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A Novel Approach for Modelling Future Airport Noise Exposure

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Abstract

Aircraft noise emissions are a major negative consequence of civil aviation. In order to support the development of effective noise mitigation strategies, authorities and the aviation industry require modelling capabilities that allow quantitative predictions of aircraft noise emissions at airports. Therefore, this thesis presents the formulation and implementation of a novel method for the assessment of future airport noise exposure. The method combines three fundamental modelling areas. Firstly, an approach to model future flight plans (including future fleet mixes) is presented. Based on a flight plan of a baseline year, flight plan evolution is derived from scenario-specific inputs for air traffic growth, aircraft retirement, aircraft introduced to the fleet, airport capacity, and flight route distribution. Secondly, aircraft noise is modelled at the vehicle level according to an approach proposed by the European Civil Aviation Conference. Thirdly, airport-level noise is calculated using the Aviation Environmental Design Tool. A validation of the flight plan modelling is presented by comparing model predictions to historic operations at Munich Airport. The different capabilities of the method are demonstrated by several simulations of a generic two-runway study airport. A baseline simulation presents a plausible evolution of noise contour areas for an unconstrained airport up to the year 2040. The results predict roughly constant day-evening-night levels despite a doubling in passenger traffic. Further simulations examine the impact of air traffic growth, the airport's operating direction, the fleet renewal process, airport capacity constraints, and a particularly noise-reduced future narrow-body study aircraft on the future development of airport noise. The presented method may provide aviation stakeholders useful insights and support in the definition of aircraft-level, airport-level, and fleet-level noise mitigation strategies.

Wie oft lenkt uns der Lärm der Welt von den eigentlich wichtigen Dingen ab.

Unbekannt

Kommt her zu mir, alle ihr Mühseligen und Beladenen, und ich werde euch Ruhe geben.

Jesus Christus

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Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

A/C	Aircraft
AEDT	Aviation Environmental Design Tool
AIP	Aeronautical Information Publication
ANP	Aircraft Noise and Performance
APU	Auxiliary Power Unit
AS	Available Seats
ASIF	AEDT Standard Input File
ASL	Above Sea Level
ATC	Air Traffic Control
ATM	Air Traffic Management
ATS	Air Transport System
CAA	Civil Aviation Authority
CAEP	Committee on Aviation Environmental Protection
CEAC	Conférence Européenne de l'Aviation Civile
CNEL	Community Noise Equivalent Level
CT	Current Technology
DEN	Day-Evening-Night Level
DNL	Day-Night Level
EASA	European Aviation Safety Agency
ECAC	European Civil Aviation Conference
EIS	Entry Into Service
EOP	End Of Production
EP	Exit Point
ERCD	European Research and Consultancy Department
EU	European Union
FAA	Federal Aviation Agency
FANAM	Future Airport Noise Assessment Method
FESG	Forecasting and Economic Analysis Support Group
FFDT	Future Flight Plan Development Tool
FFEA	Future Flight Plan Estimation Approach

FMG	Flughafen München GmbH
GMF	Global Market Forecast
GUI	Graphical User Interface
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
INM	Integrated Noise Model
NB	Narrow-Body Aircraft
NM	Nautical Mile
NPD	Noise Power Distance
NT-1	New Technology 1
NT-2	New Technology 2
OAG	Official Airline Guide
OEM	Original Equipment Manufacturer
OPS	Operations
PAX	Passengers
RPK	Revenue Passenger Kilometres
SAE	Society of Automotive Engineers
SEL	Sound Exposure Level (L_{AX})
SID	Standard Instrument Departure
SLF	Seat Load Factor
STAR	Standard Arrival Route
TRL	Technology Readiness Level
UK	United Kingdom
USA	United States of America
WB	Wide-Body Aircraft
XML	Extensible Markup Language

Greek Symbols

β_I	Retirement coefficient 1
β_{II}	Retirement coefficient 2

Latin Symbols

a	Aircraft age	$[years]$
$AOTC$	Adjusted ordered transport capacity	$[seats]$
AS	Available seats	$[seats]$
C	Tone correction factor	$[EPNdB]$
D	Duration factor	$[EPNdB]$

$EISF$	Entry-into-service factor	$[-]$
$EPNL$	Effective perceived noise level	$[EPNdB]$
g	Air traffic growth rate	$[-]$
g_x	Time-dependent weighting factor	$[-]$
G	Flight plan gap	$[seats]$
I	Transport capacity of introduced aircraft	$[seats]$
L_{AX}	Sound exposure level (SEL; A-weighted)	$[dB(A)]$
$L_{A,eq}$	Equivalent continuous sound level (A-weighted)	$[dB(A)]$
$L_{A,max}$	Maximum sound pressure level (A-weighted)	$[dB(A)]$
L_{den}	Day-evening-night level (A-weighted)	$[dB(A)]$
L_{dn}	Day-night level (A-weighted)	$[dB(A)]$
L_{EQ}	Equivalent continuous sound level (general form)	$[dB]$
L_{max}	Maximum sound pressure level	$[dB]$
L_{night}	Equivalent continuous sound level for night (A-weighted)	$[dB(A)]$
L_p	Sound pressure level	$[dB]$
$L_{p,A}$	Sound pressure level (A-weighted)	$[dB(A)]$
n	Number of active aircraft	$[-]$
n_o	Number of produced aircraft	$[-]$
N_g	Number of sound events	$[-]$
p	Sound pressure	$[Pa]$
p_0	Reference sound pressure	$[Pa]$
PNL	Perceived noise level	$[EPNdB]$
$PNLT$	Tone corrected perceived noise level	$[EPNdB]$
$PNLTM$	Maximum tone corrected perceived noise level	$[EPNdB]$
POS	Percentage of survival	$[-]$
R	Transport capacity after retirement	$[seats]$
sf	Swap factor	$[-]$
T	Assessed period of time	$[s]$
t	Time	$[s]$
t_0	Baseline year	$[years]$
t_e	Effective duration	$[s]$
t_{10}	10-dB-down time	$[s]$
$TOTC$	Total ordered transport capacity	$[seats]$

Subscripts

A/C	Aircraft type index
APP	Approach procedures
app	Approach certification point
DEP	Departure procedures

fly	Flyover certification point
i	Flight plan entry index (of baseline flight plan)
j	Flight plan entry index (of introduced aircraft)
k	World region index
lat	Lateral certification point
m	Aircraft type index (of flight plan gap aircraft)
n	Aircraft type index (of introduced aircraft)
p	Aircraft type index
q	Aircraft cluster index
t	Time index
x	Sound event index

1 Introduction

1.1 Motivation

Aviation has brought significant advantages to mankind by providing fast, affordable and reliable mobility. At the same time, aviation brings about noticeable drawbacks by negatively affecting the environment, among other aspects, through noise emitted by aircraft. As air traffic has grown throughout the last decades, so has the challenge posed by aircraft noise.

We can look at aircraft noise from two different perspectives. The first is that of residents who live in the vicinity of an airport and are affected by the noise emissions of aircraft operations. These residents usually feel negatively affected by aircraft noise. In Germany, for instance, around 9% of the population feels "strongly" or "extremely" disturbed or annoyed by aircraft noise (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, 2017).[1] A study at the Cologne Bonn Airport revealed that among all the negative aspects residents associate with the nearby airport, aircraft noise is by far the most frequently named (Bartels and Müller, 2018). What is more, for the residents affected by aircraft noise, the exposure to noise is not only a subjective matter of annoyance. Aircraft noise is correlated with negative effects on human development and health. Aircraft noise during the night, for example, may significantly disturb sleep (Basner et al., 2006). Exposure to aircraft noise correlates with an increased risk of heart failure and hypertensive heart disease (Seidler et al., 2016). Aircraft noise emissions also have negative effects on children's reading comprehension and recognition memory (Stansfeld et al., 2005). Thus, it can be stated that aircraft noise emissions are able to negatively affect humans to a significant extent.

The second perspective on aircraft noise is that of the aviation industry. For aviation stakeholders, aircraft noise is an undesired, yet inevitable companion of providing mobility to travellers. As a result of efforts to reduce the negative effects of aircraft noise, the aviation industry is faced with multiple consequences. For instance, global restrictions have been established that prohibit the aviation industry from operating aircraft types that exceed specified noise levels.[2] Further, at the airport level, aircraft may be required to fly longer

[1] Originally, in German, „stark“ and „äußerst“.
[2] See the noise limits specified by the different chapters of Annex 16 to the Convention on International Civil Aviation on environmental protection (ICAO, 2011).

flight routes for noise mitigation reasons, causing increases in fuel consumption. In addition, various airports have implemented noise-specific landing fees with the purpose of encouraging aircraft operators to use quieter aircraft. Moreover, endeavours to reduce or avoid aircraft noise during the night have led to night-time operating restrictions or bans for an increasing amount of airports. At capacity-constrained airports, one of the main reasons for residents to oppose airport extensions is aircraft noise emissions. Therefore, it can be summarised that aircraft noise and its consequences represent a considerable challenge to the aviation industry.

It is useful to briefly reflect on how noise-related trends have developed during recent years and how they may continue to develop in the future. During the last decades, air traffic demand has grown tremendously. Since the 1980's, global annual traffic has approximately doubled every 15 years (Airbus, 2017b) with a corresponding increased number of noise events in the vicinity of airports. However, the increased air traffic volume has been accompanied by significant reductions in the noise emitted by a single aircraft operation (Sustainable Aviation, 2013). In this process, the reduction of aircraft-level noise emissions has mainly been achieved by a continuous increase in the bypass ratio of jet engines, which has allowed for a decrease in jet noise levels due to lower jet velocities.

In the future, major aviation stakeholders expect air traffic to continue to grow significantly (Airbus, 2017b; Boeing, 2017). However, the increase in bypass ratio of future jet engines is expected to be comparatively small, which in turn, will only allow for minor reductions in engine noise (ICAO, 2014). In the past, engine noise usually dominated the total aircraft noise emission since it was significantly louder than other noise sources. Yet, after the successes in engine noise reduction, airframe noise sources have generally also become significant, especially during approach procedures. Consequently, future aircraft noise reductions might require both engine noise and airframe noise to be reduced (Dobrzynski, 2010). As a result, further aircraft-level noise reductions of conventional tube-and-wing aircraft concepts are likely to become more challenging in the future.

In addition to the development of physical noise levels[3], changes in the subjective perception of aircraft noise by humans might worsen the situation. It is well known that different individuals perceive the same noise levels differently, for example in terms of subjective annoyance. Psychoacoustic research indicates that the same noise levels today on average cause higher annoyance levels than in the past (Guski et al., 2017). In the future, it is possible that this trend of increased sensitivity towards aircraft noise will continue.

The combination of the discussed effects leads to the conclusion that the challenges posed by aircraft noise could intensify in the future. While air traffic is expected to strongly grow, future aircraft-level noise reduction, particularly from a plain increase in the bypass ratio of jet engines, may be limited and insufficient. On top of this, human sensitivity towards

[3] This means a plain description of aircraft noise by physical sound pressure levels.

aircraft noise might further increase. The aviation industry therefore needs to give adequate attention to noise-related challenges. Furthermore, the aviation stakeholders should review and ideally quantify the current noise reduction strategies and possibly develop additional ones.

1.2 Objective

A fundamental prerequisite for the evaluation and quantification of suitable strategies is the capability to model the exposure to aircraft noise in dependence on the underlying noise-relevant effects. A considerable amount of previous research has dealt with the modelling of single-event aircraft noise.[4] The focus of such research has usually been either on noise-optimised flight trajectories or on the noise emissions of novel aircraft concepts. Yet, besides the evaluation of single-event noise, it is important to also evaluate the cumulated aircraft noise at the airport level.[5] Several commercial tools[6] exist to model current airport noise exposure defined by a given flight schedule for a modern aircraft fleet. However, in the definition and evaluation of noise-mitigation strategies, it is desirable to also model the evolution of airport noise in the future. The fundamental question that may be posed is: how will airport-level noise develop in the future? Moreover, it is of great interest to answer the question: to what extent would different noise-mitigation measures be able to reduce future airport-level noise? Not much research has addressed these important questions so far.[7] Therefore, the objective of this thesis is to formulate and implement a method that allows the assessment of future airport noise considering user-defined, noise-relevant scenario definitions. The two primary goals of this thesis can be summarised as follows:

1. The theoretical development of a method for the assessment of future airport noise.
2. The practical implementation of modelling capabilities that enable the application of the developed method.

The method must principally allow the assessment of noise-mitigation strategies at three different levels. Firstly, it must be able to consider the impact of aircraft type-individual noise emissions on future airport noise and, hence, of possible future aircraft-level noise reductions. Secondly, the method must be able to account for noise-relevant effects at the airport level, such as airport-specific flight routes, airport capacity constraints, and air traffic growth. Thirdly, the method must be able to take into account fleet-level impacts,

[4] The noise footprint of a single flight operation (either departure or arrival).
[5] The cumulated aircraft noise from an entire day's (or year's) flight schedule, usually quantified by continuous sound levels (see Section 2.1.2).
[6] For example, the Integrated Noise Model by the FAA, the software CadnaA by the company DataKustik, or the software SoundPLAN Noise by the company SoundPLAN.
[7] An overview of published noise studies at the airport level is presented in Section 2.3.

mainly the retirement of aircraft and the introduction of new aircraft to the fleet.[8] A detailed discussion of the scope and intended capabilities of the method is given in Section 3.1.1.

1.3 Structure of Work

An overview of the structure of this thesis is presented in Fig. 1-1. As can be seen, the thesis is structured in five main chapters. Chapter 1 introduces the topic of the thesis. Chapter 2 presents fundamental knowledge about acoustics and aircraft noise that is required throughout this work. Moreover, the chapter gives an overview on the state of the art of airport-level noise research. Chapter 3 holds the main contributions of this thesis describing the development of a novel method for the assessment of future airport noise. The design of a framework, which represents the fundamental approach of the method, is first explained (Section 3.1). Subsequently, the different modelling areas of the method are discussed in detail (Sections 3.2 to 3.4). Furthermore, the chapter includes a section describing the implementation of a corresponding tool and its validation (Sections 3.5 and 3.6). Chapter 4 presents an application case that applies the developed framework to a generic two-runway study airport. The definition of a study airport (Section 4.1) is followed by the presentation of the modelling of a status quo case and of six future scenarios that each demonstrate a different modelling capability of the method (Sections 4.2 to 4.8). The chapter then summarises several scenario-specific results of the application case (Section 4.9). Finally, the principle capabilities and limitations of the developed method are discussed (Section 4.10). Chapter 5 provides a summary of the main findings and additionally offers multiple suggestions for future work.

[8] It is important to note that the first and the third level are closely connected to each other. New and quieter aircraft will be able to mitigate airport noise under two conditions: firstly, new aircraft must be available, that is, ready to be actually produced by a manufacturer. However, secondly, in addition to market availability, the aircraft must also enter the operating fleet and gain significant shares. Both the aircraft-level noise reductions and the aircraft's fleet penetration will determine the noise mitigation effect at the airport level. Consequently, new aircraft at the aircraft level (first level) as well as the fleet renewal process (third level) must be modelled.

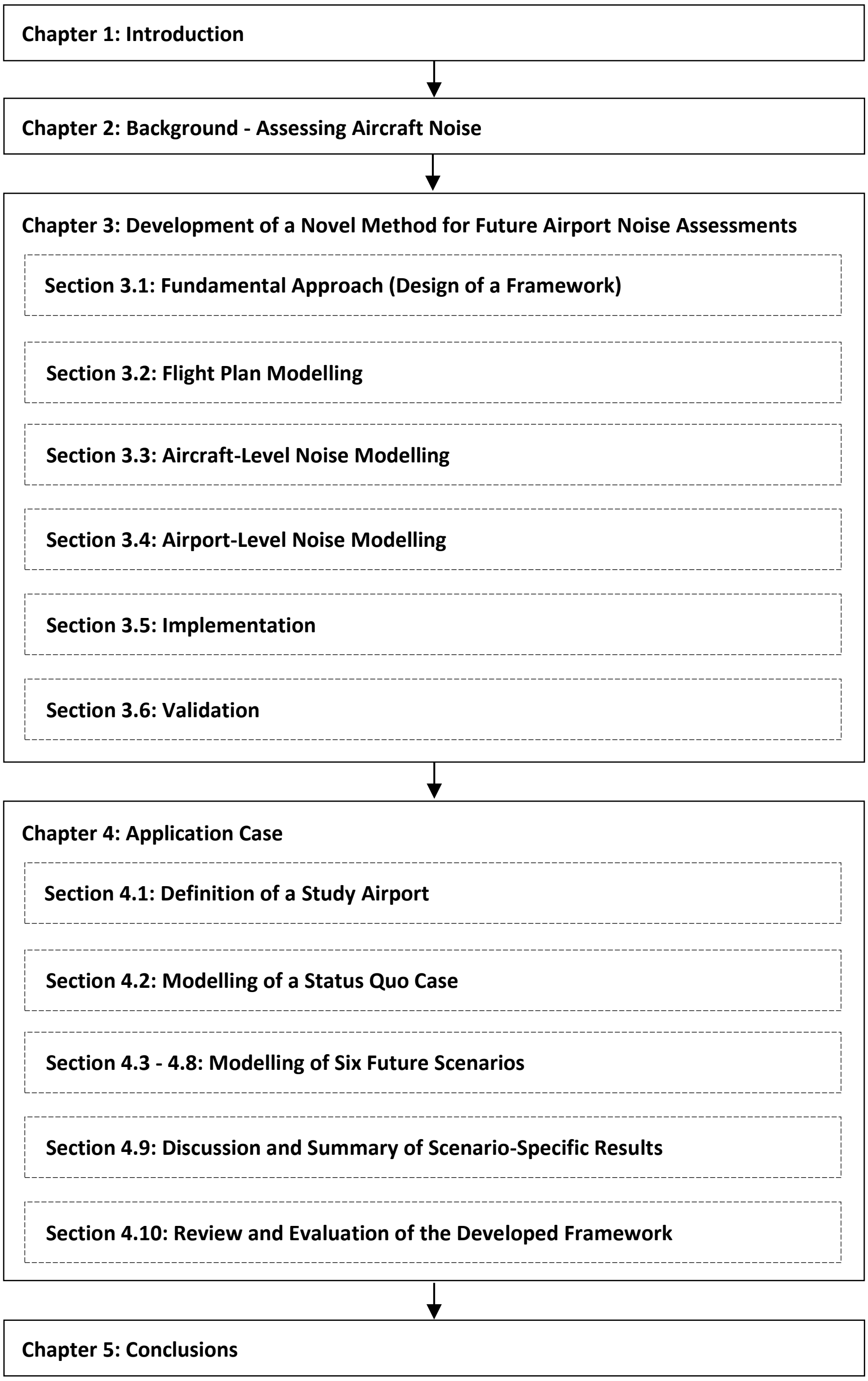

Fig. 1-1 Structure of the thesis

2 Background: Assessing Aircraft Noise

The following chapter presents relevant theoretical background knowledge required throughout this thesis. In Section 2.1, fundamental acoustic principles and metrics are introduced. Section 2.2 is devoted specifically to aircraft noise, discussing the main noise sources and the noise certification process. Section 2.3 presents a discussion of the state of the art in airport-level noise research related to the content of this thesis.

2.1 Acoustic Foundations

Acoustics is the scientific field that deals with the theory of sound. Whereas *sound* is a neutral term for mechanical oscillations in the range of human audibility, the term *noise* describes undesired sound. Principally, a sound event can be described by its frequency and by its sound pressure. For humans, the frequency range of audible sound approximately is from 16 Hz to 16 kHz. In terms of sound pressure, humans are able to perceive a range over seven orders of magnitude. Due to this wide range, sound pressure is usually quantified on a logarithmic scale as the sound pressure level (SPL or L_p) in dB. It is calculated from the sound pressure p in Pa according to equation (2.1) with the reference pressure $p_0 = 2 * 10^{-5}$ Pa. A difference in sound pressure level of 10 dB is approximately perceived as a doubling in loudness. A difference of 1 dB is the approximate threshold of perceivable difference of two sound events. (Müller and Möser, 2004)

$$L_p = 20 * \log \frac{p}{p_0} \tag{2.1}$$

A further important characteristic of the human hearing lies in the fact that its sensitivity varies considerably over the range of audible frequencies. The human's maximum sensitivity is approximately found for sound between 1000 Hz and 5000 Hz. A sound event of identical sound pressure levels outside this range may be perceived as much less loud. In order to account for the frequency dependence of the human hearing different frequency weightings have been developed. Two exemplary weighting filters are shown in Fig. 2-1, which specify a correction of the physical sound pressure level as a function of frequency.[9] The blue curve presents the A-weighting, the red curve indicates the C-weighting. The A-

[9] The correction (in dB) is added to the physical sound pressure level (in dB).

weighting (in blue) is the most commonly used frequency weighting in acoustics. A-weighted sound pressure levels $L_{p,A}(t)$ are indicated by the unit dB(A).[10] (Müller and Möser, 2004)

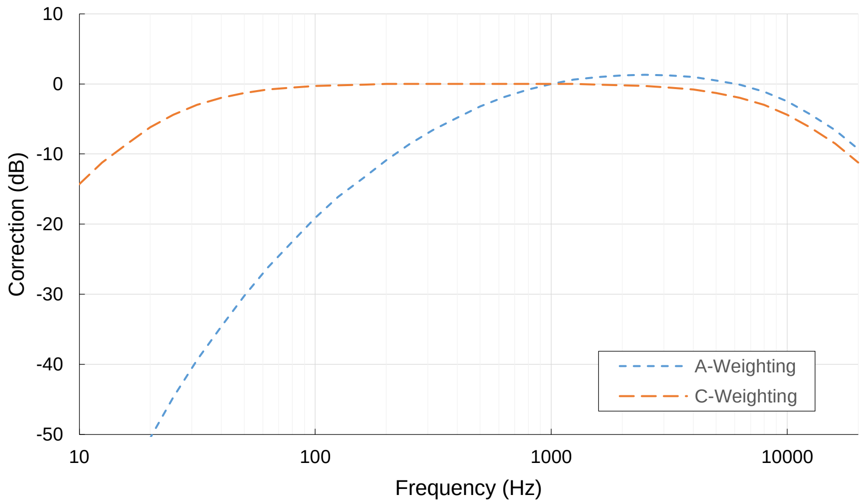

Fig. 2-1 Different frequency weightings: A- and C-weighting after Müller and Möser (2004)

2.1.1 Single Event Noise Metrics

Single event noise metrics are metrics that describe a single sound event, that is, speaking of aircraft noise, a single overflight. In the following, a number of single event noise metrics relevant throughout this thesis are introduced.

Maximum sound pressure level

The maximum sound pressure level L_{max} is the simplest metric to describe a sound event. From a sound event's recorded sound pressure time history, the L_{max} marks the maximum sound pressure. In most cases, as mentioned, the physical sound pressure is subject to an A-weighting, hence, the resulting maximum sound pressure level is denoted as $L_{A,max}$. The formal definition of the $L_{A,max}$ is given by equation (2.2). The advantage of the $L_{A,max}$ is its simplicity in terms of measurements and with respect to communication to the public. A main downturn lies in the fact that the $L_{A,max}$ does not take into account the duration of a sound event, which may be an important characteristic in the actual disturbance caused by a sound event. (Jones and Cadoux, 2009)

$$L_{A,max} = \max(L_{p,A}(t)) \tag{2.2}$$

An illustration of the time history of a sound event is presented in Fig. 2-2. In the figure,

[10] Accordingly, C-weighted sound pressure levels are specified by dB(C).

the maximum sound pressure level L_{max} is indicated.[11] Next to the maximum sound pressure level, the time history can be described by a typical sound duration. As shown in Fig. 2-2, two different characteristics describing the duration of a sound event are common. The first metric is the 10-dB-down time t_{10}, which characterises the duration where the sound level is at least 10 dB below the L_{max}. The second metric describing the sound duration is the effective duration t_e, which is defined by equation (2.3). Hence, t_e is the duration of a sound event with the constant sound level L_{max}, which has the same sound energy as the actual sound event described by the time history $L(t)$. (Isermann and Schmid, 1999)

$$t_e * 10^{L_{max}/10} = \int_{-\infty}^{\infty} 10^{L_p(t)/10} dt \qquad (2.3)$$

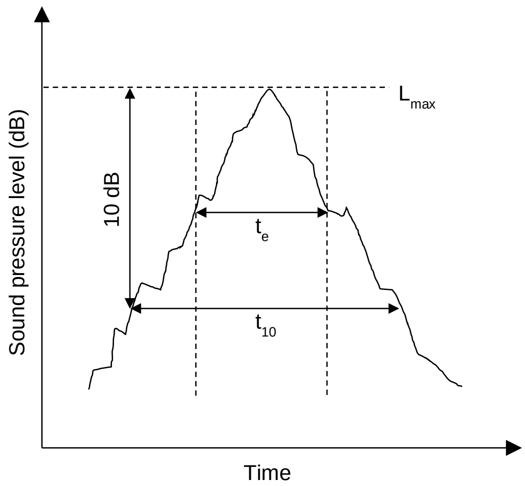

Fig. 2-2 Duration definitions of single event noise after Isermann and Schmid (1999)

Sound exposure level (SEL)

The sound exposure level L_{AX}, also commonly abbreviated as SEL, is a single event noise metric that takes into account the timely evolution of a sound event by an integration of sound energy. In the same way as the maximum sound pressure level, it is based on the recorded pressure time history $L_{A,max}$. From this, the sound exposure level integrates the sound energy of a sound event according to equation (2.4) with the reference time $t_{ref} = 1\ sec$. Hence, the L_{AX} represents the dB(A) value of a corresponding sound event of one second that has the same sound energy as the sound event to be described. The advantage of the sound exposure level is its consideration of the duration of a sound event. For example, for a constant level sound event, a doubled duration of the sound event is equivalent to an increase by ca. +3 dB.[12] (Isermann and Schmid, 1999; Jones and Cadoux, 2009)

[11] In the general case L_{max}; if the A-weighting is applied the $L_{A,max}$.
[12] Because the sound energy is doubled (log(2) = 0.301 and 10*log(2) = 3.01).

$$L_{AX} = 10\log\left(\frac{1}{t_{ref}}\int 10^{L_{p,A}(t)/10}\,dt\right) \tag{2.4}$$

Effective perceived noise level (EPNL)

The effective perceived noise level is a single event noise metric specifically developed for aircraft noise. The intension in the design of the EPNL was to better reflect the subjective effects of aircraft noise on humans than previously existing noise metrics. The EPNL is an important metric because it is the required metric for aircraft noise certifications (see Section 2.2.2). It is determined according to a comprehensive procedure as described by the Annex 16 to the Convention on International Civil Aviation (International Civil Aviation Organization, 2008a). In short, the EPNL consists of a metric called the perceived noise level (*PNL*) added by a "tone correction" and by a "duration correction". (Jones and Cadoux, 2009)

In more detail, to evaluate effective perceived noise levels, the sound pressure time history of a sound event is measured in increments of 0.5 sec for 24 one-third octave bands.[13] For each of the 24 one-third octave bands, a value of perceived noisiness is determined, which are then combined to a perceived noise level.[14] Furthermore, for each spectrum, a tone correction factor C is determined to take into account particular tonal content of a sound event. From the perceived noise level and the tone correction factor, for each half-second increment a tone corrected perceived noise level (*PNLT*) is then calculated according to equation (2.5). (International Civil Aviation Organization, 2008a)

$$PNLT = PNL + C \tag{2.5}$$

Furthermore, from the integration of the tone corrected perceived noise level, a duration factor D is determined. Finally, the duration factor D is added to the maximum tone corrected perceived noise level (*PNLTM*) of the sound event according to equation (2.6). The resulting noise levels are specified by the unit EPNdB. (International Civil Aviation Organization, 2008a)

$$EPNL = PNLTM + D \tag{2.6}$$

2.1.2 Cumulative Noise Metrics

In the description of accumulated noise situations, it is important not only to quantify single noise events, but also the noise exposure over longer durations. These noise metrics

[13] While the term "octave" describes a difference in frequency by the factor 2 (e.g. 1000 Hz and 2000 Hz), the term "one-third octave" refers to a subdivision of an octave into three further intervals (e.g. 1000 Hz, 1250 Hz, 1600 Hz, 2000 Hz).

