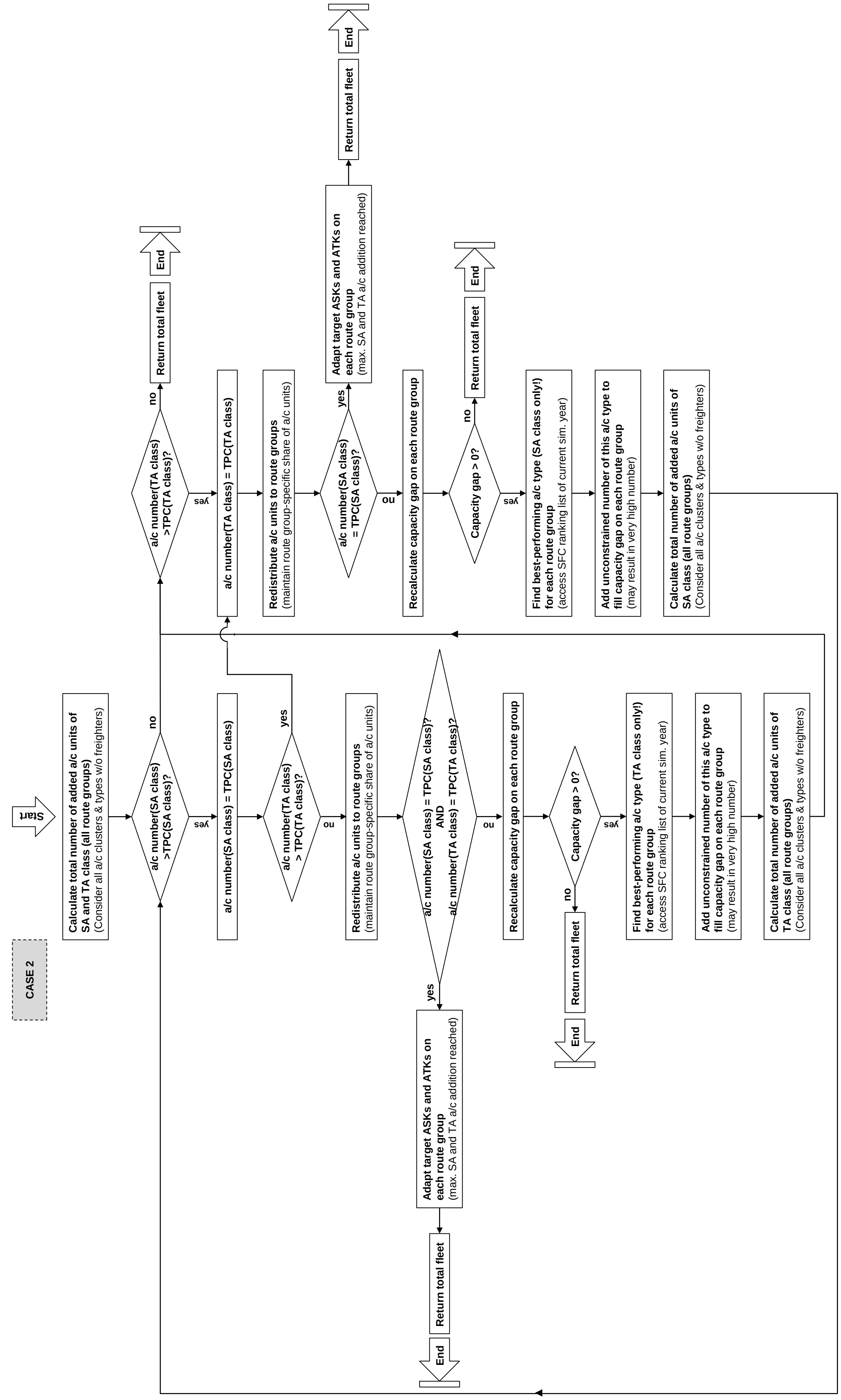


Figure B-2 **Case 2 aircraft addition sequence**

Only after this point, the algorithm checks whether the newly determined number of additions of TA-class aircraft exceeds the corresponding TPC. If this is the case, it will lower this number to meet the TPC and afterwards redistribute the remaining aircraft again while maintaining the original route group-specific aircraft share.

At this point, both the maximum numbers of additions of SA-class and TA-class aircraft have been reached. The algorithm can no longer add any further aircraft to the fleet, which will eventually make the algorithm unable to fill the capacity gap if the gap is still greater than zero. It must accordingly reduce the originally calculated target values of ASKs and ATKs of each route group (→Section 4.3.4.3) being affected by the above measures.

The algorithm associated with Case 2 must handle more cases than the one described above. These cases are not described here, as the corresponding sequential steps are similar to the above ones. The reader is referred to Figure B-2 for information regarding the various sequences within Case 2.

B.4 Case 1

Case 1 is the most complex aircraft addition case, as it constrains both the SPCs of the newly introduced aircraft types and the global TPC. Yet, it is certainly able to reproduce real-life aircraft commissioning practices most realistically among all cases implemented in the FSDM, as it captures both the individual production ramp-up functions of new types and the global aircraft production limitations.

Case 1 is essentially a composition of Case 2 (TPC constrained) and Case 3 (SPC constrained) with some adaptations that were necessary for the Case 2 sequence. Therefore, the detailed sequence of Case 1 is not described here again. Instead, the particularities of Case 1 relative to the Cases 2 and 3 are explained.

Figure B-3 shows that the initial part of the sequence of Case 1 (→Figure B-3, left part) proceeds in the exact same manner as the sequence of Case 3. Here, the goal is to ensure that the SPCs of the newly introduced aircraft types (i.e., not cluster 1 through 9 aircraft) are not exceeded. This part of the sequence will only be exited if either the SPCs of all new aircraft types (other than clusters 1 through 9) available in the respective year of simulation are entirely exhausted or the capacity gap has been filled completely with these new types only.

In the latter situation, the algorithm stops and returns the final mix of aircraft additions to the FSDM main routine. This also means that the ASK and ATK target values of the respective year could actually be achieved, or, in other words, the TPCs of the SA and TA aircraft classes have not been exceeded.[153] In the former situation, the algorithm must select aircraft belonging to the clusters 1 through 9 to fill the remaining gap.[154] This is accomplished in the second part of the algorithm (→Figure B-3, right part: 'Case 2'). The sequence of Case 2 is executed under the particular condition that the previously determined numbers of additions of new aircraft types are not changed. This ensures that the algorithm adds the maximum possible number of new aircraft types while maintaining the total number of aircraft additions below the SA and TA TPCs.

---

[153] By definition, the TPC is always equal or bigger than the sum of all SPCs (→Section 4.3.4.6).

[154] These aircraft will feature the exact same performance characteristics as aircraft belonging to the initial fleet. In the FSDM, a specific aircraft unit features the same technological performance level relative to an aircraft of the same type being introduced into the fleet earlier or later (→Section 4.3.2.4).

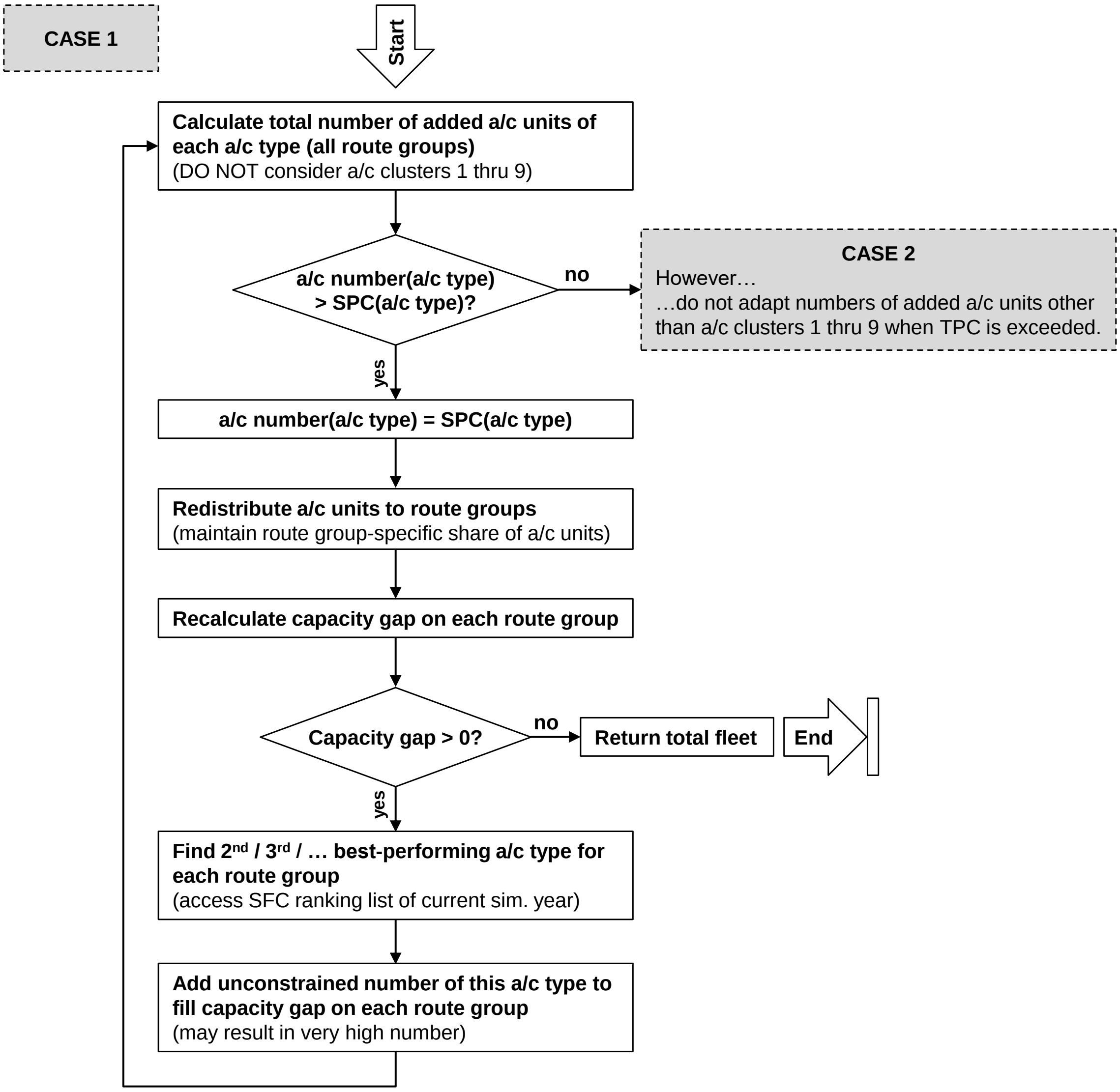


Figure B-3 Case 1 aircraft addition sequence

Appendix C Initial-fleet statistics

Table C-1 **OAG aircraft types and clusters considered by the FSDM**
Data source: OAG (2008)

SPECIFICACFT (OAG)	SPECIFICACFTNAME (OAG)	FSDM Cluster No.
M11	Boeing (Douglas) MD-11 Passenger	1
74M	Boeing 747 (Mixed Configuration)	1
74E	Boeing 747-400 (Mixed Configuration)	1
380	Airbus A380-800 Passenger	2
747	Boeing 747 (Passenger)	2
743	Boeing 747-300 / 747-100/200 Sud (Pax)	2
744	Boeing 747-400 (Passenger)	2
773	Boeing 777-300 Passenger	2
ABF	Airbus A300 (Freighter)	3
ABX	Airbus A300B4 /A300C4 /A300F4	3
31Y	Airbus A310-300 Freighter	3
D1F	Boeing (Douglas) DC10 (Freighter)	3
D8F	Boeing (Douglas) DC8 Freighter	3
75F	Boeing 757-200PF (Freighter)	3
76F	Boeing 767 Freighter	3
IL7	Ilyushin IL-76	3
318	Airbus A318	4
AR1	Avro RJ100	4
AR8	Avro RJ85	4
72F	Boeing 727 (Freighter)	4
73F	Boeing 737 (Freighter)	4
732	Boeing 737-200 Passenger	4
736	Boeing 737-600 Passenger	4
CRJ	Canadair Regional Jet	4
CR2	Canadair Regional Jet 200	4
CR7	Canadair Regional Jet 700	4
CR9	Canadair Regional Jet 900	4
E70	Embraer 170	4
E75	Embraer 175	4
E90	Embraer 190	4
ERJ	Embraer RJ 135 /140 /145	4
ER4	Embraer RJ145	4
100	Fokker 100	4
TU3	Tupolev TU134	4
M1F	Boeing (Douglas) MD-11 (Freighter)	5

(Table continued on next page)

Table C-1 (continued)

SPECIFICACFT (OAG)	SPECIFICACFTNAME (OAG)	FSDM Cluster No.
74F	Boeing 747 (Freighter)	5
74X	Boeing 747-200 (Freighter)	5
74Y	Boeing 747-400F (Freighter)	5
AT7	ATR 72	6
AB6	Airbus A300-600 Passenger	7
310	Airbus A310 Passenger	7
313	Airbus A310-300 Passenger	7
330	Airbus A330	7
333	Airbus A330-300	7
757	Boeing 757 (Passenger)	7
75W	Boeing 757-200 (winglets) Passenger	7
752	Boeing 757-200 Passenger	7
753	Boeing 757-300 Passenger	7
767	Boeing 767 Passenger	7
762	Boeing 767-200 Passenger	7
763	Boeing 767-300 Passenger	7
T20	Tupolev TU-204 /tu-214	7
332	Airbus A330-200	8
340	Airbus A340	8
342	Airbus A340-200	8
343	Airbus A340-300	8
345	Airbus A340-500	8
346	Airbus A340-600	8
764	Boeing 767-400 Passenger	8
777	Boeing 777 Passenger	8
772	Boeing 777-200 Passenger	8
77L	Boeing 777-200LR	8
77W	Boeing 777-300ER Passenger	8
IL9	Ilyushin Il-96 Passenger	8
32S	Airbus A318 /319 /320 /321	9
319	Airbus A319	9
320	Airbus A320	9
321	Airbus A321	9
M80	Boeing (Douglas) MD-80	9
M81	Boeing (Douglas) MD-81	9
M82	Boeing (Douglas) MD-82	9
M83	Boeing (Douglas) MD-83	9
M88	Boeing (Douglas) MD-88	9
M90	Boeing (Douglas) MD-90	9
717	Boeing 717-200	9
737	Boeing 737 Passenger	9
733	Boeing 737-300 Passenger	9
734	Boeing 737-400 Passenger	9
735	Boeing 737-500 Passenger	9
73W	Boeing 737-700 (winglets) Passenger	9

(Table continued on next page)

Table C-1 (continued)

SPECIFICACFT (OAG)	SPECIFICACFTNAME (OAG)	FSDM Cluster No.
73G	Boeing 737-700 Passenger	9
73H	Boeing 737-800 (winglets) Passenger	9
738	Boeing 737-800 Passenger	9
739	Boeing 737-900 Passenger	9
D9S	McD-Douglas DC9 30 /40 /50	9
TU5	Tupolev TU154	9

Table C-2 **Size and age distribution of the global aircraft fleet in 2008**
Data source: Flightglobal (2008)

Age	Number of aircraft units per aircraft cluster no.								
[years]	1	2	3	4	5	6	7	8	9
0	0	0	10	191	16	33	36	128	615
1	0	1	11	170	13	15	29	123	619
2	0	6	13	237	11	6	41	94	491
3	0	5	14	285	13	8	39	81	426
4	0	17	8	266	10	7	53	83	390
5	0	15	6	264	17	15	63	103	447
6	0	20	17	264	14	14	92	103	575
7	0	13	8	200	18	13	89	110	522
8	0	47	13	164	19	24	105	125	541
9	1	55	15	135	18	19	109	95	462
10	3	36	24	76	13	20	90	95	301
11	5	23	24	38	13	11	77	58	179
12	6	19	21	32	17	26	99	30	164
13	7	27	28	37	18	27	116	24	208
14	4	47	40	56	31	27	143	20	275
15	4	52	48	49	42	25	172	5	412
16	1	49	30	42	34	27	167	1	458
17	2	52	32	22	16	14	144	1	363
18	0	40	27	25	6	6	97	0	284
19	2	12	42	11	6	0	102	0	249
20	0	9	26	32	10	0	58	0	204
21	2	21	25	20	3	0	48	0	170
22	4	10	40	26	4	0	34	0	128
23	2	5	34	58	2	0	19	0	39
24	1	6	41	59	2	0	19	0	31
25	0	0	1	0	0	0	0	0	0
26-30	32	25	131	470	34	0	3	0	148
31-35	7	6	30	206	11	0	0	0	46
> 35	0	1	110	72	0	0	0	0	96
sum	**83**	**619**	**869**	**3,507**	**411**	**337**	**2044**	**1,279**	**8,843**

Table C-3 **Transport supply of the initial aircraft fleet in 2008**
Data source: OAG (2008)

Route group ID	Route group name	ASK-supply [x10^{11}]	ATK-supply [x10^{10}]
1	EUEU	7.552	1.413
2	EUAS	5.081	5.452
3	EUME	1.410	1.777
4	EUAF	1.765	1.099
5	EULA	2.204	1.518
6	EUNA	5.549	3.826
7	ASAS	11.712	6.030
8	ASME	1.696	1.888
9	ASAF	0.275	0.180
10	ASLA	0.041	0.012
11	ASNA	3.858	5.055
12	MEME	0.462	0.176
13	MEAF	0.489	0.299
14	MELA	0.026	0.014
15	MENA	0.458	0.206
16	AFAF	0.627	0.259
17	AFLA	0.018	0.081
18	AFNA	0.141	0.060
19	LALA	1.872	1.124
20	LANA	2.242	1.135
21	NANA	12.438	3.854
sum		**59.917**	**35.457**

Table C-4 **Characteristic stage lengths**
Data source: OAG (2008)

Route	Aircraft cluster no.								
group	1	2	3	4	5	6	7	8	9
EUEU	253	455	1,681	697	1,419	294	1,757	1,563	993
EUAS	7,976	9,151	4,612	2,041	7,446	385	5,495	8,439	2,628
EUME	4,075	4,274	3,468	1,629	4,601	444	3,727	4,720	2,572
EUAF	6,668	7,820	3,563	1,396	5,089	362	4,379	6,748	1,937
EULA	8,905	8,327	9,786	n/a	8,875	n/a	8,017	8,386	8,454
EUNA	7,066	7,046	4,495	5,882	6,772	n/a	6,333	6,808	6,676
ASAS	1,698	2,237	1,484	772	2,527	369	1,601	2,394	1,003
ASME	2,862	4,591	2,518	1,644	5,651	n/a	3,811	4,492	2,519
ASAF	n/a	10,330	3,833	n/a	7,517	n/a	5,577	8,165	n/a
ASLA	n/a	18,483	n/a	n/a	n/a	n/a	4,909	9,834	n/a
ASNA	10,043	10,195	5,808	5,558	7,783	n/a	7,353	10,187	7,327
MEME	n/a	980	1,272	614	869	319	902	894	806
MEAF	n/a	2,044	2,705	1,174	2,927	n/a	2,569	3742	1,887
MELA	n/a		n/a	n/a	n/a	n/a	12,973	11,981	10,577

(Table continued on next page)

Table C-4 (continued)

Route	Aircraft cluster no.								
group	1	2	3	4	5	6	7	8	9
MENA	n/a	9,610	n/a	10,301	10,821	n/a	9,477	10,581	10,334
AFAF	449	1,180	2,087	723	2,745	334	1,820	2,138	1,068
AFLA	6,193	6,883	n/a	n/a	5,506	n/a	2,747	7,434	n/a
AFNA	n/a	5,750	n/a	n/a	16,081	n/a	7,310	7,963	10,824
LALA	1,438	812	1,370	652	2,194	342	2,172	1,731	950
LANA	n/a	6,172	2,863	1,458	4,011	323	3,232	7,103	2,196
NANA	1,091	4,210	1,874	807	3,760	346	2,270	3,324	1,333

Table C-5 **Characteristic seat capacities**
Data source: OAG (2008)

Route	Aircraft cluster no.								
group	1	2	3	4	5	6	7	8	9
EUEU	0	379	0	76	0	69	218	277	153
EUAS	255	374	0	76	0	72	213	288	139
EUME	294	365	0	93	0	72	223	271	148
EUAF	282	342	0	103	0	72	237	277	154
EULA	273	400	0	n/a	0	n/a	247	279	148
EUNA	242	353	0	74	0	n/a	221	275	101
ASAS	260	374	0	71	0	69	245	296	150
ASME	270	380	0	86	0	n/a	223	283	158
ASAF	n/a	374	0	n/a	0	n/a	214	284	n/a
ASLA	n/a	384	n/a	n/a	n/a	n/a	214	262	n/a
ASNA	289	382	0	0	0	n/a	240	288	143
MEME	n/a	382	0	87	0	68	222	261	143
MEAF	n/a	377	0	81	0	n/a	231	273	145
MELA	n/a	n/a	n/a	n/a	n/a	n/a	205	293	152
MENA	n/a	430	n/a	0	0	n/a	212	307	114
AFAF	294	368	0	83	0	69	219	273	139
AFLA	270	359	n/a	n/a	0	n/a	185	250	n/a
AFNA	n/a	447	n/a	n/a	0	n/a	225	293	172
LALA	294	340	0	78	0	65	199	258	144
LANA	n/a	384	0	53	0	64	204	253	143
NANA	0	384	0	58	0	65	193	301	135