[14] The perceived noise level is a metric developed by Karl D. Kryter based on psychoacoustic experiments. It evaluates a given sound event in terms of experienced "noisiness" in comparison to a precisely defined reference sound event. The according unit is "noy".

are called cumulative noise metrics or exposure-based metrics. Multiple cumulative noise metrics exist in the literature, however, the most common metrics are based on the A-weighted equivalent continuous sound pressure level $L_{A,eq}$ as described by equation (2.7). As can be seen, the $L_{A,eq}$ integrates the sound energy over a specified time.

$$L_{A,eq} = 10 * \log\left[\frac{1}{T}\int_{o}^{T} 10^{\frac{L_{p,A}(t)}{10}} dt\right] \tag{2.7}$$

T Assessed period of time

Another version of the previous technical definition of the continuous sound pressure level[15] is presented in equation (2.8), which offers a calculation based on the maximum sound pressure levels of the specific noise events within the assessed period of time. Furthermore, as introduced by equation (2.8), a number of derivations of the continuous sound pressure level exist as discussed in the following. These metrics aim at a reflection of the varying human sensitivity towards noise during different times of the day.[16] (Isermann and Schmid, 1999)

$$L_{EQ} = 10 * \log\left[\frac{1}{T}\sum_{x}^{N_g} g_x * 10^{L_{A,max,x}/10} * t_e\right] \tag{2.8}$$

x Sound event index

N_g Number of sound events during time period T

g_x Time-dependent weighting factor for sound event x

t_e Effective duration

Different specifications of the time-dependent weighting factor g_x in equation (2.8) allow the definition of different cumulative noise metrics. Three metrics commonly used are defined according to the values specified by Tab. 2-1. The first metric other than the $L_{A,eq}$ is the L_{night} for assessments of noise exposure during the night.[17] A noise metric that considers the entire 24 hours of a day with additional noise penalties for night-time noise events is the L_{dn}. The L_{dn} is often refered to as Day-Night Level (DNL). It penalises noise events during the night by +10 dB. A noise metric that additionally includes noise penalties for noise events during the evening by +5 dB is the L_{den}.[18] The L_{den} is also named the Day-Evening-Night Level (DEN). (Isermann and Schmid, 1999)

[15] Or only „continuous sound level“.

[16] In the definition of the metrics, it is assumed that noise during the evening or night is more disturbing than during the day.

[17] The definitions of “day“, “evening“, and “night“ may not be identical in different studies and may depend on the country of the conducted study. In this thesis, the period “day” is defined from 7 am to 7 pm, the period “evening“ from 7 pm to 11 pm, and the period “night“ from 11 pm to 7 am according to the recommendation by the European Union (Official Journal of the European Communities, 2002).

[18] The weighting factor 3.162 corresponds to a noise penalty of +5 dB (10*log(3.162) = 5.0).

Tab. 2-1 Overview of different metrics based on the equivalent continuous sound level: Definition of the time-dependent weighting factor (Isermann and Schmid, 1999)

Metric	*Day*	*Evening*	*Night*
$L_{A,eq}$	1	1	1
L_{night}	0	0	3
L_{dn}	1	1	10
L_{den}	1	3.162	10

2.2 Aircraft Noise Foundations

2.2.1 Aircraft Noise Sources

The general term *aircraft noise* is commonly used to describe the cumulated noise emitted by an aircraft. However, in reality, aircraft noise emissions consist of noise emitted from a variety of sources. Principally, aircraft noise sources can be categorised into two different groups, which are engine noise and airframe noise. Whereas engine noise includes all noise sources associated to the engines of an aircraft, the term airframe noise refers to non-engine noise sources. In the following, a brief overview of the noise sources of current commercial aircraft is given. (Smith, 2009)

In the category of engine noise, the major noise sources of a typical aircraft jet engine can be associated to the following sources (Müller and Möser, 2004):

1. Jet noise[19]
2. Fan
3. Turbine
4. Combustion chamber
5. Compressor

During departures with engine power settings close to the maximum, jet noise and fan noise usually dominate. During approaches, however, with much lower engine power settings, jet noise and fan noise are generally much less dominant and noise emissions from the turbine, the combustion chamber, and the compressor may become significant, too. (Müller and Möser, 2004)

As of airframe noise, the major noise sources are emitted from the following components of a state-of-the art civil aircraft (Dobrzynski, 2010):

1. Landing gear

[19] The term *jet noise* describes the noise generated by the process of the accelerated air leaving the jet engine and mixing with the surrounding air outside the engine.

2. Slotted slat
3. Flap and slat side edge
4. Flap and slat track
5. Spoilers

The listed order represents the typical order of emitted sound levels. For example, the noise emission from landing gears generally is the most significant from all airframe noise sources. However, the presented order may differ depending on the particular aircraft design. For example, for regional aircraft and single-aisle aircraft, noise from high-lift devices may lie at levels comparable to noise from the landing gear. On the other hand, for wide-body aircraft, noise emissions from the landing gear usually are significantly stronger than other airframe noise sources. (Dobrzynski, 2010)

In the comparison of engine noise sources and airframe noise sources it can be stated that in the past, engine noise used to dominate the cumulated noise emission of an aircraft. However, during the last decades engine noise could be strongly reduced, mainly due to an increase in the engines' bypass ratio, allowing a reduction of jet velocities and, hence, of jet noise emissions. As a result, for approaching aircraft airframe noise can today be as relevant as jet noise.[20] (Sustainable Aviation, 2013)

2.2.2 Aircraft Noise Certification

The aviation industry knows a plethora of certification procedures that are required before an aircraft may be produced and operated. In line with this, aircraft also need to undergo noise certifications. The required noise certification process is described by the ICAO in the Annex 16 to the Convention on International Civil Aviation (International Civil Aviation Organization, 2008a). For this, the Annex 16 defines the flight procedures of the noise certification flights as well as the positions of the microphones and the allowed maximum noise levels.

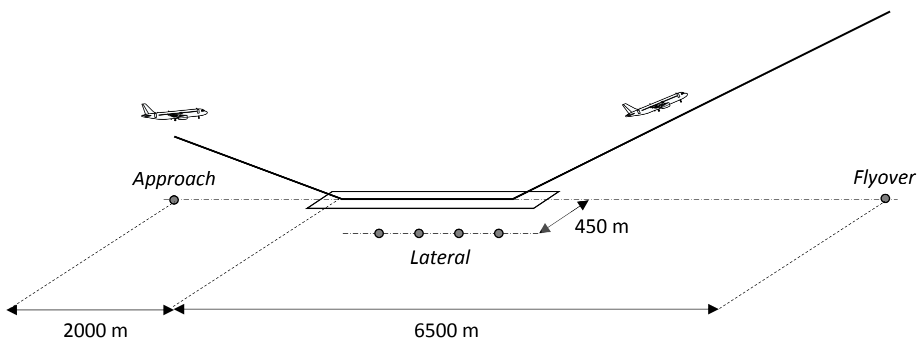

Fig. 2-3 Aircraft noise certification: Location of the reference noise measurement points (simplified)

[20] During departures, engine noise generally is still more significant.

A simplified overview of the noise certification process is illustrated in Fig. 2-3. As can be seen, aircraft noise is measured for approach and departure operations. The approach noise measurement point is located 2000 m from the threshold on the extended centre line of the runway.[21] For departure operations, two different noise levels are determined. Firstly, the lateral noise measurement point is situated on a line parallel to the runway at a distance of 450 m from the centre line. In this, the maximum noise level from an array of microphones is relevant. Secondly, a flyover noise measurement point is positioned on the extended centre line at a distance of 6500 m from the start of roll.

For each of the three measured noise levels, the Annex 16 specifies maximum allowed noise levels. Oftentimes, single-event aircraft noise is characterised by its "cumulative certification noise". This term refers to the noise value as a result of an addition of the noise levels at the three measurement points. Note that, according to the Annex 16, certification noise levels are quantified in the metric EPNdB (see Section 2.1.1).

Historically, the definition of the certification noise limits has become more stringent. The first certification noise limits have been applicable since the year 1972, known as the Chapter 2 noise levels. In the following years, reduced noise levels have been specified by Chapter 3, Chapter 4, and Chapter 14.[22] The development of the according noise levels is visualised in Fig. 2-4. Compared to the Chapter 2 noise limits, the Chapter 3 cumulated noise limits were reduced by 16 dB. The maximum cumulated noise levels were further tightened in Chapter 4 by additional 10 dB and in Chapter 14 by another 7 dB. Fig. 2-4 also specifies the applicable years of the different Chapters.

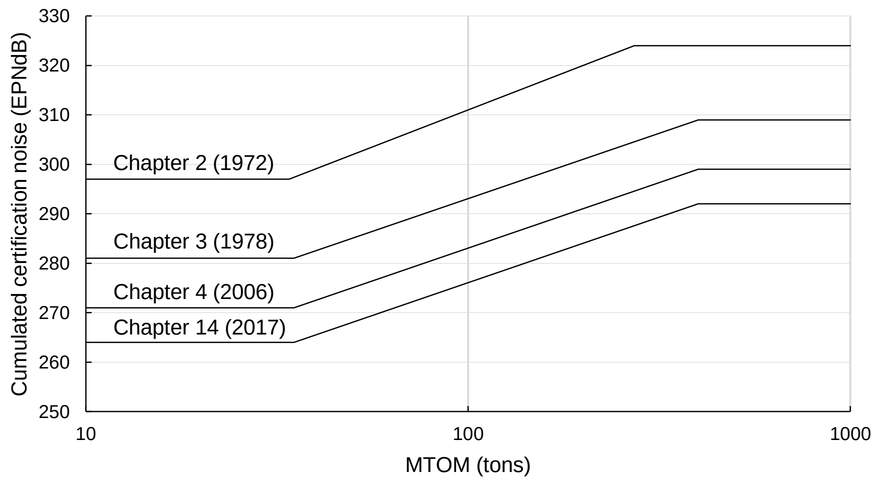

Fig. 2-4 ICAO Annex 16: Maximum cumulated certification noise levels (simplified) and years of applicability after Dickson (2013)

[21] The approaching aircraft is required to follow a 3.0 degree glide slope.
[22] "Chapter 2/3/4" because the corresponding noise levels are specified in the second/third/fourth chapter of Annex 16. The latest noise standard was named "Chapter 14" as Annex 16 already included thirteen chapters.

2.2.3 The Balanced Approach

In order to engage the problem of aircraft noise, the ICAO has published a policy called the Balanced Approach to Aircraft Noise Management (short: the Balanced Approach). The purpose of the Balanced Approach is to provide ICAO contracting states with measures to identify and alleviate noise problems at its airports. The four main elements of the Balanced Approach are illustrated in Fig. 2-5, which are briefly discussed in the following. (International Civil Aviation Organization, 2008b)

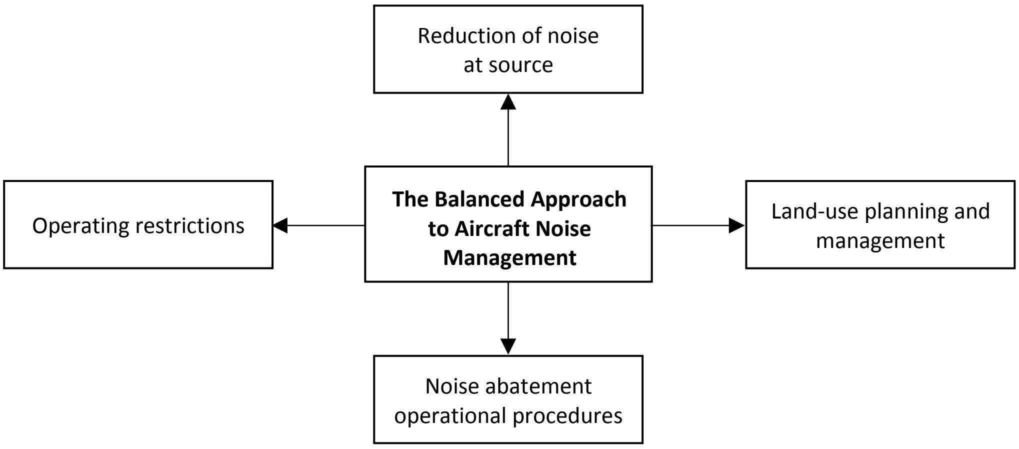

Fig. 2-5 The four elements of ICAO's Balanced Approach to Aircraft Noise Management (ICAO, 2008b)

The first element is the reduction of noise at source through improved aircraft technology. The Balanced Approach states that in this first element, not only the aircraft-level noise reduction levels, but also the integration of new aircraft into the fleet are important to consider. The second element is land-use planning and management, which considers the fact that the number of people affected by aircraft noise depends on the usage of land around airports, particularly the placement of residential areas. The stated goal of effective land-use planning is to steer incompatible land use, e.g. houses and schools, further away from affected areas, while locating compatible land, e.g. industry, closer to the airport. The third element is noise abatement operational procedures, which encompasses in-flight and ground-based noise reduction procedures. As examples, the Balanced Approach specifically names the use of noise preferential runways, the use of noise preferential flight routes, and the use of noise abatement take-off and approach procedures. The fourth element is operating restrictions, which describes measures that limit or reduce an aircraft's access to an airport[23]. In this, the Balanced Approach names four principle types of restrictions: global restrictions, aircraft-specific restrictions, partial restrictions (e.g. only for certain periods of the day), and progressive restrictions (gradually intensifying restrictions). Note that, in practice, the different elements of the Balanced Approach lie in the sphere of responsibility of different stakeholders. (International Civil Aviation Organization, 2008b)

[23] The Balanced Approach highlights that operating restrictions should not be implemented as a "first resort".

2.3 Existing Work in the Field

In the literature, several studies are found whose scope is related to the scope of this thesis. In the following, a brief summary of the studies is given. For each study, the scope of the work and available information of the underlying methodologies are discussed.[24]

2.3.1 ANOTEC Consulting (2003)

A study by the Spanish company ANOTEC Consulting S.L. is devoted to the future development of aircraft noise at European airports (ANOTEC Consulting, 2003). In its report for the European Community, the company has analysed the accumulated situation of 53 EU airports. In terms of the applied methodology, assumptions on the future air traffic rely on growth assumptions of aircraft movement numbers.[25] In the definition of the aircraft fleet mix, the future fleet shares of the considered aircraft types are determined based on the share of the baseline year, on a fixed retirement age[26] for all aircraft and on open aircraft orders. Future aircraft types without available noise model are modelled through a substitution with existing aircraft models.[27] The method also includes a simple consideration of the effect of airport capacity constraints on future airport noise.[28] For the airport noise calculations, the model SONDEO is applied, which has been developed by ANOTEC Consulting according to the procedures of ECAC Doc.29 (European Civil Aviation Conference, 2005b). The study evaluates airport noise using the metrics L_{den} (DEN) and L_{night}.

2.3.2 ERCD / CAA (2007)

A study by the European Research and Consultancy Department (ERCD) of the UK's Civil Aviation Authority (CAA) focusses on the future evolution of aircraft noise at Heathrow Airport (Rhodes and Beaton, 2007). As in the ANOTEC study, the determination of future flight plans is based on the growth of aircraft movement numbers. The development of the future fleet mix is not actively modelled. Instead, for future aircraft types to enter the fleet, specific entry into service years are assumed; the precise determination of a future fleet mix is not stated by the report. Future aircraft types are considered through a surrogate aircraft approach, which models future aircraft types based on available aircraft models. In this, the noise reduction of future aircraft is considered according to predictions of noise certification levels. As airport noise model, the UK aircraft noise contour model ANCON is used. Airport noise is quantified by the continuous sound level $L_{A,eq}$.

[24] It is to mention, though, that the publications do not always provide sufficient information about the applied methodology.
[25] Rather than on the growth of passenger numbers.
[26] 25 years for passenger aircraft and 35 years for cargo aircraft.
[27] Furthermore, "depending on available noise predictions, this substitution might be adjusted by means of a conversion factor" ANOTEC Consulting (2003). Unfortunately, the conversion factor is not further specified by the report.
[28] At capacity constrained airports it is assumed that aircraft movement numbers are shifted towards larger aircraft (seven "generic classes" of different aircraft sizes; a shift of 1% per year towards larger generic classes assumed).

2.3.3 ICAO / CAEP (2013)

A publication by the ICAO presents the results of the Committee on Aviation Environmental Protection (CAEP), which projects future aircraft noise at the global level (International Civil Aviation Organization, 2013).[29] The publication corresponds to the results of a previous study by Fleming et al. (Fleming et al., 2011) and to an earlier report by the ICAO (International Civil Aviation Organization, 2010). Future air traffic is considered based on the assumed growth in aircraft movement numbers. Although the ICAO reports do not discuss the future fleet mix modelling, a related publication indicates that the CAEP fleet and operations module (FOM) may have been used (Fleming et al., 2008). In the consideration of future aircraft types, the methodology is not specified by the reports. As assumed noise reduction, an annual noise reduction rate is postulated for future aircraft to enter the fleet.[30] To calculate airport noise three different models are used for the different studied airports: The FAA's Aviation Environmental Design Tool (AEDT), Eurocontrol's SysTem for AirPort noise Exposure Studies (STAPES), and the CAA's model ANCON. The noise metric evaluated is the L_{dn} (DNL).

2.3.4 Sustainable Aviation (2013)

A further related study is provided by Sustainable Aviation, a group of major UK aviation stakeholders (Sustainable Aviation, 2013). The report presents an estimation of future UK aircraft noise of several airports combined. The airport noise modelling relies on assumptions on future aircraft movement numbers. As of the future fleet mix, the fleet mix development is not actively modelled. Rather, for different aircraft generations and sizes, linear transitions are assumed between the aircraft generations based on the specification of a start year and an end year. The methodology of modelling future aircraft types is not discussed. The applied noise reduction levels are used according to two different approaches. For 'Generation 1' aircraft types, which are entering service currently or in the near future, noise certification levels are applied. For 'Generation 2' aircraft types, noise reductions according to annual noise reduction rates are assumed.[31] The report indicates that for the airport noise modelling, the CAA's model ANCON is used. As noise metric, the continuous sound level $L_{A,eq}$ is chosen.

2.3.5 Bernardo et al. (2016)

A study of Bernardo et al. analyses the impact of aircraft technology improvements on future aircraft noise at the fleet level using design of experiments (Bernardo et al., 2016).[32] A main interest of this study is the analysis of noise-related effects at different airport categories. As of modelling air traffic, future air traffic is based on assumptions on aircraft

[29] In total, 207 airports combined representing more than 75% of global aircraft operations.
[30] A pessimistic scenario assumes a noise reduction rate of -0.1 dB/year, an optimistic scenario assumes a noise reduction rate of -0.3 dB/year.
[31] Also, a pessimistic and an optimistic noise reduction scenario is applied with -0.1 and -0.3 dB/year, respectively.
[32] By cumulating airport noise of eight generic airports.

movement growth. The future fleet mix development is not actively modelled, instead, assumptions on the penetration of novel aircraft types to the fleet are stated based on literature review. Future aircraft types are considered through an "equivalency assumption", which considers the noise reduction of future aircraft by the percentage of operations of a baseline aircraft.[33] The particular noise reduction levels rely on a literature review. As airport noise model, the Airport Noise Grid Integration Method (ANGIM) developed by Bernardo is applied, which is a simplified airport noise model allowing reduced calculation times for more efficient fleet-level studies.[34] The metric evaluated is L_{dn} (DNL).

2.3.6 Torija et al. (2017)

Compared to the previous five studies, the research by Torija et al. has the research objectives most similar to this thesis. The principle goal of Torija et al. are "multi-disciplinary strategic environmental assessment[s]" (Torija et al., 2017). However, recent research has focused on the development of a novel and efficient airport-level noise model. The methodology to model future air traffic is based on the projection of future aircraft movement numbers. The approach furthermore does not include a dedicated fleet mix modelling. Instead, for different aircraft generations, entry into service and end of service years are assumed. As of the timely evolution of the different aircraft generations the authors indicates that a linear transition is assumed between the generations (Torija et al., 2016). Future aircraft types are modelled by a surrogate aircraft approach. The noise reduction levels of future aircraft follow published values by Sustainable Aviation (Sustainable Aviation, 2013) and by the ICAO (International Civil Aviation Organization, 2014). The applied airport noise model is the Rapid Aviation Noise Evaluator (RANE), which is the above named novel airport noise model.[35] The evaluated noise metric is the continuous sound level $L_{A,eq}$.

2.3.7 LeVine et al. (2018)

A study by LeVine et al. deals with the future development of gaseous emissions and of aircraft noise at the fleet level (LeVine et al., 2018).[36] His noise-related content is based on and uses models of Bernardo's research (see Section 2.3.5). The methodology considers future air traffic based on aircraft movement growth assumptions. The fleet mix development is modelled with the Global and Regional Environmental Aviation Trade-off (GREAT) tool by Jimenez et al. (2012), which applies aircraft retirement curves and assumptions on the future aircraft introduction to determine the future fleet mix. The method of considering future aircraft types is not discussed by the publication.[37] As airport

[33] The study assumes an equivalent reduction in noise at all three certification points.
[34] The ANGIM has been developed in a previous dissertation (Bernardo, 2013). One relevant simplification of the model is the assumption of straight ground tracks.
[35] According to the authors, the current version of the model is limited to single-runway airports and to straight-in/straight-out flight trajectories Torija et al. (2017).
[36] By cumulating airport noise of eight generic airports.
[37] Possibly it relies on the equivalency assumption of Bernardo's airport noise modelling tool ANGIM (see Section 2.3.5).

noise model, the ANGIM developed by Bernardo is applied. The calculated noise metric is the L_{dn} (DNL).

2.3.8 Summary and Comparison

In Tab. 2-2, a summary of the discussed studies is provided. In addition, for comparison, the FANAM method developed in this thesis (see Section 3.1.2) is listed.[38] While Tab. 2-2 is only able to compare the different methodologies at a fundamental level, further differences between the cited studies can obviously be found in the more detailed modelling approach and in the capabilities of the methodologies.

[38] At this point, it may be mentioned that the developed FANAM method considers future air traffic at a passenger transport level rather than at an aircraft movement level as further described in Chapter 3. This allows the average seat capacity of a future aircraft fleet to remain a degree of freedom. It may also be mentioned that FANAM's modelling of airport capacity constraints is a unique capability from all of the cited studies.

Tab. 2-2 Overview of related research and their fundamental methodologies

Study	***Sector***	***Determination of the Future Fleet Mix***	***Modelling of Future Aircraft Types***	***Airport Noise Modelling***
ANOTEC Consulting (2003)	*Industry*	*Static assumptions on future aircraft type shares (based on analysis of current fleet, aircraft retirement and open aircraft orders)*	*Not exactly specified (principally, a Surrogate Aircraft Approach)*	*SONDEO*
ERCD / CAA (2007)	*Industry*	*Static assumptions on future aircraft type shares*	*Surrogate Aircraft Approach*	*ANCON*
ICAO / CAEP (2013)	*Industry/ Politics*	*Using the CAEP fleet and operations module (FOM)*	*Not specified*	*AEDT/STAPES/ANCON*
Sustainable Aviation (2013)	*Industry*	*Static assumptions on future aircraft type shares*	*Not specified*	*ANCON*
Bernardo et al. (2016)	*Research*	*Static assumptions on future aircraft type shares*	*Equivalency Assumption*	*ANGIM*
Torija et al. (2017)	*Research*	*Static assumptions on future aircraft type shares*	*Surrogate Aircraft Approach*	*RANE*
LeVine et al. (2018)	*Research*	*Using the Global and Regional Environmental Aviation Trade-off (GREAT) tool*	*Not specified (possibly Equivalency Assumption)*	*ANGIM*
FANAM	*Research*	*Modelled at annual basis depending on scenario-specific traffic growth, aircraft retirement, and aircraft introduction input*	*Surrogate Aircraft Approach*	*AEDT*

3 Development of a Novel Method for Future Airport Noise Assessments

This chapter describes the development of a novel method for the assessment of future airport noise. In Section 3.1, the design of a framework is introduced, which combines the three fundamental modelling areas of the method. The subsequent sections present the modelling of future flight plans (Section 3.2), the aircraft-level noise modelling (Section 3.3), and the airport-level noise modelling (Section 3.4). The implementation of the method is discussed in Section 3.5. The chapter is concluded with a validation of the implemented tool in Section 3.6.

3.1 Fundamental Approach: Design of a Framework

The following section focuses on the principle design of the method. The objectives in the development of the method are discussed in Section 3.1.1, the fundamental approach of the developed framework is presented in Section 3.1.2, and some necessary definitions are stated in Section 3.1.3.

3.1.1 Scope and Objectives

The objectives of this research, as introduced in Section 1.2, are the theoretical development of a method for future airport noise assessments and the practical implementation of tools that enable the application of the developed method. The intended purpose of the resulting modelling capabilities is impact assessments with respect to future airport noise exposure. The primary objective, thus, is the quantification of relative differences between scenarios in order to study impacts on future noise exposure in contrast to absolute noise quantifications. In the development of the method, four specific goals are defined, which are briefly discussed in the following.

1. Applicability to different airports: The method shall be applicable to any given airport. Consequently, the resulting modelling capabilities shall be applicable to different airport runway layouts, different flight track geometries, and different flight plans.
2. Flexibility in scenario definition: The method and the resulting modelling capabilities shall allow maximum flexibility in the definition of scenario-specific input

data, for example, the definition of the target year for which future airport noise is to be assessed.

3. Aircraft fleet mix as a degree of freedom: The method and resulting modelling capabilities shall leave the future aircraft fleet mix as a free, non-predetermined parameter that results from scenario-specific input data. For research purposes the proportion of new-technology to old-technology aircraft in future fleets, for instance, or the average number of installed seats per aircraft may be of interest. Consequently, the proportion of aircraft technology as well as the number of seats per aircraft shall remain a degree of freedom in order to enable the assessment of both effects on future airport noise.
4. High degree of automation: The method and resulting modelling capabilities shall offer a high degree of automation in their application. This shall minimise, firstly, the user's required background knowledge of the underlying methods and, secondly, enable a reasonably fast set-up, execution, and evaluation of calculations.

Furthermore, it is useful to explicitly define areas that shall be excluded by the method. The scope of this thesis is limited to the following content:

1. Only noise emissions of in-flight aircraft are considered by the approach. Thus, noise emissions from aircraft ground operations (e.g. taxiing) and from non-aircraft noise sources in the vicinity of airports (e.g. other vehicle noise) are not considered.
2. ATM rules are assumed to remain constant, hence, possible future ATM changes are not considered by the approach. As a result, the definitions of flight routes[39] and flight procedures[40] are unchanged when modelling future years.
3. Only physics-based noise metrics are evaluated by the approach. Therefore, psychoacoustic effects, which consider different subjective perceptions of noise by humans, are not considered by the approach.

Two further boundary conditions in the development of the method are briefly named. Firstly, aircraft source noise models were not available in the development of the approach; the dissertation of Figlar, for instance, showed the difficulty of gaining access to aircraft source noise models, for example owned by aircraft OEMs (Figlar, 2013). Secondly, due to the high effort of gaining aircraft noise emission data by flight experiments and own noise measurements such measures were excluded a priori. The fundamental approach developed considering the discussed research scope, objectives and boundary conditions is presented in the following.

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[39] Which determine horizontal flight tracks.
[40] Which determine vertical flight profiles.

3.1.2 The Future Airport Noise Assessment Method

In order to model future airport noise exposure, three different systems need to be modelled at the top level as depicted by Fig. 3-1. Firstly, a flight plan needs to be derived for the considered airport for the future year of interest. Furthermore, aircraft noise emission for aircraft types contained in the future flight plan must be modelled at the aircraft level. Finally, future airport noise exposure can be estimated from the future flight plan and the aircraft noise models. As illustrated in Fig. 3-1, the three necessary modelling areas are bound together by an overarching framework, which is named the *Future Airport Noise Assessment Method* (*FANAM*).

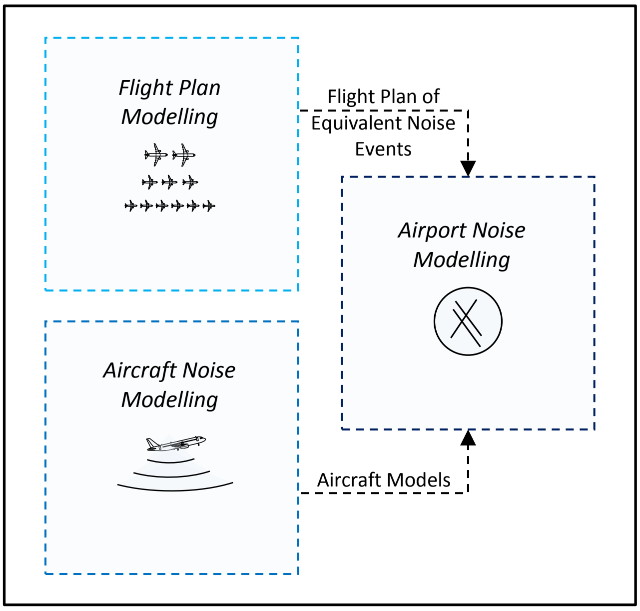

Fig. 3-1 Top-level approach of the Future Airport Noise Assessment Method (FANAM) modified from Will et al. (2017)

The development of FANAM's flight plan modelling capabilities is detailed in Section 3.2. Therein, FANAM uses a specifically developed flight plan structure called the *flight plan of equivalent noise events* as further introduced in Section 3.2.2.

In the modelling of aircraft noise at the vehicle level, the method considers the aircraft fleet at an aircraft type level. Thus, aircraft movements are assigned to noise models specifically describing the particular aircraft type, in contrast to modelling the entire fleet with only a few representative aircraft types. The method used for the aircraft noise modelling is presented in Section 3.3.

The airport noise modelling capabilities used by FANAM are presented in Section 3.4. In this thesis, the metric used in the quantification of airport noise is the DEN (see Section 2.1.2)[41]. The DEN is recommended as airport-level noise metric, for instance, by the European Union (Official Journal of the European Communities, 2002).

[41] FANAM principally allows the evaluation of other noise metrics, too.

3.1.3 Introduction of Definitions

In the following, several necessary terms used throughout this thesis are defined.

As result of research and development efforts, aircraft technology has continuously improved during the past. In order to differentiate between aircraft technologies, this thesis differentiates between three *aircraft generations*:

- Current Technology Aircraft (*CT Aircraft*): Aircraft types in service that airlines have generally used throughout the last one or two decades.
- New Technology 1 Aircraft (*NT-1 Aircraft*): New aircraft types, which airlines have started to introduce to their fleets within the last years, or aircraft types that are about to enter service within the next few years. Specifically, all aircraft types with entry into service year 2007 or later are considered as NT-1 aircraft.[42]
- New Technology 2 Aircraft (*NT-2 Aircraft*): Future aircraft types, which will only be developed in future years, and cannot yet be ordered by airlines. Throughout the thesis, this aircraft generation is used to consider the introduction of new aircraft types in the medium and long term.

Furthermore, the term *baseline year* defines the status quo year that serves as starting point from which FANAM models future years. The term *target year* indicates the future year of interest to be estimated by the method. The terms *baseline fleet* and *baseline flight plan* are used to describe the baseline year's aircraft fleet, and flight plan, respectively. The term *airport noise*, as used in this thesis, refers to the noise immissions in the vicinity of an airport perceived on the ground as result of aircraft noise emissions.

3.2 Flight Plan Modelling

3.2.1 The Future Flight Plan Estimation Approach

The flight plan modelling capabilities within FANAM (see Fig. 3-1) are realized through the development of an approach described in the following sections. For the purpose of clearness throughout this thesis, the theoretical approach is named the *Future Flight Plan Estimation Approach* (FFEA). The FFEA is implemented in a tool called the *Future Flight Plan Development Tool* (FFDT) as presented in Section 3.6. An initial version of the FFDT was developed in a master's thesis by Engelke (2016). Further improvements and functional enhancements were added in a bachelor's thesis by Wunderlich (2017) and in a term thesis by Mayrhofer (2017).

The essential idea of the FFEA is to derive a future flight plan, from a given baseline flight plan, based on the incorporation of relevant impacts on the evolution of a flight plan. The principle approach of the FFEA is outlined in Fig. 3-2 showing the fundamental processing steps in the derivation of the future flight plan (right) from the baseline flight plan (left).

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[42] Hence, the Airbus A380 is already considered a NT-1 aircraft type.

Each flight plan entry (see Section 3.2.2) undergoes the processing steps depicted in Fig. 3-2.

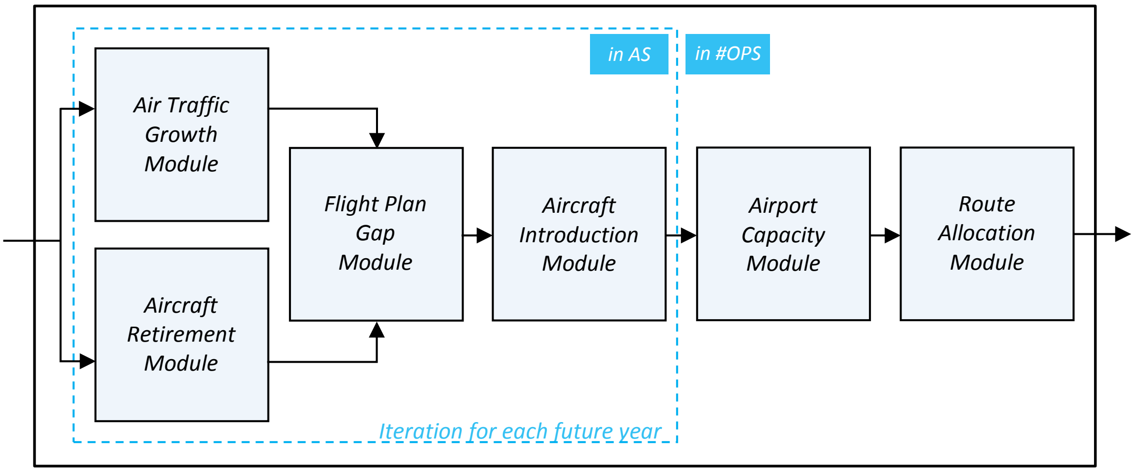

Fig. 3-2 The Future Flight Plan Estimation Approach. Approach of derivation of a future flight plan from a given flight plan of the baseline year modified from Will et al. (2017)

Altogether, the FFEA consists of six modules that consider relevant effects on future flight plans. As seen in Fig. 3-2, the FFEA consists of the Air Traffic Growth Module, the Aircraft Retirement Module, the Flight Plan Gap Module, the Aircraft Introduction Module, the Airport Capacity Module, and the Route Allocation Module. The individual modules are further described in Sections 3.2.4 to 3.2.9. The FFEA considers all aircraft at a studied airport as part of one "world airline". Note that the FFEA considers major information on the local characteristics of the studied airport by using the airport-specific baseline flight plan as input data. For example, the airport's baseline flight plan determines the absolute number of flight movements, the distribution of movements across the hours of a day, or the particular fleet mix at the airport for the baseline year.

The principle logic of the FFEA and of the subsequently implemented FFDT is, within different modules, to allow a user to apply different scenario-specific input data on a yearly basis. For instance, air traffic growth rates or the mix of future aircraft types introduced to the fleet can be specified individually for each future year. As a result, the modelling of future flight plans occurs iteratively for each future year in dependence of the particular scenario-specific input, which is indicated by the dotted blue line in Fig. 3-2. The Airport Capacity Module and the Route Allocation Module contain input data independent from time, thus the two modules are excluded from the timely iteration and are only applied to a resulting flight plan of the target year.

As defined in Section 3.1.1, one objective in the development of the FFEA is to leave average aircraft seat capacity of the future fleet a degree of freedom. Because of this, it is necessary to not model future aircraft movement numbers directly, but to consider future air traffic at a more basic level. The solution to this is to model future traffic demand as transport capacities quantified by Available Seats (AS), leaving open the particular fleet mix airlines will use to supply the demand. Only at a later stage, as a function of the scenario-specific fleet mix resulting from user input data, the amount of actual aircraft movements is determined. The FFEA, as shown in Fig. 3-2, therefore models future flight plans solely in terms of transport capacities (in AS) for the first four modules. Only prior to the Airport Capacity Module are transport capacities transferred to aircraft movements (#OPS) by application of aircraft-specific seat capacities. Furthermore, it is to mention that the FFEA does not consider operations by freighter aircraft, general aviation aircraft, and helicopters, hence, corresponding noise emissions are not considered by FANAM.[43]

3.2.2 Definition of a Noise-Relevant Flight Plan Structure

As mentioned, in the modelling of future flight plans the FFEA uses a flight plan structure that is specifically tailored to airport-level noise assessments. The motivation for the definition of such a flight plan structure is as follows. Firstly, a reduction of data per flight plan entry to solely noise-relevant information is desired both for the sake of simplicity from a user's point of view, and for reducing necessary computational memory requirements. Moreover, a reduction of the total amount of flight plan entries by consolidation of flights is desirable in order to reduce calculation times for the application of the method.

The resulting flight plan structure is named a flight plan of equivalent noise events according to its underlying philosophy of cumulating all flight events that, from a noise point of view, are equivalent, in one flight plan entry. The structure of the flight plan including an exemplary flight plan entry[44] is shown in Tab. 3-1. Note that a flight plan for arrival operations and a separate flight plan for departure operations is used by the FFEA. The flight plan of equivalent noise events consists of primary flight plan parameters (in dark blue), which sufficiently define a flight plan entry, and secondary flight plan parameters (in light blue), which are determined by the primary flight plan parameters.

Tab. 3-1 Content of a flight plan of equivalent noise events modified from Will et. al (2017a)

Time	*Airport*	*Aircraft Type*	*Period of Day*	*World Region*	*Waypoint*	*Stage Number[45]*	*Transport Capacity (in AS)*
8:00	*ACE*	*320*	*Day*	*Western Europe*	*W*	*3*	*1620*
…	…	…	…	…	…	…	…

The definition of the three primary flight plan parameters is specified in the following:

[43] At the majority of medium and large airports, the according noise emissions are assumed to be insignificant compared to the airport's total noise volume.
[44] A flight plan entry consists of one row of the flight plan.
[45] Only used for departures.

1.) 'Time': Specifies the local time, given in full hours (thus, e.g., all flights between 8:00 and 8:59 are assigned to 8:00)
2.) 'Airport': Specifies the origin/destination airport for arrival/departure operations (nomenclature: IATA code)
3.) 'Aircraft Type': Specifies the aircraft type (nomenclature: IATA code)

The FFEA considers all flights with the same combination of primary flight plan parameters as equivalent. Consequently, flight operations with the same primary flight plan parameters are cumulated into a single flight plan entry. Whereas a combination of primary flight plan parameters unambiguously defines a flight plan entry, the following secondary flight plan parameters are additionally used by the FFEA:

1.) 'Period of Day': Assigns a flight plan entry to one of the periods *day*, *evening*, or *night*; used for assigning noise penalties for non-day operations in the calculation of the DEN (see Section 2.1.2); determined by 'Time'
2.) 'World Region': Assigns a flight plan entry to one of the assumed world regions; used for applying region-specific air traffic growth rates; determined by 'Airport'
3.) 'Waypoint': Assigns a flight plan entry to one waypoint of the airport under consideration; used to define the arrival/departure route; determined by 'Airport'
4.) 'Stage Number': Assigns a flight plan entry to a stage number depending on the distance to the destination airport (only for departure operations); used to include the effect of fuel-depending departure weight on departure procedures; determined by 'Airport'

The last column of Tab. 3-1 quantifies the air traffic volume corresponding to a flight plan entry. Following the explanations in Section 3.2.1, flight plan entries in a flight plan of equivalent noise events are not, as usual in flight plans, quantified by movement numbers, but by the corresponding accumulated annual transport capacity given in AS. Also note that flight plan entries are not accumulated across different aircraft types as explained in Section 3.1.2. Instead, the level of detail of the flight plan remains at an aircraft type-individual level.

3.2.3 Flight Plan of the Baseline Year

As described before and illustrated in Fig. 3-2, the baseline flight plan serves as fundamental data source in the derivation of a future flight plan. The FFEA is able to process flight plans independently of the particular source providing a baseline flight plan as long as the structure[46] corresponds to the structure of a flight plan of equivalent noise events as introduced in Section 3.2.2.

In this work, the Official Airline Guide (OAG) is used as source for baseline flight plans, as it is a respected source also used in the scientific community (OAG Worldwide Limited, 2008; Schinwald et al., 2017). Furthermore, OAG data not only contain flights of a single

[46] Possibly after necessary pre-processing steps.

airport, but of entire networks, thus including operations of many airports in one database. Consequently, if FANAM is to be applied to an airport other than in this thesis, the identical OAG database can still be used.

The OAG database applied in this thesis of the year 2016 contains historic, scheduled flights of all days during 2016. The open question of which particular day to choose is solved by using an average of all days of the entire baseline year. A cumulated annual flight plan divided by the number of days of a year is assumed to be the most suitable baseline flight plan for representative impact assessments.

The OAG data also include aircraft seat capacities that allow the derivation of averaged seat capacity numbers of each aircraft type present in a flight plan. The according seat capacity numbers resulting from the baseline flight plan are used in further processing steps of the FFEA.

Practically, in pre-processing steps, all aircraft operations of a selected airport of interest are filtered from the OAG database. Additionally, all contained cargo flights and codeshare flights are excluded. The remaining flight plan is then transferred to the structure of a flight plan of equivalent noise events by deleting unneeded information (e.g. 'distance flown') and by cumulating flight plan entries with identical primary flight plan parameters (see Section 3.2.2). The resulting flight plan serves as baseline flight plan for the FFEA, and hence, for the implemented FFDT.

3.2.4 Air Traffic Growth Module

The following section introduces the *Air Traffic Growth Module* which aims at taking into account effects from air traffic growth on future flight plans and, hence, on future airport noise exposure.

3.2.4.1 Background

Over the past decades, global air traffic has strongly grown. According to Airbus, the world annual air traffic measured in Revenue Passenger Kilometres (RPKs) has approximately doubled between the years 1986 and 2001, and has seen another doubling between the years 2001 and 2016 (Airbus, 2017b). Driven by the many developing countries, which currently show particularly high air traffic growth rates, a strong, further growth of global passenger numbers is expected in the future by major aviation stakeholders (Airbus, 2017b; Boeing, 2017; Eurocontrol, 2013). As a result, another doubling in the world annual air traffic is estimated for the next 15 years (Airbus, 2017b).

In the analysis of the impact of air traffic growth on future airport noise, it is obvious that an increase in air traffic generally tends to increase airport noise. If average seat load factors and average aircraft seat capacities remain constant, increases in passenger numbers directly correlate with increased aircraft movements numbers, leading to increased equivalent sound levels.

With respect to airport noise, it is furthermore to mention that air traffic grows at significantly different rates in different parts of the world. For example, passenger growth rates for flights within Europe may be well below the growth rates of flights between Europe and Asia. For future airport noise, this may be of interest in two ways. Firstly, at a studied airport the usage of a specific arrival or departure route depends on the origin/destination airport of a flight. It follows that an uneven distribution of traffic growth may unevenly increase movement numbers on different flight routes, which, in turn, will unevenly increase local equivalent sound levels at the airport. Secondly, an uneven distribution of traffic growth may change the fleet mix at an airport, for instance, will more long-range aircraft fly at an airport if air traffic to distant world regions grows above average. This may be noise-relevant since, in general, long-range aircraft cause higher noise emissions than short-range aircraft.

3.2.4.2 Modelling Approach

The Air Traffic Growth Module, as described in the following, is designed in order to consider the above-mentioned effects on future flight plans.

The principle approach of the module is to calculate the traffic demand of a future year based on the transport capacity of the previous year according to scenario-specific traffic growth rates defined by the user. For each flight plan entry, the air traffic demand specified by Available Seats for all future years to be simulated is calculated according to equation (3.1). The module furthermore assumes seat load factors to remain constant for future years[47]. Note, again, that air traffic growth rates are not applied to movement numbers, but to transport capacities.

$$AS_{i,t+1} = AS_{i,t} * \left(1 + g_{t+1,k}\right) \tag{3.1}$$

AS **A**vailable **s**eats [seats]
g Air traffic **g**rowth rate [-]
i flight plan entry index [-]
t time index [years]
k world region index [-]

In terms of input data, the module allows air traffic growth rates to be differentiated in terms of time and in terms of world region as described in the following and illustrated by the so-called *growth matrix* in Tab. 3-2. For the user of FANAM, this growth matrix serves as interface to the Air Traffic Growth Module in the definition of traffic growth input data.

Firstly, the growth matrix includes traffic growth rate input for each future year to be modelled. The FFEA is thus able to model traffic growth differing over the course of future years. Secondly, in order to take into account region-specific air traffic growth, the FFEA does not uniquely apply growth rates to all flights of an airport, but further differentiates

[47] Average seat load factors currently are at around 80% and due to seasonality may experience difficulties to further increase significantly in the future (Airbus, 2017b).

according to the world region pair of a corresponding flight. In the definition of the world regions applied by the FFEA, the module follows the world region definitions of the Airbus Global Market Forecast (GMF) (Airbus, 2017b).

Tab. 3-2 Input of Air Traffic Growth Module: The growth matrix (exemplary content)

World Region	*Year 1*	*Year 2*	*Year 3*	*…*
Middle East	*4.9%*	*4.8%*	*4.7%*	*…*
South America	*3.5%*	*3.4%*	*3.4%*	*…*
USA	*3.0%*	*3.0%*	*3.0%*	*…*
…	*…*	*…*	*…*	*…*

The growth matrix may be defined by the user independently from the particular data source of the applied growth rates. For the application within this thesis, yet, mainly the air traffic growth rates specified by the Airbus GMF are applied as they offer a solid representation of the aviation industry's expectations. In order to apply the Airbus GMF growth rates, which are given in RPK for a period of 20 future years, it is assumed that the average flight distance between the defined world regions remains constant for all modelled future years. With the assumption of constant flight distances, RPK growth rates can be directly applied as AS growth rates. The application of the Airbus GMF growth rates within the application case of this thesis is further described in Chapter 4.

3.2.4.3 Review & Summary

In summary, the Air Traffic Growth Module allows FANAM to consider and analyse impacts from air traffic growth on future flight plans and, hence, on future airport noise. In the definition of the air traffic growth input, growth rates may be differentiated both according to individual future years as well as according to different world regions. Principally, the module is designed with the ability to process arbitrary growth rate numbers. Consequently, an infinite amount of future scenarios may be modelled. However, negative growth rates are only processed correctly as long as the flight plan gaps remain positive, which is further discussed along with the Flight Plan Gap Module in Section 3.2.6. Negative growth rates of small absolute value and all positive growth rates are processed correctly by the FFEA.[48]

[48] For future airport noise assessments, the limitation with respect to negative growth rates is assumed to be of minor importance, as air traffic is generally expected to grow further in the next decades.

3.2.5 Aircraft Retirement Module

The following section presents the *Aircraft Retirement Module*, which aims at modelling the effect of aircraft retirement on future aircraft fleets and future flight plans, and ultimately, on future airport noise.

3.2.5.1 Background

Any operating aircraft will at one point in time end active operation and will thus cease to provide transport capacity to the air transportation system. This process of ending active service of an aircraft is called *aircraft retirement*. According to research by Randt, multiple reasons may cause an airline to decide on the retirement of an aircraft, for instance, if the costs for operating an aircraft exceed the costs of purchasing and operating a new aircraft. Other reasons may be found in new regulations, which prohibit the operation of an aircraft type in certain regions, or the ceasing of maintenance support by the aircraft manufacturer (Randt, 2016).

For future airport noise assessments, the effect of aircraft retirement is of interest, because aircraft retirements change a current aircraft fleet mix, which may influence the noise exposure at an airport. Usually, those aircraft tend to be retired within a fleet that are older of age. Aircraft older of age, compared to younger aircraft, on average belong to older aircraft types, which usually consist of older technology compared to the state-of-the-art technology. Older aircraft types thereby tend to emit higher noise emissions compared to newer, state-of-the-art aircraft types. Younger aircraft fleets thus, on average, tend to expose an airport to lower noise emissions than older aircraft fleets. The modelling of aircraft retirements in the consideration of future airport noise studies therefore is of interest.

3.2.5.2 Methodical Approach

Principally, aircraft retirement can be modelled using a fixed retirement age[49]. Following this approach, the model would retire aircraft as soon as the specified retirement age is reached. A more sophisticated approach found in literature is to model aircraft retirement through retirement probabilities as a function of aircraft age. A method following this approach has been developed at the Institute of Aircraft Design in former research by Randt, which is based on empirical data of past, worldwide retirement behaviour (Randt, 2016). The Aircraft Retirement Module of the FFEA applies Randt's statistical approach as explained in the following. Further details can be found in Randt's dissertation (Randt, 2016).

Aircraft retirement approach by Randt:

Originally, the retirement modelling by Randt has been developed for research regarding the impact of the fuel-saving potential of next-generation aircraft at the global level. For this purpose, in order to model a future world fleet, the modelling of aircraft retirement was fundamental.

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[49] E.g. „All aircraft are retired at the age of 25 years".

Randt's approach uses *survival curves* as proposed by the Forecasting and Economic Analysis Support Group (FESG) of the Committee on Aviation Environmental Protection (Committee on Aviation Environmental Protection, 2008). In this context, a survival curve describes an aircraft's *percentage of survival* (POS), that is, its probability of still being in active operation, depending on the aircraft's age. For an entire aircraft fleet, the survival curve represents an aircraft type's age-specific percentage of active aircraft based on the sum of all produced aircraft as specified by equation (3.2).

$$POS_a = \frac{n_a}{n_o} \quad (3.2)$$

POS **P**ercentage **o**f **s**urvival [-]

a Aircraft **a**ge [years]

n **N**umber of active aircraft [-]

n_o **N**umber of produced aircraft [-]

Within Randt's method, an aircraft is considered as retired from active service if it is no longer intended for a resumption of operations in the long term. Thus, aircraft that are only temporarily stored, e.g. due to seasonal fluctuations, are not considered as retired. Mathematically, Randt's method describes survival curves through a logistic (s-shaped) curve according to equation (3.3) as a function of aircraft age a. Therein, the retirement coefficients $\beta_{I,II}$ determine the particular shape of a survival curve.

$$POS_a = \frac{1}{1 + e^{-\beta_I - \beta_{II} * a}} \quad (3.3)$$

β_I Retirement coefficient 1 specific for each aircraft cluster

β_{II} Retirement coefficient 2 specific for each aircraft cluster

To generate the survival curves, Randt evaluated historical data of past aircraft retirements based on two sources (Flightglobal, 2008; Verbrugge et al., 2013). As result of extensive analyses the retirement coefficients β_I and β_{II} were defined. For the definition of survival curves, Randt decided to generate survival curves at an aircraft-cluster level. This approach represents a compromise between, on the one hand, deriving just a single survival curve that is applied to all aircraft types of a fleet and, on the other hand, deriving individual survival curves for all aircraft types of a fleet. Based on a clustering process, Randt originally defined nine different aircraft clusters (Randt, 2016). The resulting survival curves for six clusters used by the Aircraft Retirement Module are presented in Fig. 3-3.[50]

As seen from Fig. 3-3, the general appearances of the different survival curves are similar based on the underlying s-shaped logistic function, yet the precise shape of the curves

[50] Cluster 1, cluster 3, and cluster 5 are not used by the FFEA, as the corresponding survival curves describe freighter aircraft.

varies according to the specific retirement coefficients β_I and β_{II}. For example, the resulting 50% survival ages range between approximately 21 and 25 years for different curves.

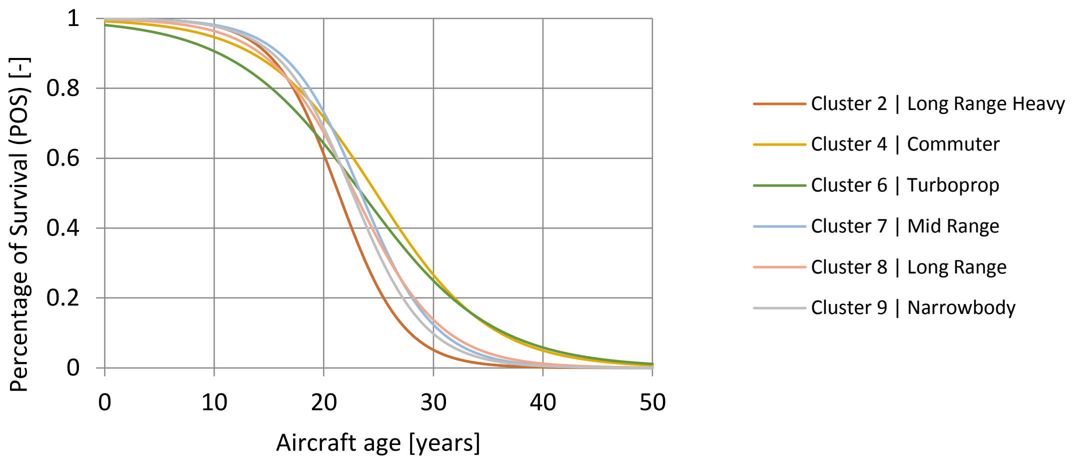

Fig. 3-3 Statistical aircraft cluster-specific retirement curves as evaluated by Randt (2016)

Furthermore, according to Randt's method, the survival curves remain unchanged for future years. This implies the assumption that in the future, the retirement behaviour, on average, remains the same. A report by Jiang supports this assumption by stating that during the last two decades no significant change has been observed regarding average aircraft retirement behaviour (Jiang, 2013).

The assignment of aircraft types to a specific aircraft cluster follows the assignment defined by Randt. Aircraft types used within FANAM that have not been assigned to a cluster by Randt are assigned to a reasonable cluster according to an aircraft's operational spectrum and passenger capacity. The assignments of aircraft types to aircraft clusters as derived by Engelke (2016) is documented, amongst other data, in Appendix B.

In addition to the aircraft cluster-specific retirement curves a further characteristic must be taken into account. The survival curves presented by Fig. 3-3 can be applied straightforwardly to an aircraft fleet through multiplication of the number of produced aircraft and a corresponding POS value if all aircraft are of the same age. However, in a real aircraft fleet, aircraft of the same type usually have different ages according to different production years. To model aircraft retirement within FANAM, it is therefore necessary to consider information on the aircraft age of a fleet. The retirement of aircraft already present in the baseline fleet occurs differently than the retirement of aircraft that enter service in future years as discussed in the following.

For aircraft of the baseline fleet, aircraft retirement based on the proposed statistical approach requires the baseline fleet's age distribution for the point in time of the baseline year. For each aircraft type, a *baseline fleet survival curve* is then determined according to equation (3.4). The baseline fleet survival curve describes the statistical survival of aircraft that belong to the baseline fleet. Equation (3.4) shows that the POS of an aircraft's baseline fleet is calculated by summation of all sub-fleets of aircraft of the same age remaining after retirement. In equation (3.4), the first fraction within the brackets describes the baseline year's relative age distribution of a specific aircraft type. The second fraction represents the cluster-specific survival curve[51]. Note that in the original research by Randt, the according baseline year was defined as 2008, consequently age distributions of 2008 are used in Randt's work. According to Randt's approach, aircraft retirements of the baseline fleet can thus be determined a priori, that is before the FFEA models future years, based on given survival curves and age distributions.

$$POS_{t,p} = \sum\nolimits_a \left(\frac{n_{p,a,t_o}}{\sum_a n_{p,a,t_0}} * \frac{POS_{q,a+t}}{POS_{q,a}}\right) \tag{3.4}$$

p Aircraft type index [-]

t_o Baseline year [years]

q Aircraft cluster index [-]

Contrary to this, the retirement of aircraft introduced to the fleet in future years by the Aircraft Introduction Module (see Section 3.2.7) cannot be determined a priori as the age distribution of aircraft introduced in the future depends on scenario-specific input data[52]. The retirement of aircraft, which are not part of the baseline fleet but introduced by the Aircraft Introduction Module, is therefore done iteratively for each future year. Therein, no age distribution must be specified from outside, as the FFEA knows the age distribution of aircraft added by the FFEA in the modelling of future years.

Update & enhancement of the aircraft retirement approach by Randt:

In this thesis, Randt's approach of retirement modelling is updated and enhanced as described in the following.

Firstly, the baseline fleet's age distributions evaluated by Randt and used within his retirement modelling date back to the year 2008. As discussed, these age distributions cannot be applied to FANAM, since the defined baseline year lies eight years later in the year 2016. Therefore, prior to an application of Randt's method within the Aircraft Retirement Module the information on the baseline year's age distributions needs to be updated.

Secondly, Randt's original approach suggested using age distributions for the same aircraft clusters as used for the survival curves. The approach thus only determined accumulated age distributions for all aircraft types within one aircraft cluster. However, since entry into service years of different aircraft types within a cluster may vary significantly, additional accuracy can be introduced to the retirement modelling if age distributions are specified at an individual aircraft-type level.

In order to realize both mentioned factors, Mayrhofer (2017) determined new age distributions for the baseline year 2016 for each considered aircraft type based on the same data

[51] Divided by a constant.

[52] E.g. it depends on the swap matrix (see Tab. 3-3).

source used by Randt (Verbrugge et al., 2017). Two exemplary age distributions are visualised in Fig. 3-4 for the aircraft types Airbus A320 and Airbus A330-300.