Table C-6 **Characteristic freight capacities in tons**
Data source: OAG (2008)

Route	Aircraft cluster no.								
group	1	2	3	4	5	6	7	8	9
EUEU	89	24.5	54	1	109	1	8	18	2
EUAS	42	20	65	7	104	0	10	14	4
EUME	46	27	40.5	2	108	5	14	20	2

(Table continued on next page)

Table C-6 (continued)

Route	Aircraft cluster no.								
group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
EUAF	43.5	17	52.5	1	101	0	9	15.5	1
EULA	46	15	45	n/a	112	n/a	10	17	4
EUNA	47.5	16	50	12	101	n/a	9	16.5	0
ASAS	54	24	51	3	104	1	13	22	1
ASME	41	25	49	6	108	n/a	11	20	2
ASAF	n/a	15	36	n/a	109	n/a	13	17	n/a
ASLA	n/a	15	n/a	n/a	n/a	n/a	13	8	n/a
ASNA	45	19	45	19	105	n/a	12	21	1
MEME	n/a	18	43.5	2	106	2	10	17	3
MEAF	n/a	20	39	0	102	n/a	12	19	1
MELA	n/a	n/a	n/a	n/a	n/a	n/a	12	15	0
MENA	n/a	16	n/a	20	113.5	n/a	12	14	0
AFAF	46	15	40	0	99.5	0	11	13	1
AFLA	41	15	n/a	n/a	90	n/a	9	0	n/a
AFNA	n/a	15	n/a	n/a	109	n/a	12	10	0
LALA	46	17	49	1	98	0	13	17	8
LANA	n/a	15	59	3	101	0	11	18.5	2
NANA	89	14	44	0	105	0	8	18	2

Table C-7 **Average sum of flight frequencies per month**

Data source: OAG (2008)

Route	Aircraft cluster no.								
group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
EUEU	5	85	628	102,925	1,196	20,759	10,393	801	347,273
EUAS	1,066	4,014	439	1,256	2,701	23	3,733	7,794	8,064
EUME	19	533	222	190	1,505	75	2,267	5,137	6,351
EUAF	150	707	61	1,243	628	64	2,813	2,924	13,423
EULA	451	975	9	0	199	0	2,305	3,973	143
EUNA	485	2,978	62	12	1,112	0	13,217	10,344	345
ASAS	775	14,411	2340	25,824	5,157	12,692	54,036	21,776	311,450
ASME	13	987	303	436	1,220	0	3,043	5,726	6,249
ASAF	0	92	24	0	20	0	390	636	0
ASLA	0	10	0	0	0	0	23	132	0
ASNA	228	4,098	32	3	2,723	0	1,017	4,632	144
MEME	0	479	146	6,738	112	900	1,427	4,389	17,199
MEAF	0	284	230	203	68	0	1,487	1,984	3,411
MELA	0	0	0	0	0	0	1	63	1
MENA	0	126	0	0	35	0	155	909	27
AFAF	29	20	200	8,864	397	2,291	1,868	1,060	22,095
AFLA	11	19	0	0	131	0	38	71	0
AFNA	0	1	0	0	0	0	325	267	12
LALA	120	102	755	31,023	319	4,272	3,609	523	88,371
LANA	0	44	908	6,027	297	1,124	12,255	620	28,344
NANA	16	164	2345	296,042	2,640	2,818	47,731	1,866	370,603

Table C-8 **Initial fleet allocation statistically determined (sub-optimal fleet fuel consumption)**

Route group	Aircraft cluster no.								
	1	2	3	4	5	6	7	8	9
EUEU	0	0	54	792	8	142	85	4	2,265
EUAS	33	145	124	28	85	0	94	223	126
EUME	0	9	29	4	31	1	40	77	104
EUAF	4	20	11	26	13	0	62	64	171
EULA	17	34	4	0	8	0	98	109	8
EUNA	13	78	13	0	31	0	395	227	10
ASAS	5	128	167	206	55	109	454	181	2,012
ASME	0	18	35	9	30	0	55	86	107
ASAF	0	4	3	0	1	0	10	17	0
ASLA	0	0	0	0	0	0	0	4	0
ASNA	10	169	8	0	91	0	38	160	6
MEME	0	2	8	52	0	7	6	12	85
MEAF	0	2	23	3	1	0	19	24	40
MELA	0	0	0	0	0	0	0	3	0
MENA	0	6	0	0	0	0	7	35	1
AFAF	0	0	16	77	4	18	16	7	141
AFLA	0	0	0	0	3	0	0	2	0
AFNA	0	0	0	0	0	0	11	7	1
LALA	1	0	48	229	3	32	33	3	519
LANA	0	1	145	68	5	8	173	13	382
NANA	0	3	182	2,013	43	21	447	22	2,864

Table C-9 **Engine type assignment to the aircraft types of the initial fleet**
Based on Engelke (2015)

Cluster no.	1	2	3	4	5	6	7	8	9
Representative aircraft type	Boeing MD-11	Boeing 747-400	Boeing 767-300F	Embraer 190	Boeing 747-400F	ATR 72-500	Boeing 767-300	Boeing 777-200	Airbus A320
Engine type	Pratt & Whitney PW4460	General Electric CF6-80C2B1F	Pratt & Whitney PW4060	General Electric CF34-10E6	General Electric CF6-80C2B1F	Pratt & Whitney PW127F	Pratt & Whitney PW4060	General Electric GE90-90B	CFM Intl. CFM56-5B4

Appendix D Production capacity limits

Table D-1 **Total annual production capacity limits (statistically determined)**
Data source: based on Engelke (2014)

Year	Total production capacity SA class	Total production capacity TA class
2008	1,012	337
2009	1,041	342
2010	1,069	347
2011	1,098	352
2012	1,127	357
2013	1,155	363
2014	1,184	368
2015	1,213	373
2016	1,242	378
2017	1,270	383
2018	1,299	388
2019	1,328	393
2020	1,357	398
2021	1,385	403
2022	1,414	408
2023	1,443	414
2024	1,471	419
2025	1,500	424
2026	1,529	429
2027	1,558	434
2028	1,586	439
2029	1,615	444
2030	1,644	449
2031	1,673	454
2032	1,701	459
2033	1,730	464
2034	1,759	470
2035	1,787	475
2036	1,816	480
2037	1,845	485
2038	1,874	490
2039	1,902	495
2040	1,931	500
2041	1,960	505

(Table continued on next page)

Table D-1 (continued)

Year	Total production capacity SA class	Total production capacity TA class
2042	1,989	510
2043	2,017	515
2044	2,046	521
2045	2,075	526
2046	2,103	531
2047	2,132	536
2048	2,161	541
2049	2,190	546
2050	2,218	551

Table D-2 **Single annual production capacity limits (statistically determined)**
Data source: based on Engelke (2014)

Year of introduction of new type	Single production capacity SA class	Single production capacity TA class
1	1	5
2	18	7
3	35	10
4	52	12
5	69	15
6	86	17
7	103	20
8	120	22
9	137	25
10	154	27
11	171	30
12	188	32
13	205	35
14	222	37
15	239	40
16	256	42
17	273	45
18	290	47
19	307	50
20	324	52
21	341	55
22	358	57
23	375	60
24	392	62
25	409	65
26	426	67
27	443	70
28	460	72

(Table continued on next page)

Table D -2 (continued)

Year of introduction of new type	Single production capacity SA class	Single production capacity TA class
29	477	75
30	494	77
31	511	80
32	528	82
33	545	85
34	562	87
35	579	90
36	596	92
37	613	95
38	630	97
39	647	100
40	664	102
41	681	105
42	698	107

Appendix E Single flight validation data

Table E-1 **Comparison of real-life flight data and simulation data generated by the FCECT for validation purposes of individual flight simulations**
Real-life flight data provided by a major European airline

FLIGHT 1

Great circle distance (O-D pair)	A/C type	Engine type	Payload factor assumed[155]	Payload mass	Initial cruise altitude
483 km	Airbus A320-214	CFM56-5B4-2	59.4%	12,771 kg	33,000 ft

	Real-life data	Simulation data	Delta
Initial mission mass	57,334 kg	57,060 kg	-0.5%
Distance actually flown	596 km	555 km	-6.9%
No. of step climbs	0	0	
Fuel burn	2,540 kg	2,240 kg	-11.8%
Block time[156]	58 minutes	49 minutes	-14.7%
CO_2 emissions (grams per ton-kilometer flown)	1,053	997	-5.3%

FLIGHT 2

Great circle distance (O-D pair)	A/C type	Engine type	Payload factor assumed	Payload mass	Initial cruise altitude
756 km	Airbus A320-214	CFM56-5B4-2	91.3%	19,630 kg	36,000 ft

	Real-life data	Simulation data	Delta
Initial mission mass	65,245 kg	65,158 kg	-0.1%
Distance actually flown	864 km	858 km	-0.7%
No. of step climbs	0	0	
Fuel burn	3,411 kg	3,130 kg	-8.2%
Block time	1 hour 13 minutes	1 hours 10 minutes	-3.4%
CO_2 emissions (grams per ton-kilometer flown)	635	586	-7.6%

(Table continued on next page)

---

[155] All payload factors indicated in the table represent assumed values due to lack of real-life data (→Ittel (2014, pp. 47–78)).

[156] The block times indicated in the table do not comprise taxi times for both the real-life data and the simulation data.

Table E-1 (continued)

FLIGHT 3

Great circle distance (O-D pair)	A/C type	Engine type	Payload factor assumed	Payload mass	Initial cruise altitude
1,488 km	Airbus A320-214	CFM56-5B4-2	88.8%	19,092 kg	37,000 ft

	Real-life data	Simulation data	Delta
Initial mission mass	66,696 kg	66,958 kg	+0.4%
Distance actually flown	1,539 km	1,655 km	+7.5%
No. of step climbs	0	0	
Fuel burn	5,661 kg	5,271 kg	-6.9%
Block time	1 hour 58 minutes	2 hours 8 minutes	+8.9%
CO_2 emissions (grams per ton-kilometer flown)	608	526	-13.4%

FLIGHT 4

Great circle distance (O-D pair)	A/C type	Engine type	Payload factor assumed	Payload mass	Initial cruise altitude
2,434 km	Airbus A320-214	CFM56-5B4-2	65.6%	14,104 kg	38,000 ft

	Real-life data	Simulation data	Delta
Initial mission mass	64,229 kg	64,416 kg	+0.3%
Distance actually flown	2,570 km	2,667 km	+3.8%
No. of step climbs	0	0	
Fuel burn	8,056 kg	7,629 kg	-5.3%
Block time	3 hours 13 minutes	3 hours 22 minutes	+4.8%
CO_2 emissions (grams per ton-kilometer flown)	701	640	-8.7%

FLIGHT 5

Great circle distance (O-D pair)	A/C type	Engine type	Payload factor assumed	Payload mass	Initial cruise altitude
4,844 km	Airbus A330-223	PW4168A	75.5%	35,787 kg	39,000 ft

	Real-life data	Simulation data	Delta
Initial mission mass	199,366 kg	198,789 kg	-0.3%
Distance actually flown	5,249 km	5,199 km	-1.0%
No. of step climbs	1	0	
Fuel burn	36,215 kg	32,542 kg	-10.1%
Block time	6 hours 18 minutes	6 hours 8 minutes	-3.4%
CO_2 emissions (grams per ton-kilometer flown)	608	552	-9.3%

(Table continued on next page)

Table E-1 (continued)

FLIGHT 6

Great circle distance (O-D pair)	A/C type	Engine type	Payload factor assumed	Payload mass	Initial cruise altitude
6,546 km	Airbus A330-223	PW4168A	87.4%	41,428 kg	32,000 ft

	Real-life data	Simulation data	Delta
Initial mission mass	224,042 kg	223,317 kg	-0.3%
Distance actually flown	7022 km	6960 km	-0.9%
No. of step climbs	2	2	
Fuel burn	50,876 kg	49,336 kg	-3.0%
Block time	8 hours 17 minutes	8 hours 4 minutes	-2.7%
CO_2 emissions (grams per ton-kilometer flown)	552	540	-2.2%

FLIGHT 7

Great circle distance (O-D pair)	A/C type	Engine type	Payload factor assumed	Payload mass	Initial cruise altitude
6,349 km	Airbus A340-313	CFM56-5C4/P	55.8%	26,226 kg	37,000 ft

	Real-life data	Simulation data	Delta
Initial mission mass	214,820 kg	217,004 kg	+1.0%
Distance actually flown	6,432 km	6,757 km	+5.1%
No. of step climbs	1	1	
Fuel burn	41,324 kg	47,555 kg	+15.1%
Block time	6 hours 50 minutes	8 hours 9 minutes	+19.5%
CO_2 emissions (grams per ton-kilometer flown)	773	847	+9.5%

FLIGHT 8

Great circle distance (O-D pair)	A/C type	Engine type	Payload factor assumed	Payload mass	Initial cruise altitude
6,349 km	Airbus A340-313	CFM56-5C4/P	81.2%	38,164 kg	34,000 ft

	Real-life data	Simulation data	Delta
Initial mission mass	234,556 kg	233,977 kg	-0.2%
Distance actually flown	6,788 km	6,757 km	-0.5%
No. of step climbs	2	1	
Fuel burn	54,820 kg	51,767 kg	-5.6%
Block time	8 hours 15 minutes	8 hours 7 minutes	-1.4%
CO_2 emissions (grams per ton-kilometer flown)	668	633	-5.1%

(Table continued on next page)

Table E-1 (continued)

FLIGHT 9

Great circle distance (O-D pair)	A/C type	Engine type	Payload factor assumed	Payload mass	Initial cruise altitude
9,035 km	Airbus A340-313	CFM56-5C4/P	85.4%	40,138 kg	33,000 ft

	Real-life data	Simulation data	Delta
Initial mission mass	260,806 kg	261,947kg	+0.4%
Distance actually flown	9,356km	9,510 km	+1.6%
No. of step climbs	0	2	
Fuel burn	74,884 kg	75,349 kg	+0.6%
Block time	10 hours 8 minutes	11 hours 20 minutes	+12.1%
CO_2 emissions (grams per ton-kilometer flown)	629	623	-1.0%

FLIGHT 10

Great circle distance (O-D pair)	A/C type	Engine type	Payload factor assumed	Payload mass	Initial cruise altitude
9,035 km	Airbus A340-313	CFM56-5C4/P	75.9%	35,673 kg	33,000 ft

	Real-life data	Simulation data	Delta
Initial mission mass	255,454 kg	255,992 kg	+0.2%
Distance actually flown	9,411 km	9,510 km	+1.1%
No. of step climbs	1	2	
Fuel burn	72,743 kg	74,078 kg	+1.8%
Block time	10 hours 25 minutes	11 hours 20 minutes	+9.0%
CO_2 emissions (grams per ton-kilometer flown)	684	696	+0.8%

Appendix F Next-generation aircraft types

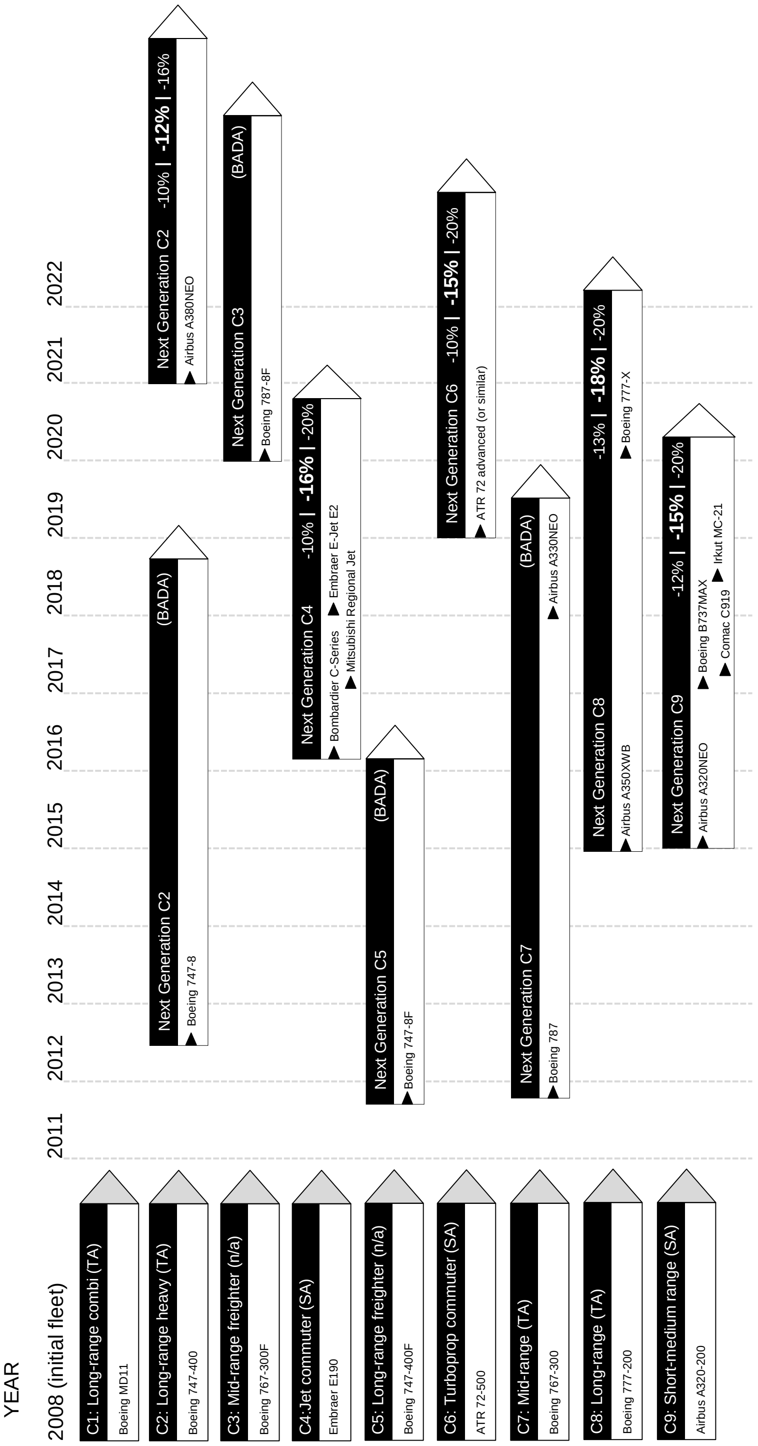


Figure F-1 **Next-generation aircraft types considered**
(incl. estimated entry-into-service year and gain in fuel efficiency relative to predecessor type)

Table F-1 **Next-generation aircraft types newly modeled in BADA**
Data sources: OAG (2008), author's calculations

Derivative A/C type	Basic A/C type (BADA)	Profile of characteristic flight mission					
		Stage length [km]	Seat capacity [seats] *(SLF = 80%)*	Freight capacity [tons] *(FLF = 40%)*	Mission fuel burn [kg]		
					Derivative A/C type	Basic A/C type	Delta
Airbus A320neo	Airbus A320-231	1,284	156	1.2	4,019	4,647	-13.5%
Airbus A350-900	Boeing 777-200ER	3,929	295	18	26,335	32,266	-18.4%
Airbus A380-800neo	Airbus A380-800	7,506	471	16.4	102,051	115,624	-11.7%
ATR 72adv	ATR 72-500	326	68	0.6	504	595	-15.3%
Bombardier CS100	Embraer 190	1,085	97	0.4	2,733	3,247	-15.8%

Table F-2 **Production rates p.a. of next-generation aircraft types (statistically determined)**
Data sources: Engelke (2014), author's estimations