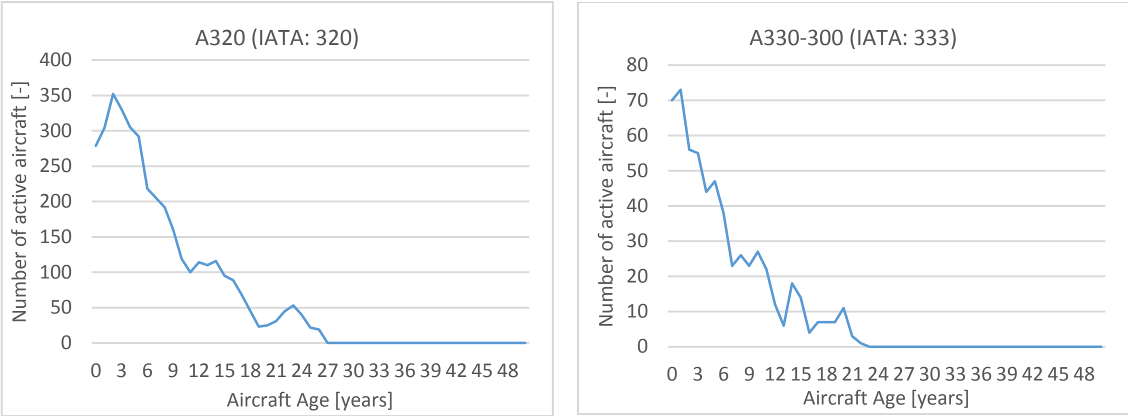

Fig. 3-4 World fleet age distribution applied by the FFEA for two exemplary aircraft types as of 2016 (evaluated from Verbrugge et al., 2017)

Ultimately, for each flight plan entry the FFEA calculates the transport capacity remaining after retirement based on the according traffic demand of the preceding year and the POS value of the corresponding survival curve according to equation (3.5):

$$R_{i,t+1} = AS_{i,t} * POS_{t+1,p} \tag{3.5}$$

R Transport capacity after retirement [seats]

The modelled transport capacity after retirement $R_{i,t+1}$ and the modelled air traffic demand $AS_{i,t+1}$ (see Section 3.2.4), as detailed in Section 3.2.6, define the resulting gap in transport capacity, which requires new aircraft to be introduced to the fleet.

3.2.5.3 *Review & Summary*

The statistical retirement approach of using aircraft survival curves represents an adequate method developed and validated in former research by Randt. In this thesis, Randt's approach was updated to age distributions of the year 2016 and enhanced through the determination of aircraft type-specific age distributions instead of relying on aircraft cluster-specific age distributions.

Within this thesis, Randt's aircraft cluster-specific survival curves remain unchanged and are applied as presented above. However, the Aircraft Retirement Module without difficulty allows changes in the definition of the survival curves. Consequently, the aircraft survival curves may principally be regarded as a scenario-specific input parameter within the FANAM method, too.

A limitation of the applied retirement approach is that aircraft retirements follow a strictly statistical manner, not influenced by current air traffic demand. In reality, in seasons of strong traffic growth, airlines may delay planned retirements. Such short-term effects on aircraft retirement as result of airline strategy decisions cannot be modelled by the Aircraft

Retirement Module. Yet, for the intention of long-term airport noise studies of FANAM, as also assumed by Randt, this limitation is considered as of low significance.

In total, the applied approach of retirement modelling can be regarded as a sophisticated method that acceptably considers and quantifies aircraft retirement for the purpose of impact assessments regarding future airport noise.

3.2.6 Flight Plan Gap Module

The following section briefly describes the *Flight Plan Gap Module*, which quantifies the gap in transport capacity that needs to be filled by new aircraft introduced to the fleet in future years.

3.2.6.1 Background

In aircraft fleet planning, it is common to determine a future *capacity gap* based on current, given transport capacities as well as on assumptions concerning aircraft retirement and air traffic growth (Belobaba, 2009). This approach is illustrated in Fig. 3-5, which shows, on the left, the transport capacity of a current year that is fully supplied by an operating fleet, and on the right, the future transport capacity remaining after aircraft retirement. As result of air traffic growth and aircraft retirement, a capacity gap arises, which consists of a corresponding *growth gap* and a *retirement gap*.

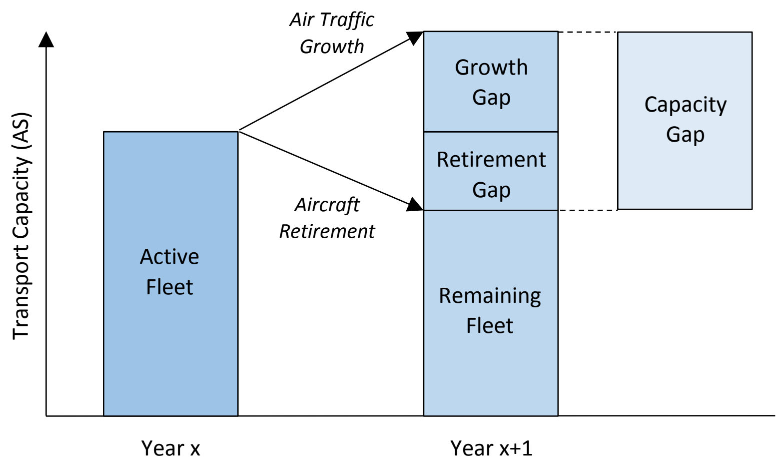

Fig. 3-5 Determination of a future transport capacity gap modified from Will et al. (2017)

The capacity gap is of interest in fleet planning, because, if air traffic demand shall be met, the gap quantifies the transport capacity that needs to be covered by new aircraft introduced to the fleet.

3.2.6.2 Modelling Approach

Within the FFEA, the concept of capacity gaps is applied to the flight plan entries of a flight plan. For all future years to be modelled, growth gaps and retirement gaps are determined by the Air Traffic Growth Module and by the Aircraft Retirement Module as described in Section 3.2.4 and Section 3.2.5.

Subsequently, the Flight Plan Gap Module calculates a capacity gap for each flight plan entry according to equation (3.6). Note that capacity gaps of different flight plan entries may evolve differently according to the corresponding world region-specific growth rates and according to the retirement behaviour of the particular aircraft type.

$$G_{i,t+1} = AS_{i,t+1} - R_{i,t+1} \tag{3.6}$$

G Flight plan **g**ap [seats]

3.2.6.3 Review & Summary

Unlike the previous modules of the FFEA, the Flight Plan Gap Module does not require input data specified by the user. The module solely determines, for each flight plan entry and each future year to be modelled, the gaps in transport capacity that need to be supplied by new aircraft introduced to the fleet.

At this point, the limitation concerning negative growth rates named in section 3.2.4.3 can be understood. As mentioned, the FFEA currently only processes negative air traffic growth rates correctly if the total capacity gap remains positive. Principally, the FFEA successfully deals with negative growth gaps, yet, only as long as the absolute value of the negative growth gap is not larger than the retirement gap (see Fig. 3-5). If this happens, no additional aircraft retirement occurs beyond that specified by the statistical retirement approach. In future work, this limitation may be addressed (see Section 5.2). However, for future airport noise assessments, this limitation is of minor importance, as air traffic is generally expected to grow further in the next decades.

3.2.7 Aircraft Introduction Module

The following section presents the *Aircraft Introduction Module*, which allows the definition of the introduction of aircraft to the fleet in future years based on the flight plan gaps determined by the Gap Module.

3.2.7.1 Background

In reality, airlines need to decide on their fleet planning strategies with considerable time spans into the future. Oftentimes, it takes years between the placements of aircraft orders at an aircraft OEM until the first aircraft is actually delivered to the particular airline. Furthermore, in the process of fleet planning, an airline has significant freedom in how an assumed future capacity gap (see Section 3.2.6) will be filled in the future. Even though OEMs may only offer several different aircraft types, arbitrary combinations of different aircraft types principally allow very different fleet mixes to provide an airline's future transport demand.

With respect to future airport noise, the single-event noise of future aircraft introduced to the fleet is of interest. As result of research and development efforts, new aircraft types generally emit lower noise levels than older aircraft types. For a given aircraft size, airlines principally may choose between the purchase of aircraft types that are older or newer from a technological point of view. As the list price of older aircraft types generally is less expensive than of a comparable, new aircraft type, airlines may still choose to order a louder aircraft. Single-event noise therefore is an important degree of freedom in the definition of a future aircraft fleet.

Furthermore, airlines generally may choose to supply a given air traffic demand with, on average, smaller or larger aircraft.[53] A larger average seat capacity of aircraft introduced to the fleet allows to supply a given air traffic demand by less aircraft movements, which reduces continuous sound levels. On the contrary, larger aircraft are likely to be subject to increased single-event noise, which tempts to increase airport noise exposure. Hence, the future size of aircraft introduced to the fleet is a further relevant degree of freedom in the assessment of future airport noise.

In addition, the future introduction of aircraft is of particular interest for impact assessments because of its comparatively high influence by the aviation industry. Whereas on several aspects determining future airport noise the aviation industry only has a minor influence, for example on air traffic demand, the aviation industry is rather free in the decision on what kind of aircraft types to develop and introduce to the fleet in the future. Therefore, the capability of a detailed representation of the future aircraft introduction within the FFEA is desirable. The methodical approach of the Aircraft Introduction Module is introduced in the following.

3.2.7.2 Methodical Approach

The objective in the development of the Aircraft Introduction Module is to allow a precise definition on a yearly basis of the particular mix of new aircraft introduced to the fleet. The modelling of a wide range of aircraft combinations to enter service including the effects discussed in the previous section shall be possible.

A fundamental assumption made by the Aircraft Introduction Module is that throughout the modelled years, air traffic supply equals air traffic demand.[54] Consequently, the flight plan gaps, as determined by the Flight Plan Gap Module (see Section 3.2.6), are entirely filled by new aircraft introduced to the fleet.

[53] As extreme example, wide-body aircraft may increasingly be used on short-haul flights in the future. In 2016 more than 20 % of all short-haul operations in Asia-Pacific were performed by wide-body aircraft (Airbus, 2017b).

[54] Thus, aircraft OEMs are principally assumed to be able to produce a sufficient amount of aircraft.

The underlying logic of the Aircraft Introduction Module is illustrated in Fig. 3-6. A flight plan gap of a specific aircraft type is filled by a scenario-specific combination of new aircraft types introduced to the fleet. Therein, the Aircraft Introduction Module allows any combination of aircraft types introduced both in terms of the amount of new aircraft types introduced (in Fig. 3-6: three), and in terms of the individual aircraft type-specific shares (in Fig. 3-6: 20/50/30%). The method allows a flight plan gap to be filled by new aircraft types that are not yet in a current aircraft fleet, as well as by aircraft types that are already present in the baseline fleet. In this way, the FFEA is able to determine arbitrary future fleet mixes of aircraft added to the fleet.

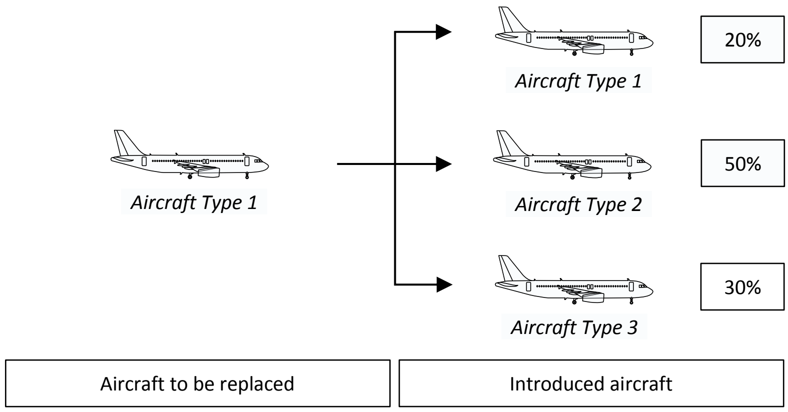

Fig. 3-6 Approach of filling a flight plan gap of a specific aircraft type by new aircraft introduced to the fleet

Fig. 3-6 represents a so-called *swap rule*, which is to be read as: "A flight plan gap of 1 AS of Aircraft Type 1 is filled with 20% by Aircraft Type 1, 50% Aircraft Type 2, and 30% Aircraft Type 3". In this way, a swap rule defines the share in flight plan gap of a specific aircraft type that is filled by a particular mix of aircraft types entering service. In order to take into account changes in aircraft introduction over time, the Aircraft Introduction Module allows swap rules to be defined for each future year individually. In this way, for example, the transition of an aircraft type to its successor, such as the ceasing production of the A320 in favour of the A320neo, can be modelled.

The application of the module relies on the user's definition of a so-called *swap matrix* that includes swap rules for each aircraft of the fleet, as presented in Tab. 3-3. As seen in the table, in the swap matrix, for each aircraft type active in a fleet (first column), the aircraft types to be introduced are listed (second column) followed by *swap factors* for all future years to be modelled. In this way, for each future year and each aircraft type operating in a fleet, the swap matrix distinctly defines how arising gaps in transport capacity are filled.

Tab. 3-3 Input of Aircraft Introduction Module: The swap matrix defining future aircraft introduction (exemplary numbers)

Aircraft Type m (flight plan gap)	*Aircraft Type n (introduced)*	*Year 1*	*Year 2*	*Year 3*	*...*
A/C Type 1	*A/C Type 1*	*20%*	*18%*	*15%*	*...*
	A/C Type 3	*50%*	*52%*	*55%*	*...*
	A/C Type 4	*30%*	*30%*	*30%*	*...*
A/C Type 2	*A/C Type 2*	*10%*	*5%*	*0%*	*...*
	A/C Type 5	*45%*	*47.5%*	*50%*	*...*
	A/C Type 6	*45%*	*47.5%*	*50%*	*...*
...	*...*	*...*	*...*	*...*	*...*

Practically, in the modelled flight plan, for new aircraft types introduced to the fleet the FFEA appends new flight plan entries to the existing entries of the flight plan. The corresponding transport capacity of aircraft introduced to the fleet is calculated according to equation (3.7).

$$I_{j,t+1} = G_{i,t+1} * sf_{(m,n),t+1} \tag{3.7}$$

I Transport capacity of **i**ntroduced aircraft [seats]
sf **S**wap **f**actor (of swap matrix) [-]
j flight plan entry index (of introduced aircraft) [-]
m aircraft type index (of flight plan gap aircraft) [-]
n aircraft type index (of introduced aircraft) [-]

3.2.7.3 Review & Summary

The developed Aircraft Introduction Module allows a user to define arbitrary aircraft introduction scenarios through the definition of a swap matrix. In this way, principally an infinite amount of introduction scenarios may be applied.

At this point, no actual swap factors defining a swap matrix have yet been determined. In the application case, the applied aircraft introduction inputs are documented for each scenario. The definition of worst-case introduction scenarios (e.g. only old technology aircraft added) or best-case introduction scenarios (e.g. only new technology aircraft added) is usually straightforward.[55] A realistic aircraft introduction scenario, which is based on the evaluation of OEMs' open aircraft orders, is presented in Section 3.6.1.

55 For instance, a worst-case aircraft technology scenario may be described by a swap matrix, in which any aircraft type is entirely replaced by its same type. This leads to swap rules according to the scheme: "A flight plan gap of 1 AS of aircraft type x is filled by 100% with aircraft type x for all future years."

A general advantage of the presented approach is the ability to define aircraft introduction on a yearly basis, thus, in combination with the Aircraft Retirement Module, the FFEA is able to model continuous fleet mix developments based on scenario-specific input. Another advantage of the approach is its flexibility to consider any number and combination of new aircraft types to enter a fleet. As a result, in the technology assessment of future aircraft types, principally any desired introduction scenario can be studied. For example, different proportions of a NT-2 aircraft type from all aircraft introduced to the fleet can be modelled as well as different entry into service years of a NT-2 aircraft.

3.2.8 Airport Capacity Module

The following section introduces the *Airport Capacity Module* which aims at taking into account effects from airport capacity constraints on future flight plans and hence, on future airport noise.

3.2.8.1 Background

Historically, many airports that today carry the main load of civil air traffic have been planned and constructed in a time when total passenger numbers were far below present levels. Throughout the last decades, caused by the increase in traffic demand, aircraft movement numbers at most airports have significantly risen.

However, airports cannot handle an infinite amount of aircraft movements. Each airport rather has a specific maximum capacity throughput, which is determined, for instance, by the number and layout of its runways and on current weather conditions (Mensen, 2007). Maximum airport capacity throughputs are quantified by the amount of possible aircraft movements[56] per time, for planning reasons usually specified for periods of 60 minutes or 15 minutes.

A potential solution to airport capacity problems is the expansion of airport infrastructure, namely the addition of a new runway to an airport's runway system. Yet, in reality, airport expansions may be difficult to realize, which is particularly true for Western countries. As result of an increased air traffic and the difficulties in expanding airport infrastructure, airports are increasingly faced with problems resulting from capacity constraints. In the future, it is likely that effects from capacity constraints will aggravate.

For the analysis of future airport noise, it is to mention that airport capacity constraints influence airport noise in different ways. Generally, the effects of airport capacity constraints on future airport noise significantly depend on non-trivial strategic and economic considerations by the involved aviation stakeholders. In this thesis, it is not the goal to analyse these effects in detail. However, three principle noise-relevant effects resulting from capacity constraints are named in the following:

1. Shift of aircraft movements to other times of the day

[56] An aircraft movement is either an arrival operation or a departure operation.

2. Tendency to use aircraft with higher seat capacity
3. Demand spill: Parts of traffic demand aren't met

Firstly, if airport capacity is reached at a specific time of the day, that is, if no more slots are available, airlines may consider flying at other times of the day instead. An airline may attempt to gain slots as close to the actually desired time as possible. Concerning airport noise, a shift of aircraft movements may increase noise exposure, if movements are shifted beyond the periods defined by the DEN (e.g. from 'day' to 'evening' or 'night').

Secondly, in response to airport capacity constraints, airlines may tempt to increase their capacity without requiring additional movements at the airport by using aircraft with higher seat capacity. Airlines may particularly consider using larger aircraft at capacity-constrained airports.

Thirdly, at capacity constrained airports it is likely that the actual air traffic demand will only be partially met, which can be understood as traffic demand spill. For example, airlines may consider to operate at other, nearby airports instead of a capacity-constrained airport.

3.2.8.2 Methodical Approach

The Airport Capacity Module takes into account the first effect discussed in the previous section. The module thus concentrates on the modelling of the possible shifting of aircraft operations to less frequented times of the day if the airport's maximum throughput is reached. Other effects on future flight plans, and thus, on future airport noise, are not considered.

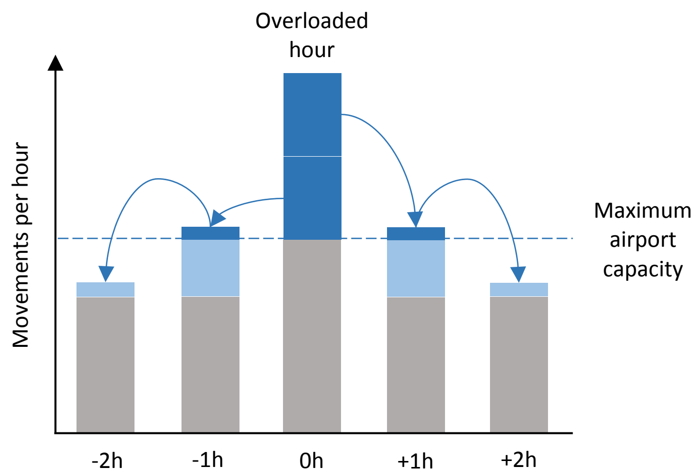

Fig. 3-7 Working method of the Airport Capacity Module modified from Will et al. (2017)

The FFEA's previously described modules solely quantify future flight plans by according transport capacities. Prior to the Airport Capacity Module, as depicted in Fig. 3-2, are transport capacities transferred to actual flight movement numbers by division with aircraft type-specific seat capacities. For aircraft of the baseline flight plan, the seat capacity characteristics specified by the baseline flight plan are applied (Section 3.2.3). For aircraft introduced by the Aircraft Introduction Module, seat capacities may be specified by the user for each aircraft type. In this thesis, the seat assumptions of aircraft introduced to the fleet are aligned with the numbers specified by the OAG baseline flight plan of 2016[57]. Consequently, aircraft-specific seat capacities remain unchanged for all modelled years.

Based on the FFEA's derived flight plan of the target year quantified through flight movement numbers, airport capacity constraints are considered. The principle working method of the Airport Capacity Module is illustrated in Fig. 3-7. In the flight plan of the target year, the module's algorithm searches for the hour with maximum flight movements. If the number of movements exceeds the user-defined maximum capacity (see Tab. 3-4), excess flight operations are equally shifted to the two neighbouring hours.[58] If the neighbouring hours are not able to receive sufficient movements, which is the case depicted in Fig. 3-7, movements are further transferred to the next neighbouring hours. This procedure is repeatedly conducted as long as hours of the day exceed the maximum hourly throughput.[59]

Tab. 3-4 Input of the Airport Capacity Module: maximum throughput to be defined by the user (for target year; exemplary number)

Maximum Throughput (Mov./hour):	***100***

The result of the Airport Capacity Module is a future flight plan of the target year, quantified by aircraft movement numbers, whose hourly movements remain within the maximum airport-specific capacity.

3.2.8.3 Review & Summary

The Airport Capacity Module proposes a simple method to incorporate the effect of airport capacity constraints on future airport noise exposure within the FFEA. Excess flight movements that would surpass the maximum hourly airport capacity are assumed to be entirely transferred to other, less frequented periods of the day.

In reality, it is probably that, to some degree, not all flights that are shifted to neighbouring hours would actually take place. Yet, more complex effects resulting from airport capacity constraints are neglected by the Airport Capacity Module. Taking into account further effects might require, for instance, knowledge of the strategies of the main airlines operating at a studied airport.

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[57] The applied seat capacities of NT-1 aircraft types are assumed to be unchanged compared to an according predecessor CT aircraft type. For instance, the seat capacity of a NT-1 aircraft A330-800neo is assumed the same as the corresponding CT aircraft A330-200.

[58] The Airport Capacity Module does not select single flight plan entries to be shifted. Rather the same proportion of movements of all flight plan entries of the overloaded hour is shifted.

[59] In the extreme case that all 24 hours have reached the maximum throughput, remaining excess movements are deleted (hence not operated).

Despite its limitations, the Airport Capacity Module introduces additional accuracy to the FFEA. For impact assessments, the module offers the ability to evaluate the order of magnitude that airport capacity constraints have on future airport noise. Because the module assumes to provide all air traffic demand without any traffic demand spill, the quantification of effects from capacity constraints can be regarded as a conservative, worst-case estimation with respect to future noise exposure.

3.2.9 Route Allocation Module

In the following section the *Route Allocation Module* is introduced, which assigns flight movements to specific flight routes at the airport based on user-defined input and on the corresponding airport's runway layout.

3.2.9.1 Background

The future flight plan, as resulting from the Airport Capacity Module, does carry significant information relevant to future airport noise. However, no information is included yet on characteristics that locally describe the flight movements at an airport. Local characteristics are essential for the particular noise situation at an airport as discussed in the following.

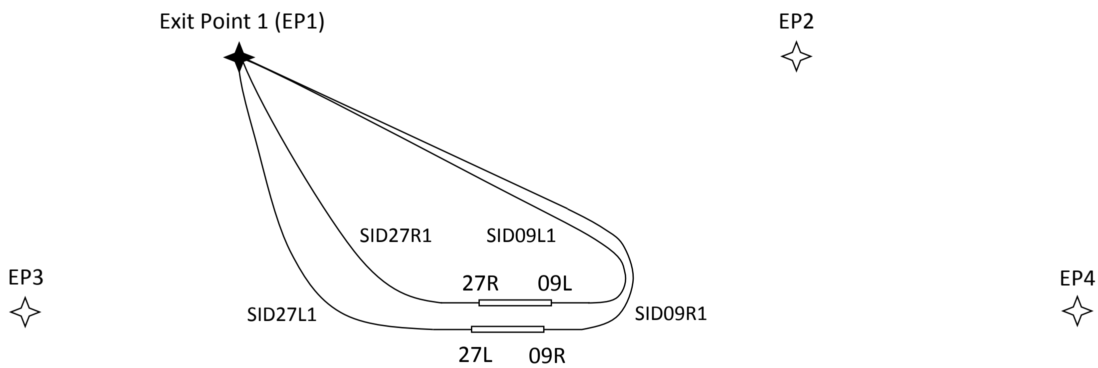

Fig. 3-8 Different SIDs linking an airport's runways to a specific exit point

Fig. 3-8 gives an overview of typical, local airport characteristics from the example of a two-runway airport. For the case of departures, as illustrated in the figure, usually multiple *exit points* ("EP") exist in a sufficient distance to the airport distributed over different geographic directions. These waypoints, defined by their coordinates, usually represent the connections of a local aerodrome to the ATS routes, which serve as air traffic routes in en-route altitudes (International Civil Aviation Organization, 2006). Any departing flight is assigned to an exit point according to its destination airport, wherein, for example, flights to northern destinations are assigned to an exit point north of the airport.

Furthermore, airports usually have a set of designated *Standard Departure Routes* (SIDs). These SIDs connect a specified runway to an exit point by defining the ground track of a departing flight, as illustrated in Fig. 3-8. Note, that the vertical flight profile of a departing aircraft is not determined by the SID. Generally, each runway may be connected to an exit point by a corresponding SID, as in Fig. 3-8, where four different SIDs lead from the four runway ends to the same exit point EP1.[60] For arrival operations the same applies as for departure operations. In this case, arriving aircraft are assigned to an *entry point* depending on the origin airport of the flight. From the entry points, aircraft are navigated to the airport by a *Standard Arrival Route* (STAR).

With respect to airport noise, two airport-specific characteristics are important to consider:

1. The geometrical definition of SIDs and STARs
2. The route distribution of flights onto the different routes

Firstly, it is obvious that the particular geometrical definition of the SIDs and STARs is important to the resulting airport noise. Only minor changes in the horizontal definition of flight routes may change local sound levels significantly. Usually, SIDs and STARs are defined such as to minimize the noise impact on residents of an airport.

Secondly, as seen from Fig. 3-8, principally any runway may guide a departing aircraft to an exit point, and an arriving aircraft may principally be lead to any runway, respectively. Therefore, the route distribution, which defines the distribution of flights onto the different routes of an airport, is relevant for airport noise, too.

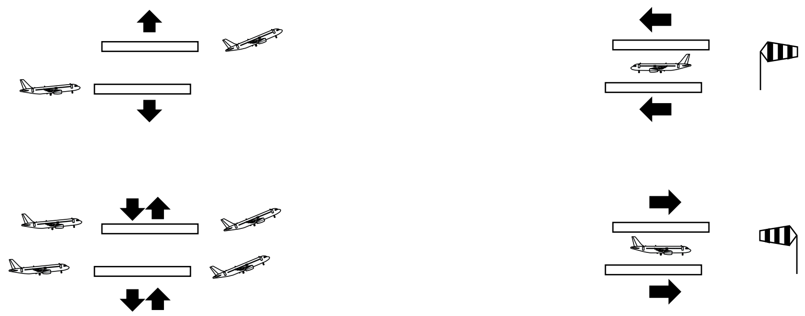

Fig. 3-9 Different airport runway usages: On the left arrivals and departures seperated (top) versus mixed-mode (bottom). On the right western versus eastern operation.

Different possibilities in the definition of the route distribution as result from different runway usages are explained in Fig. 3-9. On the left, as first option, a runway usage is shown that uses each runway solely for arrivals or departures (top left), whereas a second option would be to use both runways for arrivals and departures in mixed-mode (bottom left). On the right, it is illustrated that a runway may principally be operated in two operating directions, which is usually defined based on current wind directions.[61] With respect

[60] In reality, more than one SID may exist between a runway end and an exit point.

[61] Arrivals and departures ideally are operated with headwind. Principally, a runway may be also used at (low) tailwind conditions. This can be regarded as a possible noise-mitigation measure, also called *preferential runway usage*, which may be reasonable if one side of an airport is much denser populated than the other side.

to airport noise, different operating directions may lead to strong differences in resulting local noise levels.

The two named, relevant characteristics differ in terms of an air traffic controller's possibility to influence airport noise exposure. Whereas, for a given airport, the definition of SIDs and STARs is independent from current, local conditions and usually remains unchanged over the course of many years, the current route distribution may be influenced by the air traffic control considering the current weather or traffic volume.

3.2.9.2 Methodical Approach

Both airport-specific characteristics described in the previous section are considered by FANAM. Yet, the two characteristics are specified within different modelling areas. On the one hand, the geometrical definition of SIDs and STARs occurs in the Airport Noise Modelling area and is introduced in Section 3.4. On the other hand, the route distribution of flights to an airport's different SIDs and STARs is considered by the Route Allocation Module. In the following, the module's approach of assigning departure movements to specific SIDs is introduced. The assignment of arrival movements to specific STARs follows accordingly.

As discussed in Section 3.2.2, the FFEA allocates each flight plan entry distinctly to a specific waypoint. Departure operations are assigned to an exit point based on the according destination airport. The Route Allocation Module then assigns the movements of a flight plan entry to specific SIDs through the user's definition of the *route usage matrix* as shown in Tab. 3-5. The presented exemplary route usage matrix assumes only one SID to connect a runway end to an exit point. The Route Allocation Module principally also allows more than one SID to connect a given runway end and a given exit point.

Tab. 3-5 Input of the Route Allocation Module: The route usage matrix for departure operations (exemplary numbers)

Runway/ Exit Point	*09R*	*09L*	*27R*	*27L*	$\sum$
EP1	*0%*	*40%*	*60%*	*0%*	*100%*
EP2	*0%*	*40%*	*60%*	*0%*	*100%*
EP3	*20%*	*20%*	*30%*	*30%*	*100%*
EP4	*20%*	*20%*	*30%*	*30%*	*100%*
...	*...*	*...*	*...*	*...*	*...*
	40%		*60%*		

In the route usage matrix, the exit points of an airport are listed in the rows (see Tab. 3-5). The different SIDs of an airport are represented by the columns of the matrix. Each field of the route usage matrix then quantifies the share of flight movements that uses a dedicated SID for the specified exit point. For example, in Tab. 3-5 the first row is to be read as: "Flights departing via Exit Point 1 use Runway 09L by 40%, and Runway 27R by 60%."[62] For the exemplary numbers of Tab. 3-5, the runway direction distribution is 60% westerly (27) and 40% easterly (09). Furthermore, according to Tab. 3-5, for departures to the northern exit points (EP1, EP2), only the northern runway (09L/27R) is used, whereas for the exit points EP3 and EP4 both runways are equally used.

The Route Allocation Module is designed to account for different numbers of exit points, different numbers of SIDs and different runway system layouts. The route usage matrix can include any number of exit points and SIDs as specified by the user. Also, the matrix allows any number of runways to be able to correspond to the runway layout modelled in the Airport Noise Modelling area (see Section 3.4).

Based on the definition of the route usage matrix the according route distributions are uniquely applied to all flight plan entries of the modelled flight plan. In this way, all flight movements of a modelled flight plan are entirely assigned to one of the SIDs of the studied airport. As mentioned, the assignment of entry points to the STARs of an airport follows accordingly by definition of a second route usage matrix for arrival operations.

3.2.9.3 Review & Summary

The Route Allocation Module assigns each flight movement of the FFEA's flight plan to a specific SID or STAR at the airport. Therein, the module is able to consider different user-defined route distributions, which may be of considerable significance to an airport's particular noise exposure. The module offers the user a high flexibility in the definition of exit/entry points, SIDs/STARs or the number of runways. Different operating directions at a given airport can be simply defined by the two route usage matrices[63].

As minor limitation it is to mention that a given route distribution is applied in the same way to all arrival/departure movements of a flight plan. In reality, flight route assignment may additionally depend on the aircraft type of a flight.[64] A differentiation with respect to aircraft types is not done by the Route Allocation Module.

3.2.10 Definition of an Aircraft Introduction Reference Scenario

In this section, a specific reference scenario defining the future aircraft introduction is proposed. The scenario serves as input of the Aircraft Introduction Module for several simulations throughout this thesis.

[62] In the example, the specific runway end (e.g. 09R) distinctly defines the particular SID (e.g. SID09R1) as only one SID is specified to connect a runway end with an exit point.
[63] One matrix for departure operations and one matrix for arrival operations.
[64] For instance, the air traffic controller may assign heavier aircraft types, which are bound to relatively flat vertical departure profiles, to special SIDs.

3.2.10.1 General approach

Principally, the Aircraft Introduction Module introduced in Section 3.2.7 allows a user to define arbitrary aircraft introduction scenarios. As discussed previously, the definition of best-case and worst-case aircraft technology introduction scenarios usually is straight-forward. At the same time, it is also desirable to consider aircraft introduction scenarios that aim at modelling a realistic fleet behaviour. For this purpose, an *aircraft introduction reference scenario* was developed by Mayrhofer (2017) as described in the following.

In order to define the scenario by the specification of a corresponding swap matrix (see Tab. 3-3), an approach visualised by Fig. 3-10 is used. Therein, *open aircraft orders*[65] published by OEMs serve as foundation to consider future aircraft introduction. The idea behind this approach is that current backlog numbers indicate the aircraft types and associated fleet shares that, once produced, will enter the fleet in future years. As seen in Fig. 3-10, *ordered transport capacities* are subsequently derived based on backlog numbers and aircraft type-specific seat capacities.

Furthermore, as additional information, end of production (EOP) years of aircraft types already present in a current fleet and entry into service (EIS) years of future aircraft types to enter the fleet are considered. From the ordered transport capacities and assumed EIS/EOP years, aircraft type-specific swap factors are determined that ultimately define the scenario's swap matrix according to Section 3.2.7. The procedure to define the aircraft introduction reference scenario is detailed in the following section.

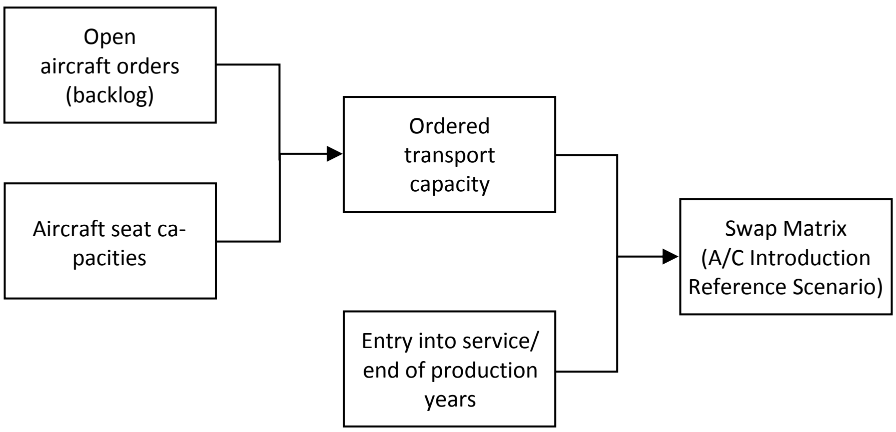

Fig. 3-10 Definition of the aircraft introduction reference scenario

3.2.10.2 Detailed description

In the specification of the aircraft introduction reference scenario it is decided to suggest a definition up to the year 2040. The scenario assumes that wide-body aircraft are always replaced by wide-body aircraft, and narrow-body aircraft are always replaced by narrow-body aircraft. This assumption is supported by an analysis of press releases of several airlines on fleet strategies that showed no indication of contrary aircraft replacements

[65] Also called *order backlog*.

(Engelke, 2016). Thus, in the following, the introduction of aircraft can be separately regarded for the two groups of narrow-body and wide-body aircraft.

Principally, the Aircraft Introduction Module allows to define individual swap rules for each aircraft type to be replaced (see Tab. 3-3). As mentioned, the aircraft introduction reference scenario does differentiate between narrow-body and wide-body aircraft. However, it is refrained from defining individual swap rules for each specific aircraft type to be replaced. Instead, the same set of swap rules is applied to all narrow-body aircraft, and to all wide-body aircraft, respectively. As a result, a gap in flight plan, for instance of an Airbus A319 and of an Airbus A321, is filled by the same share of aircraft types to enter service.

Following the definition of the baseline year in 2016, Mayrhofer (2017) has evaluated open aircraft orders as of 2016.[66] For each aircraft type, from open order numbers and aircraft seat capacities, total ordered transport capacities are determined according to equation (3.8). In case that a CT aircraft type by 2016 was still in production, the according backlog numbers are accumulated with the backlog numbers of its successor NT-1 type.[67] Aircraft seat capacities are assumed as derived from the OAG flight plan[68] for aircraft types present in the baseline flight plan. Seat capacities of aircraft types not found in the baseline flight plan are assumed according to seat numbers as specified by the according OEM.

$$TOTC_{A/C} = Orders_{A/C} * \ Seats_{A/C} \tag{3.8}$$

$TOTC$ **T**otal **o**rdered **t**ransport **c**apacity [seats]

A/C **A**ir**c**raft type index [-]

$Orders$ Number of open aircraft orders [-]

$Seats$ Number of seats per aircraft [seats]

For the aircraft introduction reference scenario, only aircraft types are considered that have a share of >1% in $TOTC$ of all narrow-body aircraft for narrow-body aircraft and of all wide-body aircraft for wide-body aircraft. An overview of the aircraft types thus considered is given in Tab. 3-6, specifying narrow-body aircraft on the left, and wide-body aircraft on the right.

Furthermore, as introduced by Fig. 3-10, aircraft type-specific EIS years and EOP years are considered. For each aircraft type, the aircraft's total ordered transport capacity is multiplied by an aircraft type-specific *entry-into-service factor* according to equation (3.9). The purpose of the entry-into-service factor is to take into account the assumed production period of an aircraft type.

$$AOTC_{A/C,t} \ = TOTC_{A/C} * \ EISF_{A/C,t} \tag{3.9}$$

$AOTC$ **A**djusted **o**rdered **t**ransport **c**apacity [seats]

$EISF$ **E**ntry-**i**nto-**s**ervice **f**actor [-]

[66] Each as of 31st December.

[67] For instance, A320 and A320neo, or B737-800 and B737-MAX8.

[68] As used in the application case (see Chapter 4).

Tab. 3-6 Aircraft types considered by the aircraft introduction reference scenario for future aircraft introduction

OEM	***Aircraft type (narrow-body)***	***Included generations***	***OEM***	***Aircraft type (wide-body)***	***Included generations***
Airbus	*320 (ceo/neo)*	*CT/NT-1*	*Airbus*	*332 (-200/-800neo)*	*CT/NT-1*
Airbus	*321 (ceo/neo)*	*CT/NT-1*	*Airbus*	*333 (-300/-900neo)*	*CT/NT-1*
Bombardier	*CS3*	*NT-1*	*Airbus*	*359*	*NT-1*
Boeing	*738 (-800/-MAX8)*	*CT/NT-1*	*Airbus*	*351*	*NT-1*
Boeing	*739 (-900/-MAX9)*	*CT/NT-1*	*Airbus*	*380*	*NT-1*
			Boeing	*777 (-300ER/X)*	*CT/NT-1*
			Boeing	*788*	*NT-1*
			Boeing	*789*	*NT-1*
			Boeing	*781*	*NT-1*

The entry-into-service factor, as illustrated by Fig. 3-11, specifies an aircraft type's production period through the definition of an EIS year and EOP year. As a result, in the aircraft introduction reference scenario the according aircraft type is only introduced to the fleet from the specified EIS year on while introduction to the fleet ceases with the specified EOP year. Note, again, that the Aircraft Introduction Module only defines the particular *shares* of aircraft types to enter service, whereas the absolute amount of transport capacity added to the fleet is defined by the size of the flight plan gap (see Section 3.2.6).

If, for an introduced aircraft type, information on real EIS or EOP years is publicly available, for instance, by press releases of airlines or OEMs, real years are applied. The according years assumed by the aircraft introduction reference scenario as researched by Mayrhofer (2017) are listed in Appendix B. If an aircraft type's EOP year cannot be defined based on public sources, further assumptions are needed, which is the case for all NT-1 aircraft types. Therein, in order to still take into account the ceasing production of NT-1 aircraft types, an average number of production years is assumed. Based on the analysis of historic data of the first and the last delivery year of multiple relevant aircraft types, an average production period of approximately 24 years was determined by Mayrhofer (2017). Consequently, in case of unknown EOP year, a production period of 24 years is applied as shown in Fig. 3-11 for the NT-1 aircraft types A320neo and B737-MAX8.

Furthermore, in the three years following the EIS and in the three years prior to the EOP, the EIS factors assume a linear transition between zero and one as seen in Fig. 3-11 [69]. The overlapping period of simultaneous production of an aircraft type and a successor aircraft type (see Fig. 3-11) is assumed to be three years based on the analysis of historic first and last aircraft delivery years by Mayrhofer (2017).

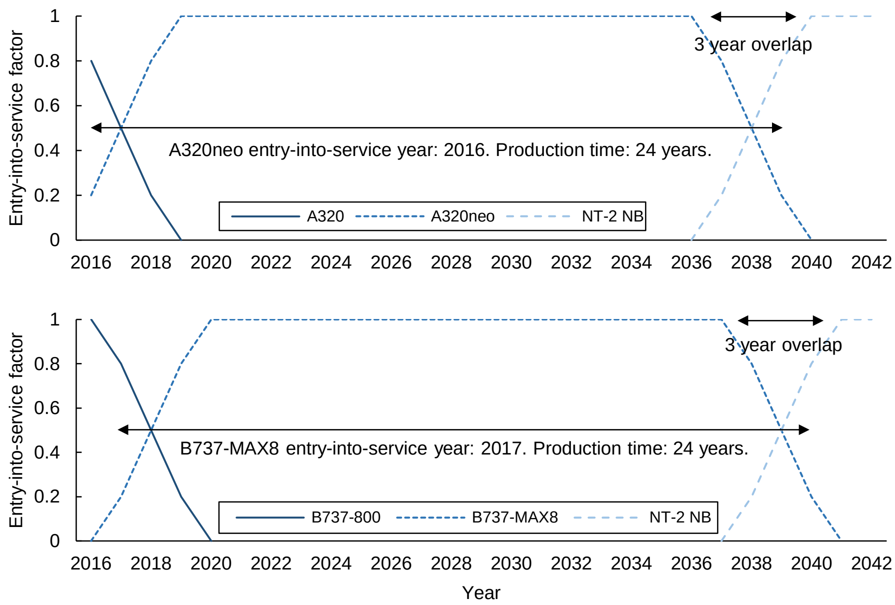

Fig. 3-11 Concept of entry-into-service factors specifying the production period of different aircraft types

Finally, based on the aircraft type's ordered transport capacities and its specific entry-into-service factors, swap rules are formulated by the swap factors sf for future years according to equation (3.10).

$$sf_{A/C,t} = \frac{AOTC_{A/C,t}}{\sum_{A/C} AOTC_{A/C,t}} \tag{3.10}$$

Assumptions on NT-2 aircraft types:

Lastly, to define aircraft introduction up to the year 2040, assumptions on NT-2 aircraft types are stated, which in the aircraft introduction reference scenario follow the ending production of NT-1 aircraft types. Due to the large uncertainties in which aircraft types will follow the currently produced variety of NT-1 aircraft types, only one NT-2 narrow-body aircraft type, and one NT-2 wide-body aircraft type is postulated. These NT-2 aircraft types thus represent the actual variety of real future NT-2 aircraft types. In Fig. 3-11 the NT-2 narrow-body aircraft is denoted by "NT-2 NB", which is consequently used as successor aircraft of both the A320neo and the B737-MAX8.

[69] The precise EIS factors are determined to 0.2 (year 1), 0.5 (year 2), and 0.8 (year 3).

The representative NT-2 aircraft types assumed by the aircraft introduction reference scenario follow the long-term noise reduction goals published by the ICAO's Committee on Aviation and Environmental Protection (CAEP) (International Civil Aviation Organization, 2014). The CAEP has specified goals in noise reduction levels[70] relative to a reference aircraft's noise certification levels. The according noise reduction levels and corresponding reference aircraft types are summarized in Tab. 3-7. As can be seen, while the noise reduction goals for the approach point is -5 dB for both aircraft, the goals are more ambitious for the two departure points. The lateral noise reduction goal is -10 dB for the wide-body aircraft and even -12 dB for the narrow-body aircraft. The resulting noise margin below the Chapter 4 noise limits are 29.5 dB for the NT-2 narrow-body and 28 dB for the NT-2 wide-body aircraft[71].

In FANAM, both NT-2 aircraft types are modelled based on the specified reference aircraft type according to the aircraft-level noise modelling approach described by Section 3.3. The NT-2 narrow-body aircraft type is assumed with a capacity of 180 seats, the NT-2 wide-body aircraft type with 280 seats.

Tab. 3-7 Long-term noise reduction goals with respect to the specified reference aircraft according to the ICAO (International Civil Aviation Organization, 2014)

Representative NT-2 aircraft type	*NT-2 Narrow-body*	*NT-2 Wide-body*
Reference Aircraft type	*737-800*	*A330-300*
Approach	*-5.0 dB*	*-5.0 dB*
Flyover	*-7.5 dB*	*-7.0 dB*
Lateral	*-12.0 dB*	*-10.0 dB*

An illustration of the resulting swap factors for narrow-body and wide-body aircraft for all years up to 2040 as proposed by the aircraft introduction reference scenario is presented in Appendix D.[72] In this way, the aircraft introduction reference scenario sufficiently specifies the future aircraft introduction in the structure required by the FFEA.

3.2.11 Review & Summary of Flight Plan Modelling Approach

In the following, a review of the developed flight plan modelling approach FFEA is presented. The discussion highlights the major capabilities and limitations of the approach.

[70] The long-term noise reduction goals are given for the year 2030 at TRL6.
[71] The narrow-body reference aircraft selected by the CAEP has a cumulative noise margin respective Chapter 4 of -5 dB, the wide-body reference aircraft an according margin of -6 dB.
[72] On top, for narrow-body aircraft, below for wide-body aircraft. From the visualisation, the effect of ramp-up and ramp-down of a given aircraft type as well as its modelled production duration can be seen.

Major capabilities

The developed FFEA features multiple capabilities, which have been discussed in depth in the previous sections. The major capabilities of the developed FFEA can be summarized as followed:

1. Applicability to any airport: The FFEA may be applied to any given airport. As such, the FFEA is capable to process arbitrary airport-specific baseline flight plans and maximum airport throughputs as well as arbitrary amounts of runways and flight routes.
2. Consideration of numerous impacts: At a given airport, the FFEA is able to model a considerable amount of different noise-relevant impacts on future flight plans. The FFEA takes into account the impact of air traffic growth, aircraft retirement and aircraft introduction on future flight plans and thereby dynamically models future aircraft fleet mixes. In this, the FFEA leaves the average aircraft seat capacity a non-predetermined degree of freedom. In terms of future aircraft introduction, the FFEA allows to consider future aircraft types with arbitrary entry into service years. Moreover, in addition to impacts that influence future fleet mixes, the FFEA is able to consider the impact of airport capacity constraints and different flight route distributions[73] on future flight plans.
3. Flexibility in the scenario inputs: In the definition of all input data, the FFEA principally allows a user to specify arbitrary, scenario-specific data.[74] Thus, a wide range of relevant future airport noise scenarios can be modelled by the FFEA.
4. Modelling at a yearly basis: The FFEA iteratively models future flight plans at an annual basis. The scenario input may thus also be specified at a yearly basis, allowing the analysis of impacts at a reasonably fine timely resolution. Besides, the FFEA thereby allows the definition of any desired target year specified by the user[75].

Major limitations

As with any other simulation method, the FFEA is subject to limitations, which result from the stated assumptions and the restrictions regarding the scope of this research. The major limitations of the developed FFEA are as follows:

1. One “world airline”: The FFEA assumes a single world airline to operate at a studied airport and does not differentiate flights according to different airlines. As a result, airport-specific fleet effects resulting from individual airlines’ fleet strategies are not considered be the FFEA.[76]

[73] The definition of route distribution includes the specification of different operating directions, e.g. due to different wind directions.
[74] As exception, the FFEA is restricted with respect to negative growth rates (see ‘Major Limitations’).
[75] Obviously, with increasing time horizon the accuracy of the results are likely to decrease along with the decreasing accuracy of the scenario inputs (e.g. with respect to air traffic growth).
[76] For instance, if an airline chooses to abruptly replace all aircraft of a given type by another aircraft type.

2. Consideration only of airliners: The FFEA solely takes into account flights of airliners and does not consider operations by freighter aircraft, general aircraft, and helicopters. The FANAM method thus neglects an airport's noise emissions from non-airliner air traffic.
3. Statistical retirement approach: The FFEA considers aircraft retirement in a strict statistical manner based on past retirement data. Consequently, aircraft retirement behaviour is regarded as independent from other developments.[77]
4. Negative air traffic growth rates: The FFEA is limited in the representation of negative air traffic growth. For negative growth gaps that by absolute value exceed the corresponding retirement gap, no more aircraft are retired as defined by the FFEA's retirement approach. It follows that for sufficiently large negative traffic growth rates, the current version of the FFEA introduces errors.

Altogether, despite its limitations, the FFEA may be regarded as a suitable and powerful method for the purpose of future airport noise assessments.

3.3 Aircraft-Level Noise Modelling

The following section describes the aircraft-level noise modelling approach used by FANAM. The aircraft-level noise modelling, as previously described, represents the second modelling area of the developed framework.

3.3.1 Principal Approach

The goal of the aircraft-level noise modelling is to describe the single-event noise of an aircraft during departure and approach operations. The noise modelling approach in FANAM follows the modelling procedures proposed by the ECAC.CEAC Doc. 29 (3rd Edition) "Report on Standard Method of Computing Noise Contours around Civil Airports" (European Civil Aviation Conference, 2005b). With respect to single-event noise, this report, firstly, suggests a method to describe the flight path of an aircraft. Subsequently, based on the modelled flight path, single event aircraft noise can be calculated through the consideration of aircraft noise emission data.

For the flight path modelling, the ECAC method distinguishes an aircraft's *ground track* (2-D), and its *flight profile* (2-D), that in combination formulate a 3-D *flight trajectory*. Ground tracks, representing the projection of the flight trajectory on level ground, are airport-specific and not described by the ECAC method[78]. The vertical flight profiles, yet, are characteristics of specific aircraft types and thus defined by the method.

A comprehensive database supporting the ECAC methodology of single-event noise modelling is given through the Aircraft Noise and Performance (ANP) database provided by

77 As discussed in Section 3.2.5, the FFEA considers aircraft retirement in the same manner during periods of strong and weak air traffic growth.
78 Ground tracks are defined in FANAM's airport-level noise modelling area (see Section 3.4).

Eurocontrol. This free online database[79] contains all aircraft-specific information to model an aircraft's single-event noise based on the method defined by ECAC Doc. 29. The according ANP dataset of an aircraft type is collected by the aircraft manufacturer usually during noise certification tests and is subsequently provided to Eurocontrol (European Civil Aviation Conference, 2005a, G-1). An overview of the principle content of an aircraft's ANP dataset is given in Fig. 3-12.

As fundamental decision with respect to aircraft noise modelling it is decided that FANAM applies an aircraft type-specific noise modelling. This stands in contrast to the possible simpler alternative of grouping the variety of aircraft types into several categories and then substitute all aircraft within one category by one representative aircraft type. Although this aircraft type-individual modelling poses an increased effort, comparatively strong fleet mix simplifications resulting from aircraft groupings can thus be avoided.

Engine Coefficients	*Specifies the characteristics of the aircraft's engines*
Aerodynamic Coefficients	*Specifies the aerodynamic characteristics for different flap settings*
Weights	*Specifies take-off weights for different stage lengths*
Departure/ Approach Steps	*Describes departure/approach procedures by the definition of several flight segments ("steps")*
Noise Power Distance Data	*Specifies the noise levels for several power settings and 10 slant distances*
Spectral Classes	*Specifies the noise spectra for 24 one-third octave bands*

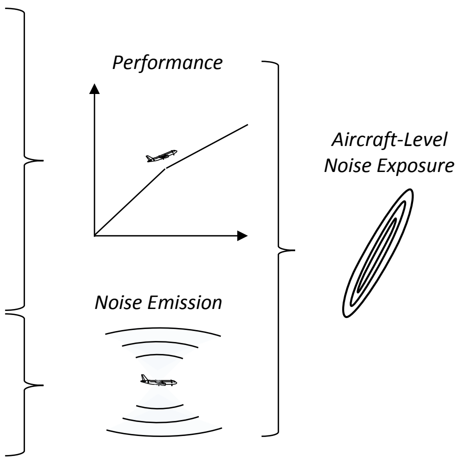

Fig. 3-12 Principle content of an Aircraft Noise and Performance (ANP) dataset following the noise modelling approach according to ECAC Doc. 29.

Two particularly relevant characteristics of ANP datasets are further detailed in the following. At first, an explanation of the modelling of flight procedures by an ANP dataset is given. Subsequently, a brief overview of Noise Power Distance data is given, which represent the substantial information on an aircraft's noise emission.

<u>Departure/Approach Flight Procedures:</u>

Principally, the ECAC method allows to model flight procedures in two ways:

1. Flight profiles by fixed-point profiles
2. Flight profiles by procedural steps

As indicated by its name, *fixed-point profiles* describe a flight path by fixed points defined through a specified altitude at an according distance from the take-off/landing point. The advantage of this method is its simplicity, the disadvantage its inflexibility as it describes

[79] www.aircraftnoisemodel.org

a profile only for a specific set of airport ambient conditions (e.g. altitude, temperature, wind).

A more sophisticated approach to describing vertical profiles is given through *procedure steps*, which define the flight condition (e.g. thrust, flap settings, speed) of several consecutive flight segments (e.g. 'take-off', 'climb', 'accelerate') rather than fixed points. Based on the step definitions and using an aircraft type's engine coefficients, aerodynamic coefficients, and weights (see Fig. 3-12) the vertical profile is then calculated according to ECAC Doc. 29. The advantage of the more complex modelling by procedure steps is that resulting flight profiles depend on the specific airport's ambient conditions, which may have a significant influence, for example, on departure profiles.

If procedural steps exist in the ANP dataset of a given aircraft, which is the case for the majority of aircraft types, procedural steps are applied by FANAM. In case that a ANP dataset only includes fixed-point profiles for a specific aircraft type, the fixed-point profile is used.

Noise Power Distance (NPD) Data:

The NPD data represent the decisive information on the noise emission of a specific aircraft. NPD data include measured noise levels perceived on the ground from an aircraft's horizontal overflight at a constant speed of 160 knots (European Civil Aviation Conference, 2005a). Distinct noise levels are specified for several engine power settings typical for the specific aircraft type, and for ten different, given distances[80] between aircraft and ground. ANP datasets typically specify NPD data for four different noise metrics (*PNLTM*, *EPNL*, $L_{A,max}$, *SEL*). A visualisation of a NPD data for the metric *EPNL* is found in Fig. 3-14.

Different NPD data are specified for approach and departure operations. This reflects the fact that an aircraft's noise emission is considerably different during approach and departure. During approaches, for instance, airframe noise may be significant, whereas for departures usually engine noise clearly dominates. This is due to the fact that during approach, engine thrust levels, and hence, engine noise levels, are lower than during departure. In addition, airframe noise during approach is generally higher due to flap and landing gear settings.

From an aircraft's NPD data, ground noise can thus be determined by consideration of an aircraft's current thrust level and its according distance to a receiver's point. To model noise emission between the specific thrust and distance values of the NPD data, a linear interpolation is used between the thrust levels of the NPD data and a logarithmic interpolation between the distances (European Civil Aviation Conference, 2005a).

[80] Starting at 200 ft with increasing intervals up to 25.000 ft.

The FFEA specifies aircraft types according to the IATA codes of aircraft naming. In order to combine the ANP database with the FFEA, each IATA aircraft type needs to be assigned to the nomenclature of the ANP database. The according assignment as derived by Engelke (2016) and applied by the application case is documented in Appendix B by the columns "IATA / FFDT Aircraft Code" and "ANP / AEDT Aircraft Code".

3.3.2 Modelling of Future Aircraft Types

Eurocontrol's ANP database provides datasets for the majority of today's aircraft types. However, new aircraft types, which have only entered service recently, may not have published ANP datasets yet. Also, ANP datasets aren't available for future aircraft types that are still under development or for NT-2 aircraft. As a result, a method is required that enables the consideration of aircraft types without ANP dataset within FANAM.

The modelling of future aircraft types in this thesis follows an approach proposed by ECAC.CEAC Doc. 29 (European Civil Aviation Conference, 2005b). In the following, the assumptions concerning future aircraft modelling based on ECAC.CEAC Doc. 29 are explained.

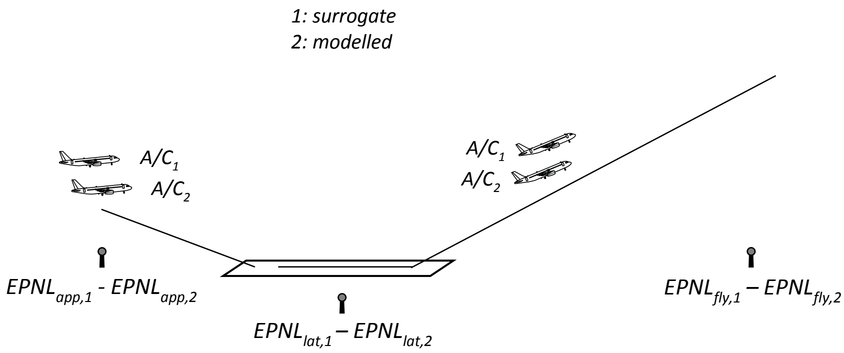

Fig. 3-13 Aircraft-level noise modelling of future aircraft types

The principle idea of the approach is the selection of a surrogate aircraft type resembling the aircraft type to be modelled and the subsequent generation of a corresponding new set of NPD data. The aircraft type to be modelled is based on the ANP dataset of its surrogate aircraft type. As fundamental information on the noise emission of the modelled future aircraft type, certification noise levels are used, which are published by the EASA in type-certificate data sheets for noise (European Aviation Safety Agency, 2018). As mentioned, during noise certification, noise levels in EPNdB are determined at three specified points (see Section 2.2). Herein, for FANAM a relevant advantage lies in the fact that aircraft noise certification levels are usually published a significant time before ANP datasets are provided by Eurocontrol. Furthermore, with respect to NT-2 aircraft, it is of relevance that medium- and long-term noise reduction goals of future aircraft are oftentimes quantified in EPNL noise levels at the three certification points.