	C1	C2		C3	C4	C5	C6	C7	C8	C9
	Representative next-generation aircraft types									
YEAR	n/a	747-8	A380-800neo	787-8F	CS100	747-8F	ATR 72adv	787-8	A350-900	A320neo
2011	0	0	0	0	0	Inf	0	5	0	0
2012	0	5	0	0	0	Inf	0	7	0	0
2013	0	7	0	0	0	Inf	0	10	0	0
2014	0	10	0	0	0	Inf	0	12	0	0
2015	0	12	0	0	0	Inf	0	15	5	1
2016	0	15	0	0	1	Inf	0	17	7	18
2017	0	17	0	0	19	Inf	0	20	10	37
2018	0	20	0	0	54	Inf	0	27	12	89
2019	0	22	0	0	105	Inf	2	32	15	157
2020	0	25	0	Inf	156	Inf	36	37	22	225
2021	0	27	5	Inf	207	Inf	70	42	27	293
2022	0	30	7	Inf	258	Inf	104	47	32	361
2023	0	32	10	Inf	309	Inf	138	52	37	429
2024	0	35	12	Inf	360	Inf	172	57	42	497
2025	0	37	15	Inf	411	Inf	206	62	47	565
2026	0	40	17	Inf	462	Inf	240	67	52	633
2027	0	42	20	Inf	513	Inf	274	72	57	701
2028	0	45	22	Inf	564	Inf	308	77	62	769
2029	0	47	25	Inf	615	Inf	342	82	67	837
2030	0	50	27	Inf	666	Inf	376	87	72	905
2031	0	52	30	Inf	717	Inf	410	92	77	973
2032	0	55	32	Inf	768	Inf	444	97	82	1,041

(Table continued on next page)

Table F-2 (continued)

	C1	C2		C3	C4	C5	C6	C7	C8	C9
					Representative next-generation aircraft types					
YEAR	n/a	747-8	A380-800neo	787-8F	CS100	747-8F	ATR 72adv	787-8	A350-900	A320neo
2033	0	57	35	Inf	819	Inf	478	102	87	1,109
2034	0	60	37	Inf	870	Inf	512	107	92	1,177
2035	0	62	40	Inf	921	Inf	546	112	97	1,245
2036	0	65	42	Inf	972	Inf	580	117	102	1,313
2037	0	67	45	Inf	1,023	Inf	614	122	107	1,381
2038	0	70	47	Inf	1,074	Inf	648	127	112	1,449
2039	0	72	50	Inf	1,125	Inf	682	132	117	1,517
2040	0	75	52	Inf	1,176	Inf	716	137	122	1,585
2041	0	77	55	Inf	1,227	Inf	750	142	127	1,653
2042	0	80	57	Inf	1,278	Inf	784	147	132	1,721
2043	0	82	60	Inf	1,329	Inf	818	152	137	1,789
2044	0	85	62	Inf	1,380	Inf	852	157	142	1,857
2045	0	87	65	Inf	1,431	Inf	886	162	147	1,925
2046	0	90	67	Inf	1,482	Inf	920	167	152	1,993
2047	0	92	70	Inf	1,533	Inf	954	172	157	2,061
2048	0	95	72	Inf	1,584	Inf	988	177	162	2,129
2049	0	97	75	Inf	1,635	Inf	1,022	182	167	2,197
2050	0	100	77	Inf	1,686	Inf	1,056	187	172	2,265

Table F-3 **Next-generation aircraft types: operational profile**

Data sources: manufacturers' homepages, author's estimations

A/C type	Entry-into-service year	Affiliation to cluster no.	Predecessor A/C type (Initial fleet)	Seat capacity	Freight capacity [tons]
Boeing 747-8F	2011	5	Boeing 747-400F	0	112
Boeing 787-8	2011	7	Boeing 767-300	242	14
Boeing 747-8	2012	2	Boeing 747-400	467	20
Airbus A350-900	2015	8	Boeing 777-200	315	34
Airbus A320neo	2015	9	Airbus A320-200	150	4
Bombardier CS100	2016	4	Embraer 190	97	2
ATR 72 advanced	2019	6	ATR 72-500	68	0
Boeing 787-8F	2020	3	Boeing 767-300F	0	52
Airbus A380neo	2021	2	Boeing 747-400	520	27

Appendix G Status-quo validation data

Table G-1 **Average RPK growth rates p.a. from 2008 to 2013 (Boeing CMO)**
Data source: Boeing CMO 2014

2008-2013	AF	LA	ME	EU	NA	AS
AS	-5.0%	17.9%	12.9%	1.5%	3.7%	9.2%
NA	14.2%	5.3%	16.4%	0.4%	0.5%	
EU	2.2%	3.1%	11.3%	1.6%		
ME	15.3%	8.7%	6.4%			
LA	17.9%	10.8%				
AF	5.2%					

Table G-2 **Average RTK growth rates p.a. from 2008 to 2013 (Boeing CMO)**
Data source: Boeing CMO 2014

2008-2013	AF	LA	ME	EU	NA	AS
AS	5.4%	3.1%	6.9%	1.0%	0.2%	1.1%
NA	4.4%	2.1%	5.9%	0.0%	-0.8%	
EU	5.2%	3.0%	6.7%	0.8%		
ME	11.1%	8.9%	12.7%			
LA	7.4%	5.1%				
AF	9.7%					

Table G-3 **Historical fleet size and composition (Boeing CMO)**
Data source: Boeing CMO (reports of 2009, 2010, 2011, 2012, 2013, and 2014)

No. of aircraft	2008	2009	2010	2011	2012	2013
Large widebody	870	800	770	790	780	740
Medium widebody[157]	3,510	3,500	3,640	3,710	1,520	1,580
Small widebody	n/a	n/a	n/a	n/a	2,310	2,390
Single aisle	11,360	11,580	12,100	12,610	13,040	13,580
Regional jets	3,060	3,010	2,900	2,780	2,660	2,620
All	**18,800**	**18,890**	**19,410**	**19,890**	**20,310**	**20,910**

---

[157] In the CMO reports of 2008, 2009, 2010, and 2011, Boeing does not distinguish between medium and small widebody aircraft.

Table G-4 **Historical global seat and freight transport supply and payload factors (Boeing CMO)**
Data sources: Boeing CMO (reports of 2009, 2010, 2011, 2012, 2013, and 2014); data related to air freight derived from Boeing Commercial Airplanes (2014c); data related to payload factors derived from IATA (2014) and ICAO (2014)

	2008	2009	2010	2011	2012	2013
RPKs [in trillions]	4.639	4.564	4.939	5.262	5.585	5.898
Change [% year-on-year]	n/a	-1.6	8.2	6.6	6.1	5.6
ASKs [in trillions]	6.120	5.958	6.324	6.755	7.097	7.400
Seat load factor [%]	75.8	76.6	78.1	77.9	78.7	79.7
RTKs[158] [in billions]	169	154	185	185	183	184
Change [% year-on-year]	n/a	-9.1	20.2	0.4	-1.4	0.5
ATKs [in billions]	367	341	362	378	381	390
Freight load factor [%]	46	45	51	49	48	47

Table G-5 **Historical global fuel consumption and exhaust gas emissions (Boeing CMO)**
Data sources: fuel consumption and CO_2 emissions derived from EIA (2015) for the years 2008-2010; CO_2 emissions per ASK based on ASK data published by Schäfer (2012, p. 222); NO_x/CO/UHC/PM emissions derived from Schäfer (2012, p. 222) for the years 2008-2010; all indicated data from 2011-2013 derived from the 'Baseline Scenario' published by Schäfer (2012, p. 222)

	2008	2009	2010	2011	2012	2013
Fuel consumption [Mio. tons]	185.1	175.0	183.6	198.3	208.4	219.0
Emissions of CO_2 [Mio. tons]	584.1	552.2	579.3	625.8	657.7	691.2
Emissions of CO_2 [Grams per ASK]	97.1	93.3	91.6	93.6	93.1	92.6
Emissions of NO_x [Mio. tons]	2.589	2.516	2.670	2.824	2.976	3.136
Emissions of CO [Mio. tons]	0.621	0.583	0.604	n/a	n/a	n/a
Emissions of UHC [Mio. tons]	0.071	0.062	0.062	n/a	n/a	n/a
Emissions of PM [Mio. kg]	6.170	5.755	6.089	n/a	n/a	n/a

---

[158] Scheduled freight considered only.

Table G-6 **Historical RPK growth rates (Boeing CMO)**

Data source: Boeing CMO 2014

2008-2009	AF	LA	ME	EU	NA	AS
AS	-23.9%	25.0%	17.6%	-8.0%	-7.2%	1.1%
NA	39.6%	-4.1%	40.7%	-6.2%	-6.1%	
EU	2.0%	-1.3%	13.9%	-5.4%		
ME	32.0%	5.6%	8.3%			
LA	25.0%	2.9%				
AF	5.5%					

2009-2010	AF	LA	ME	EU	NA	AS
AS	37.1%	26.7%	17.8%	4.7%	8.3%	14.3%
NA	29.0%	7.5%	10.0%	3.2%	3.4%	
EU	5.7%	0.2%	9.6%	2.4%		
ME	10.8%	20.1%	13.6%			
LA	26.7%	26.6%				
AF	10.9%					

2010-2011	AF	LA	ME	EU	NA	AS
AS	5.4%	10.9%	9.9%	5.1%	10.4%	11.1%
NA	0.7%	4.4%	10.1%	2.8%	3.2%	
EU	-1.0%	4.3%	6.6%	3.0%		
ME	8.3%	9.0%	5.7%			
LA	10.9%	12.3%				
AF	4.9%					

2011-2012	AF	LA	ME	EU	NA	AS
AS	-21.4%	19.1%	6.5%	6.6%	6.2%	10.0%
NA	10.8%	12.6%	13.4%	0.6%	0.9%	
EU	4.7%	8.8%	16.1%	2.6%		
ME	23.2%	-0.1%	-7.2%			
LA	19.1%	7.0%				
AF	6.8%					

2012-2013	AF	LA	ME	EU	NA	AS
AS	-10.5%	8.7%	13.2%	-0.1%	2.0%	9.9%
NA	-3.5%	6.6%	10.8%	2.0%	1.4%	
EU	0.0%	3.7%	10.6%	5.5%		
ME	4.4%	9.9%	12.9%			
LA	8.7%	6.8%				
AF	-1.5%					

Table G-7 **Historical RTK growth rates (Boeing CMO)**
Data source: Boeing World Air Cargo Forecast 2014-2015

2008-2009	AF	LA	ME	EU	NA	AS
AS	-7.2%	-5.8%	-2.6%	-10.8%	-9.6%	-6.7%
NA	-10.1%	-8.6%	-5.4%	-13.7%	-12.4%	
EU	-11.3%	-9.9%	-6.7%	-14.9%		
ME	-3.1%	-1.6%	1.6%			
LA	-6.2%	-4.8%				
AF	-7.7%					

2009-2010	AF	LA	ME	EU	NA	AS
AS	31.5%	22.3%	25.1%	19.1%	18.4%	23.3%
NA	26.6%	17.4%	20.1%	14.2%	13.4%	
EU	27.4%	18.1%	20.9%	15.0%		
ME	33.3%	24.1%	26.8%			
LA	30.6%	21.3%				
AF	39.8%					

2010-2011	AF	LA	ME	EU	NA	AS
AS	-4.0%	3.5%	2.0%	0.1%	-2.1%	-4.8%
NA	-1.3%	6.1%	4.7%	2.8%	0.5%	
EU	0.9%	8.4%	6.9%	5.0%		
ME	2.8%	10.3%	8.8%			
LA	4.3%	11.7%				
AF	-3.2%					

2011-2012	AF	LA	ME	EU	NA	AS
AS	5.9%	-4.1%	4.4%	-3.9%	-3.3%	-5.5%
NA	8.2%	-1.9%	6.6%	-1.7%	-1.0%	
EU	7.5%	-2.5%	5.9%	-2.4%		
ME	15.8%	5.7%	14.2%			
LA	7.3%	-2.7%				
AF	17.4%					

2012-2013	AF	LA	ME	EU	NA	AS
AS	0.6%	-0.4%	5.6%	0.3%	-2.6%	-0.8%
NA	-1.3%	-2.3%	3.7%	-1.6%	-4.5%	
EU	1.7%	0.7%	6.7%	1.4%		
ME	6.9%	5.9%	11.9%			
LA	1.0%	-0.1%				
AF	2.0%					

Table G-8 Fleet size and composition (Simulation data)

A/C cluster no./ A/C type	2008	2009	2010	2011	2012	2013
1	83	71	55	44	27	17
2	619	557	532	504	467	431
3	234	233	264	267	266	264
4	3,507	3,198	3,099	3,001	2,906	2,812
5	271	269	354	366	365	361
6	337	330	322	314	247	185
7	2,044	1,994	2,235	2,464	2,699	2,885
8	1,279	1,235	1,259	1,289	1,306	1,353
9	8,843	9,235	10,007	10,795	11,600	12,420
Boeing 747-8F	0	0	0	0	12	22
Boeing 787-8	0	0	0	0	5	11
Boeing 747-8	0	0	0	0	0	5
SUM	17,216	17,121	18,127	19,045	19,899	20,766

Table G-9 Global seat transport supply and payload factors (Simulation data)

	2008	2009	2010	2011	2012	2013
RPKs [in trillions]	4.662	4.569	4.788	5,012	5,226	5,441
Change [% year-on-year]	n/a	-2.0	4.8	4.7	4.3	4.1
ASKs [in trillions]	5.992	5.873	6.155	6.442	6.717	6.993
Seat load factor [%]	77.8	77.8	77.8	77.8	77.8	77.8

Table G-10 Global fuel consumption and exhaust emissions (Simulation data)

	2008	2009	2010	2011	2012	2013
Fuel consumption [Mio. tons]	183.2	178.8	190.1	198.1	205.4	212.8
Emissions of CO_2 [Mio. tons]	578.3	564.2	600.0	625.2	648.3	671.5
Emissions of CO_2 [Grams per ASK]	96.5	96.1	97.5	97.1	96.5	96.0
Emissions of NO_x [Mio. tons]	2.751	2.688	2.856	2.981	3.095	3.215
Emissions of CO [Mio. tons]	0.470	0.461	0.493	0.516	0.536	0.557
Emissions of UHC [Mio. tons]	0.064	0.062	0.066	0.069	0.071	0.073
Emissions of PM [Mio. kg]	0.407	0.403	0.433	0.456	0.478	0.503

Table G-11 Fleet size and composition (Simulation data / Case study 1: constrained aircraft addition)

A/C cluster no./ A/C type	2008	2009	2010	2011	2012	2013
1	83	71	66	60	55	51
2	619	557	531	500	467	432
3	234	233	265	267	266	264
4	3,507	3,198	3,099	3,001	2,905	2,811
5	270	268	354	366	364	361
6	337	330	322	314	237	232
7	2,044	1,994	1,975	1,937	1,853	1,761
8	1,279	1,235	1,233	1,230	1,212	1,195
9	8,843	9,235	11,736	13,980	16,306	18,179
Boeing 747-8F	0	0	0	0	14	25
Boeing 787-8	0	0	0	0	33	45
Boeing 747-8	0	0	0	0	0	61
SUM	17,216	17,121	19,759	21,655	23,713	25,416

Table G-12 Global seat transport supply and payload factors (Simulation data / Case study 1: constrained aircraft addition)

	2008	2009	2010	2011	2012	2013
RPKs [in trillions]	4.662	4.569	4.933	5.242	5.551	5.837
Change [% year-on-year]	n/a	-2.0	8.0	6.3	5.9	5.2
ASKs [in trillions]	5.992	5.873	6.341	6.737	7.135	7.503
Seat load factor [%]	77.8	77.8	77.8	77.8	77.8	77.8

Table G-13 Global fuel consumption and exhaust emissions (Simulation data / Case study 1: constrained aircraft addition)

	2008	2009	2010	2011	2012	2013
Fuel consumption [Mio. tons]	183.2	178.8	194.3	204.5	214.4	223.4
Emissions of CO_2 [Mio. tons]	578.30	564.22	613.23	645.42	676.54	705.21
Emissions of CO_2 [Grams per ASK]	96.5	96.1	96.7	95.8	94.8	94.0
Emissions of NO_x [Mio. tons]	2.751	2.688	2.910	3.059	3.205	3.332
Emissions of CO [Mio. tons]	0.470	0.461	0.516	0.554	0.591	0.625
Emissions of UHC [Mio. tons]	0.064	0.062	0.070	0.075	0.080	0.083
Emissions of PM [Mio. kg]	0.407	0.403	0.458	0.499	0.539	0.578

Table G-14 Fleet size and composition (Simulation data / Case study 2: averaged growth rates)

A/C cluster no./ A/C type	2008	2009	2010	2011	2012	2013
1	83	69	54	41	27	13
2	619	583	549	518	475	478
3	234	237	238	239	238	236
4	3,507	3,367	3,237	31,14	2,997	2,893
5	270	288	298	308	305	302
6	337	330	322	314	305	295
7	2,044	2,261	2,499	2,732	2,961	3,142
8	1,279	1,305	1,333	1,357	1,377	1,393
9	8,843	9,594	10,365	11,154	11,958	12,772
Boeing 747-8F	0	0	0	0	14	31
Boeing 787-8	0	0	0	0	5	11
Boeing 747-8	0	0	0	0	0	5
SUM	17,216	18,033	18,895	19,775	20,661	21,570

Table G-15 Global seat transport supply and payload factors (Simulation data / Case study 2: averaged growth rates)

	2008	2009	2010	2011	2012	2013
RPKs [in trillions]	4.6616	4.8549	5.0676	5.2813	5.4826	5.7156
Change [% year-on-year]	n/a	4.1	4.4	4.2	3.8	4.3
ASKs [in trillions]	5.992	6.240	6.514	6.788	7.047	7.347
Seat load factor [%]	77.8	77.8	77.8	77.8	77.8	77.8

Table G-16 Global fuel consumption and exhaust emissions (Simulation data / Case study 2: averaged growth rates)

	2008	2009	2010	2011	2012	2013
Fuel consumption [Mio. tons]	183.2	190.3	197.7	205.2	212.2	220.7
Emissions of CO_2 [Mio. tons]	578.30	600.59	624.04	647.55	669.81	696.40
Emissions of CO_2 [Grams per ASK]	96.5	96.2	95.8	95.4	95.0	94.8
Emissions of NO_x [Mio. tons]	2.751	2.863	2.980	3.098	3.209	3.333
Emissions of CO [Mio. tons]	0.470	0.490	0.511	0.532	0.553	0.575
Emissions of UHC [Mio. tons]	0.064	0.066	0.068	0.070	0.072	0.074
Emissions of PM [Mio. kg]	0.407	0.429	0.451	0.474	0.497	0.519

Appendix H Future-forecasting validation data

Table H-1 **Assumed RPK growth rates according to Boeing CMO 2014**
Data source: Boeing CMO 2014

2014-2033	AF	LA	ME	EU	NA	AS
AS	7.1%	8.8%	7.4%	5.3%	4.3%	6.4%
NA	6.1%	4.7%	6.3%	3.1%	2.3%	
EU	4.9%	4.9%	5.4%	3.5%		
ME	7.3%	0.0%	5.2%			
LA	8.0%	6.9%				
AF	6.7%					

Table H-2 **Assumed RTK growth rates according to Boeing CMO 2014**
Data source: Boeing World Air Cargo Forecast 2014[159]

2014-2033	AF	LA	ME	EU	NA	AS
AS	4.7%	4.7%	4.7%	5.3%	5.4%	6.5%
NA	4.7%	5.2%	4.7%	3.1%	2.1%	
EU	4.3%	4.8%	4.0%	2.0%		
ME	4.7%	4.7%	4.7%			
LA	4.7%	4.7%				
AF	4.7%					

Table H-3 **Estimated global RPK and ASK development (Boeing CMO 2014 and simulation)**
Data sources: Boeing CMO 2014, author's calculations

	Boeing CMO 2014		Simulation data			
	RPKs [in trillions]	Change [% year-on-year]	RPKs [in trillions]	Change [% year-on-year]	ASKs [in trillions]	Seat load factor [%]
2013	5.898	n/a	6.172	n/a	7.348	84
2014	6.191	5.00	6.411	3.88	7.632	84
2015	6.498	5.00	6.655	3.80	7.922	84
2016	6.820	5.00	6.906	3.78	8.222	84
2017	7.159	5.00	7.163	3.72	8.527	84
2018	7.514	5.00	7.423	3.63	8.837	84
2019	7.887	5.00	7.686	3.55	9.150	84
2020	8.278	5.00	7.953	3.47	9.468	84

(Table continued on next page)

---

[159] Values not explicitly given in the Boeing World Air Cargo Forecast 2014 report were assumed to be at 4.7%.