ECAC.CEAC Doc. 29 suggests to use the noise levels at the three certification points of a surrogate aircraft type and of an aircraft type to be modelled as illustrated in Fig. 3-13. For approach NPD data, the difference in certification noise at the approach reference noise measurement point ("app") is applied according to equation (3.11). For departure NPD data, the difference in certification noise at the lateral reference noise measurement point ("lat") and the flyover reference noise measurement point ("fly") is used according to equation (3.12).

$$\Delta EPNL_{APP} = EPNL_{app,1} - EPNL_{app,2} \tag{3.11}$$

$EPNL$ **E**ffective **p**erceived **n**oise **l**evel [EPNdB]

APP approach procedures

app approach certification point

$$\Delta EPNL_{DEP} = EPNL_{lat,1} - EPNL_{lat,2} + EPNL_{fly,1} - EPNL_{fly,2} \tag{3.12}$$

DEP departure procedures

lat lateral certification point

fly flyover certification point

To generate a new set of NPD data, the deltas $\Delta EPNL_{APP}$ and $\Delta EPNL_{DEP}$ are then applied to the NPD data of the surrogate aircraft type by subtraction to the surrogate aircraft's noise levels. This represents a parallel shift of the surface spanned by the surrogate aircraft's NPD noise levels as illustrated in Fig. 3-14.

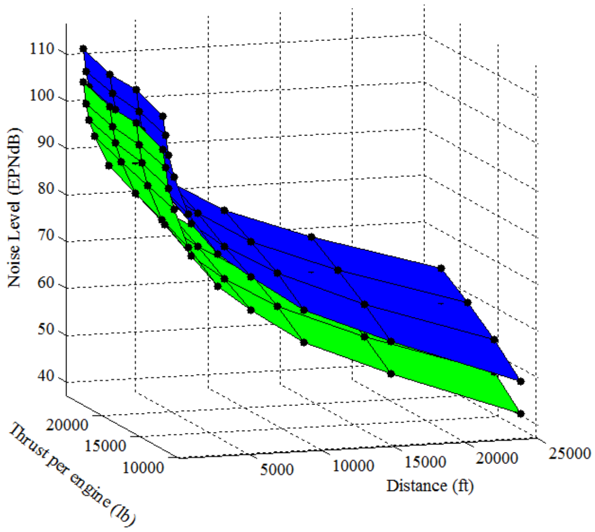

Fig. 3-14 Noise-power-distance data of a surrogate aircraft (blue) and a modelled noise-reduced aircraft (green) (Will et al., 2017)

A topic not addressed by ECAC.CEAC Doc. 29 is posed by different noise metrics applied. For the quantification of airport-level noise exposure in A-weighted continuous sound levels (e.g. the DEN), NPD curves in the metric *SEL* are required. However, the metric quantifying noise levels during the noise certification process is *EPNL*. The two metrics principally differ in the filtering applied to the sound pressure time histories and in an additional tone-correction penalty made by the *EPNL* (see Section 2.1.1). It can be stated that, for modern aircraft engines, the tone correction made by the metric *EPNL* tends "to be zero or small", leading to the fact that "the differences [between *EPNL* and *SEL*] are fairly consistent across a wide range of current aircraft types" (Jones and Cadoux, 2009, p. 5). Based on this, the future aircraft modelling approach in this thesis assumes that *EPNL* sound level differences are identical to *SEL* sound level differences. Following this assumption, the noise level differences between surrogate and modelled aircraft type $\Delta EPNL_{DEP}$ and $\Delta EPNL_{ARR}$ are accordingly applied to the NPD curves in the metric *SEL*.

With respect to the selection of a suitable surrogate aircraft type, ECAC.CEAC Doc 29 suggests an aircraft type with similar weight, same number of engines and similar installed thrust-to-weight ratio (European Civil Aviation Conference, 2005b). Furthermore, if possible, the document supposes that the surrogate aircraft is from the same aircraft manufacturer as the modelled aircraft type. Although not specifically mentioned by the document, the requirement of same propulsion type (jet engine/propeller) is additionally applied by this thesis.

Tab. 3-8 NT-1 aircraft types modelled according to the surrogate aircraft approach: Selected surrogate aircraft type and according noise reduction levels

Modelled aircraft type	*MTOW*	*Surrogate aircraft type*	*MTOW*	$\Delta EPNL_{DEP}$	$\Delta EPNL_{ARR}$
A320neo	*79 t*	*A320*	*77 t*	*-3.6 dB*	*-2.2 dB*
A321neo	*93 t*	*A321*	*89 t*	*-3.7 dB*	*-1.0 dB*
CS100	*61 t*	*E195*	*52 t*	*-6.2 dB*	*-1.4 dB*
CS300	*64 t*	*E195*	*52 t*	*-5.5 dB*	*-0.5 dB*
B787-9	*253 t*	*B787-8*	*228 t*	*+1.5 dB*	*+0.8 dB*
A350-900	*275 t*	*A330-200*	*233 t*	*-5.4 dB*	*-0.5 dB*
A350-1000	*308 t*	*A330-200*	*233 t*	*-2.5 dB*	*+0.0 dB*
B737-MAX8	*79 t*	*B737-800*	*79 t*	*-5.0 dB*	*-2.3 dB*

If, for a real aircraft type to be modelled, no noise certification levels have yet been published, a substitution by a similar aircraft type is applied by FANAM. The selection of the substitution type follows the same procedure as the previously described selection of a surrogate aircraft type. In the selection of a substitution aircraft type, official aircraft substitution tables published by Eurocontrol for this very purpose are considered, too[81]. For each aircraft type, the applied aircraft modelling method and the chosen surrogate and

[81] See www.aircraftnoisemodel.org.

substitution aircraft type is presented in Appendix B.[82] The noise level differences $\Delta EPNL_{DEP}$ and $\Delta EPNL_{ARR}$ applied by the surrogate aircraft approach as researched from EASA's noise certification data are detailed in Tab. 3-8.

As of NT-2 aircraft types, the according aircraft-level modelling approach follows the presented surrogate aircraft approach. Corresponding noise reduction levels may be defined depending on scenario-specific assumptions.

3.3.3 Review & Summary

In the following, an evaluation of the aircraft-level noise modelling approach is given. It focusses on the discussion of the major capabilities and limitations of the approach.

Major capabilities

The following characteristics and capabilities of the proposed single-event noise modelling approach are considered as relevant:

1. Modelling at the aircraft type-level: For single-event noise modelling, aircraft are considered at an aircraft type-level rather than relying on a substitution of the fleet through a number of representative aircraft types. In this way, FANAM does not introduce modelling inaccuracies as inevitable through simplifications of the fleet.
2. Accepted modelling approach: The single-event noise modelling follows an approach suggested by ECAC Doc. 29, a well-accepted source for aircraft noise modellers. A validation of the approach is thus not necessary prior to its application within FANAM.
3. Validated aircraft database by Eurocontrol: Aircraft data, which describe actual aircraft types according to the mentioned ECAC approach, are used as published by Eurocontrol. All required aircraft-specific data is included in the validated ANP database by Eurocontrol.
4. Modelling of flight profiles by procedure steps: Aircraft-specific flight profiles are modelled by procedure steps instead of fixed-point profiles[83]. This is of advantage for FANAM, because if the method is to be applied to different airports, realistic flight profiles are computed according to the airport's specific ambient conditions.[84]
5. Reasonable assumptions for unavailable aircraft models: New aircraft types that have only entered service recently or will enter service in the near future may not have a published ANP dataset. These aircraft types are considered by FANAM

[82] In the Appendix, "ANP" denotes a native ANP dataset as published by Eurocontrol. The term "NRV-Method" refers to the proposed surrogate aircraft modelling approach, while "Substitution" indicates the substitution approach.
[83] If such profiles are included in the published ANP dataset, which is true for most aircraft types.
[84] An aircraft's particular flight profile depends on the ambient conditions (e.g. temperature, altitude).

through a surrogate aircraft approach as suggested by ECAC Doc. 29. Relevant information on the noise emission of a modelled aircraft type is used from certification noise levels as provided by the EASA[85].

Major limitations

In terms of limitations of the applied single-event noise modelling approach, one relevant characteristic needs to be highlighted:

1. Flight performance of future aircraft types based on surrogate aircraft: The applied approach states the simplification that the flight performance modelling of aircraft without published ANP dataset is identical to the flight performance of its surrogate aircraft. As a result, noise-relevant performance changes of future aircraft types, for example steeper climb procedures during departure, are not modelled by the approach.
   In the modelling of future aircraft types this simplification may be significant, in particular for possible radical aircraft designs, such as blended-wing body configurations. On the other side, its practical significance may be limited. For approaches, it is to note that in reality aircraft are usually required to approach an airport at a given, airport-specific glide-slope angle.[86] If future aircraft may be able to fly considerably steeper approach angles, these will only reduce airport noise if current ATM rules are changed. For departures, it is to note that the suggested approach considers the noise-relevant effect of different aircraft performances implicitly by using certification noise levels, which depend on an aircraft's flight performance. In other words, in addition to noise reductions purely driven by source noise reductions, improvements in climb performance are also perceived as reduced ground noise levels and consequently considered by reduced NPD levels in the future aircraft's ANP dataset.

3.4 Airport-Level Noise Modelling

The following section describes the airport-level noise modelling capabilities applied by the FANAM method. In the following, a brief introduction of the used tool is given in Section 3.4.1. Subsequently, corresponding input data relevant for future airport noise studies are discussed in Section 3.4.2, and an evaluating review of the modelling capabilities is given in Section 3.4.3.

[85] As mentioned earlier, certification noise levels are usually published a significant time before an aircraft's ANP data.
[86] At most airports, the glide-slope angle of the ILS system is 3.0 degree. Frankfurt Airport, for instance, has increased the glide slope angle of its newest runway 25/07 to 3.2 degrees (Forum Flughafen & Region, 2010).

3.4.1 The Aviation Environmental Design Tool

As previously described, based on a modelled future flight plan and the description of aircraft noise at the vehicle level, the resulting noise exposure at the airport level can be determined (see Fig. 3-1). The airport noise modelling capabilities used by FANAM are provided by the Aviation Environmental Design Tool (AEDT).[87]

The AEDT is a software by the Federal Aviation Agency (FAA) that models aircraft operations in the vicinity of airports for the purpose of aircraft noise assessments and for analysis of fuel consumption, gaseous emissions, and the resulting local air quality (Federal Aviation Administration, 2016). For the AEDT's application within FANAM, only its noise emissions capabilities are used.

With respect to noise assessments, the AEDT is the successor of the Integrated Noise Model (INM) (Roof et al., 2012). In the USA, the use of the AEDT instead of INM has become required for airport noise assessments (Federal Aviation Administration, 2016). As detailed in the AEDT's Technical Manual, the noise calculations of the AEDT are based on multiple reports formulating detailed mathematical procedures, for instance, the "SAE-AIR-1845 Procedure for the Calculation of Airplane Noise in the Vicinity of Airports" (Federal Aviation Administration, 2016; Society of Automotive Engineers, 1986). The principle approach of the AEDT is for each modelled flight to calculate the single-event noise, and to subsequently determine the multi-event noise exposure resulting from the summation of all modelled flights.

In the context of this thesis, it is relevant to introduce the definition and set-up of AEDT studies that are to be calculated. Herein, a significant difference can be found compared to the approach of the INM. In INM, studies are defined through the import of multiple input files, which are specified in cumbersome dBase database files (.dbf) (Federal Aviation Administration, 2008). Contrary to this, the AEDT allows input data to be read in an improved, more user-friendly way, leaving the user two different options:

1. Study definition through the AEDT's graphical user interface
2. Study definition through AEDT Standard Input Files

The first option is to define a specific study inside the AEDT through a graphical user interface, where the user defines, for instance, the airport's flight route geometries or the number of flight movements for different aircraft types on a given route. The second option offered by the AEDT is the definition of an *AEDT Standard Input File (ASIF)*, which contains all required information to define an entire AEDT study in a single file. ASIFs are based on the XML[88] file format, which is a text-based file format that can be easily read by both humans and computers (Federal Aviation Administration, 2015).

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[87] The version used in this thesis is AEDT 2b (service pack 2).
[88] For *Extensible Markup Language*.

For FANAM, it is decided to define all noise studies through ASIFs. This is of advantage, because the XML-based ASIFs may be generated computationally, thus principally allowing the automation of AEDT study definitions. Consequently, by using ASIFs the set-up time of AEDT simulations may be reduced drastically, as simulations may be defined by loading a single ASIF into the AEDT instead of manually defining simulations through the GUI. An automated generation of ASIFs is of particular interest if many different noise studies are to be defined, which may be the case during the application of FANAM for the purpose of impact assessments. An exemplary excerpt of an ASIF, which represents the geometrical definition of a modelled flight route[89], is shown in Fig. 3-15.

```
<!-- This is the example of a track geometry definition -->
<track>
   <name>SID_example</name>
   <optype>D</optype>
   <wingtype>F</wingtype>
   <runway>09L</runway>
   <subtrack>
       <id>1</id>
       <dispersionWeight>1.0</dispersionWeight>
       <trackVectors>
       <trackVector>
           <type>S</type>
           <distance>34800</distance>
       </trackVector>
       <trackVector>
           <type>L</type>
           <angle>92</angle>
           <radius>12500</radius>
       </trackVector>
       <trackVector>
           <type>S</type>
           <distance>70700</distance>
       </trackVector>
       </trackVectors>
   </subtrack>
</track>
```

Fig. 3-15 Excerpt of an XML-based AEDT Standard Input File presenting the definition of an exemplary SID route

It is to note that the AEDT actually does not allow to calculate the DEN. However, the AEDT is able to quantify airport noise in a relatively uncommon metric called the CNEL (Community Noise Equivalent Level). While the CNEL's penalty of noise events during the night is identical to the DEN penalty (10 dB), the CNEL's penalty of noise events during the evening is 4.78 dB instead of 5 dB, and thus slightly lower (Jones and Cadoux, 2009). According to the FAA, this small difference is assumed to have no practical consequence in the simulation of DEN levels (Federal Aviation Administration, 2008).[90] In particular, this difference can be regarded as irrelevant for relative comparisons between different scenarios.

[89] In the nomenclature of the AEDT, a flight route is called *track*.
[90] Note that in the application case (Chapter 4), the presented DEN levels have been originally calculated in the metric CNEL.

3.4.2 Airport-Specific Input Definition

FANAM defines significant information required for the estimation of an airport's future noise exposure through the future flight plan as result of the FFEA (see Section 3.2). However, further significant information is not defined through the FFEA, but within the airport noise modelling area. An overview of the additionally required, airport-specific characteristics is presented in Tab. 3-9. As found in the table, information on the airport's runway system, its arrival and departure routes, its ambient conditions, and the applied noise receptor grid are defined. Whereas the first three parameters of the table are characteristics that physically describe the airport, the fourth parameter is a computational characteristic required to define a particular noise simulation. Each of the four parameters is briefly explained as followed.

Tab. 3-9 Required airport-specific input data to be defined by the user

Information on	*Number of elements in the ASIF*	*Specification of the following characteristics*
Runway system	*one per runway*	*runway end positions (latitude, longitude, elevation)*
Arrival/departure routes	*one per flight route*	*ground tracks consisting of several segments (straight or curve) quantified by segment length or curve radius/angle*
Ambient conditions	*one*	*average temperature, pressure, humidity, wind speed, wind direction*
Noise receptor grid	*at least one*	*position (latitude, longitude), dimensions and resolution of grid (number of and distance between receptor points)*

First of all, as seen in Tab. 3-9, the airport's *runway system* is defined. Therein, each runway to be modelled is specified by its two runway ends through the definition of the coordinates (latitude/longitude) and elevation (above sea level) of the runway end.

Secondly, the *arrival and departure routes* are defined, which specify the particular ground track of a flight. In this, each modelled track is determined by a combination of straight and curved segments. For departure routes, so-called *vector tracks* are used, which specify the according distance of a straight segment, and the turn radius and turn angle in case of a curved segment[91]. For arrival routes, *point tracks* are used, which define a track through coordinates. In an ASIF, each track definition is subsequently followed by a specification of all flight movements using the particular track.

Thirdly, the airport's average *ambient conditions* are defined. For this, the modelled temperature is specified as well as the pressure, the relative humidity, the wind speed, and the

[91] E.g., the track specified by Fig. 3-15 consists of two straight segments and a turn in between.

modelled wind direction at the studied airport. Information on the environmental conditions at the airport are used to determine the airport-specific flight profiles (see Section 3.3.1) and to allow the AEDT the definition of local acoustic propagation characteristics, for instance the atmospheric absorption.

Lastly, a rectangular *noise receptor grid* is specified. During the noise simulations, the AEDT calculates the noise levels at each receptor point of the receptor grid. For this purpose, one corner of the receptor grid is defined by its coordinates (latitude/longitude). Additionally, the grid's width and height as well as its resolution is specified by the number of receptor points and by the according distance between two receptor points. Depending on the desired quality of the noise simulations results, the receptor grid may be defined finer or coarser by the user.

3.4.3 Review & Summary

The following section briefly discusses the capabilities and limitations of the airport-level noise capabilities applied by FANAM.

Major capabilities

In terms of capabilities, two advantageous characteristics are considered as relevant for the scope of this thesis:

1. Accepted modelling approach: FANAM relies on the modelling capabilities of the AEDT, which is the FAA's official successor of the widely accepted airport noise modelling software INM. The INM has been used in more than 65 countries both within aviation industry and research (Federal Aviation Administration, 2008). The airport noise modelling approach in this thesis can therefore be regarded as accepted and reliable. A validation of the airport noise modelling capabilities used by FANAM is not necessary.
2. Automation efforts simplified: Because, in contrast to the INM, the AEDT allows the definition of airport noise studies by a single XML-based file, an automation in the definition of AEDT studies principally is simplified. This advantage is used by FANAM through the automated generation of AEDT Standard Input Files as further described in Section 3.5.

Major limitations

The noise calculation results of FANAM obviously are subject to the modelling accuracy of the AEDT. The following simplification may introduce differences between the simulation noise levels and measured real noise levels at an airport:

1. Utilisation of inflexible flight routes: The geometry of the flight routes modelled by the AEDT is independent of current traffic conditions at the airport and is thus applied to all modelled flights alike. In reality, aircraft may not follow the ground

track as specified by a published SID or STAR. As of departures, aircraft usually follow the assigned SID up to a specific altitude, where, after permission by the air traffic controller, aircraft are allowed to leave the SID. With respect to arrivals, in the same way, air traffic controllers may redefine the particular route of an arriving aircraft, for instance, in periods of lower air traffic to allow shorter routes than those defined by STARs.

As the described effect generally only occurs above certain flight altitudes, this modelling inaccuracy is mainly of significance for areas exposed to lower noise levels farther from the airport. Whereas the discussed inaccuracies may locally be noticeable[92], they are considered as of low significance for the purpose of multi-event impact studies assessed at the airport level[93].

3.5 Implementation

In this section, a brief description of the implementation of the previously introduced methods is given. The resulting tool is able to generate complete AEDT standard input files that define an airport noise simulation based on user-defined input data.

The main goal of this research, as mentioned earlier, is the theoretical development of methods and the practical implementation of according tools for the purpose of future airport noise studies. To model future flight plans the Future Flight Plan Estimation Approach (FFEA) has been designed as introduced in Section 3.2. Based on the FFEA the Future Flight Plan Development Tool (FFDT) is developed, which practically implements the methods defined by the FFEA. Moreover, the FFDT generates an entire AEDT Standard Input File including all required information concerning the aircraft level and the airport level of a study. This ASIF then fully defines an AEDT airport noise simulation. In summary, the two tasks of the FFDT are:

1. To calculate a future flight plan depending on user-defined airport- and scenario-specific input and according to the method defined by the FFEA
2. To generate a complete ASIF based on the calculated future flight plan and based on required aircraft-level and airport-level information

The structure of an according ASIF, representing the ultimate output of the FFDT, is presented in Fig. 3-16. As can be seen, the ASIF consists of five different parts that define relevant characteristics of a specific airport noise study. Firstly, the airport's runway system is specified as described in Section 3.4. Secondly, the applied noise receptor grid is defined as also described in Section 3.4. Thirdly, all aircraft types modelled according to the surrogate aircraft approach, as suggested by Section 3.3, are defined. Fourthly, the air-

[92] Of course, this is mainly relevant for single-event noise levels.
[93] Noise exposure at the airport level is usually quantified by the area enclosed by a given isophone.

port's ambient conditions are defined as detailed in Section 3.4. Finally, the aircraft movements at the study airport are defined. As can be seen from Fig. 3-16 the track geometry is defined for each modelled flight track. Each track definition is then followed by the quantification of operations of a specific aircraft type at a given hour of the day. With this information, an entire AEDT study is sufficiently defined.

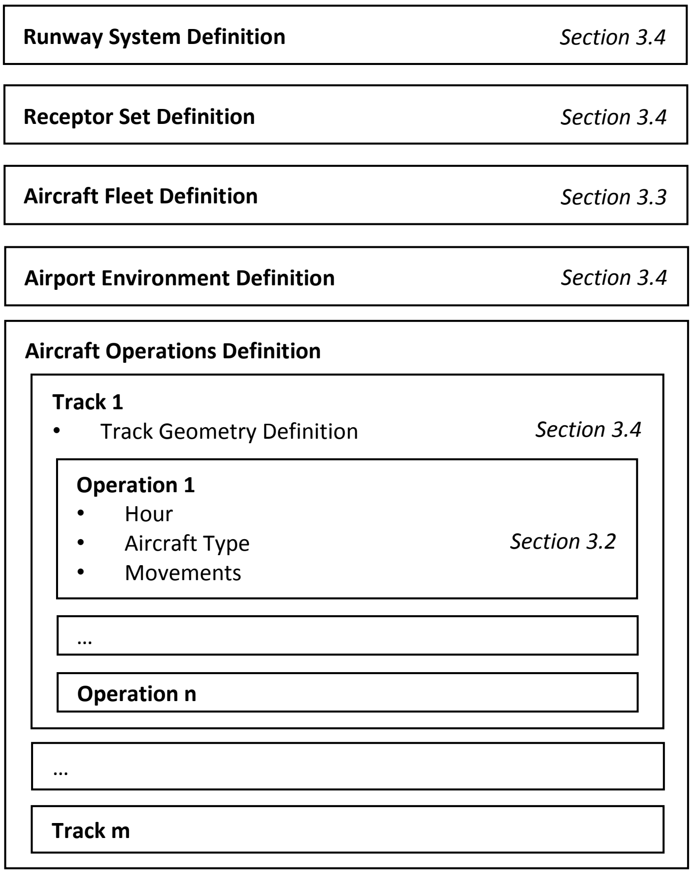

Fig. 3-16 Definition of an airport noise simulation through an AEDT standard input file (ASIF)

The fundamental FANAM workflow is illustrated in Fig. 3-17. As can be seen, firstly, preprocessing steps are required to transfer an underlying flight plan source to the flight plan structure used by the FFDT. Furthermore, all input data for the scenario of interest need to be defined. From this, the FFDT calculates a future flight plan according to the method defined by the FFEA and based on the user-defined scenario input. Furthermore, the FFDT generates an ASIF according to the structure presented in Fig. 3-16. Note that in the ASIF the same operating time is assigned to all movements within one period of the day in order to speed up the AEDT simulations.[94] The implementation of the FFDT is realised through the programming language MATLAB. Scenario-specific input data may be specified in separate input tables, for instance with Microsoft Excel, which are then read by the FFDT.

[94] 11:00 am for 'day', 8:00 pm for 'evening', 1:00 am for 'night' operations.

The generated ASIF is then loaded into the AEDT, and the according airport noise simulation is undertaken. Finally, in post-processing steps, the model results are evaluated and visualised.

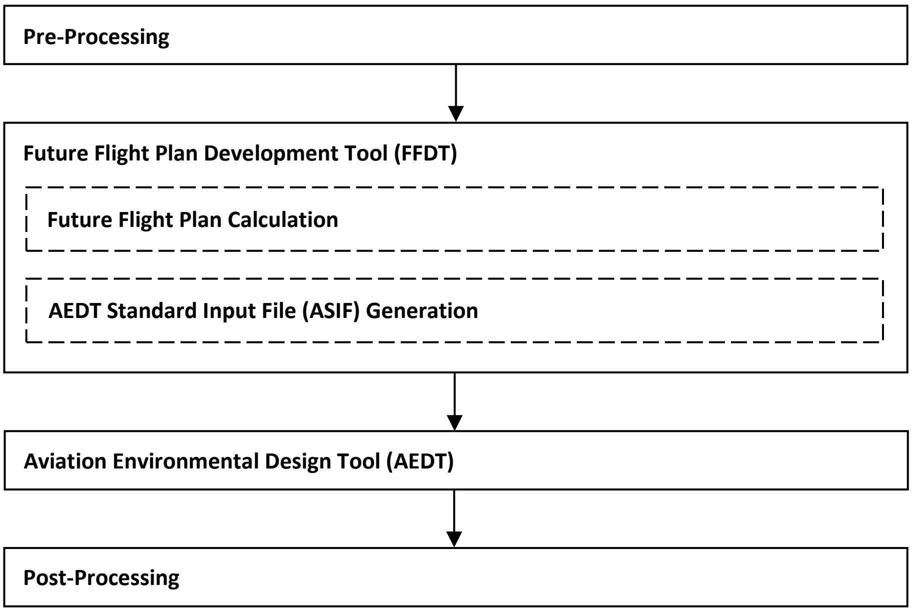

Fig. 3-17 Overview of the fundamental FANAM workflow

3.6 Validation

This section presents a validation of the developed Future Flight Plan Development Tool. For this purpose, FFDT simulations are conducted and the results are compared to reference data of a real airport.

3.6.1 Validation Approach

The objective of the validation is two-fold. Firstly, the validation simulations shall prove the overall functionality of the implemented FFDT. Secondly, the validation shall offer insights into the accuracy of the simulation results.[95] For this, the FFDT is used to model a future flight plan of the target year 2016 based on the baseline year 2008 (Will et al., 2017b). A period of eight already past years is selected, because for this time period, real-world data are available at the Institute that allow a detailed comparison of the simulation results with historic data.

[95] Note that, since the FFDT primarily is a scenario-based tool, simulation result accuracies obviously depend on the accuracy of the scenario-specific input data.

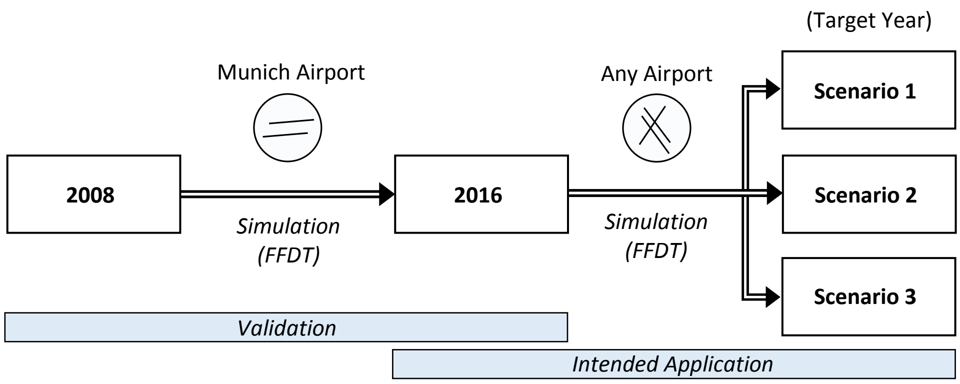

Fig. 3-18 The FFDT validation approach

As mentioned earlier, the FFDT is developed for the intend of impact assessments, hence, for the quantification of relative differences between future scenarios as visualised by Fig. 3-18. During the validation simulations of Section 3.6, on the contrary, the FFDT results are compared to absolute, real-world numbers. Possible deviations between validation results and real-world data therefore do not prohibit the FFDT to be used for impact assessments.

As reference airport for the validation simulations, Munich Airport[96] is selected, which is an international airport with a typical, parallel two-runway system. For Munich Airport, historic data describing the airport's real operations between 2008 and 2016 are available from two different sources. Firstly, official publications of Munich Airport's operator, the FMG, are used in the following (Flughafen München GmbH, 2009-2016). Additionally, for more detailed insights, OAG flight plan data of the year 2008 and 2016 are used (OAG Worldwide Limited, 2016, 2008).

3.6.2 Scenario Definition

In the following, the scenario inputs of the Validation Case are presented. For further background on the structure and content of the input data required by the FFDT, please refer to Sections 3.2 and 3.5.

Baseline flight plan:

As suggested by Section 3.2.3, the 2008 baseline flight plan of Munich Airport is obtained from the OAG database (OAG Worldwide Limited, 2008). Note that, rather than using the months January to December 2008, the months November 2007 to October 2008 are used due to data availability at the Institute. Following Section 3.2.3, the aircraft operations including Munich Airport are selected from the database and, from this, a corresponding flight plan of equivalent noise events is derived.

[96] ICAO code: EDDM.

Air traffic growth input:

Two different cases are simulated with respect to air traffic growth, which differ in the air traffic growth input assumptions as followed.

Firstly, air traffic growth rates as specified by the Airbus Global Market Forecast 2009 are applied for the modelled future years 2009 to 2016 (Airbus, 2009).[97] Since Munich Airport is assigned to the world region 'Western Europe' the world region-pair specific growth rates including 'Western Europe' are applied.

Secondly, historic, real growth rates of Munich Airport are used as model input according to published numbers by the FMG (Flughafen München GmbH, 2009-2016). The required transport capacity growth rates is derived from numbers on seat load factors and passenger numbers as presented in Tab. 3-10. Note that the historic numbers are only given for total passenger numbers and not further detailed into specific world regions. Thus, in the case of historic growth rates, air traffic growth is applied equally to all operations of the baseline flight plan. (2017)

Tab. 3-10 Historic seat load factors (SLF) and passenger numbers (PAX) of Munich Airport serving as input for the Validation Case based on historic traffic growth rates (Flughafen München GmbH, 2009-2016)

Year	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*
SLF	*72.8%*	*71.5%*	*73.8%*	*73.7%*	*74.5%*	*75.2%*	*75.9%*	*76.6%*	*75.1%*
PAX (in Mio.)	*34.5*	*32.7*	*34.7*	*37.8*	*38.4*	*38.7*	*39.7*	*41.0*	*42.3*

Aircraft retirement input:

As discussed in Section 3.2.5, the FFDT assumes the aircraft retirement curves to remain unchanged in the future. Consequently, in the Validation Case, the retirement curves remain unchanged, too.[98] On the contrary, the aircraft age distributions depend on the particular baseline year of a simulation. As mentioned earlier, all age distributions derived in Section 3.2.5 represent the point in time 2016 since the FFDT's intended applications of future scenarios are based on the year 2016 (see Fig. 3-18). For the purpose of the Validation Case, yet, the age distributions of aircraft types present in the 2008 baseline flight plan are re-evaluated according to the approach introduced by Section 3.2.5.

[97] As analysed by Wunderlich (2017). As discussed in Section 3.2.4 the Airbus GMF's growth rates (given in RPK) are applied as growth rates in AS under the assumption of constant flight distances between the different world regions.
[98] As originally derived by Randt (see Section 3.2.5).

Aircraft introduction input:

The aircraft introduction input of the Validation Case is defined according to the aircraft introduction reference scenario as introduced in Section 3.2.10. Since in the validation simulations, aircraft are introduced from the year 2008 on, OEM backlog numbers are re-analysed for the point in time 2008 following the approach proposed by Section 3.2.10 (Airbus, 2017a; Boeing, 2018; Bombardier, 2018; Embraer, 2018).[99] A list of all aircraft types introduced by the Aircraft Introduction Module in the Validation Case is provided in Tab. 3-11. The according introduction shares as defined by the swap factors are illustrated in the Appendix A.

Tab. 3-11 Aircraft types considered for aircraft introduction by the Validation Case

OEM	*Aircraft type (narrow-body)*	*OEM*	*Aircraft type (wide-body)*
Airbus	*A319*	*Airbus*	*A330-200*
Airbus	*A320*	*Airbus*	*A330-300*
Airbus	*A321*	*Airbus*	*A350-900*
Boeing	*737-800*	*Airbus*	*A380-800*
Bombardier	*DH4*	*Boeing*	*747-8*
Embraer	*E190*	*Boeing*	*777-200LR*
		Boeing	*777-300ER*
		Boeing	*787-8*
		Boeing	*787-9*

Airport capacity input:

Following the actual capacity of Munich Airport, a maximum airport throughput of 90 movements per hour is applied during validation simulations (Regierung von Oberbayern, 2011).

Route allocation input:

As input for the Route Allocation Module, the Validation Case assumes a distribution of 40% easterly operations (operating direction 08) to 60% westerly operations (operating direction 26).

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99 Evaluation date is 31st December 2008 for Airbus and Boeing aircraft, which make up for the majority of aircraft introduced. For Bombardier and Embraer aircraft, published backlog numbers were only available for a slightly later point in time (31st January 2009 for Bombardier, 31st March 2010 for Embraer aircraft). The according influence on the resulting aircraft introduction shares is expected to be minor.

3.6.3 Validation Results

Following the approach depicted by Fig. 3-18, the FFDT is used to model the future flight plan evolution up to the year 2016 based on the 2008 baseline flight plan and based on the input data specified by the previous section. The simulation results are presented in the following, alongside with a comparison of real, historic data of Munich Airport.

The evolution of transport capacity (in AS) is presented in Fig. 3-19 for the period 2008 to 2016. The first bar (light blue) represents the real transport capacity as derived from FMG's publications. The further two colours (darker blue) visualise the FFDT simulation results. While the second bar represents model results based on real, historic growth rates, the third bar represents model results based on Airbus GMF growth rates (see Section 3.6.2). Note that all other input data is identical between the two FFDT simulations.

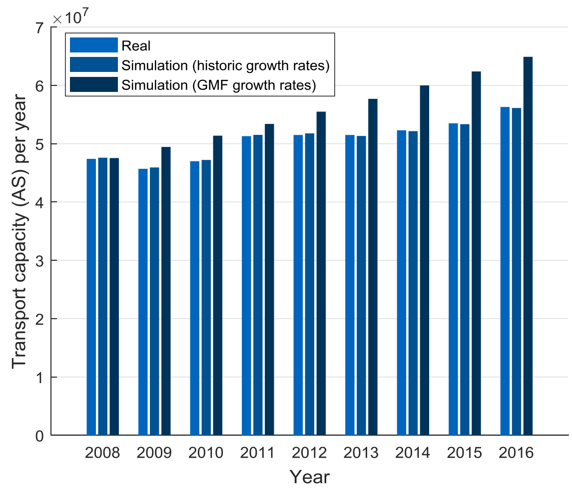

Fig. 3-19 Validation Case: Modelled evolution of transport capacity

As seen in Fig. 3-19, the simulation based on GMF growth rates shows a continuous growth of transport capacity, which is reasonable according to the positive traffic growth rates assumed by the GMF. Contrary to this, the simulations based on historic growth rates do not represent a continuous growth, as seen by the considerable drop in transport capacity in the first modelled year 2009. The simulation results based on historic growth rates follow the real data well, which is reasonable, because real traffic growth rates are used as model input.[100] The results shown in Fig. 3-19 thus demonstrate the FFDT's capabilities to take into account effects resulting from different air traffic growth scenarios on future flight plan evolution, and, ultimately, in the FANAM approach on future airport noise.

[100] At this point the before-mentioned limitation concerning negative traffic growth rates (see Sections 3.2.4 and 3.2.6) is noticeable. Through a minor modification of the original FFDT implementation, the FFDT is able to correctly process negative growth rates in the first modelled year (traffic growth model input 2009: -3.5%). In subsequent years, however, negative growth rates still introduce errors in the modelled transport capacity, which can be observed for the negative growth in the year 2013 (traffic growth model input 2013: -0.2%). As stated before, for airport noise impact assessments this limitation is of minor importance, as air traffic on the long-term is expected to grow significantly.

For the results of the validation simulations, transport capacity shares according to the FFDT's different world regions are shown in Fig. 3-20. Therein, real data for the years 2008 and 2016 are presented as evaluated from OAG data (top left and bottom left). Additionally, the FFDT results based on historic growth rates (top right) and based on GMF growth rates (bottom right) are shown.

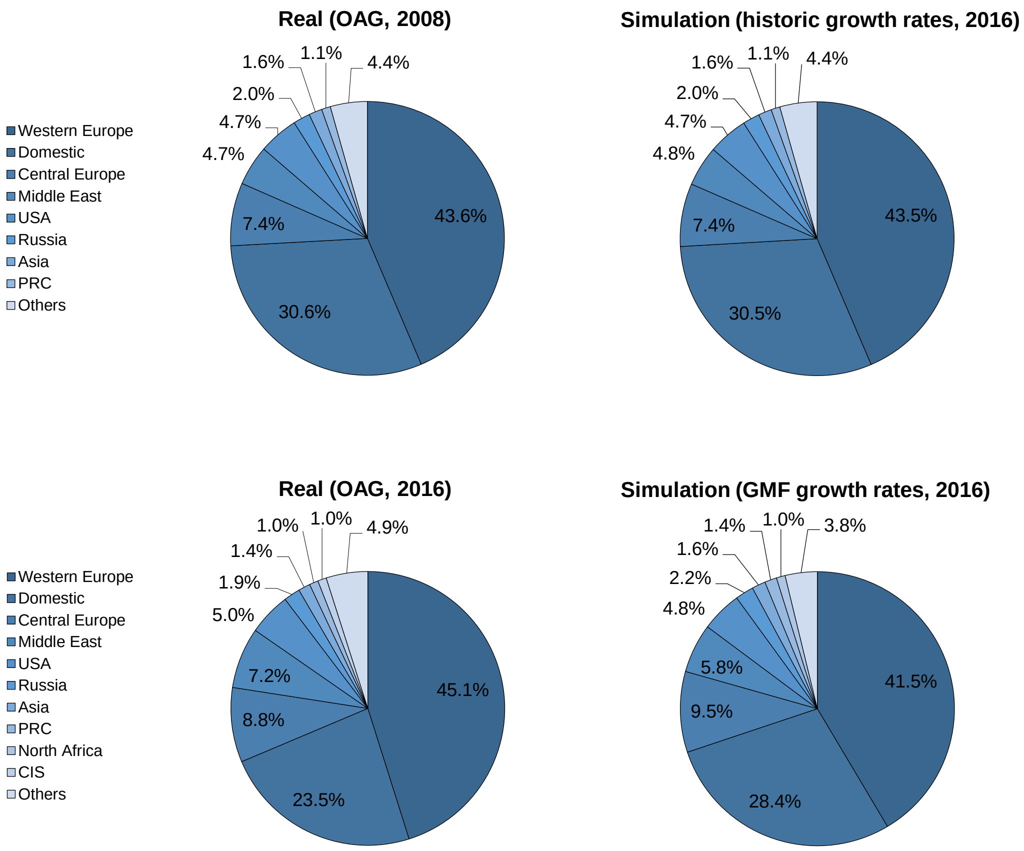

Fig. 3-20 Validation Case: Transport capacity shares according to world regions

The FFDT results for the year 2016 based on historic growth rates show transport capacity shares practically identical to the real shares of the year 2008. This is to be expected, because in this scenario, air traffic growth is assumed to be distributed identically over all world regions (see Section 3.6.2), hence, the relative shares remain unchanged. The FFDT simulation based on Airbus GMF growth rates shows different transport capacity shares compared to the real shares of 2008. While the shares of 'Western Europe' and 'Domestic' (Germany) decline, the share of other world regions increases, following the traffic growth assumptions of the Airbus GMF. As seen, the GMF-based simulation results deviate from the real shares (according to 2016 OAG data), too, which reveals the differences in the regional distribution of air traffic growth between the Airbus GMF assumptions and the actual, historic traffic growth.

The evolution of aircraft movement numbers is visualised in Fig. 3-21. In the same way as in Fig. 3-19, the figure presents real aircraft movement numbers according to FMG publications (first bar). Also, it shows the simulation results based on historic growth rates (second bar) and based on Airbus GMF growth rates (third bar).

Similarly, as seen for transport capacity, the aircraft movement simulations based on the Airbus GMF growth rates show a continuous increase from 2008 to 2016. On the contrary, the simulations based on historic growth rates as well as the real aircraft movements show numbers significantly below the GMF based simulations. Additionally, a deviation between the simulations based on historic growth rates and real movement numbers can be observed, which increases with ongoing years.

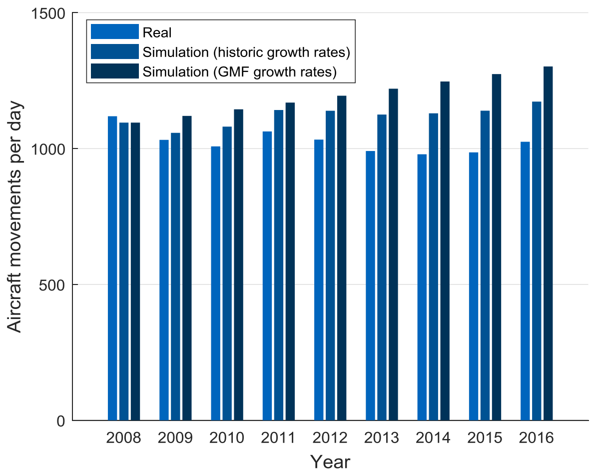

Fig. 3-21 Validation Case: Modelled evolution of aircraft movement numbers

In the discussion of the observed aircraft movement numbers as presented in Fig. 3-21 the following can be stated:

1. The deviations between real data and simulation data already present in the baseline year 2008 originate from different data sources. Whereas the FFDT simulations are based on the 2008 OAG flight plan, which contains only scheduled flights, the real movement numbers as published by the FMG contain actually operated flights.[101]
2. The deviations between real data and the simulations based on historic growth rates are caused by deviations in the particular fleet mix supplying the required transport capacity. On the one hand, due to the “one world airline” approach (see Section 3.2.1), the world fleet behaviour is assumed by the FFDT simulations with respect to fleet turnover.[102] On the other hand, the real movement numbers are a

[101] The published FMG numbers additionally contain freighter and postal flights. Furthermore, the OAG data are based on the months November 2007 to October 2008 rather than January 2008 to December 2008 (see Section 3.6.2).
[102] The world fleet behaviour is assumed for both future aircraft retirement (Section 3.2.5) and future aircraft introduction (Section 3.2.10).

result of the actual fleet behaviour at Munich Airport, which includes deviations compared to the world fleet behaviour. In reality, the required transport capacity at Munich Airport was generally provided by larger aircraft compared to the FFDT simulation as analysed in more detail in the following (see Fig. 3-22). As result of, on average, larger aircraft, less aircraft movements than modelled by the FFDT were required to provide the traffic demand.

3. The general evolution of modelled aircraft movement numbers is plausible following the underlying transport capacities (see Fig. 3-19).

Fig. 3-22 presents an overview of aircraft seat capacities of the FFDT simulations for the year 2016. In addition, it shows real seat capacity numbers of Munich Airport for the years 2008 and 2016 as evaluated from OAG data. The seat capacities are averaged across movement numbers. As seen, the real aircraft seat capacity for the year 2008 (119 seats) is below all numbers for the year 2016. Comparing the FFDT results, the simulations based on GMF growth rates show larger aircraft seat capacity (137 seats) than the simulations based on historic growth rates (131 seats). The real Munich Airport seat capacity average is still significantly larger than the simulation results (154 seats).

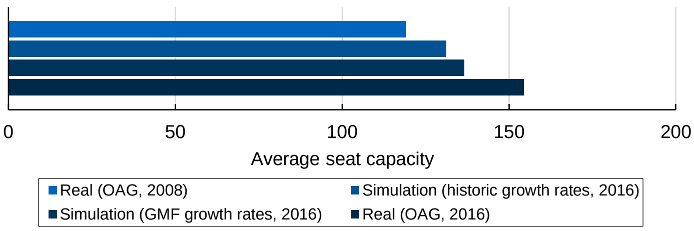

Fig. 3-22 Validation Case: Average aircraft seat capacity

In the discussion of the average aircraft seat capacity numbers the following observations and conclusions can be made:

1. Generally, according to Fig. 3-22 at Munich Airport, from 2008 to 2016, average aircraft seat capacities increased. This is caused by the fact that over time, on average, larger aircraft are operated at the airport. A further reason may be found in a tendency towards denser seating within given aircraft types.
2. The FFDT simulations based on GMF growth rates lead to higher seat capacities in 2016 than the simulations based on historic seat capacities, because the larger air traffic growth requires more aircraft to be introduced to the fleet (see Fig. 3-19).[103]
3. The numbers presented by Fig. 3-22 indicate that, in reality, between 2008 and 2016, the seat capacity of the real fleet operating at Munich Airport has increased disproportionately large compared to the world fleet behaviour[104]. This temporary,

[103] Aircraft entering the fleet in future years as specified by the aircraft introduction reference scenario (see Section 3.2.10) on average have higher seat capacities than aircraft present in the baseline fleet.

[104] Interestingly, these effects have also been discussed in debates over a possible third runway of Munich Airport.

particularly strong increase in average aircraft seat capacity is confirmed, for instance, by FMG publications, describing the change of Lufthansa's regional fleet from smaller propeller aircraft to larger jet aircraft (Flughafen München GmbH, 2009). During the considered time period, Lufthansa[105], the largest operator at Munich Airport, replaced comparatively small propeller aircraft (e.g. ATR 42, capacity of around 50 seats) with the Embraer ERJ195, having a seat capacities of over 100 (Flughafen München GmbH, 2009). According to evaluations of the OAG flight plans, for instance, the share of ATR 42 aircraft decreased from ca. 4% in 2008 to 0% in 2016.[106] Simultaneously, according to OAG data, the share of ERJ195 aircraft rose from 0% in 2008 to ca. 15% in 2016.

4. Consequently, since the FFDT does not take into account individual airlines' fleet strategies and rather relies on the modelling of the average world fleet behaviour, average aircraft seat capacities of FFDT simulations remain below the real numbers.
5. From the underestimation of aircraft seat capacity growth, it is also plausible why the FFDT simulations overestimate the aircraft movement numbers (see Fig. 3-21) compared to real movement numbers at Munich Airport.

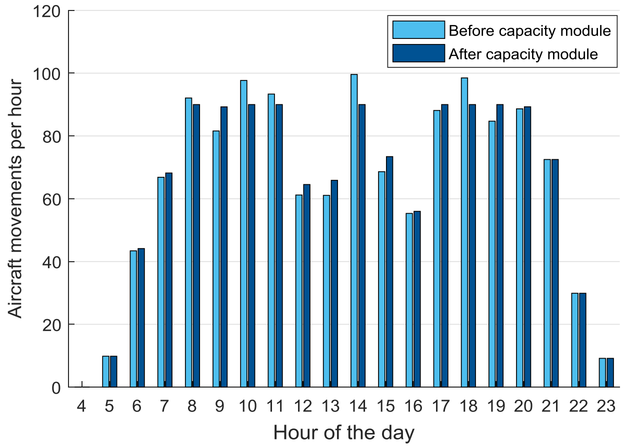

Fig. 3-23 Validation Case based on Airbus GMF traffic growth rates: Effect of the airport capacity module in 2016

At last, the results of the FFDT's Airport Capacity Module (see Section 3.2.8) are analysed from Fig. 3-23. The chart shows the hourly distribution of aircraft movement numbers of the simulated flight plan for the year 2016 based on Airbus GMF growth rates. In lighter blue, the flight plan prior to the Airport Capacity Module is shown, in darker blue, the flight plan after the according shifting of flight movements by the module. As seen, for five hours, the specified maximum airport throughput of 90 movements per hour is reached. The distribution after movement shifting shows that excess flight movements are shifted, as intended, to both sides of the specific peak. As desired, the resulting flight plan thus

[105] Precisely, Lufthansa CityLine and the associated airlines Augsburg Airways and Air Dolomiti.
[106] Similarly, from 2008 to 2016, according to OAG data the share of ATR 72 aircraft decreased from ca. 5% to 0%, and the share of Dash 8 aircraft from ca. 4% to 1%.

remains within the specified airport capacity limits during all hours of the day. Note that in the example of Fig. 3-23, hardly any shifting relevant to DEN levels occurs as only a minor number of aircraft movements is moved beyond the limits of the original period of day[107].

During numerous testing simulations, as exemplarily presented by the Validation Case, the FFDT has proven to be a reliable tool in the modelling of future flight plans (Kalsi, 2018). As a summary of Chapter 3, it can thus be stated that the FFDT can be regarded as an adequate instrument for future airport noise assessments.

[107] The respective periods begin, as mentioned, at 7 am (day), 7 pm (evening), and 11 pm (night).

4 Application Case

In Chapter 4, the previously developed methods are applied to a specific airport. The purpose of this chapter is to demonstrate the principle capabilities of the FANAM approach[108]. The study airport, to which the approach is applied, is briefly introduced in Section 4.1. The simulation of several relevant scenarios is presented in Sections 4.2 to 4.8. A discussion of the scenario-specific findings is then given in Section 4.9. A general evaluation of the FANAM approach in Section 4.10 concludes the chapter.

4.1 Definition of a Study Airport

As study airport, a generic airport developed in a term thesis by Mayrhofer is used (Mayrhofer, 2017). Based on a previous airport analysis by Öttl, Mayrhofer derived a specific airport infrastructure for airport-level noise studies. According to Öttl's cluster analysis of the 100 largest airports worldwide, an operational case using two runway is the most representative (Öttl, 2014). From the clusters derived by Öttl, the specific airport cluster characterised by two parallel runways operated with a mixed runway usage is selected[109]. Through averaging runway layout and flight route characteristics of the actual airports contained within the selected cluster, a representative airport geometry is derived. The resulting airport runway layout is illustrated in Fig. 4-1. As seen, the airport's parallel runways 09L/27R and 09R/27L are aligned in easterly/westerly direction. Both runways are ca. 3.4 km long, laterally separated by ca. 1.8 km, and offset by ca. 1.0 km (Mayrhofer, 2017).

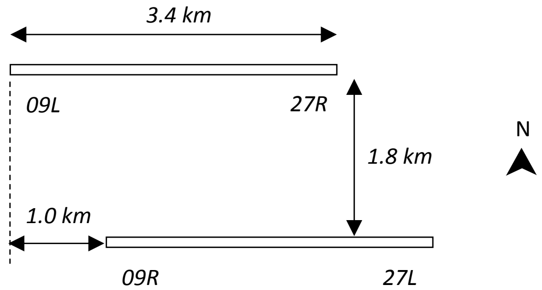

Fig. 4-1 Study Airport Runway System

[108] As such, obviously not all questions of interest that could be studied with the FANAM approach are examined.
[109] Cluster 8 according to Öttl's analysis.

Concerning flight routes at the study airport, altogether four arrival routes and eight departure routes are modelled (see also Fig. 4-2). The STARs are modelled as straight segments in the extension of the runways. As of SIDs, one straight and one curved departure route is modelled per runway end. Therein, the curved SIDs consist of an initial straight segment of ca. 7 km, followed by a 92° turn away from the airport's centreline and, subsequently, followed by another straight segment. Following the definition of the STARs and SIDs, four different exit point (*North*, *East*, *South*, *West*) used for departures, and two entry points (*North*, *South*) used for approaches are defined at the study airport (Mayrhofer, 2017).

In order to base the calculations on a flight plan as realistic as possible, a real airport's flight plan is used. For this, in accordance with the generic airport's parallel two-runway system, the application case uses actual flight plans of Munich Airport as baseline flight plans. Aircraft operations of the original Munich Airport flight plan are assigned to one of the generic airport's exit and entry points depending on the original direction of the corresponding arrival or origin airport[110] (Mayrhofer, 2017). The study airport consequently is assigned to the world region 'Western Europe'.

Note that the simulation results of this study airport cannot be interpreted as simulations of Munich Airport given the differences in geometrical[111] and operational[112] airport characteristics. Also, note that the FANAM approach may be applied to any given airport. As detailed in Chapter 3, FANAM is able to process both arbitrary airport geometries and arbitrary baseline flight plans. For demonstration purposes, a generic airport representing a typical international two-runway hub-and-spoke airport is studied in the following.

4.2 Status Quo Case

In this section, a *Status Quo Case* describing the baseline year 2016 is presented. The Status Quo Case will serve as useful reference in the interpretation of the modelled results of future years.

4.2.1 Simulation Input

For the Status Quo Case, no FFDT simulations are necessary, thus no FFDT inputs need to be specified. Rather, the baseline flight plan can be used straightforwardly to calculate airport noise exposure using the simulation capabilities introduced in Section 3.4. For this, as described by Section 3.2.3, a baseline flight plan for Munich Airport is extracted from the OAG database 2016 (OAG Worldwide Limited, 2016). As share of the two operating

[110] For arrivals: 270° to 90° assigned to arrival point *North*, 90° to 270° assigned to arrival point *South*.
For departures: 315° to 45°/45° to 135°/135° to 225°/225° to 315° assigned to exit points *North*/*East*/*South*/*West*.
[111] For instance, flight route geometries.
[112] For instance, as in the Reference Case (see Section 4.3), route distribution.

directions, a distribution of 40% easterly operations (direction 09) to 60% westerly operations (direction 27) is specified. In the assignment of exit and entry points to a specific runway end it is assumed that all flights to/from the exit/entry point *North* are operated via the northern runway 09L/27R. Vice versa, all flights to/from the exit/entry point *South* are operated via the southern runway 09R/27L. Flights departing via the exit points *East* and *West* are distributed evenly over the southern and the northern runway. With respect to the airport noise simulations a rectangular noise receptor grid of 510 x 220 receptor points distributed over an area of 51 NM x 22 NM[113] is applied.

4.2.2 Simulation Results

The airport noise simulations are based on a flight plan of an annual transport capacity of 58.3 Million AS. This transport capacity is provided by 1030 flights per day, consisting of 515 daily inbound and 515 outbound flights. In total, 91% of aircraft movements are attributed to narrow-body aircraft, while the remaining 9% consist of wide-body aircraft.

The visualised airport noise contours as simulated using the AEDT are presented in Fig. 4-2. Illustrated are the calculated DEN noise contours, which represent closed lines of constant DEN levels, from 45 dB up to 70 dB in steps of 5 dB. In the figure, ground tracks of the SIDs are depicted in grey, ground tracks of the STARs in red. As seen, the orientation of the major noise contour lobes lies in east-west direction as result of the according runway orientation. Furthermore, noise contour lobes are found underneath the curved SIDs representing departures to southern and northern directions.

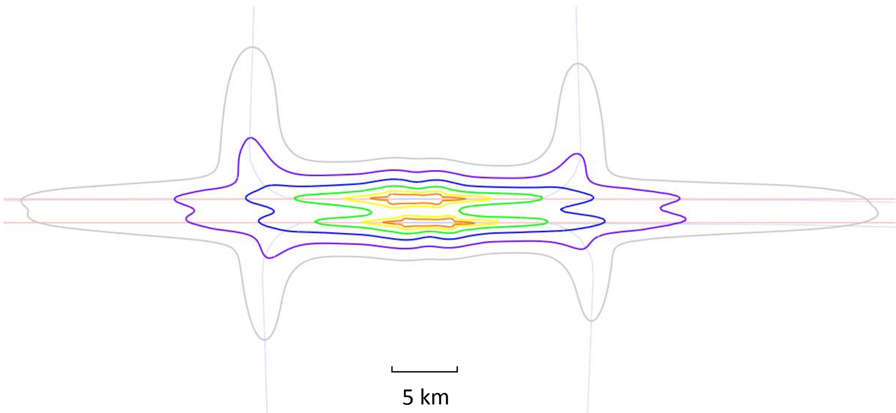

Fig. 4-2 Status Quo Case: DEN noise contours from 45 dB to 70 dB (in 5 dB steps)

For a quantitative assessment of airport noise, the area included by a given noise contour is specified. Note that the “Upper Noise Limit“[114] introduced at Frankfurt Airport in 2017 is also defined by noise contour areas (Hessisches Ministerium für Wirtschaft, Energie, Verkehr und Landesentwicklung, 2017). In the following analyses, primarily the 55 dB and the 65 dB noise contours are assessed. The Status Quo Case is characterised by a 55 dB

[113] The noise receptor grid is aligned in east-west direction according to the layout of the runway system and the resulting noise contours.
[114] In German “Lärmobergrenze”.

noise contour area of 93.7 km^2 and by a 65 dB noise contour area of 15.1 km^2. For the scenarios modelled in subsequent sections, the relative change in noise contour area compared to the Status Quo Case will be a useful indication of the development of airport noise exposure.