Table H-3 (continued)

	Boeing CMO 2014		Simulation data			
	RPKs [in trillions]	Change [% year-on-year]	RPKs [in trillions]	Change [% year-on-year]	ASKs [in trillions]	Seat load factor [%]
2021	8.689	5.00	8.226	3.43	9.793	84
2022	9.120	5.00	8.504	3.38	10.124	84
2023	9.573	5.00	8.790	3.36	10.464	84
2024	10.048	5.00	9.083	3.34	10.813	84
2025	10.547	5.00	9.384	3.31	11.172	84
2026	11.070	5.00	9.692	3.27	11.538	84
2027	11.619	5.00	10.004	3.22	11.909	84
2028	12.196	5.00	10.319	3.15	12.284	84
2029	12.801	5.00	10.635	3.06	12.660	84
2030	13.436	5.00	10.950	2.96	13.036	84
2031	14.103	5.00	11.263	2.85	13.408	84
2032	14.803	5.00	11.571	2.74	13.775	84
2033	15.538	5.00	11.874	2.62	14.136	84

Table H-4 **Route-group specific RPKs p.a. (Boeing CMO 2014 and simulation)**

Data sources: Boeing CMO 2014, author's calculations

	RPKs in billions			
	Boeing CMO 2014		Simulation data	
Route Group	2013	2033	2013	2033
AFAF	53.701	197.608	66.578	174.614
EUAF	140.447	368.614	162.893	273.522
AFME	50.760	206.007	80.396	201.574
AFNA	12.184	40.114	22.291	59.015
AFAS	4.157	14.984	18.252	43.311
LALA	212.462	810.734	254.803	721.471
EULA	184.438	477.241	212.604	378.023
NALA	217.510	549.042	239.059	470.425
ASAS	1,437.926	4,825.834	1,483.727	3,276.850
ASNA	292.866	641.260	382.667	618.398
EUAS	332.931	929.303	456.210	997.134
EUEU	713.957	1,411.445	679.405	1,095.361
EUME	196.803	561.588	191.073	418.589
EUNA	441.791	817.891	469.479	773.470
MEME	86.338	239.854	51.899	116.969
MENA	63.236	214.550	76.560	178.378
MEAS	174.078	704.300	252.491	788.251
NANA	998.423	1,565.847	1,058.090	1,259.263

Table H-5 **Fleet size and composition (Boeing CMO 2014 and simulation)**
Data sources: Boeing CMO 2014, author's calculations

	Boeing CMO 2014						Simulation data					
	RJ	SA	SW	MW	LW	SUM	RJ	SA	SW	MW	LW	SUM
2013	2,620	13,580	2,390	1,580	740	**20,910**	3,181	12,778	3,399	1,407	787	**21,553**
2014							3,064	13,615	3,594	1,424	787	**22,485**
2015							2,950	14,469	3,785	1,440	792	**23,436**
2016							2,836	15,342	3,979	1,463	799	**24,420**
2017							2,725	16,233	4,194	1,481	807	**25,440**
2018							2,630	17,123	4,413	1,495	819	**26,480**
2019							2,570	17,993	4,635	1,504	837	**27,539**
2020							2,557	18,825	4,859	1,512	860	**28,613**
2021							2,593	19,616	5,076	1,521	889	**29,694**
2022							2,675	20,363	5,287	1,524	935	**30,784**
2023							2,760	21,107	5,495	1,525	991	**31,879**
2024							2,840	21,853	5,700	1,526	1,056	**32,974**
2025							2,916	22,598	5,899	1,528	1,130	**34,071**
2026							2,990	23,339	6,094	1,530	1,213	**35,167**
2027							3,061	24,073	6,282	1,533	1,307	**36,257**
2028							3,132	24,796	6,461	1,539	1,409	**37,336**
2029							3,202	25,502	6,629	1,547	1,520	**38,400**
2030							3,274	26,188	6,783	1,561	1,640	**39,445**
2031							3,349	26,851	6,920	1,579	1,770	**40,468**
2032							3,428	27,489	7,038	1,603	1,908	**41466**
2033	2,640	29,500	5,570	3,680	790	**42,180**	3,512	28,103	7,137	1,633	2,055	**42,440**

Table H-6 **RPKs per aircraft (Boeing CMO 2014 and simulation)**
Data sources: Boeing CMO 2014, author's calculations

	RPKs in billions	
	Boeing CMO 2014	Simulation data
2013	0.3069	0.2939
2014	0.3112	0.2925
2015	0.3156	0.2913
2016	0.3199	0.2901
2017	0.3243	0.2891
2018	0.3286	0.2881
2019	0.3330	0.2871
2020	0.3373	0.2862
2021	0.3417	0.2855
2022	0.3460	0.2849
2023	0.3504	0.2846
2024	0.3547	0.2845
2025	0.3591	0.2847
2026	0.3634	0.2851
2027	0.3678	0.2856
2028	0.3721	0.2863
2029	0.3765	0.2871

(Table continued on next page)

Table H-6 (continued)

	RPKs in billions	
	Boeing CMO 2014	Simulation data
2030	0.3808	0.2881
2031	0.3852	0.2891
2032	0.3895	0.2902
2033	0.3939	0.2913

Table H-7 Global fuel consumption and CO_2 performance (Schäfer (2012) and simulation)

Data sources: Schäfer (2012), author's calculations

	Schäfer (2012)			Simulation		
	Fuel consumption [Mio. tons]	Emissions of CO_2 [Mio. tons]	Emissions of CO_2 [Grams per ASK]	Fuel consumption [Mio. tons]	Emissions of CO_2 [Mio. tons]	Emissions of CO_2 [Grams per ASK]
2013	219.0	691.2	92.60	221.3	698.3	95.04
2014				229.5	724.4	94.91
2015	241.4	761.9	91.46	238.0	751.0	94.80
2016				246.9	779.1	94.76
2017				256.1	808.3	94.79
2018				265.5	837.9	94.82
2019				275.0	868.0	94.86
2020	293.3	925.7	88.15	284.7	898.5	94.89
2021				294.4	929.1	94.87
2022				304.4	960.6	94.88
2023				314.6	992.8	94.87
2024				325.0	1,025.7	94.85
2025	343.8	1,085.0	84.71	335.7	1,059.3	94.82
2026				346.5	1,093.7	94.79
2027				357.6	1,128.6	94.77
2028				368.8	1,164.1	94.76
2029				380.2	1,199.9	94.77
2030	404.5	1,276.6	81.67	391.6	1,235.9	94.81
2031				403.1	1,272.0	94.87
2032				414.5	1,308.3	94.97
2033				426.0	1,344.5	95.11

Table H-8 Estimated global RPK development and growth rates (case study 3)

	Reference case		Unconstrained-addition case	
	RPKs [in trillions]	Change [% year-on-year]	RPKs [in trillions]	Change [% year-on-year]
2008	5.033	n/a	5.033	n/a
2009	5.246	4.24%	5.246	4.24%
2010	5.478	4.42%	5.478	4.42%
2011	5.710	4.23%	5.710	4.23%
2012	5.940	4.03%	5.946	4.13%

(Table continued on next page)

Table H-8 (continued)

	Reference case		Unconstrained-addition case	
	RPKs [in trillions]	Change [% year-on-year]	RPKs [in trillions]	Change [% year-on-year]
2013	6.169	3.85%	6.240	4.95%
2014	6.404	3.81%	6.539	4.80%
2015	6.641	3.71%	6.854	4.82%
2016	6.884	3.65%	7.187	4.85%
2017	7.128	3.55%	7.528	4.75%
2018	7.375	3.47%	7.874	4.59%
2019	7.625	3.39%	8.223	4.44%
2020	7.878	3.32%	8.577	4.30%
2021	8.134	3.25%	8.934	4.17%
2022	8.393	3.18%	9.295	4.04%
2023	8.655	3.12%	9.660	3.92%
2024	8.919	3.05%	10.028	3.81%
2025	9.186	2.99%	10.398	3.69%
2026	9.454	2.92%	10.769	3.57%
2027	9.723	2.84%	11.139	3.43%
2028	9.989	2.75%	11.505	3.29%
2029	10.253	2.64%	11.866	3.13%
2030	10.511	2.52%	12.217	2.96%
2031	10.762	2.39%	12.557	2.78%
2032	11.005	2.26%	12.883	2.60%
2033	11.239	2.12%	13.194	2.42%

Table H-9 Fleet size and composition (case study 3)

	Reference case						Unconstrained-addition case					
	RJ	SA	SW	MW	LW	SUM	RJ	SA	SW	MW	LW	SUM
2008	3,844	8,843	2,306	1,362	866	**17,222**	3,844	8,843	2,306	1,362	866	**17,222**
2009	3,697	9,594	2,518	1,371	855	**18,034**	3,697	9,594	2,518	1,371	855	**18,034**
2010	3,559	10,365	2,746	1,382	832	**18,885**	3,559	10,365	2,746	1,382	832	**18,885**
2011	3,428	11,154	2,972	1,392	814	**19,760**	3,428	11,154	2,972	1,392	814	**19,760**
2012	3,302	11,958	3,194	1,400	797	**20,652**	3,302	11,958	3,235	1,365	789	**20,649**
2013	3,181	12,778	3,414	1,405	781	**21,559**	3,181	12,778	3,399	1,340	850	**21,548**
2014	3,064	13,615	3,639	1,418	768	**22,504**	3,064	13,615	3,513	1,314	941	**22,448**
2015	2,950	14,469	3,863	1,430	756	**23,468**	2,950	14,469	3,643	1,285	1,038	**23,385**
2016	2,836	15,342	4,088	1,443	748	**24,458**	2,836	15,342	3,522	1,619	1,020	**24,339**
2017	2,724	16,234	4,316	1,450	749	**25,473**	2,724	16,234	3,401	1,960	980	**25,299**
2018	2,610	17,143	4,550	1,452	753	**26,508**	2,610	17,143	3,279	2,300	942	**26,274**
2019	2,496	18,067	4,791	1,449	760	**27,563**	2,496	18,067	3,157	2,640	906	**27,266**
2020	2,379	19,004	5,039	1,439	772	**28,634**	2,379	19,004	3,037	2,978	874	**28,272**
2021	2,260	19,951	5,297	1424	789	**29,720**	2,260	19,951	2,919	3,315	846	**29,290**
2022	2,137	20,904	5,563	1,405	810	**30,819**	2,137	20,904	2,802	3,652	821	**30,317**
2023	2,012	21,861	5,838	1,380	836	**31,928**	2,012	21,861	2,688	3,988	801	**31,350**
2024	1,883	22,819	6,121	1,352	868	**33,041**	1,883	22,819	2,575	4,325	786	**32,387**

(Table continued on next page)

Table H-9 (continued)

	Reference case						Unconstrained-addition case					
	RJ	SA	SW	MW	LW	SUM	RJ	SA	SW	MW	LW	SUM
2025	1,752	23,774	6,409	1,321	905	**34,161**	1,752	23,774	2,463	4,662	775	**33,425**
2026	1,620	24,725	6,703	1,288	947	**35,283**	1,620	24,725	2,350	5,001	767	**34,462**
2027	1,488	25,666	7,001	1,253	995	**36,403**	1,488	25,666	2,236	5,341	764	**35,495**
2028	1,358	26,595	7,299	1,218	1,048	**37,518**	1,358	26,595	2,120	5,683	762	**36,517**
2029	1,229	27,505	7,596	1,183	1,107	**38,620**	1,229	27,505	2,001	6,026	763	**37,524**
2030	1,104	28,394	7,890	1,149	1,172	**39,709**	1,104	28,394	1,874	6,370	766	**38,509**
2031	984	29,259	8,177	1,116	1,247	**40,783**	984	29,259	1,739	6,714	771	**39,469**
2032	872	30,097	8,456	1,085	1,328	**41,838**	872	30,097	1,597	7,057	779	**40,401**
2033	766	30,908	8,727	1,056	1,416	**42,873**	766	30,908	1447	7,396	790	**41,307**

Table H-10 **Total fleet development and share of next-generation aircraft (case study 3, unconstrained-addition case only)**

	No. of initial-fleet aircraft units	No. of next-generation aircraft units	Share of next-generation aircraft units in total fleet
2008	17,222	0	0.00%
2009	18,034	0	0.00%
2010	18,885	0	0.00%
2011	19,760	0	0.00%
2012	20,414	236	1.14%
2013	21,134	414	1.92%
2014	21,831	617	2.75%
2015	22,555	831	3.55%
2016	21,893	2,446	10.05%
2017	21,226	4,073	16.10%
2018	20,540	5,734	21.82%
2019	19,840	7,426	27.24%
2020	19,120	9,151	32.37%
2021	18,380	10,910	37.25%
2022	17,618	12,699	41.89%
2023	16,834	14,517	46.30%
2024	16,023	16,364	50.53%
2025	15,188	18,237	54.56%
2026	14,328	20,134	58.42%
2027	13,444	22,051	62.12%
2028	12,537	23,980	65.67%
2029	11,605	25,918	69.07%
2030	10,651	27,858	72.34%
2031	9,679	29,790	75.48%
2032	8,697	31,704	78.47%
2033	7,718	33,589	81.31%

Table H-11 RPKs per aircraft (case study 3)

	RPKs in billions	
	Reference case	Unconstrained-addition case
2008	0.3012	0.3012
2009	0.2997	0.2997
2010	0.2984	0.2984
2011	0.2970	0.2970
2012	0.2955	0.2957
2013	0.2937	0.2971
2014	0.2922	0.2987
2015	0.2907	0.3003
2016	0.2892	0.3024
2017	0.2877	0.3043
2018	0.2863	0.3060
2019	0.2848	0.3076
2020	0.2835	0.3091
2021	0.2823	0.3105
2022	0.2812	0.3118
2023	0.2802	0.3132
2024	0.2793	0.3145
2025	0.2786	0.3158
2026	0.2779	0.3171
2027	0.2774	0.3184
2028	0.2770	0.3197
2029	0.2766	0.3208
2030	0.2762	0.3219
2031	0.2759	0.3229
2032	0.2756	0.3237
2033	0.2752	0.3244

Table H-12 Global fuel consumption and CO_2 performance (case study 3)

	Reference case		Unconstrained-addition case	
	Fuel consumption [Mio. tons]	Emissions of CO_2 [Grams per ASK]	Fuel consumption [Mio. tons]	Emissions of CO_2 [Grams per ASK]
2008	184.3	97.07	184.3	97.07
2009	191.5	96.76	191.5	96.76
2010	198.8	96.19	198.8	96.19
2011	206.3	95.76	206.3	95.76
2012	213.7	95.39	213.7	95.27
2013	221.2	95.07	222.7	94.62
2014	229.4	94.96	232.3	94.17
2015	237.7	94.89	242.4	93.76
2016	246.3	94.86	250.1	92.27
2017	255.3	94.93	257.3	90.61

(Table continued on next page)

Table H-12 (continued)

	Reference case		Unconstrained-addition case	
	Fuel consumption [Mio. tons]	Emissions of CO_2 [Grams per ASK]	Fuel consumption [Mio. tons]	Emissions of CO_2 [Grams per ASK]
2018	264.4	95.03	264.5	89.07
2019	273.7	95.16	271.9	87.65
2020	283.2	95.30	279.4	86.36
2021	293.0	95.48	287.0	85.17
2022	302.9	95.69	294.8	84.08
2023	313.1	95.92	302.8	83.09
2024	323.6	96.17	310.9	82.19
2025	334.2	96.46	319.2	81.37
2026	345.1	96.77	327.5	80.63
2027	356.1	97.11	336.0	79.96
2028	367.4	97.49	344.4	79.37
2029	378.7	97.91	352.9	78.84
2030	390.1	98.38	361.2	78.38
2031	401.7	98.95	369.4	77.98
2032	413.3	99.57	377.4	77.65
2033	425.0	100.26	385.2	77.39

Table H-13 **Global fuel consumption and CO_2 performance (case study 3: reference case without aircraft production limitations)**

	Reference case without aircraft production limitations	
	Fuel consumption [Mio. tons]	Emissions of CO_2 [Grams per ASK]
2008	184.3	97.07
2009	190.9	96.49
2010	198.2	95.93
2011	206.2	95.41
2012	214.9	94.88
2013	224.4	94.37
2014	234.9	94.26
2015	246.0	94.16
2016	257.7	94.06
2017	270.0	93.96
2018	282.9	93.87
2019	296.6	93.77
2020	311.0	93.67
2021	326.4	93.62
2022	342.6	93.58
2023	359.7	93.54
2024	377.8	93.49
2025	396.8	93.43
2026	416.9	93.38
2027	438.0	93.32

(Table continued on next page)

Table H-13 (continued)

	Reference case without aircraft production limitations	
	Fuel consumption [Mio. tons]	Emissions of CO_2 [Grams per ASK]
2028	460.4	93.27
2029	484.0	93.21
2030	509.0	93.15
2031	535.4	93.10
2032	563.3	93.04
2033	592.8	92.99

Appendix I Simulation data (Chapter 7)

Table I-1 **Assumed RPK growth rates p.a. from 2014 to 2050 (Rough Air scenario)**
Data based on Randt et al. (2015, p. 12)

	EU	EU	EU	EU	EU	EU	AS	AS	AS	AS	AS	ME	ME	ME	ME	AF	AF	AF	LA	LA	NA
	EU	AS	ME	AF	LA	NA	AS	ME	AF	LA	NA	ME	AF	LA	NA	AF	LA	NA	LA	NA	NA
2014	2.0%	6.5%	6.5%	5.5%	5.5%	2.0%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	5.5%	5.5%	5.5%	5.5%	5.5%	2.0%
2015	2.0%	6.0%	6.0%	5.3%	5.3%	2.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	5.3%	5.3%	5.3%	5.3%	5.3%	2.0%
2016	2.0%	5.5%	5.5%	5.2%	5.2%	2.0%	5.5%	5.5%	5.5%	5.5%	5.5%	5.5%	5.5%	5.5%	5.5%	5.2%	5.2%	5.2%	5.2%	5.2%	2.0%
2017	1.9%	5.0%	5.0%	5.0%	5.0%	1.9%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	1.9%
2018	1.9%	4.5%	4.5%	4.8%	4.8%	1.9%	4.5%	4.5%	4.8%	4.8%	4.5%	4.5%	4.8%	4.8%	4.5%	4.8%	4.8%	4.8%	4.8%	4.8%	1.9%
2019	1.8%	4.0%	4.0%	4.5%	4.5%	1.8%	4.0%	4.0%	4.5%	4.5%	4.0%	4.0%	4.5%	4.5%	4.0%	4.5%	4.5%	4.5%	4.5%	4.5%	1.8%
2020	1.8%	4.1%	4.1%	4.3%	4.3%	1.8%	4.1%	4.1%	4.3%	4.3%	4.1%	4.1%	4.3%	4.3%	4.1%	4.3%	4.3%	4.3%	4.3%	4.3%	1.8%
2021	1.7%	4.2%	4.2%	4.0%	4.0%	1.7%	4.2%	4.2%	4.2%	4.2%	4.2%	4.2%	4.2%	4.2%	4.2%	4.0%	4.0%	4.0%	4.0%	4.0%	1.7%
2022	1.7%	4.3%	4.3%	4.1%	4.1%	1.7%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.1%	4.1%	4.1%	4.1%	4.1%	1.7%
2023	1.7%	4.4%	4.4%	4.1%	4.1%	1.7%	4.4%	4.4%	4.4%	4.4%	4.4%	4.4%	4.4%	4.4%	4.4%	4.1%	4.1%	4.1%	4.1%	4.1%	1.7%
2024	1.7%	4.0%	4.0%	4.2%	4.2%	1.7%	4.0%	4.0%	4.2%	4.2%	4.0%	4.0%	4.2%	4.2%	4.0%	4.2%	4.2%	4.2%	4.2%	4.2%	1.7%
2025	1.7%	3.6%	3.6%	4.2%	4.2%	1.7%	3.6%	3.6%	4.2%	4.2%	3.6%	3.6%	4.2%	4.2%	3.6%	4.2%	4.2%	4.2%	4.2%	4.2%	1.7%
2026	1.7%	3.5%	3.5%	4.3%	4.3%	1.7%	3.5%	3.5%	4.3%	4.3%	3.5%	3.5%	4.3%	4.3%	3.5%	4.3%	4.3%	4.3%	4.3%	4.3%	1.7%
2027	1.6%	3.3%	3.3%	4.3%	4.3%	1.6%	3.3%	3.3%	4.3%	4.3%	3.3%	3.3%	4.3%	4.3%	3.3%	4.3%	4.3%	4.3%	4.3%	4.3%	1.6%
2028	1.0%	3.2%	3.2%	4.2%	4.2%	1.0%	3.2%	3.2%	4.2%	4.2%	3.2%	3.2%	4.2%	4.2%	3.2%	4.2%	4.2%	4.2%	4.2%	4.2%	1.0%
2029	0.6%	3.0%	3.0%	4.1%	4.1%	0.6%	3.0%	3.0%	4.1%	4.1%	3.0%	3.0%	4.1%	4.1%	3.0%	4.1%	4.1%	4.1%	4.1%	4.1%	0.6%
2030	0.2%	3.0%	3.0%	4.0%	4.0%	0.2%	3.0%	3.0%	4.0%	4.0%	3.0%	3.0%	4.0%	4.0%	3.0%	4.0%	4.0%	4.0%	4.0%	4.0%	0.2%
2031	0.0%	3.0%	3.0%	3.9%	3.9%	0.0%	3.0%	3.0%	3.9%	3.9%	3.0%	3.0%	3.9%	3.9%	3.0%	3.9%	3.9%	3.9%	3.9%	3.9%	0.0%
2032	-0.1%	2.9%	2.9%	4.2%	4.2%	-0.1%	2.9%	2.9%	4.2%	4.2%	2.9%	2.9%	4.2%	4.2%	2.9%	4.2%	4.2%	4.2%	4.2%	4.2%	-0.1%
2033	-0.1%	2.7%	2.7%	4.4%	4.4%	-0.1%	2.7%	2.7%	4.4%	4.4%	2.7%	2.7%	4.4%	4.4%	2.7%	4.4%	4.4%	4.4%	4.4%	4.4%	-0.1%
2034	-0.2%	2.6%	2.6%	4.5%	4.5%	-0.2%	2.6%	2.6%	4.5%	4.5%	2.6%	2.6%	4.5%	4.5%	2.6%	4.5%	4.5%	4.5%	4.5%	4.5%	-0.2%
2035	-0.2%	2.4%	2.4%	4.6%	4.6%	-0.2%	2.4%	2.4%	4.6%	4.6%	2.4%	2.4%	4.6%	4.6%	2.4%	4.6%	4.6%	4.6%	4.6%	4.6%	-0.2%
2036	-0.3%	2.3%	2.3%	4.7%	4.7%	-0.3%	2.3%	2.3%	4.7%	4.7%	2.3%	2.3%	4.7%	4.7%	2.3%	4.7%	4.7%	4.7%	4.7%	4.7%	-0.3%
2037	-0.4%	2.2%	2.2%	4.8%	4.8%	-0.4%	2.2%	2.2%	4.8%	4.8%	2.2%	2.2%	4.8%	4.8%	2.2%	4.8%	4.8%	4.8%	4.8%	4.8%	-0.4%
2038	-0.7%	2.1%	2.1%	4.9%	4.9%	-0.7%	2.1%	2.1%	4.9%	4.9%	2.1%	2.1%	4.9%	4.9%	2.1%	4.9%	4.9%	4.9%	4.9%	4.9%	-0.7%
2039	-1.0%	2.0%	2.0%	5.0%	5.0%	-1.0%	2.0%	2.0%	5.0%	5.0%	2.0%	2.0%	5.0%	5.0%	2.0%	5.0%	5.0%	5.0%	5.0%	5.0%	-1.0%
2040	-1.0%	2.0%	2.0%	5.0%	5.0%	-1.0%	2.0%	2.0%	5.0%	5.0%	2.0%	2.0%	5.0%	5.0%	2.0%	5.0%	5.0%	5.0%	5.0%	5.0%	-1.0%
2041	-1.0%	2.0%	2.0%	5.0%	5.0%	-1.0%	2.0%	2.0%	5.0%	5.0%	2.0%	2.0%	5.0%	5.0%	2.0%	5.0%	5.0%	5.0%	5.0%	5.0%	-1.0%
2042	-0.8%	2.2%	2.2%	4.8%	4.8%	-0.8%	2.2%	2.2%	4.8%	4.8%	2.2%	2.2%	4.8%	4.8%	2.2%	4.8%	4.8%	4.8%	4.8%	4.8%	-0.8%
2043	-0.5%	2.3%	2.3%	4.5%	4.5%	-0.5%	2.3%	2.3%	4.5%	4.5%	2.3%	2.3%	4.5%	4.5%	2.3%	4.5%	4.5%	4.5%	4.5%	4.5%	-0.5%
2044	-0.3%	2.5%	2.5%	4.3%	4.3%	-0.3%	2.5%	2.5%	4.3%	4.3%	2.5%	2.5%	4.3%	4.3%	2.5%	4.3%	4.3%	4.3%	4.3%	4.3%	-0.3%
2045	0.0%	2.6%	2.6%	4.0%	4.0%	0.0%	2.6%	2.6%	4.0%	4.0%	2.6%	2.6%	4.0%	4.0%	2.6%	4.0%	4.0%	4.0%	4.0%	4.0%	0.0%
2046	0.3%	2.7%	2.7%	4.3%	4.3%	0.3%	2.7%	2.7%	4.3%	4.3%	2.7%	2.7%	4.3%	4.3%	2.7%	4.3%	4.3%	4.3%	4.3%	4.3%	0.3%
2047	0.5%	2.8%	2.8%	4.5%	4.5%	0.5%	2.8%	2.8%	4.5%	4.5%	2.8%	2.8%	4.5%	4.5%	2.8%	4.5%	4.5%	4.5%	4.5%	4.5%	0.5%

(Table continued on next page)

Table I-1 (continued)

	EU EU	EU AS	EU ME	EU AF	EU LA	EU NA	AS AS	AS ME	AS AF	AS LA	AS NA	ME ME	ME AF	ME LA	ME NA	AF AF	AF LA	AF NA	LA LA	LA NA	NA NA
2048	0.8%	2.9%	2.9%	4.8%	4.8%	0.8%	2.9%	2.9%	4.8%	4.8%	2.9%	2.9%	4.8%	4.8%	2.9%	4.8%	4.8%	4.8%	4.8%	4.8%	0.8%
2049	1.0%	3.0%	3.0%	5.0%	5.0%	1.0%	3.0%	3.0%	5.0%	5.0%	3.0%	3.0%	5.0%	5.0%	3.0%	5.0%	5.0%	5.0%	5.0%	5.0%	1.0%
2050	1.0%	3.0%	3.0%	5.0%	5.0%	1.0%	3.0%	3.0%	5.0%	5.0%	3.0%	3.0%	5.0%	5.0%	3.0%	5.0%	5.0%	5.0%	5.0%	5.0%	1.0%

Table I-2 Assumed RTK growth rates p.a. from 2014 to 2050 (Rough Air scenario)

Data based on Randt et al. (2015, p. 12)

	EU EU	EU AS	EU ME	EU AF	EU LA	EU NA	AS AS	AS ME	AS AF	AS LA	AS NA	ME ME	ME AF	ME LA	ME NA	AF AF	AF LA	AF NA	LA LA	LA NA	NA NA
2014 - 2050	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%

Table I-3 Fleet-level results data of simulation B_I

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	29,910	+4.7%	73,633	+3.5%
RPKs [Trillions]	5.153	8.302	+4.1%	18.518	+3.1%
ASKs [Trillions]	5.992	9.654	+4.1%	21.532	+3.1%
Total fuel burn [Mio. tons]	184.8	290.6	+3.8%	765.7	+3.4%
CO_2 performance [Grams of CO_2 per ASK]	97.32	95.01	-0.2%	112.23	+0.3%

Table I-4 Adapted fleet-level results data of simulation B_I (Variant 1)

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	29,910	+4.7%	73,633	+3.5%
RPKs [Trillions]	4.454	10.050	+7.0%	28.379	+4.5%
ASKs [Trillions]	5.837	12.024	+6.2%	31.364	+4.1%
Total fuel burn [Mio. tons]	180.0	362.0	+6.0%	1,115.3	+4.4%
CO_2 performance [Grams of CO_2 per ASK]	97.32	95.01	-0.2%	112.23	+0.3%

Table I-5 Adapted fleet-level results data of simulation B_I (Variant 2)

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	23,333	+2.6%	92,793	+4.1%
RPKs [Trillions]	4.454	7.776	+4.8%	36.399	+5.1%
ASKs [Trillions]	5.837	9.304	+4.0%	40.229	+4.7%
Total fuel burn [Mio. tons]	180.0	280.1	+3.8%	1,430.5	+5.1%
CO_2 performance [Grams of CO_2 per ASK]	97.32	95.01	-0.2%	112.23	+0.3%

Table I-6 Fleet-level results data of simulation B_II

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	29,890	+4.7%	72,054	+3.5%
RPKs [Trillions]	5.153	8.383	+4.1%	20.850	+3.4%
ASKs [Trillions]	5.992	9.748	+4.1%	24.244	+3.4%
Total fuel burn [Mio. tons]	184.8	292.3	+3.9%	764.4	+3.4%
CO_2 performance [Grams of CO_2 per ASK]	97.32	94.63	-0.2%	99.51	+0.1%

Table I-7 Adapted fleet-level results data of simulation B_II (Variant 1)

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	29,890	+4.7%	72,054	+3.5%
RPKs [Trillions]	4.454	10.049	+7.0%	28.392	+4.5%
ASKs [Trillions]	5.837	12.023	+6.2%	31.379	+4.1%
Total fuel burn [Mio. tons]	180.0	360.5	+6.0%	989.4	+4.1%
CO_2 performance [Grams of CO_2 per ASK]	97.32	94.63	-0.2%	99.51	+0.1%

Table I-8 Adapted fleet-level results data of simulation B_II (Variant 2)

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	23,317	+2.6%	90,360	+4.0%
RPKs [Trillions]	4.454	7.777	+4.8%	36.055	+5.1%
ASKs [Trillions]	5.837	9.305	+4.0%	39.848	+4.7%
Total fuel burn [Mio. tons]	180.0	279.0	+3.7%	1,256.5	+4.7%
CO_2 performance [Grams of CO_2 per ASK]	97.32	94.63	-0.2%	99.51	+0.1%

Table I-9 Fleet-level results data of simulation B_III

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	29,886	+4.7%	71,822	+3.5%
RPKs [Trillions]	5.153	8.397	+4.2%	21.400	+3.4%
ASKs [Trillions]	5.992	9.764	+4.2%	24.884	+3.4%
Total fuel burn [Mio. tons]	184.8	292.5	+3.9%	768.3	+3.5%
CO_2 performance [Grams of CO_2 per ASK]	97.32	94.54	-0.2%	97.45	+0.0%

Table I-10 Adapted fleet-level results data of simulation B_III (Variant 1)

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	29,886	+4.7%	71,822	+3.5%
RPKs [Trillions]	4.454	10.049	+7.0%	28.391	+4.5%
ASKs [Trillions]	5.837	12.023	+6.2%	31.378	+4.1%
Total fuel burn [Mio. tons]	180.0	360.2	+6.0%	968.8	+4.1%
CO_2 performance [Grams of CO_2 per ASK]	97.32	94.54	-0.2%	97.45	+0.0%

Table I-11 Adapted fleet-level results data of simulation B_III (Variant 2)

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	23,314	+2.6%	90,029	+4.0%
RPKs [Trillions]	4.454	7.777	+4.8%	36.012	+5.1%
ASKs [Trillions]	5.837	9.305	+4.0%	39.801	+4.7%
Total fuel burn [Mio. tons]	180.0	278.7	+3.7%	1,228.9	+4.7%
CO_2 performance [Grams of CO_2 per ASK]	97.32	94.54	-0.2%	97.45	+0.0%

Table I-12 Fleet-level results data of simulation B_IV

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	29,431	+4.6%	69,321	+3.4%
RPKs [Trillions]	5.153	8.914	+4.7%	22.212	+3.5%
ASKs [Trillions]	5.992	10.366	+4.7%	25.828	+3.5%
Total fuel burn [Mio. tons]	184.8	283.5	+3.6%	652.3	+3.0%
CO_2 performance [Grams of CO_2 per ASK]	97.32	86.33	-1.0%	79.70	-0.5%

Table I-13 Adapted fleet-level results data of simulation B_IV (Variant 1)

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	29,431	+4.6%	69,321	+3.4%
RPKs [Trillions]	4.454	9.990	+7.0%	28.215	+4.5%
ASKs [Trillions]	5.837	11.952	+6.2%	31.183	+4.1%
Total fuel burn [Mio. tons]	180.0	326.9	+5.1%	787.5	+3.6%
CO_2 performance [Grams of CO_2 per ASK]	97.32	86.33	-1.0%	79.70	-0.5%

Table I-14 Adapted fleet-level results data of simulation B_IV (Variant 2)

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	23,062	+2.5%	89,386	+4.0%
RPKs [Trillions]	4.454	7.788	+4.8%	36.614	+5.1%
ASKs [Trillions]	5.837	9.318	+4.0%	40.466	+4.7%
Total fuel burn [Mio. tons]	180.0	254.9	+2.9%	1,021.9	+4.2%
CO_2 performance [Grams of CO_2 per ASK]	97.32	86.33	-1.0%	79.70	-0.5%

Table I-15 Fleet-level results data of simulation R_I

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	29,330	+4.5%	65,986	+3.3%
RPKs [Trillions]	5.153	8.134	+3.9%	17.323	+2.9%
ASKs [Trillions]	5.992	9.458	+3.9%	20.143	+2.9%
Total fuel burn [Mio. tons]	184.8	276.7	+3.4%	566.6	+2.7%
CO_2 performance [Grams of CO_2 per ASK]	97.32	92.35	-0.4%	88.77	-0.2%

Table I-16 Adapted fleet-level results data of simulation R_I (Variant 1)

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	29,330	+4.5%	65,986	+3.3%
RPKs [Trillions]	4.454	9.936	+6.9%	27.187	+4.4%
ASKs [Trillions]	5.837	11.887	+6.1%	30.047	+4.0%
Total fuel burn [Mio. tons]	180.0	347.8	+5.6%	845.1	+3.8%
CO_2 performance [Grams of CO_2 per ASK]	97.32	92.35	-0.4%	88.77	-0.2%

Table I-17 **Adapted fleet-level results data of simulation R_I (Variant 2)**

Parameter	**2008**	**2020**		**2050**	
	Value	**Value**	**Change p.a. (rel. to 2008)**	**Value**	**Change p.a. (rel. to 2008)**
Total fleet size [aircraft units]	17,221	21,810	+2.0%	39,904	+2.0%
RPKs [Trillions]	4.454	7.336	+4.2%	16.269	+3.1%
ASKs [Trillions]	5.837	8.776	+3.5%	17.981	+2.7%
Total fuel burn [Mio. tons]	180.0	256.8	+3.0%	505.8	+2.5%
CO_2 performance [Grams of CO_2 per ASK]	97.32	92.35	-0.4%	88.77	-0.2%

Table I-18 **Fleet-level results data of simulation R_II**

Parameter	**2008**	**2020**		**2050**	
	Value	**Value**	**Change p.a. (rel. to 2008)**	**Value**	**Change p.a. (rel. to 2008)**
Total fleet size [aircraft units]	17,221	29,227	+4.5%	63,803	+3.2%
RPKs [Trillions]	5.153	8.162	+3.9%	17.925	+3.0%
ASKs [Trillions]	5.992	9.491	+3.9%	20.843	+3.0%
Total fuel burn [Mio. tons]	184.8	276.7	+3.4%	523.3	+2.5%
CO_2 performance [Grams of CO_2 per ASK]	97.32	92.01	-0.5%	79.23	-0.5%

Table I-19 **Adapted fleet-level results data of simulation R_II (Variant 1)**

Parameter	**2008**	**2020**		**2050**	
	Value	**Value**	**Change p.a. (rel. to 2008)**	**Value**	**Change p.a. (rel. to 2008)**
Total fleet size [aircraft units]	17,221	29,330	+4.5%	65,986	+3.3%
RPKs [Trillions]	4.454	9.904	+6.9%	26.472	+4.3%
ASKs [Trillions]	5.837	11.849	+6.1%	29.258	+3.9%
Total fuel burn [Mio. tons]	180.0	345.4	+5.6%	734.5	+3.4%
CO_2 performance [Grams of CO_2 per ASK]	97.32	92.01	-0.5%	79.23	-0.5%

Table I-20 Adapted fleet-level results data of simulation R_II (Variant 2)

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	21,799	+2.0%	39,442	+2.0%
RPKs [Trillions]	4.454	7.336	+4.2%	16.275	+3.1%
ASKs [Trillions]	5.837	8.777	+3.5%	17.987	+2.7%
Total fuel burn [Mio. tons]	180.0	255.9	+3.0%	451.6	+2.2%
CO_2 performance [Grams of CO_2 per ASK]	97.32	92.01	-0.5%	79.23	-0.5%

Table I-21 Fleet-level results data of simulation R_III

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	29,210	+4.5%	63,699	+3.2%
RPKs [Trillions]	5.153	8.166	+3.9%	17.946	+3.0%
ASKs [Trillions]	5.992	9.496	+3.9%	20.867	+3.0%
Total fuel burn [Mio. tons]	184.8	276.6	+3.4%	516.7	+2.5%
CO_2 performance [Grams of CO_2 per ASK]	97.32	91.94	-0.5%	78.15	-0.5%

Table I-22 Adapted fleet-level results data of simulation R_III (Variant 1)

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	29,210	+4.5%	63,699	+3.2%
RPKs [Trillions]	4.454	9.899	+6.9%	26.440	+4.3%
ASKs [Trillions]	5.837	11.843	+6.1%	29.221	+3.9%
Total fuel burn [Mio. tons]	180.0	345.0	+5.6%	723.6	+3.4%
CO_2 performance [Grams of CO_2 per ASK]	97.32	91.94	-0.5%	78.15	-0.5%

Table I-23 Adapted fleet-level results data of simulation R_III (Variant 2)

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	21,797	+2.0%	39,416	+2.0%
RPKs [Trillions]	4.454	7.336	+4.2%	16.275	+3.1%
ASKs [Trillions]	5.837	8.777	+3.5%	17.987	+2.7%
Total fuel burn [Mio. tons]	180.0	255.7	+3.0%	445.4	+2.2%
CO_2 performance [Grams of CO_2 per ASK]	97.32	91.94	-0.5%	78.15	-0.5%

Table I-24 Fleet-level results data of simulation R_IV

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	28,679	+4.3%	62,835	+3.1%
RPKs [Trillions]	5.153	8.403	+4.2%	18.536	+3.1%
ASKs [Trillions]	5.992	9.771	+4.2%	21.554	+3.1%
Total fuel burn [Mio. tons]	184.8	264.8	+3.0%	476.0	+2.3%
CO_2 performance [Grams of CO_2 per ASK]	97.32	85.53	-1.1%	69.70	-0.8%

Table I-25 Adapted fleet-level results data of simulation R_IV (Variant 1)

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	28,679	+4.3%	62,835	+3.1%
RPKs [Trillions]	4.454	9.772	+6.8%	26.227	+4.3%
ASKs [Trillions]	5.837	11.692	+6.0%	28.986	+3.9%
Total fuel burn [Mio. tons]	180.0	316.8	+4.8%	640.2	+3.1%
CO_2 performance [Grams of CO_2 per ASK]	97.32	85.53	-1.1%	69.70	-0.8%

Table I-26 **Adapted fleet-level results data of simulation R_IV (Variant 2)**

Parameter	2008	2020		2050	
	Value	Value	Change p.a. (rel. to 2008)	Value	Change p.a. (rel. to 2008)
Total fleet size [aircraft units]	17,221	21,646	+1.9%	39,091	+2.0%
RPKs [Trillions]	4.454	7.341	+4.3%	16.288	+3.1%
ASKs [Trillions]	5.837	8.783	+3.5%	18.001	+2.7%
Total fuel burn [Mio. tons]	180.0	238.0	+2.4%	397.6	+1.9%
CO_2 performance [Grams of CO_2 per ASK]	97.32	85.53	-1.1%	69.70	-0.8%

Table I-27 **Adapted results data (Variant 2): Total fuel burn and fleet-wide CO_2 performance for simulations B_II, B_IV, R_II, and R_IV**

	B_II		B_IV		R_II		R_IV	
	Fuel burn [Mio. tons]	CO_2 performance [gCO_2/ASK]	Fuel burn [Mio. tons]	CO_2 performance [gCO_2/ASK]	Fuel burn [Mio. tons]	CO_2 performance [gCO_2/ASK]	Fuel burn [Mio. tons]	CO_2 performance [gCO_2/ASK]
2008	180.0	97.32	180.0	97.32	180.0	97.32	180.0	97.32
2009	185.3	97.01	185.3	97.01	185.3	97.01	185.3	97.01
2010	190.6	96.43	190.6	96.43	190.6	96.43	190.6	96.43
2011	196.8	96.00	196.8	96.00	196.8	96.00	196.8	96.00
2012	203.7	95.61	203.4	95.50	203.7	95.61	203.4	95.50
2013	211.3	95.27	210.4	94.85	211.3	95.27	210.4	94.85
2014	219.4	95.14	217.8	94.40	218.5	94.81	217.0	94.08
2015	228.0	95.02	225.6	93.98	225.6	94.35	223.4	93.38
2016	237.3	94.99	231.2	92.49	232.5	93.94	227.1	91.67
2017	246.9	94.90	236.4	90.78	238.8	93.42	229.8	89.86
2018	257.0	94.80	242.1	89.21	244.7	92.94	232.6	88.29
2019	267.7	94.72	248.3	87.73	250.2	92.48	235.2	86.87
2020	279.0	94.63	254.9	86.33	255.9	92.01	238.0	85.53
2021	290.7	94.47	262.0	85.00	261.6	91.50	241.0	84.24
2022	302.8	94.25	269.5	83.75	267.7	91.00	244.3	83.00
2023	315.5	94.02	277.7	82.57	274.1	90.48	248.0	81.81
2024	329.0	93.80	286.4	81.47	280.2	89.93	251.6	80.70
2025	343.2	93.59	295.8	80.45	285.9	89.37	255.1	79.69
2026	358.3	93.39	305.9	79.53	291.6	88.80	258.8	78.74
2027	374.2	93.21	316.9	78.73	297.2	88.22	262.4	77.85
2028	391.2	93.06	328.9	78.02	302.2	87.65	265.7	77.02
2029	409.2	92.93	341.8	77.39	306.8	87.10	268.8	76.26
2030	428.3	92.83	355.7	76.83	311.3	86.57	271.9	75.56
2031	448.7	92.76	370.7	76.38	315.7	86.04	275.0	74.90

(Table continued on next page)

Table I-27 (continued)

	B_II		B_IV		R_II		R_IV	
	Fuel burn [Mio. tons]	CO_2 performance [gCO_2/ASK]	Fuel burn [Mio. tons]	CO_2 performance [gCO_2/ASK]	Fuel burn [Mio. tons]	CO_2 performance [gCO_2/ASK]	Fuel burn [Mio. tons]	CO_2 performance [gCO_2/ASK]
2032	470.4	92.74	387.0	76.00	320.3	85.51	278.4	74.27
2033	493.5	92.75	404.4	75.68	324.8	84.99	281.8	73.69
2034	518.3	92.80	423.1	75.42	329.5	84.48	285.5	73.14
2035	544.6	92.89	443.2	75.22	334.2	84.01	289.2	72.64
2036	572.8	93.02	464.8	75.09	339.0	83.54	293.1	72.18
2037	602.9	93.19	488.0	75.01	343.8	83.09	297.2	71.78
2038	635.0	93.41	513.0	75.00	348.7	82.65	301.5	71.43
2039	669.4	93.66	539.9	75.04	353.5	82.22	306.0	71.13
2040	706.1	93.96	568.9	75.15	358.7	81.83	311.0	70.89
2041	745.5	94.30	600.1	75.31	364.5	81.50	316.4	70.69
2042	787.6	94.68	633.8	75.54	371.0	81.19	322.5	70.52
2043	832.7	95.11	670.0	75.82	378.0	80.88	329.1	70.38
2044	881.1	95.58	709.1	76.15	385.7	80.58	336.4	70.25
2045	933.0	96.11	751.0	76.53	393.8	80.30	344.2	70.14
2046	988.8	96.68	796.1	76.94	403.1	80.05	353.0	70.05
2047	1,048.7	97.31	844.7	77.41	413.6	79.82	362.7	69.96
2048	1,113.0	97.99	896.9	77.90	425.3	79.61	373.5	69.87
2049	1,182.3	98.72	956.2	78.70	438.2	79.41	385.3	69.78
2050	1,256.5	99.51	1,021.9	79.70	451.6	79.23	397.6	69.70

Appendix J Simulation data (Chapter 8)

Table J-1 **Simulated development of fleet size and composition (P42C_R_I)**

	Total fleet size	Total fleet size (adapted, Variant 2)	Initial-fleet units	Initial-fleet units (adapted, Variant 2)	Next-generation units	Next-generation units (adapted, Variant 2)	P-420/C units	P-420/C units (adapted, Variant 2)
2008	17,221	17,221	17,221	17,221	0	0	0	0
2009	18,035	17,458	18,035	17,458	0	0	0	0
2010	18,886	17,736	18,886	17,736	0	0	0	0
2011	19,761	18,081	19,761	18,081	0	0	0	0
2012	20,653	18,488	20,653	18,488	0	0	0	0
2013	21,560	18,959	21,560	18,959	0	0	0	0
2014	22,478	19,417	22,478	19,417	0	0	0	0
2015	23,416	19,863	23,416	19,863	0	0	0	0
2016	24,374	20,295	24,374	20,295	0	0	0	0
2017	25,605	20,702	25,605	20,702	0	0	0	0
2018	26,841	21,085	26,841	21,085	0	0	0	0
2019	28,070	21,432	28,070	21,432	0	0	0	0
2020	29,330	21,810	29,330	21,810	0	0	0	0
2021	30,612	22,207	30,612	22,207	0	0	0	0
2022	31,925	22,646	31,925	22,646	0	0	0	0
2023	33,,267	23,125	33,267	23,125	0	0	0	0
2024	34,601	23,590	34,601	23,590	0	0	0	0
2025	35,922	24,037	35,922	24,037	0	0	0	0
2026	37,267	24,516	37,263	24,513	0	0	5	3
2027	38,594	24,981	38,582	24,974	0	0	11	7
2028	39,891	25,417	39,870	25,404	0	0	21	13
2029	41,156	25,824	41,123	25,804	0	0	33	21
2030	42,402	26,228	42,355	26,199	0	0	47	29
2031	43,642	26,645	43,577	26,606	0	0	64	39
2032	44,878	27,086	44,794	27,035	0	0	84	51
2033	46,101	27,536	45,995	27,473	0	0	106	63
2034	47,313	28,000	47,183	27,923	0	0	130	77
2035	48,506	28,469	48,349	28,377	0	0	157	92
2036	49,688	28,953	49,501	28,844	0	0	186	108
2037	50,858	29,451	50,640	29,325	0	0	218	126
2038	52,010	29,954	51,758	29,809	0	0	252	145
2039	53,148	30,469	52,860	30,304	0	0	288	165
2040	54,294	31,022	53,967	30,835	0	0	327	187
2041	55,443	31,609	55,075	31,399	0	0	368	210

(Table continued on next page)

Table J-1 (continued)

	Total fleet size	Total fleet size (adapted, Variant 2)	Initial-fleet units	Initial-fleet units (adapted, Variant 2)	Next-generation units	Next-generation units (adapted, Variant 2)	P-420/C units	P-420/C units (adapted, Variant 2)
2042	56,618	32,258	56,208	32,024	0	0	411	234
2043	57,806	32,950	57,350	32,690	0	0	456	260
2044	59,012	33,703	58,509	33,416	0	0	503	287
2045	60,207	34,500	59,655	34,183	0	0	552	316
2046	61,400	35,402	60,798	35,055	0	0	602	347
2047	62,594	36,405	61,940	36,024	0	0	654	380
2048	63,788	37,519	63,081	37,103	0	0	707	416
2049	64,983	38,727	64,222	38,273	0	0	761	453
2050	66,182	39,984	65,366	39,491	0	0	816	493

Table J-2 **Simulated development of fleet size and composition (P42C_R_II)**

	Total fleet size	Total fleet size (adapted, Variant 2)	Initial-fleet units	Initial-fleet units (adapted, Variant 2)	Next-generation units	Next-generation units (adapted, Variant 2)	P-420/C units	P-420/C units (adapted, Variant 2)
2008	17,221	17,221	17,221	17,221	0	0	0	0
2009	18,035	17,458	18,035	17,458	0	0	0	0
2010	18,886	17,736	18,886	17,736	0	0	0	0
2011	19,761	18,081	19,761	18,081	0	0	0	0
2012	20,650	18,485	20,632	18,469	19	17	0	0
2013	21,554	18,952	21,506	18,911	47	42	0	0
2014	22,468	19,407	22,393	19,342	76	65	0	0
2015	23,402	19,850	23,293	19,757	109	93	0	0
2016	24,362	20,283	24,210	20,157	152	126	0	0
2017	25,573	20,691	25,357	20,516	216	175	0	0
2018	26,789	21,076	26,462	20,819	328	258	0	0
2019	27,995	21,423	27,455	21,010	540	413	0	0
2020	29,228	21,799	28,346	21,141	882	658	0	0
2021	30,476	22,191	29,111	21,197	1,365	994	0	0
2022	31,742	22,623	29,802	21,240	1,940	1,383	0	0
2023	33,027	23,095	30,432	21,280	2,595	1,814	0	0
2024	34,291	23,553	30,963	21,267	3,328	2,286	0	0
2025	35,530	23,992	31392	21,198	4,138	2,794	0	0
2026	36,778	24,457	31,741	21,108	5,032	3,346	5	3
2027	37,998	24,907	32,017	20,987	5,969	3,913	11	8
2028	39,194	25,327	32,230	20,827	6,943	4,486	21	14
2029	40,359	25,715	32,367	20,622	7,960	5,072	33	21
2030	41,508	26,097	32,435	20,393	9,026	5,675	47	30
2031	42,643	26,487	32,429	20,143	10,150	6,304	64	40
2032	43,771	26,899	32,349	19,879	11,338	6,968	84	52
2033	44,882	27,319	32,187	19,592	12,589	7,663	106	64
2034	45,980	27,751	31,953	19,285	13,897	8,387	130	79

(Table continued on next page)

Table J-2 (continued)

	Total fleet size	Total fleet size (adapted, Variant 2)	Initial-fleet units	Initial-fleet units (adapted, Variant 2)	Next-generation units	Next-generation units (adapted, Variant 2)	P-420/C units	P-420/C units (adapted, Variant 2)
2035	47,063	28,191	31,646	18,956	15,260	9,141	157	94
2036	48,139	28,650	31,277	18,615	16,675	9,925	186	111
2037	49,205	29,125	30,849	18,259	18,139	10,736	218	129
2038	50,256	29,602	30,369	17,888	19,635	11,566	252	148
2039	51,294	30,087	29,846	17,506	21,160	12,412	288	169
2040	52,342	30,611	29,288	17,128	22,727	13,291	327	191
2041	53,402	31,175	28,706	16,758	24,329	14,203	368	215
2042	54,494	31,809	28,114	16,411	25,968	15,158	411	240
2043	55,601	32,489	27,510	16,075	27,635	16,148	456	266
2044	56,739	33,235	26,908	15,761	29,328	17,179	503	295
2045	57,895	34,029	26,303	15,460	31,040	18,244	552	324
2046	59,104	34,926	25,717	15,197	32,785	19,373	602	356
2047	60,363	35,919	25,153	14,967	34,556	20,563	654	389
2048	61,619	37,022	24,550	14,750	36,363	21,847	707	425
2049	62,877	38,218	23,920	14,539	38,197	23,217	761	462
2050	64,135	39,459	23,280	14,323	40,039	24,634	816	502

Table J-3 Simulated development of fleet size and composition (P42C_R_IV)

	Total fleet size	Total fleet size (adapted, Variant 2)	Initial-fleet units	Initial-fleet units (adapted, Variant 2)	Next-generation units	Next-generation units (adapted, Variant 2)	P-420/C units	P-420/C units (adapted, Variant 2)
2008	17,221	17,221	17,221	17,221	0	0	0	0
2009	18,035	17,458	18,035	17,458	0	0	0	0
2010	18,886	17,736	18,886	17,736	0	0	0	0
2011	19,,761	18,081	19,761	18,081	0	0	0	0
2012	20,650	18,485	20,414	18,273	236	211	0	0
2013	21,549	18,949	21,134	18,585	415	365	0	0
2014	22,425	19,399	21,839	18,891	586	507	0	0
2015	23,314	19,838	22,555	19,192	759	646	0	0
2016	24,190	20,253	21,889	18,326	2,302	1,927	0	0
2017	25,293	20,623	21,210	17,294	4,083	3,329	0	0
2018	26,412	20,978	20,518	16,297	5,894	4,681	0	0
2019	27,533	21,296	19,816	15,327	7,717	5,969	0	0
2020	28,681	21,646	19,094	14,411	9,586	7,235	0	0
2021	29,847	22,015	18,352	13,536	11,495	8,479	0	0
2022	31,039	22,425	17,586	12,706	13,453	9,719	0	0
2023	32,258	22,878	16,800	11,915	15,457	10,963	0	0
2024	33,474	23,321	15,992	11,142	17,482	12,179	0	0
2025	34,685	23,747	15,162	10,381	19,523	13,366	0	0
2026	36,065	24,203	14,310	9,603	21,228	14,246	528	354
2027	37,442	24,669	13,434	8,851	22,947	15,119	1,061	699

(Table continued on next page)

Table J-3 (continued)

	Total fleet size	Total fleet size (adapted, Variant 2)	Initial-fleet units	Initial-fleet units (adapted, Variant 2)	Next-generation units	Next-generation units (adapted, Variant 2)	P-420/C units	P-420/C units (adapted, Variant 2)
2028	38,746	25,105	12,533	8,120	24,615	15,949	1,599	1,036
2029	39,981	25,510	11,604	7,404	26,235	16,739	2,143	1,367
2030	41,208	25,910	10,652	6,697	27,864	17,520	2,692	1,693
2031	42,464	26,318	9,681	6,000	29,536	18,306	3,247	2,012
2032	43,785	26,749	8,701	5,316	31,277	19,108	3,807	2,326
2033	45,146	27,192	7,723	4,651	33,052	19,907	4,371	2,633
2034	46,550	27,648	6,762	4,016	34,847	20,697	4,940	2,934
2035	47,922	28,110	5,835	3,423	36,574	21,453	5,513	3,234
2036	49,274	28,587	4,959	2,877	38,223	22,176	6,092	3,534
2037	50,612	29,080	4,151	2,385	39,787	22,861	6,673	3,834
2038	51,937	29,579	3,424	1,950	41,258	23,497	7,255	4,132
2039	53,258	30,091	2,785	1,574	42,637	24,090	7,836	4,427
2040	54,573	30,642	2,237	1,256	43,922	24,661	8,414	4,724
2041	55,880	31,229	1,778	993	45,117	25,213	8,986	5,022
2042	57,179	31,882	1,400	781	46,230	25,777	9,549	5,324
2043	58,469	32,584	1,095	610	47,275	26,345	10,099	5,628
2044	59,750	33,353	853	476	48,266	26,942	10,631	5,934
2045	61,030	34,179	672	376	49,217	27,563	11,141	6,239
2046	62,300	35,110	534	301	50,143	28,258	11,624	6,551
2047	63,558	36,136	430	244	51,053	29,026	12,075	6,865
2048	64,802	37,272	352	202	51,958	29,884	12,492	7,185
2049	66,040	38,506	294	171	52,873	30,829	12,874	7,506
2050	67,261	39,783	251	148	53,791	31,816	13,219	7,819

Table J-4 Simulated development of fleet size and composition (P42G_R_I)

	Total fleet size	Total fleet size (adapted, Variant 2)	Initial-fleet units	Initial-fleet units (adapted, Variant 2)	Next-generation units	Next-generation units (adapted, Variant 2)	P-420/G units	P-420/G units (adapted, Variant 2)
2008	17,221	17,221	17,221	17,221	0	0	0	0
2009	18,035	17,458	18,035	17,458	0	0	0	0
2010	18,886	17,736	18,886	17,736	0	0	0	0
2011	19,761	18,081	19,761	18,081	0	0	0	0
2012	20,653	18,488	20,653	18,488	0	0	0	0
2013	21,560	18,959	21,560	18,959	0	0	0	0
2014	22,478	19,417	22,478	19,417	0	0	0	0
2015	23,416	19,863	23,416	19,863	0	0	0	0
2016	24,374	20,295	24,374	20,295	0	0	0	0
2017	25,605	20,702	25,605	20,702	0	0	0	0
2018	26,841	21,085	26,841	21,085	0	0	0	0
2019	28,070	21,432	28,070	21,432	0	0	0	0

(Table continued on next page)

Table J-4 (continued)

	Total fleet size	Total fleet size (adapted, Variant 2)	Initial-fleet units	Initial-fleet units (adapted, Variant 2)	Next-generation units	Next-generation units (adapted, Variant 2)	P-420/G units	P-420/G units (adapted, Variant 2)
2020	29,330	21,810	29,330	21,810	0	0	0	0
2021	30,612	22,207	30,612	22,207	0	0	0	0
2022	31,925	22,646	31,925	22,646	0	0	0	0
2023	33,267	23,125	33,267	23,125	0	0	0	0
2024	34,601	23,590	34,601	23,590	0	0	0	0
2025	35,922	24,037	35,922	24,037	0	0	0	0
2026	37,267	24,516	37,263	24,513	0	0	5	3
2027	38,593	24,981	38,582	24,974	0	0	11	7
2028	39,890	25,417	39,869	25,404	0	0	21	13
2029	41,154	25,824	41,121	25,804	0	0	33	21
2030	42,400	26,228	42,352	26,199	0	0	47	29
2031	43,639	26,645	43,574	26,606	0	0	64	39
2032	44,874	27,086	44,790	27,035	0	0	84	51
2033	46,096	27,537	45,990	27,473	0	0	106	63
2034	47,307	28,001	47,177	27,924	0	0	130	77
2035	48,498	28,470	48,342	28,378	0	0	157	92
2036	49,679	28,953	49,493	28,845	0	0	186	108
2037	50,848	29,452	50,630	29,326	0	0	218	126
2038	51,998	29,955	51,746	29,810	0	0	252	145
2039	53,135	30,470	52,847	30,305	0	0	288	165
2040	54,279	31,024	53,952	30,837	0	0	327	187
2041	55,426	31,611	55,059	31,401	0	0	368	210
2042	56,600	32,261	56,189	32,026	0	0	411	234
2043	57,786	32,953	57,330	32,693	0	0	456	260
2044	58,992	33,706	58,489	33,418	0	0	503	287
2045	60,187	34,502	59,636	34,186	0	0	552	316
2046	61,380	35,404	60,778	35,057	0	0	602	347
2047	62,574	36,407	61,920	36,027	0	0	654	380
2048	63,768	37,521	63,061	37,105	0	0	707	416
2049	64,963	38,729	64,203	38,275	0	0	761	454
2050	66,162	39,985	65,346	39,492	0	0	816	493

Table J-5 **Simulated development of fleet size and composition (P42G_R_II)**

	Total fleet size	Total fleet size (adapted, Variant 2)	Initial-fleet units	Initial-fleet units (adapted, Variant 2)	Next-generation units	Next-generation units (adapted, Variant 2)	P-420/G units	P-420/G units (adapted, Variant 2)
2008	17,221	17,221	17,221	17,221	0	0	0	0
2009	18,035	17,458	18,035	17,458	0	0	0	0
2010	18,886	17,736	18,886	17,736	0	0	0	0
2011	19,761	18,081	19,761	18,081	0	0	0	0

(Table continued on next page)

Table J-5 (continued)

	Total fleet size	Total fleet size (adapted, Variant 2)	Initial-fleet units	Initial-fleet units (adapted, Variant 2)	Next-generation units	Next-generation units (adapted, Variant 2)	P-420/G units	P-420/G units (adapted, Variant 2)
2012	20,650	18,485	20,632	18,469	19	17	0	0
2013	21,554	18,952	21,506	18,911	47	42	0	0
2014	22,469	19,407	22,393	19,342	76	65	0	0
2015	23,402	19,850	23,293	19,757	109	93	0	0
2016	24,362	20,283	24,210	20,157	152	126	0	0
2017	25,573	20,691	25,357	20,516	216	175	0	0
2018	26,789	21,076	26,462	20,819	328	258	0	0
2019	27,995	21,423	27,455	21,010	540	413	0	0
2020	29,228	21,799	28,346	21,141	882	658	0	0
2021	30,476	22,191	29,111	21,197	1,365	994	0	0
2022	31,743	22,623	29,803	21,240	1,940	1,383	0	0
2023	33,027	23,095	30,433	21,280	2,595	1,814	0	0
2024	34,290	23,553	30,963	21,267	3,328	2,286	0	0
2025	35,530	23,992	31,392	21,198	4,138	2,794	0	0
2026	36,777	24,457	31,741	21,108	5,032	3,346	5	3
2027	37,997	24,907	32,017	20,987	5,969	3,913	11	8
2028	39,192	25,327	32,229	20,827	6,942	4,486	21	14
2029	40,358	25,715	32,366	20,623	7,959	5,071	33	21
2030	41,505	26,097	32,434	20,393	9,024	5,674	47	30
2031	42,640	26,487	32,427	20,143	10,148	6,304	64	40
2032	43,767	26,899	32,347	19,880	11,336	6,967	84	52
2033	44,877	27,319	32,185	19,593	12,587	7,662	106	64
2034	45,974	27,751	31,950	19,286	13,894	8,387	130	79
2035	47,056	28,192	31,642	18,957	15,257	9,141	157	94
2036	48,130	28,650	31,273	18,616	16,672	9,924	186	111
2037	49,196	29,125	30,844	18,260	18,134	10,736	218	129
2038	50,245	29,603	30,363	17,889	19,630	11,565	252	148
2039	51,281	30,087	29,839	17,507	21,154	12,411	288	169
2040	52,328	30,611	29,280	17,128	22,721	13,291	327	191
2041	53,386	31,175	28,697	16,758	24,322	14,203	368	215
2042	54,476	31,809	28,104	16,410	25,960	15,159	411	240
2043	55,581	32,489	27,499	16,074	27,627	16,149	456	267
2044	56,717	33,236	26,895	15,760	29,319	17,181	503	295
2045	57,871	34,029	26,289	15,458	31,030	18,246	552	324
2046	59,078	34,926	25,703	15,195	32,774	19,375	602	356
2047	60,334	35,919	25,137	14,965	34,544	20,565	654	389
2048	61,591	37,023	24,535	14,748	36,349	21,850	707	425
2049	62,849	38,219	23,906	14,537	38,182	23,218	761	463
2050	64,108	39,459	23,268	14,322	40,024	24,635	816	502

Table J-6 **Simulated development of fleet size and composition (P42G_R_IV)**

	Total fleet size	Total fleet size (adapted, Variant 2)	Initial-fleet units	Initial-fleet units (adapted, Variant 2)	Next-generation units	Next-generation units (adapted, Variant 2)	P-420/G units	P-420/G units (adapted, Variant 2)
2008	17,221	17,221	17,221	17,221	0	0	0	0
2009	18,035	17,458	18,035	17,458	0	0	0	0
2010	18,886	17,736	18,886	17,736	0	0	0	0
2011	19,761	18,081	19,761	18,081	0	0	0	0
2012	20,650	18,485	20,414	18,273	236	211	0	0
2013	21,549	18,949	21,134	18,585	415	365	0	0
2014	22,425	19,399	21,839	18,891	586	507	0	0
2015	23,314	19,838	22,555	19,192	759	646	0	0
2016	24,190	20,253	21,889	18,326	2,302	1,927	0	0
2017	25,293	20,623	21,210	17,294	4,083	3,329	0	0
2018	26,412	20,978	20,518	16,297	5,894	4,681	0	0
2019	27,533	21,296	19,816	15,327	7,717	5,969	0	0
2020	28,681	21,646	19,094	14,411	9,586	7,235	0	0
2021	29,847	22,015	18,352	13,536	11,495	8,479	0	0
2022	31,039	22,425	17,586	12,706	13,453	9,719	0	0
2023	32,258	22,878	16,800	11,915	15,458	10,963	0	0
2024	33,474	23,321	15,992	11,142	17,482	12,179	0	0
2025	34,685	23,747	15,162	10,381	19,523	13,366	0	0
2026	35,982	24,204	14,310	9,625	21,144	14,223	528	355
2027	37,275	24,669	13,434	8,891	22,780	15,076	1,061	702
2028	38,495	25,105	12,533	8,173	24,363	15,889	1,599	1,043
2029	39,644	25,511	11,604	7,467	25,898	16,665	2,142	1,379
2030	40,784	25,911	10,652	6,767	27,441	17,434	2,691	1,710
2031	41,953	26,319	9,681	6,074	29,025	18,209	3,246	2,037
2032	43,185	26,751	8,701	5,390	30,678	19,004	3,806	2,358
2033	44,457	27,194	7,723	4,724	32,364	19,796	4,371	2,673
2034	45,772	27,650	6,762	4,085	34,070	20,581	4,940	2,984
2035	47,104	28,114	5,835	3,482	35,757	21,341	5,512	3,290
2036	48,464	28,592	4,959	2,926	37,418	22,075	6,087	3,591
2037	49,804	29,086	4,151	2,424	38,988	22,770	6,664	3,892
2038	51,151	29,588	3,424	1981	40,481	23,416	7,246	4,191
2039	52,484	30,104	2,785	1,598	41,874	24,018	7,824	4,488
2040	53,804	30,655	2,237	1,275	43,168	24,596	8,398	4,785
2041	55,118	31,244	1,778	1,008	44,371	25,152	8,969	5,084
2042	56,426	31,900	1,400	792	45,494	25,719	9,532	5,389
2043	57,728	32,603	1,095	619	46,551	26,291	10,081	5,693
2044	59,024	33,373	853	482	47,558	26,891	10,612	6,000
2045	60,322	34,200	672	381	48,529	27,514	11,121	6,305
2046	61,615	35,132	534	304	49,478	28,212	11,603	6,616
2047	62,900	36,159	429	247	50,417	28,983	12,054	6,929
2048	64,177	37,295	351	204	51,355	29,844	12,471	7,247
2049	65,453	38,531	293	172	52,309	30,793	12,851	7,565
2050	66,718	39,810	250	149	53,272	31,787	13,197	7,874

Table J-7 **Simulated development of the fleet-wide fuel demand and CO_2 performance (R_I vs. P42C_R_I)**

	R_I			P42C_R_I		
	Total fuel burn [Mio. tons]	Total fuel burn [Mio. tons] (adapted, Variant 2)	CO_2 performance [gCO_2/ASK]	Total fuel burn [Mio. tons]	Total fuel burn [Mio. tons] (adapted, Variant 2)	CO_2 performance [gCO_2/ASK]
2008	184.8	180.0	97.32	184.8	180.0	97.32
2009	192.0	185.3	97.01	192.0	185.3	97.01
2010	199.3	190.6	96.43	199.3	190.6	96.43
2011	206.7	196.8	96.00	206.7	196.8	96.00
2012	214.2	203.7	95.62	214.2	203.7	95.62
2013	221.7	211.4	95.30	221.7	211.4	95.30
2014	229.1	218.6	94.84	229.1	218.6	94.84
2015	236.7	225.7	94.42	236.7	225.7	94.42
2016	244.4	232.7	94.01	244.4	232.7	94.01
2017	252.8	239.0	93.53	252.8	239.0	93.53
2018	260.9	245.1	93.09	260.9	245.1	93.09
2019	268.7	250.8	92.71	268.7	250.8	92.71
2020	276.7	256.8	92.35	276.7	256.8	92.35
2021	285.0	263.0	92.00	285.0	263.0	92.00
2022	293.8	269.6	91.66	293.8	269.6	91.66
2023	303.1	276.7	91.32	303.1	276.7	91.32
2024	312.2	283.6	91.01	312.2	283.6	91.01
2025	321.1	290.2	90.72	321.1	290.2	90.72
2026	330.2	297.1	90.46	330.4	297.3	90.54
2027	339.2	303.9	90.22	339.4	304.1	90.28
2028	347.8	310.3	90.00	348.0	310.5	90.04
2029	355.9	316.3	89.81	356.0	316.4	89.83
2030	364.0	322.3	89.64	364.0	322.3	89.64
2031	372.2	328.5	89.52	372.2	328.4	89.51
2032	380.7	334.9	89.43	380.6	334.8	89.40
2033	389.3	341.5	89.34	389.1	341.3	89.29
2034	398.1	348.2	89.27	397.7	347.9	89.19
2035	406.8	354.9	89.20	406.3	354.4	89.10
2036	415.6	361.7	89.14	414.9	361.1	89.01
2037	424.5	368.7	89.09	423.7	368.0	88.92
2038	433.4	375.7	89.05	432.4	374.8	88.84
2039	442.3	382.7	89.02	441.2	381.7	88.79
2040	451.5	390.1	88.99	450.4	389.1	88.76
2041	461.2	397.9	88.98	459.9	396.8	88.71
2042	471.7	406.5	88.95	470.2	405.2	88.66
2043	482.7	415.5	88.91	480.9	414.0	88.59
2044	494.3	425.3	88.86	492.1	423.5	88.51
2045	506.1	435.5	88.81	503.2	433.5	88.41
2046	517.9	447.0	88.78	514.4	444.7	88.32
2047	529.9	459.8	88.76	525.7	457.1	88.26
2048	542.0	474.0	88.75	537.1	471.0	88.19
2049	554.2	489.6	88.76	548.5	486.2	88.14
2050	566.6	505.8	88.77	560.1	501.9	88.11

Table J-8 **Simulated development of the fleet-wide fuel demand and CO_2 performance (R_II vs. P42C_R_II)**

	R_II			P42C_R_II		
	Total fuel burn [Mio. tons]	Total fuel burn [Mio. tons] (adapted, Variant 2)	CO_2 performance [gCO_2/ASK]	Total fuel burn [Mio. tons]	Total fuel burn [Mio. tons] (adapted, Variant 2)	CO_2 performance [gCO_2/ASK]
2008	184.8	180.0	97.32	184.8	180.0	97.32
2009	192.0	185.3	97.01	192.0	185.3	97.01
2010	199.3	190.6	96.43	199.3	190.6	96.43
2011	206.7	196.8	96.00	206.7	196.8	96.00
2012	214.2	203.7	95.61	214.2	203.7	95.61
2013	221.8	211.3	95.27	221.8	211.3	95.27
2014	229.3	218.5	94.81	229.3	218.5	94.81
2015	237.1	225.6	94.35	237.1	225.6	94.35
2016	245.1	232.5	93.94	245.1	232.5	93.94
2017	253.4	238.8	93.42	253.4	238.8	93.42
2018	261.4	244.7	92.94	261.4	244.7	92.94
2019	269.0	250.2	92.48	269.0	250.2	92.48
2020	276.7	255.9	92.01	276.7	255.9	92.01
2021	284.5	261.6	91.50	284.5	261.6	91.50
2022	292.8	267.7	91.00	292.8	267.7	91.00
2023	301.4	274.1	90.48	301.4	274.1	90.48
2024	309.6	280.2	89.93	309.6	280.2	89.94
2025	317.4	285.9	89.37	317.4	285.9	89.38
2026	325.3	291.6	88.80	325.6	291.9	88.88
2027	332.9	297.2	88.22	333.2	297.4	88.29
2028	340.0	302.2	87.65	340.2	302.4	87.72
2029	346.5	306.8	87.10	346.7	307.0	87.15
2030	352.8	311.3	86.57	352.9	311.4	86.60
2031	359.0	315.7	86.04	359.1	315.8	86.06
2032	365.4	320.3	85.51	365.4	320.3	85.52
2033	371.7	324.8	84.99	371.7	324.8	84.97
2034	378.1	329.5	84.48	377.9	329.3	84.43
2035	384.5	334.2	84.01	384.1	333.8	83.92
2036	390.9	339.0	83.54	390.4	338.5	83.42
2037	397.4	343.8	83.09	396.7	343.2	82.94
2038	403.8	348.7	82.65	402.8	347.9	82.46
2039	410.1	353.5	82.22	408.9	352.5	82.00
2040	416.8	358.7	81.83	415.5	357.6	81.58
2041	424.1	364.5	81.50	422.5	363.1	81.20
2042	432.2	371.0	81.19	430.4	369.5	80.85
2043	440.7	378.0	80.88	438.7	376.3	80.51
2044	450.0	385.7	80.58	447.8	383.8	80.19
2045	459.8	393.8	80.30	457.3	391.7	79.87
2046	470.9	403.1	80.05	468.1	400.8	79.58
2047	483.2	413.6	79.82	480.0	410.9	79.31
2048	496.2	425.3	79.61	492.3	422.4	79.06
2049	509.6	438.2	79.41	504.9	435.0	78.83
2050	523.3	451.6	79.23	517.6	448.1	78.62

Table J-9 Simulated development of the fleet-wide fuel demand and CO_2 performance (R_IV vs. P42C_R_IV)

	R_IV			P42C_R_IV		
	Total fuel burn [Mio. tons]	Total fuel burn [Mio. tons] (adapted, Variant 2)	CO_2 performance [gCO_2/ASK]	Total fuel burn [Mio. tons]	Total fuel burn [Mio. tons] (adapted, Variant 2)	CO_2 performance [gCO_2/ASK]
2008	184.8	180.0	97.32	184.8	180.0	97.32
2009	192.0	185.3	97.01	192.0	185.3	97.01
2010	199.3	190.6	96.43	199.3	190.6	96.43
2011	206.7	196.8	96.00	206.7	196.8	96.00
2012	214.2	203.4	95.50	214.2	203.4	95.50
2013	223.2	210.4	94.85	223.2	210.4	94.85
2014	231.9	217.0	94.08	231.9	217.0	94.08
2015	240.5	223.4	93.38	240.5	223.4	93.38
2016	246.2	227.1	91.67	246.2	227.1	91.68
2017	250.9	229.8	89.86	250.9	229.8	89.86
2018	255.7	232.6	88.29	255.7	232.7	88.29
2019	260.1	235.2	86.87	260.1	235.2	86.87
2020	264.8	238.0	85.53	264.8	238.0	85.53
2021	269.7	241.0	84.24	269.7	241.0	84.25
2022	274.9	244.3	83.00	274.9	244.3	83.00
2023	280.6	248.0	81.81	280.6	248.1	81.82
2024	286.1	251.6	80.70	286.1	251.6	80.71
2025	291.4	255.1	79.69	291.4	255.1	79.69
2026	297.0	258.8	78.74	295.4	257.5	78.34
2027	302.5	262.4	77.85	299.9	260.2	77.20
2028	307.6	265.7	77.02	304.0	262.7	76.14
2029	312.4	268.8	76.26	307.7	264.9	75.15
2030	317.1	271.9	75.56	311.3	267.0	74.21
2031	321.9	275.0	74.90	314.9	269.2	73.31
2032	326.8	278.4	74.27	318.6	271.5	72.44
2033	331.9	281.8	73.69	322.4	273.9	71.62
2034	337.2	285.5	73.14	326.3	276.5	70.84
2035	342.4	289.2	72.64	330.1	279.1	70.12
2036	347.9	293.1	72.18	333.7	282.0	69.46
2037	353.6	297.2	71.78	337.4	285.1	68.85
2038	359.4	301.5	71.43	341.3	288.3	68.32
2039	365.4	306.0	71.13	345.7	292.0	67.90
2040	372.0	311.0	70.89	350.4	296.2	67.55
2041	379.0	316.4	70.69	355.5	300.9	67.27
2042	386.8	322.5	70.52	360.8	306.3	67.03
2043	395.1	329.1	70.38	366.3	312.3	66.84
2044	404.2	336.4	70.25	372.0	319.0	66.69
2045	413.8	344.2	70.14	378.1	326.4	66.61
2046	424.5	353.0	70.05	384.3	334.9	66.56
2047	436.3	362.7	69.96	390.6	344.4	66.54
2048	449.3	373.5	69.87	397.1	355.1	66.56
2049	462.6	385.3	69.78	403.9	367.2	66.65
2050	476.0	397.6	69.70	410.8	379.7	66.75

Table J-10 Simulated development of the fleet-wide fuel demand and CO_2 performance (R_I vs. P42G_R_I)

	R_I			P42G_R_I		
	Total fuel burn [Mio. tons]	Total fuel burn [Mio. tons] (adapted, Variant 2)	CO_2 performance [gCO_2/ASK]	Total fuel burn [Mio. tons]	Total fuel burn [Mio. tons] (adapted, Variant 2)	CO_2 performance [gCO_2/ASK]
2008	184.8	180.0	97.32	184.8	180.0	97.32
2009	192.0	185.3	97.01	192.0	185.3	97.01
2010	199.3	190.6	96.43	199.3	190.6	96.43
2011	206.7	196.8	96.00	206.7	196.8	96.00
2012	214.2	203.7	95.62	214.2	203.7	95.62
2013	221.7	211.4	95.30	221.7	211.4	95.30
2014	229.1	218.6	94.84	229.1	218.6	94.84
2015	236.7	225.7	94.42	236.7	225.7	94.42
2016	244.4	232.7	94.01	244.4	232.7	94.01
2017	252.8	239.0	93.53	252.8	239.0	93.53
2018	260.9	245.1	93.09	260.9	245.1	93.09
2019	268.7	250.8	92.71	268.7	250.8	92.71
2020	276.7	256.8	92.35	276.7	256.8	92.35
2021	285.0	263.0	92.00	285.0	263.0	92.00
2022	293.8	269.6	91.66	293.8	269.6	91.66
2023	303.1	276.7	91.32	303.1	276.7	91.32
2024	312.2	283.6	91.01	312.2	283.6	91.01
2025	321.1	290.2	90.72	321.1	290.2	90.72
2026	330.2	297.1	90.46	330.4	297.3	90.53
2027	339.2	303.9	90.22	339.4	304.1	90.28
2028	347.8	310.3	90.00	348.0	310.4	90.04
2029	355.9	316.3	89.81	356.0	316.4	89.83
2030	364.0	322.3	89.64	364.0	322.3	89.64
2031	372.2	328.5	89.52	372.1	328.4	89.50
2032	380.7	334.9	89.43	380.6	334.8	89.39
2033	389.3	341.5	89.34	389.1	341.2	89.28
2034	398.1	348.2	89.27	397.6	347.8	89.18
2035	406.8	354.9	89.20	406.2	354.4	89.08
2036	415.6	361.7	89.14	414.8	361.1	88.99
2037	424.5	368.7	89.09	423.6	367.9	88.90
2038	433.4	375.7	89.05	432.3	374.7	88.82
2039	442.3	382.7	89.02	441.0	381.6	88.76
2040	451.5	390.1	88.99	450.2	388.9	88.72
2041	461.2	397.9	88.98	459.7	396.6	88.68
2042	471.7	406.5	88.95	470.0	405.0	88.62
2043	482.7	415.5	88.91	480.7	413.8	88.55
2044	494.3	425.3	88.86	491.9	423.3	88.46
2045	506.1	435.5	88.81	503.1	433.2	88.36
2046	517.9	447.0	88.78	514.3	444.4	88.27
2047	529.9	459.8	88.76	525.6	456.8	88.20
2048	542.0	474.0	88.75	537.0	470.6	88.13
2049	554.2	489.6	88.76	548.4	485.8	88.07
2050	566.6	505.8	88.77	560.0	501.5	88.03

Table J-11 **Simulated development of the fleet-wide fuel demand and CO_2 performance (R_II vs. P42G_R_II)**

	R_II			P42G_R_II		
	Total fuel burn [Mio. tons]	**Total fuel burn [Mio. tons] (adapted, Variant 2)**	**CO_2 performance [gCO_2/ASK]**	**Total fuel burn [Mio. tons]**	**Total fuel burn [Mio. tons] (adapted, Variant 2)**	**CO_2 performance [gCO_2/ASK]**
2008	184.8	180.0	97.32	184.8	180.0	97.32
2009	192.0	185.3	97.01	192.0	185.3	97.01
2010	199.3	190.6	96.43	199.3	190.6	96.43
2011	206.7	196.8	96.00	206.7	196.8	96.00
2012	214.2	203.7	95.61	214.2	203.7	95.61
2013	221.8	211.3	95.27	221.8	211.3	95.27
2014	229.3	218.5	94.81	229.3	218.5	94.81
2015	237.1	225.6	94.35	237.1	225.6	94.35
2016	245.1	232.5	93.94	245.1	232.5	93.94
2017	253.4	238.8	93.42	253.4	238.8	93.42
2018	261.4	244.7	92.94	261.4	244.7	92.94
2019	269.0	250.2	92.48	268.9	250.2	92.48
2020	276.7	255.9	92.01	276.7	255.9	92.01
2021	284.5	261.6	91.50	284.5	261.6	91.50
2022	292.8	267.7	91.00	292.8	267.7	91.00
2023	301.4	274.1	90.48	301.4	274.1	90.48
2024	309.6	280.2	89.93	309.6	280.2	89.94
2025	317.4	285.9	89.37	317.4	285.9	89.38
2026	325.3	291.6	88.80	325.6	291.9	88.88
2027	332.9	297.2	88.22	333.2	297.4	88.29
2028	340.0	302.2	87.65	340.2	302.4	87.71
2029	346.5	306.8	87.10	346.7	307.0	87.15
2030	352.8	311.3	86.57	352.9	311.4	86.60
2031	359.0	315.7	86.04	359.1	315.7	86.05
2032	365.4	320.3	85.51	365.4	320.2	85.50
2033	371.7	324.8	84.99	371.6	324.7	84.96
2034	378.1	329.5	84.48	377.8	329.2	84.42
2035	384.5	334.2	84.01	384.0	333.8	83.90
2036	390.9	339.0	83.54	390.2	338.4	83.40
2037	397.4	343.8	83.09	396.5	343.1	82.91
2038	403.8	348.7	82.65	402.7	347.7	82.43
2039	410.1	353.5	82.22	408.8	352.4	81.97
2040	416.8	358.7	81.83	415.3	357.5	81.55
2041	424.1	364.5	81.50	422.3	363.0	81.16
2042	432.2	371.0	81.19	430.2	369.3	80.81
2043	440.7	378.0	80.88	438.5	376.1	80.47
2044	450.0	385.7	80.58	447.5	383.5	80.14
2045	459.8	393.8	80.30	457.0	391.4	79.82
2046	470.9	403.1	80.05	467.8	400.5	79.52
2047	483.2	413.6	79.82	479.7	410.6	79.25
2048	496.2	425.3	79.61	491.9	422.0	79.00
2049	509.6	438.2	79.41	504.5	434.6	78.77
2050	523.3	451.6	79.23	517.3	447.7	78.55

Table J-12 Simulated development of the fleet-wide fuel demand and CO_2 performance (R_IV vs. P42G_R_IV)

	R_IV			P42G_R_IV		
	Total fuel burn [Mio. tons]	Total fuel burn [Mio. tons] (adapted, Variant 2)	CO_2 performance [gCO_2/ASK]	Total fuel burn [Mio. tons]	Total fuel burn [Mio. tons] (adapted, Variant 2)	CO_2 performance [gCO_2/ASK]
2008	184.8	180.0	97.32	184.8	180.0	97.32
2009	192.0	185.3	97.01	192.0	185.3	97.01
2010	199.3	190.6	96.43	199.3	190.6	96.43
2011	206.7	196.8	96.00	206.7	196.8	96.00
2012	214.2	203.4	95.50	214.2	203.4	95.50
2013	223.2	210.4	94.85	223.2	210.4	94.85
2014	231.9	217.0	94.08	231.9	217.0	94.08
2015	240.5	223.4	93.38	240.5	223.4	93.38
2016	246.2	227.1	91.67	246.2	227.1	91.68
2017	250.9	229.8	89.86	250.9	229.8	89.86
2018	255.7	232.6	88.29	255.7	232.7	88.29
2019	260.1	235.2	86.87	260.1	235.2	86.87
2020	264.8	238.0	85.53	264.8	238.0	85.53
2021	269.7	241.0	84.24	269.7	241.0	84.25
2022	274.9	244.3	83.00	274.9	244.3	83.00
2023	280.6	248.0	81.81	280.6	248.1	81.82
2024	286.1	251.6	80.70	286.1	251.6	80.71
2025	291.4	255.1	79.69	291.4	255.1	79.69
2026	297.0	258.8	78.74	295.2	257.3	78.29
2027	302.5	262.4	77.85	299.5	259.9	77.10
2028	307.6	265.7	77.02	303.4	262.2	76.00
2029	312.4	268.8	76.26	306.9	264.2	74.96
2030	317.1	271.9	75.56	310.3	266.2	73.98
2031	321.9	275.0	74.90	313.7	268.2	73.04
2032	326.8	278.4	74.27	317.3	270.3	72.13
2033	331.9	281.8	73.69	320.9	272.6	71.27
2034	337.2	285.5	73.14	324.6	275.0	70.46
2035	342.4	289.2	72.64	328.4	277.5	69.70
2036	347.9	293.1	72.18	332.3	280.1	69.00
2037	353.6	297.2	71.78	336.3	283.1	68.36
2038	359.4	301.5	71.43	340.5	286.2	67.79
2039	365.4	306.0	71.13	345.2	289.7	67.34
2040	372.0	311.0	70.89	350.3	293.7	66.96
2041	379.0	316.4	70.69	355.6	298.2	66.65
2042	386.8	322.5	70.52	361.1	303.5	66.38
2043	395.1	329.1	70.38	366.9	309.3	66.17
2044	404.2	336.4	70.25	372.9	315.9	65.99
2045	413.8	344.2	70.14	379.2	323.1	65.89
2046	424.5	353.0	70.05	385.7	331.4	65.81
2047	436.3	362.7	69.96	392.3	340.6	65.77
2048	449.3	373.5	69.87	399.0	351.1	65.75
2049	462.6	385.3	69.78	406.1	362.9	65.82
2050	476.0	397.6	69.70	413.4	375.3	65.90

Appendix K Optional adaptation method for raw simulation data

THIS appendix briefly presents a method that allows integrating dynamic development functions of both the average aircraft utilization (i.e., the average RPKs supply per aircraft unit and year of simulation) and the seat load factor into the fleet simulations, provided that adequate raw results are available beforehand. With this method, the simulation data can thus be improved in terms of representing a more realistic development of the absolute fleet-wide transport supply and fuel burn.

The principle of the method is to adapt the total transport supply (measured in RPKs and ASKs) of the simulated fleet by taking into account predefined mathematical functions that stipulate the dynamic development of the aircraft utilization and the seat load factor. Therefore, the method fundamentally relies on these two functions. In doing so, the method does not affect the technology-driven fuel-burn and CO_2 performance of the simulated fleet (i.e., the absolute quantity of fuel burned or CO_2 emitted per ASK), as this would obviously deteriorate the overall simulation quality.

Figure K-1 shows the functions employed by the method that defines the dynamic evolution of the aircraft utilization and the seat load factor from 2008 to 2050. Table K-1 shows the corresponding function values for each year. These functions were generated using data of the Boeing CMO 2014-2033 report and data provided by ICAO (2014). The shapes of the functions reveal that neither the RPKs produced per aircraft nor the seat load factor exceed certain maximum levels in the future. Instead, they feature a logistic behavior.

With these two functions, the raw data of the fleet simulations can be adapted through the following steps (referred to as ***Variant 2***).

1. Determine the annual target RPKs through the RPK growth rates defined by the future scenario, starting with an initial amount of RPKs in the base year.
2. Determine the annual target ASKs through application of the seat-load-factor function displayed in Figure K-1 (b).
3. Determine the total fleet size (of passenger aircraft only!) for each year of simulation required to supply the RPKs determined in step 1 through application of the RPKs-per-Pax-A/C function displayed in Figure K-1 (a).
4. Add the freighter aircraft originally determined by the fleet simulation to the fleet determined in step 3.
5. Determine the ratio between the ASKs originally determined by the fleet simulation and the ASKs determined in step 2.
6. Determine the total fuel burn using the ASKs-ratio determined in step 5. This ratio is exactly equal to the ratio with which the total fuel burn that has originally been

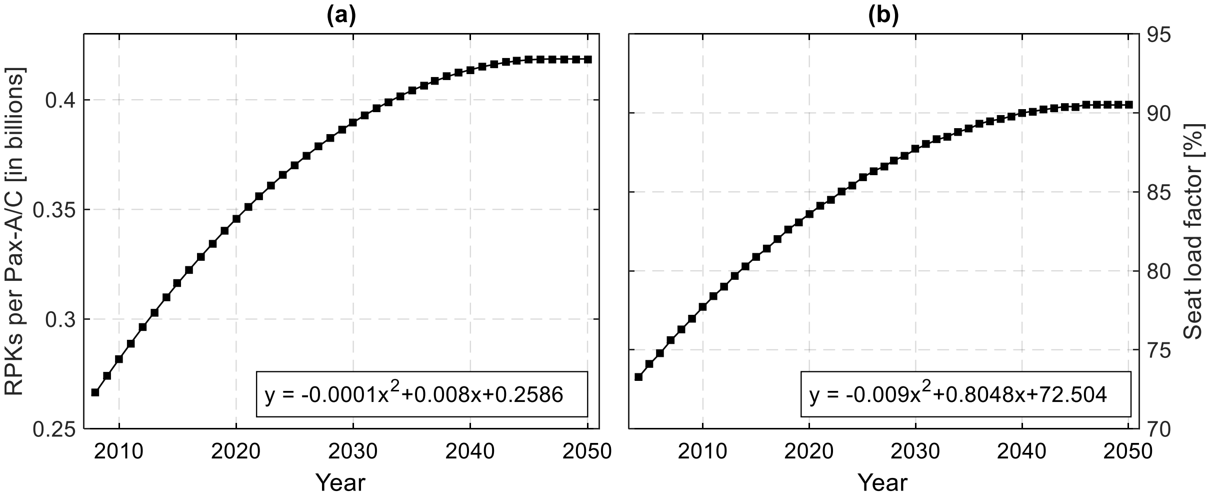


Figure K-1 **Dynamic development functions: (a) average transport supply per aircraft per year, (b) seat load factor**

Data source: author's calculations based on Boeing CMO 2014 and ICAO (2014)

determined by the fleet simulation changes when determining the total fuel burn of the adapted fleet.

Applying these steps will yield *an adapted fleet* that is now able to supply exactly the amount of target RPKs required by the future market scenario in each year of simulation. The same is equally true for the total ASKs and the fuel burn required by this fleet. Yet, the fleet-wide fuel and CO_2 performance characteristics are not affected and hence, consistent technology investigation and assessment studies are still possible.

Another way of application of the two functions of Figure K-1 is to determine the amount of RPKs and ASKs that are supplied by the *fleet originally determined by the simulation* while taking into account the dynamic evolution of the aircraft utilization and the seat load factor (referred to as ***Variant 1***). Again, several steps must be accomplished to achieve the corresponding fleet adaptations.

1. Determine the total fleet size of passenger aircraft by subtracting the air freighters from the total fleet originally determined by the simulation.
2. Determine the total RPKs per year that the fleet determined in step 1 is able to supply through application of the RPKs-per-Pax-A/C function displayed in Figure K-1 (a).
3. Determine the total ASKs per year through application of the seat-load-factor function displayed in Figure K-1 (b).
4. Determine the ratio between the ASKs originally determined by the fleet simulation and the ASKs determined in step 3.
5. Determine the total fuel burn using the ASKs-ratio determined in step 4. This ratio is exactly equal to the ratio with which the total fuel burn that has originally been determined by the fleet simulation changes when determining the total fuel burn of the adapted fleet.

Again, these steps do not affect the fleet-wide fuel and CO_2 performance characteristics.

Table K-1 **Values of the dynamic development functions of the average aircraft utilization characteristics and the seat load factor**

Data sources: Boeing CMO 2014, ICAO (2014), author's assumptions

	Aircraft utilization [Annual RPKs per aircraft in billions]	Seat load factor [%]
2008	0.2665	76.3
2009	0.2742	77.0
2010	0.2817	77.7
2011	0.2890	78.4
2012	0.2961	79.0
2013	0.3030	79.7
2014	0.3097	80.3
2015	0.3162	80.9
2016	0.3225	81.4
2017	0.3286	82.0
2018	0.3345	82.6
2019	0.3402	83.1
2020	0.3457	83.6
2021	0.3510	84.1
2022	0.3561	84.5
2023	0.3610	85.0
2024	0.3657	85.4
2025	0.3702	85.9
2026	0.3745	86.3
2027	0.3786	86.6
2028	0.3825	87.0
2029	0.3862	87.3
2030	0.3897	87.7
2031	0.3930	88.0
2032	0.3961	88.3
2033	0.3990	88.5
2034	0.4017	88.8
2035	0.4042	89.0
2036	0.4065	89.3
2037	0.4086	89.5
2038	0.4105	89.6
2039	0.4122	89.8
2040	0.4137	90.0
2041	0.4150	90.1
2042	0.4161	90.2
2043	0.4170	90.3
2044	0.4177	90.4
2045	0.4182	90.4
2046	0.4185	90.5
2047	0.4186	90.5
2048	0.4186	90.5
2049	0.4186	90.5
2050	0.4186	90.5

Appendix L List of student theses supervised

1. Arnold, C. (2012), *Clustering ziviler Flugzeuge: Bewertung möglicher Methoden und Anwendung [in German]*, Diploma Thesis (Report No. LS-DA 12/05).
2. Assenheimer, C. (2012), *Entwicklung eines Evolutionsmodelles zur Beschreibung zukünftiger Flugzeugbetriebsarten und Entwicklungsmöglichkeiten von Flotten [in German]*, Diploma Thesis (Report No. LS-DA 12/09).
3. Beier, T. (2012), *Entwicklung eines auf Flugplandaten basierenden Modells zur Berechnung und Darstellung von Flugverkehrsdichten [in German]*, Semester Thesis (Report No. LS-SA 12/16).
4. Braun, L. (2013), *Vergleich verschiedener Studien zur Entwicklung des zivilen Luftverkehrs und Erarbeitung eines Referenz-Szenarios für die Luftfahrt [in German]*, Semester Thesis (Report No. LS-SA 13/07).
5. Dehn, F. (2014), *Analyse des Lärmverhaltens von Propellerantrieben und Abschätzung der Wirkung konstruktiver Reduktionsmaßnahmen [in German]*, Semester Thesis (Report No. LS-SA 14/12).
6. Dryancour, A. (2012), *Analyse des Emissionshandelssystems der Europäischen Union und Abschätzung seines Einflusses auf die direkten Betriebskosten einer Fluggesellschaft [in German]*, Bachelor's Thesis (Report No. LS-BA 12/06).
7. Engelke, C. (2014), *Flottenplanung und -einsatz: Untersuchungen zur Weiterentwicklung eines dynamischen Flottenmodells für Leistungsanalysen der Weltflotte [in German]*, Bachelor's Thesis (Report No. LS-BA 14/05).
8. Engelke, C. (2015), *Erweiterung eines Programmes zur Flugleistungsrechnung für die emissionsbezogene Bewertung moderner Flugzeugkonzepte und -technologien [in German]*, Semester Thesis (Report No. LS-SA 15/02).
9. Forschner, P. (2012), *Analyse von bestehenden, lokalen Emissionsentgeltsystemen im zivilen Luftverkehr und Erstellung eines Modells zu deren Quantifizierung [in German]*, Semester Thesis (Report No. LS-SA 12/09).
10. Gazdag, B. (2012), *Clustering ziviler Flugzeugmuster: Bewertung möglicher Methoden und Anwendung [in German]*, Master's Thesis (Report No. LS-MA 12/02).
11. Grindemann, P. (2013), *Entwicklung einer Methode zur Abschätzung der Kosten für die Instandhaltung von Flugzeugtriebwerken im kommerziellen Luftverkehr [in German]*, Diploma Thesis (Report No. LS-DA 13/09-EX).
12. Heinisch, M. (2014), *Analyse von Flugzeug-Bodenoperationen im zivilen Luftverkehr für die Anwendung in der Flugbetriebsmodellierung [in German]*, Semester Thesis (Report No. n/a).
13. Hörmann, J. (2013), *Beschreibung und Modellierung von Außerdienststellungsfunktionen ziviler Transportflugzeuge [in German]*, Semester Thesis (Report No. LS-SA 13/13).
14. Ittel, J. (2014), *Developing a software tool for comprehensive flight performance and mission analyses in the context of the assessment of a novel turboprop transport aircraft concept*, Master's Thesis (Report No. LS-MA 14/06).

15. Iwanizki, M. (2013), *Vorentwurf einer schweren, Propellerturbinen-getriebenen Verkehrsflugzeugkonfiguration für den Einsatz auf hochfrequentierten Kurz- und Mittelstrecken [in German]*, Master's Thesis (Report No. LS-MA 13/02).
16. Kalwar, D. (2015), *Integration of turbofan engines into the preliminary design of a high-capacity short- and medium-haul passenger aircraft and fuel efficiency analysis with a further developed parametric aircraft design software*, Master's Thesis (Report No. LS-MA 15/02).
17. Kazarow, B. (2013), *Weiterentwicklung eines Modells zur Flugplan-basierten Bestimmung von Flugverkehrswegen und –dichten [in German]*, Semester Thesis (Report No. LS-SA 13/10).
18. Kazarow, B. (2015), *Assessment of the impact of aircraft service life extension programs on the base maintenance process at Lufthansa Technik, on the Lufthansa fleet deployment, and on the retirement behavior of the global fleet*, Master’s Thesis (Report No. LS-MA 15/01-EX).
19. Kügler, M.E. (2014), *Development of a parametric aircraft design tool for design iterations of a high-capacity turboprop transport aircraft*, Master's Thesis (Report No. LS-MA 14/10).
20. Linder, A. (2012), *Untersuchung der technologischen und wirtschaftlichen Wirkung eines globalen Emissionshandelssystems auf den zivilen Luftverkehr [in German]*, Bachelor’s Thesis (LS-BA 12/05).
21. Oezer, S. (2013), *Weiterentwicklung eines auf dem Total-Energy-Modell basierenden Programms für die Flugleistungs- und Missionsrechnung [in German]*, Semester Thesis (Report No. LS-SA 13/03).
22. Osterrieder, P. (2013), *Advanced engine direct maintenance cost models for future aircraft concepts*, Bachelor’s Thesis (Report No. LS-BA 13/04-EX).
23. Sander, M. (2012), *Luftverkehr und Klima - Ortsabhängigkeit chemischer Luftverkehrseffekte [in German]*, Diploma Thesis (Report No. LS-DA 12/08-EX).
24. Shestakovskiy, Y. (2013), *Design and performance estimation of high-technology propellers and open rotors for use in aircraft conceptual design*, Semester Thesis (Report No. 13/11).
25. Soyk, C. (2012), *Techno-economic analysis of aviation fuel production from phototrophic microalgae*, Semester Thesis (Report No. LS-SA 12/06-EX).
26. Soyk, C. (2014), *Optimization of profitability in existing routes networks of hub-and-spoke airlines*, Master’s Thesis (Report No. LS-MA 14/03-EX).
27. Wache, L.H. (2014), *Szenariobasierte Modellierung der Weltflugzeugflotte unter Berücksichtigung dynamischer Einflussparameter [in German]*, Master's Thesis (Report No. LS-MA 14/15).
28. Werner, C. (2012), *Analyse und Bewertung verschiedener Modelle zur Berechnung des Kraftstoffverbrauches ziviler Transportflugzeuge und Flotten [in German]*, Semester Thesis (Report No. LS-SA 12/12).
29. Zhao, L. (2014), *Ermittlung von Systemtrajektorien für den Langstreckenlufttransport der Zukunft [in German]*, Diploma Thesis (Report No. 14/07-EX).
30. Zwenzner, S. (2014), *Potentialanalyse von Lösungsverfahren des Flottenzuweisungsproblems für die Anwendung in einem dynamischen Flottenmodell [in German]*, Semester Thesis (Report No. LS-SA 14/01).

Appendix M List of scientific publications

1. Randt, N.P., Plötner, K.O., Jeßberger, C., and Becker, A. (2013), "Air traffic growth, energy, and the environment 2040. Drivers, challenges, and opportunities for aviation," paper presented at the 17th ATRS World Conference, 26 – 29 June 2013, Bergamo, Italy.
2. Randt, N.P. "Foundations of a technology assessment technique using a scenario-based fleet system dynamics model," paper presented at the 13th Aviation Technology, Integration, and Operations Conference, 12 – 14 August 2013, Los Angeles, California, USA.
3. Büchter, K.-D. and Randt, N.P. (2013), "Capacity scaling in airborne communication networks based on air traffic scenario modeling," paper presented at the 62. Deutscher Luft- und Raumfahrtkongress (62nd German Aerospace Congress), 10 – 12 September 2013, Stuttgart, Germany.
4. Randt, N.P. and Öttl, G. (2013), "Applied scenario planning as a basis for the assessment of future aircraft technologies," paper presented at the 62. Deutscher Luft- und Raumfahrtkongress (62nd German Aerospace Congress), 10 – 12 September 2013, Stuttgart, Germany.
5. Randt, N.P., Sartorius, S., and Urban, M. (2014), "Requirements and concepts of operations for a personalized air transport system in 2050," paper presented at the 52nd Aerospace Sciences Meeting, 13 – 17 January 2014, National Harbor, Maryland, USA.
6. Iwanizki, M. and Randt, N.P., and Sartorius, S. (2014), "Preliminary design of a heavy short- and medium-haul turboprop-powered passenger aircraft," paper presented at the 52nd Aerospace Sciences Meeting, 13 – 17 January 2014, National Harbor, Maryland, USA.
7. Randt, N.P. and Wolf, S. (2014), "Automation in future air transport. A scenario-based approach to the definitions of operational requirements," paper presented at the 29th Congress of the International Council of the Aeronautical Sciences (ICAS), 7 – 12 September 2014, St. Petersburg, Russia.
8. Randt, N.P., (2014), "Perspectives of turboprop aircraft. A stakeholder-oriented evaluation using scenario planning," paper presented at the 63. Deutscher Luft- und Raumfahrtkongress (63rd German Aerospace Congress), 16 – 18 September 2014, Stuttgart, Germany.
9. Randt, N.P., Jeßberger, C., and Plötner, K.O. (2015), "Estimating the fuel saving potential of commercial aircraft in future fleet-development scenarios," paper presented at the 15th AIAA Aviation Technology, Integration, and Operations Conference, 22 – 26 June 2015, Dallas, Texas, USA.
10. Kügler, M.E. and Randt, N.P. (2015), "Development and application of a parametric design tool for design iterations of large turboprop aircraft," paper presented at the 15th AIAA Aviation Technology, Integration, and Operations Conference, 22 – 26 June 2015, Dallas, Texas, USA.

11. Randt, N.P., Jeßberger, C., Plötner, K.O., and Becker, A. (2015), "Air traffic growth, energy, and the environment 2040. Drivers, challenges, and opportunities for aviation," *International Journal of Aviation Management*, Vol. 2 No. 3/4, pp. 144-166.
12. Randt, N.P. (2015), "An approach to product development with scenario planning. The case of aircraft design," *Futures*, Vol. 71, pp. 11-28.