4.3 Reference Case

In the following section, a *Reference Case* is presented that models future airport noise up to the year 2040. The purpose of this case is to project a realistic behaviour of airport noise exposure into the future, which serves as baseline scenario in the evaluation of the subsequent cases. The underlying question is significant and can be posed as followed: At the study airport, how will future airport noise evolve over time for the stated input assumptions? In particular, it can be asked: Will the increased air traffic volume worsen the situation? Or can improved aircraft technology entering service in future years outweigh the effect of air traffic growth? In the following, Section 4.3.1 specifies the stated assumptions concerning the scenario-specific simulation inputs. Section 4.3.2 then presents the according simulation results.

4.3.1 Simulation Input

The simulation inputs of the Reference Case are defined as followed. For further background on the structure and content of the input data, please refer to the introduction of the FFDT and the underlying FFEA in Chapter 3.

Modelled time period:

The baseline year, from which future flight plan evolution begins, is defined as the year 2016. The final year of flight plans to be modelled is specified to 2040. Furthermore, airport noise exposure is calculated for the years up to 2040.

Baseline flight plan:

As introduced in Section 4.1, a real flight plan of Munich Airport serves as baseline flight plan. The baseline flight plan is extracted from the OAG database 2016 available at the Institute (OAG Worldwide Limited, 2016). A flight plan of equivalent noise events is then derived according to Section 3.2.3. As previously mentioned, note that a representative day is used as baseline flight plan through averaging the entire year's flight schedule.

Air traffic growth input:

As air traffic growth input the passenger growth rates of the Airbus GMF 2017 are applied (Airbus, 2017b).[115] In the Airbus GMF, growth rates are specified according to world region

[115] As discussed in Section 3.2.4 the Airbus GMF's growth rates (given in RPK) are applied by the FFDT as growth rates (in AS) under the assumption of constant flight distances between the different world regions.

pairs for the years up to 2036. For the Reference Case, only the world region pairs including 'Western Europe' are required and thus used as simulation input. The accordingly applied traffic growth rates are listed in Appendix C. As no growth rates are stated by the Airbus GMF for the years 2037 to 2040, the growth rates of the years 2036 are assumed for all subsequent years.

Aircraft retirement input:

The original aircraft cluster-specific retirement curves as developed by Randt and presented in Fig. 3-3 are used by the Reference Case (Randt, 2016). Regarding the required age distributions of the baseline year, the aircraft type-specific age distributions as evaluated for the year 2016 are applied (see Section 3.2.5).

Aircraft introduction input:

The previously introduced aircraft introduction reference scenario is assumed as input of the Aircraft Introduction Module. As detailed in Section 3.2.10, the scenario defines the shares[116] of future aircraft introduced based on open aircraft orders as of 31st December 2016. Furthermore, these shares as a function of the year reflect the assumed entry into service and end of production years of individual aircraft types (see Section 3.2.10). Note that, as specified by Section 3.2.10, the aircraft introduction reference scenario assumes two representative NT-2 aircraft types[117] to enter service in future years.

Airport capacity input:

For the Reference Case an unconstrained airport is assumed. By setting the maximum hourly throughput to infinity, the Airport Capacity Module remains inactive throughout the Reference Case. An additional *Constrained Case* examining the effect of airport capacity constraints on future airport noise is presented in Section 4.4.

Route allocation input:

As for the Status Quo Case, a distribution of 40% easterly operations (direction 09) to 60% westerly operations (direction 27) is assumed. In the same way as for the Status Quo Case, flights to/from the exit/entry point *North* are operated via the northern runway 09L/27R, while flights to/from the exit/entry point *South* are operated via the southern runway 09R/27L. Flights departing via the exit points *East* and *West* are distributed evenly over both runways.

Noise receptor set:

The same rectangular noise receptor set of 510 x 220 receptor points distributed over an area of 51 NM x 22 NM as used in the Status Quo Case is applied.

[116] Defined by individual *swap factors* and the resulting *swap matrix*.
[117] One narrow-body aircraft type and one wide-body aircraft type.

4.3.2 Simulation Results

In the following section, the simulation results of the Reference Case are presented. Firstly, the modelled fleet mix and flight plan results, and secondly, the calculated airport noise results are shown.

Fleet Mix and Flight Plan Results

Based on the input data as detailed in the previous section, the FFDT is used to model future flight plans up to the year 2040. Fundamental results of the simulations are depicted in Fig. 4-3. On the left, the modelled evolution in annual transport capacity is shown (Will and Hornung, 2018). On the right, the according evolution in annual aircraft movements is presented.

As can be seen from Fig. 4-3 (left), the modelled transport capacity shows a continuous growth, which is reasonable according to the growth input defined by the Airbus GMF. While global air traffic is expected to generally double within the next 15 years (Airbus, 2017b), air traffic at the modelled airport only doubles within approximately 24 years. This is plausible considering the fact that air traffic in Western Europe is expected to grow less intensely than global air traffic as a whole.

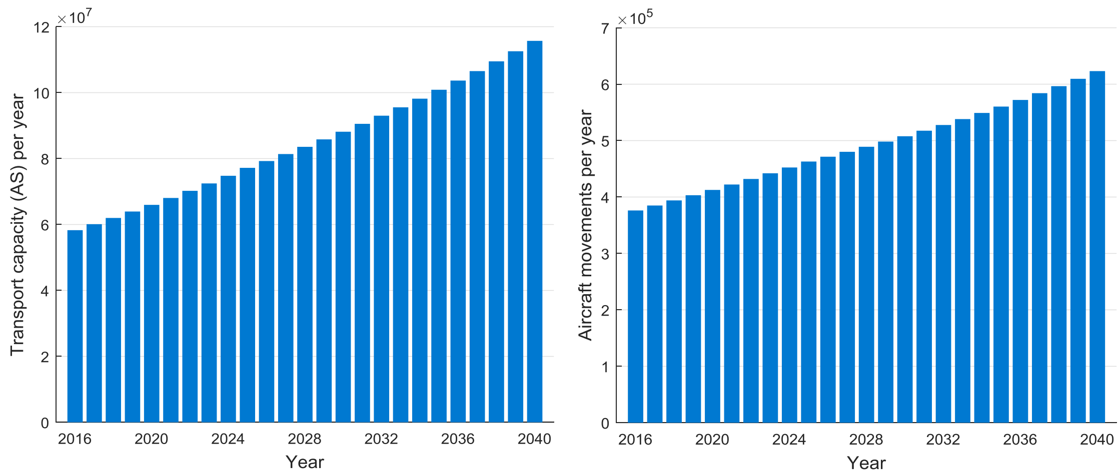

Fig. 4-3 Reference Case: Modelled evolution of transport capacity (on the left) and aircraft movement numbers (on the right) (Will and Hornung, 2018)

From Fig. 4-3 (right), it can be observed that the modelled aircraft movement numbers continuously grow, too, yet at a slower rate than the according transport capacities. Contrary to the doubling in transport capacity, aircraft movement numbers between 2016 and 2040 grow by only around 66%. Two reasons can be named for the weaker increase in aircraft movements compared to the transport capacity growth: Firstly, an increase in average seat capacity of narrow-body aircraft types, and secondly, an increase in the share of wide-body aircraft movements, both as discussed in the following.

Fig. 4-4 (on the left) presents the modelled evolution in average seat capacity per aircraft movement. As can be seen, the average seat capacity of the wide-body fleet in 2040 is at about the level of the year 2016 (282 vs. 281 seats).[118] On the other hand, the average seat capacity of the narrow-body fleet increases significantly from 143 in 2016 to 173 in 2040. Driven by the increasing seat capacity of narrow-body aircraft, the average seat capacity of the total fleet increases from about 155 in 2016 to 186 in 2040. As a result, the simulations thus illustrate the important effect of decoupling the future growth in aircraft movements from the growth in transport capacity (see Fig. 4-3).

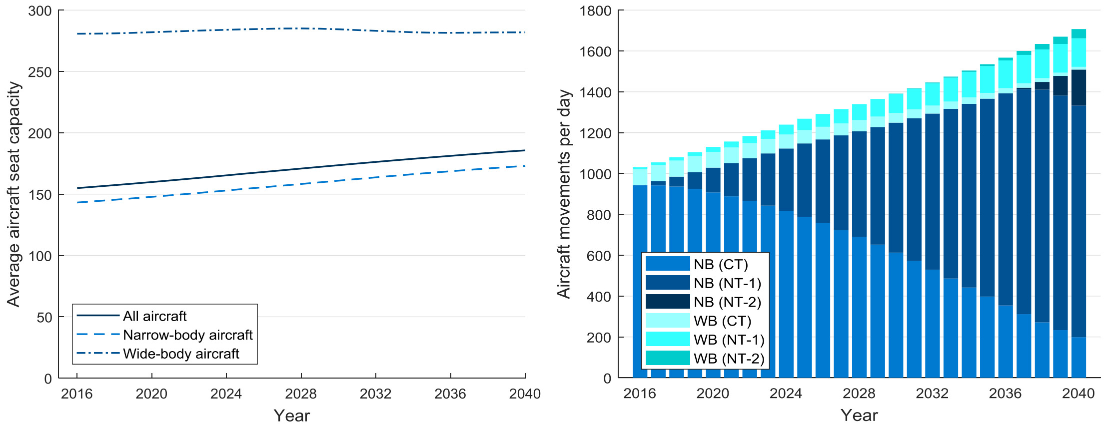

Fig. 4-4 Reference Case: Modelled evolution of average aircraft seat capacity (on the left) and of aircraft generation shares for narrow-body (NB) and wide-body (WB) aircraft (on the right) (Will and Hornung, 2018)

Furthermore, Fig. 4-4 (on the right) visualises the fleet mix evolution at the study airport over the modelled years. First of all, the figure contains information on the movement shares of narrow-body aircraft and wide-body aircraft. Generally, the wide-body aircraft movement numbers are about one order of magnitude below those of narrow-body aircraft movements. However, during the modelled period, a shift towards wide-body aircraft movements is found. While in 2016, the share of narrow-body versus wide-body aircraft is ca. 91% vs. 9%, it accounts for ca. 88% vs. 12% in the year 2040. The reason for this effect lies in the Reference Case's air traffic growth input, which assumes higher growth rates for world region pairs between Western Europe and distant world regions. For instance, the proportion of flights within the region Western Europe[119] decreases from ca. 49% in 2016 to 43% in 2040. In the same period, the shares of flights to and from the region Middle East increases from below 5% to over 8%. As a result of the fact that long-range flights are usually served by wide-body aircraft, wide-body aircraft movement numbers consequently experience a stronger increase than narrow-body aircraft movements.

[118] The seat capacity increase of wide-body aircraft during the first modelled years (see Fig. 4-4) is driven by the introduction of the aircraft type Airbus A380, which according to the baseline flight plan is considered with a seat capacity of 516. However, following the A380's end of production in 2031 as assumed by the aircraft introduction reference scenario, the average seat capacity of wide-body aircraft then slightly decreases again.
[119] Excluding domestic flights.

Moreover, Fig. 4-4 (on the right) presents a further fundamental effect in terms of fleet mix development. It visualises an ongoing fleet renewal process caused by the retirement of older aircraft and the introduction of new aircraft. In the figure, the different technology generations CT, NT-1 and NT-2 are depicted with increasing darkness of the colour. As can be seen, a continuous fleet modernisation with decreasing shares of CT aircraft in favour of newer aircraft generations can be found over the modelled years. From the first year, the share of NT-1 aircraft increases for both narrow-body and wide-body aircraft. During the last modelled years, the introduction of NT-2 aircraft can be observed, which serve as replacement for all NT-1 aircraft types ending production.[120] Fig. 4-4 (on the right) also shows that during the first modelled years, the rate of NT-1 aircraft increases at a slower rate than in subsequent years. The reason for this lies in the fact that during the first modelled years, still a significant share of CT aircraft is introduced to the fleet[121]. By the year 2040, the share of CT narrow-body aircraft has decreased to ca. 12% (2016: 91%), the share of CT wide-body aircraft to ca. 1% (2016: 8%).

Airport-Level Noise Results

From the future flight plans, airport noise exposure is subsequently calculated with the help of the AEDT. First of all, the shape of the resulting DEN noise contour is analysed. It is found that compared to the Status Quo Case (see Fig. 4-2), the principal shape[122] of the noise contours remains almost unchanged. An exemplary noise contour for the year 2030 is given in Fig. 4-5. While in the Reference Case over the course of the modelled years the noise contours may grow or shrink, the principle geometry of the noise contours remain very similar.

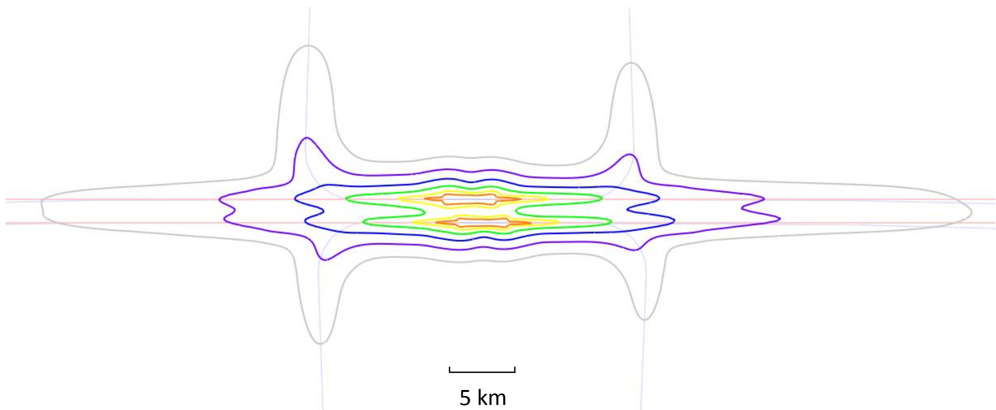

Fig. 4-5 Reference Case 2030: DEN noise contours from 45 dB to 70 dB (in 5 dB steps)

More insightful than the qualitative evaluation of noise contours is the quantitative analysis of noise contour areas. The according evolution of the 55 dB noise contour area over the modelled years is presented in Fig. 4-6 as depicted by the dark blue line (left ordinate)

[120] As defined by the aircraft introduction reference scenario (see Section 3.2.10).
[121] As result of remaining open CT aircraft orders, which are considered by the aircraft introduction reference scenario (Section 3.2.10). For further illustration, see also Appendix D.
[122] Defined by the different noise contour lobes.

(Will and Hornung, 2019). The noise contour area of the year 2016 is based on the given baseline flight plan, while the subsequent years are based on the modelled FFDT results. Additionally, the figure depicts the according evolution in transport capacity in light blue (right ordinate).

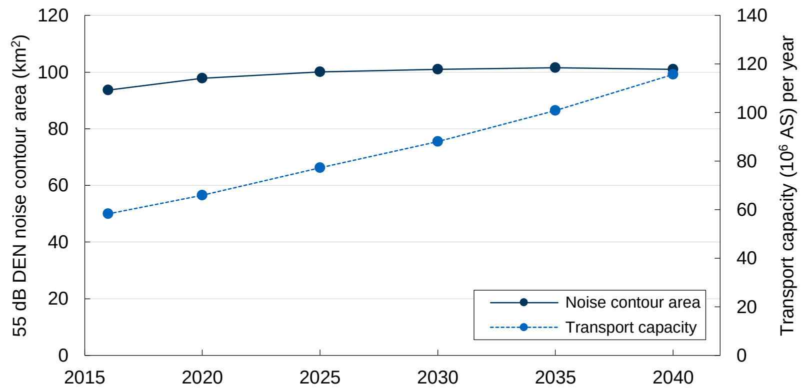

Fig. 4-6 Reference Case: Evolution of the 55 dB DEN noise contour area (Will and Hornung, 2019)

As seen from Fig. 4-6, during the first modelled years, the 55 dB noise contour area shows a moderate increase. This increase in noise contour area then flattens, peaking by the year 2035, and eventually slightly decreases again. By 2040, the noise contour area is marginally higher than in 2016. As a major finding it can thus be stated that, according to the assumed scenario input, airport noise exposure will neither improve nor worsen significantly during the studied time period. Instead, after an initial degradation of the airport noise situation, the development will level off and eventually slightly improve again.

Furthermore, Fig. 4-6 shows that in the same period, compared to the increase in noise contour area the modelled increase in transport capacity is found to be much larger. This effect can be attributed to the fleet renewal process as discussed from Fig. 4-4 (right). While, on the one hand, air traffic growth principally causes a growth in noise contours, on the other hand, the simultaneous fleet renewal process affects noise contours to the contrary. Fig. 4-6 indicates that in the near-term future the modelled fleet renewal process introducing noise-reduced aircraft types is not fully able to compensate for the assumed air traffic growth. Still, the noise-reduced aircraft are able to significantly reduce the noise-increasing effect resulting from traffic growth. On the long-term, according to the model results the benefits obtained by the fleet renewal process slightly overcompensate the negative effects resulting from air traffic growth. The initial stronger increase in noise contour area relies on the effect that in the first modelled years the share of NT-1 aircraft only increases at a lower rate than in subsequent years (see Fig. 4-4). This again is caused by the fact that during the first modelled years still a considerable share of CT aircraft is introduced to the fleet[123].

[123] As discussed above.

Similarly to Fig. 4-6, the evolution of the 65 dB noise contour area is presented in Fig. 4-7. The principle evolution in noise contour area is comparable to the 55 dB results. As can be seen, during the first modelled years the noise contour areas slightly increase, followed by a moderate decline during the last modelled years. As discussed before, the noise-reduced aircraft introduced by the fleet renewal process are able to outweigh and eventually to overcompensate the increase in air traffic.

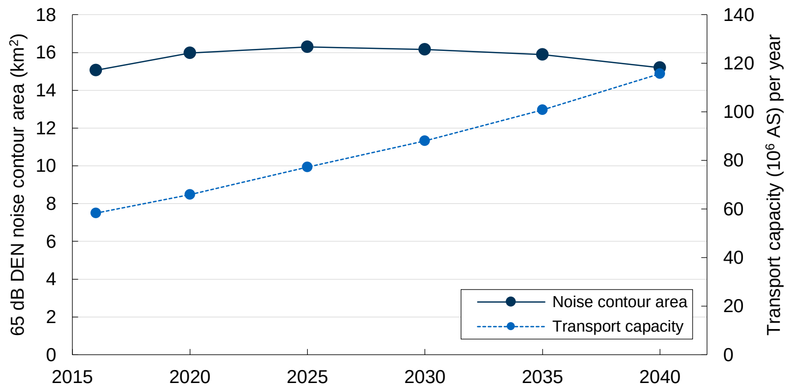

Fig. 4-7 Reference Case: Evolution of the 65 dB DEN noise contour area (Will and Hornung, 2019)

In contrast to the evolution of the 55 dB noise contour area, the maximum in 65 dB noise contour area is found earlier, namely by the year 2025. Other noise contours[124] confirm the effect that with proceeding years, louder noise contour areas tend to increase less strongly, or decrease more strongly than quieter noise contour areas. The reason for this effect is found in the different levels of noise reductions of NT-1/2 aircraft for approach and departure operations compared to CT aircraft. For the majority of NT-1 aircraft types and for both modelled NT-2 aircraft types (see Tab. 3-7), the noise reductions relative to the corresponding surrogate aircraft type is stronger for departures than for approaches[125]. Furthermore, louder noise contours are more strongly influenced by departure operations than quieter noise contours[126]. As a result, louder noise contours benefit more strongly than quieter contours from an increasing share of NT-1/2 aircraft types.

[124] For instance, the 50 dB, 60 dB or 70 dB noise contour.
[125] This is reasonable due to the following facts: During take-off and departure procedures, compared to airframe noise the engine noise dominates. Therefore, to reduce aircraft-level noise it is sufficient to solely reduce engine noise (e.g. by an increase in the engine's bypass ratio). On the contrary, as result of lower engine noise levels during approach procedures airframe noise generally has become significant, too. Consequently, to reduce aircraft-level noise in approach both the engine noise and the airframe noise needs to be reduced simultaneously, which is more difficult to realize than to solely reduce engine noise.
[126] As result of significantly higher engine power-settings during take-off/departure.

4.4 Constrained Case

In the following section, a *Constrained Case* is introduced, in which the number of aircraft movements is limited to a realistic maximum throughput for all future years. The motivation of this case is the important question: How would the noise situation evolve at a capacity-constrained airport?

4.4.1 Simulation Input

The simulation of the Constrained Case is based on the Reference Case as proposed by Section 4.3. In order to assess the isolated impact of airport capacity constraints on future airport noise, compared to the Reference Case all input data remain constant except for the definition of airport capacity constraints. As input of the Airport Capacity Module for the Constrained Case, a maximum throughput of 90 movements per hour is defined. The value represents a realistic capacity limit for an airport with an independent parallel two-runway system.

4.4.2 Simulation Results

In the following, the Constrained Case's fleet mix and flight plan results as well as the airport noise simulation results are presented.

Fleet Mix and Flight Plan Results

The FFDT is used to model flight plans up to the year 2040 based on the input data defined by the previous section. The evolution in transport capacity, the evolution in total aircraft movement numbers, and the evolution of the aircraft fleet mix are the same as in the Reference Case (see Section 4.3) since all relevant input data is the same. The modelled future flight plans of the two cases differ only from the FFDT's Airport Capacity Module on (compare Fig. 3-2). The effect of the airport capacity constraints on the resulting flight plans as modelled by the FFDT is presented in Fig. 4-8, on the left for the year 2030, on the right for the year 2040. The charts present the number of aircraft movements per hour for the unconstrained Reference Case[127] (in light blue) and for the Constrained Case (in dark blue).

As can be seen from Fig. 4-8, in the Constrained Case the Airport Capacity Module becomes active in both 2030 and 2040. In both years, specific hours of the day exceed the maximum throughput of 90 movements per hour. However, the extent, to which aircraft movements are shifted by the Airport Capacity Module, is quite different between the two observed years. In the year 2030, the maximum throughput is exceeded during five hours of the day. The Airport Capacity Module thus shifts the exceeding aircraft movements to the neighbouring hours. In 2040, yet, a significantly higher amount of aircraft movements is shifted due to capacity constraints. The maximum throughput then is exceeded during

[127] Which assumes an infinite maximum aircraft throughput (see Section 4.3.1).

12 hours of the day. Furthermore, the airport is able to process air traffic demand only through a continuous operation at the airport's maximum throughput from 5 am to 11 pm.

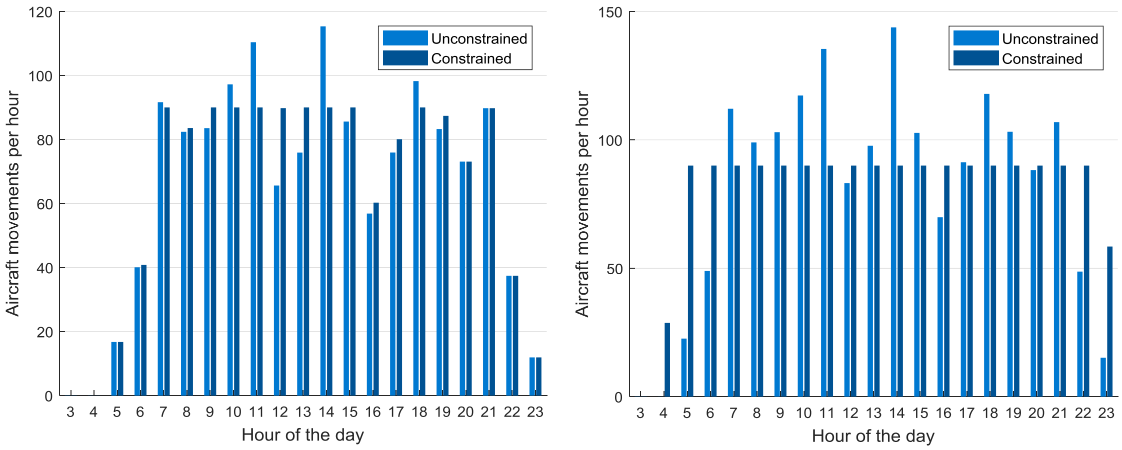

Fig. 4-8 Constrained Case vs. Reference Case (unconstrained): Aircraft movements per hour for the year 2030 (left) and 2040 (right) modified from Will and Hornung (2018)

A first conclusion may be drawn from these results. Although not in the focus of this research, the results indicate that in the future, following the traffic growth assumptions of the Airbus GMF the studied airport's two-runway system will be insufficient. In addition, it is to highlight that the baseline flight plan is a representative day's flight plan based on averaging an entire year's flight schedule. In reality, taking into account the seasonal fluctuations in air traffic demand over the period of a year, the problems resulting from capacity constraints would be even more severe during peak days of the year.

Airport-Level Noise Results

As described before, from the FFDT flight plan results, airport noise exposure is calculated for the Constrained Case. Exemplary DEN noise contours for the year 2040 are presented in Fig. 4-9. As can be seen, compared to the noise contours of the Status Quo Case (see Fig. 4-2), the contours have significantly grown while the principle shape has remained very similar.

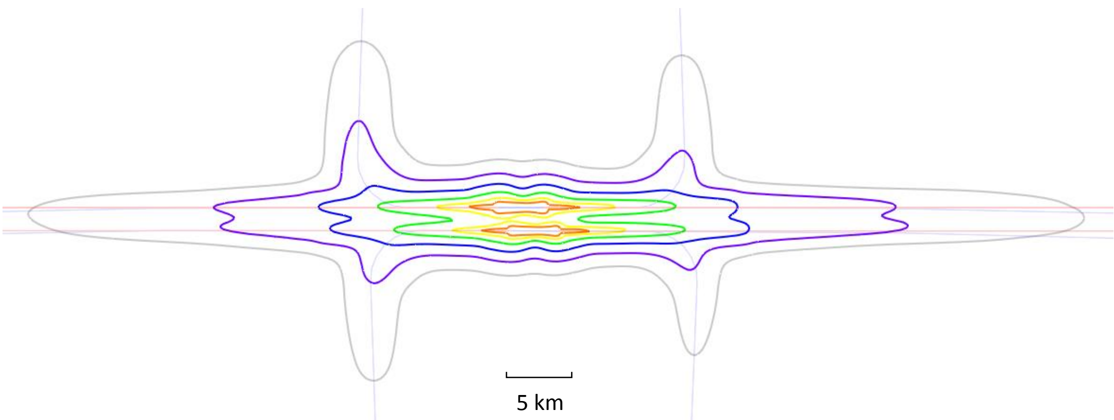

Fig. 4-9 Constrained Case 2040: DEN noise contours from 45 dB to 70 dB (in 5 dB steps)

A quantification of the resulting DEN noise contour areas up to the year 2040 is shown in Fig. 4-10, presenting the 55 dB contour on the left and the 65 dB contour on the right. The Constrained Case is depicted in dark blue, while for comparisons the unconstrained Reference Case (see Section 4.3) is given in light blue. Furthermore, for each year the figure specifies the relative increase in noise contour area of the Constrained Case compared to the according contour area of the Reference Case.

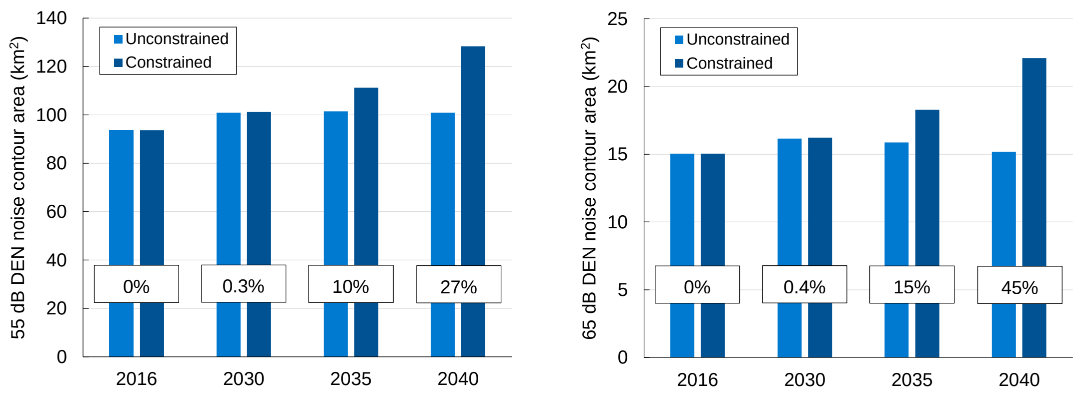

Fig. 4-10 Constrained Case vs. Reference Case (unconstrained): DEN noise contour areas for 55 dB (left) and 65 dB (right)

In the baseline year, the noise contour areas of the Constrained Case and the Reference Case are identical, as the Airport Capacity Module does not shift any aircraft movements[128]. By the year 2030, the noise contour area of the Constrained Case compared to the Reference Case is by 0.3% and 0.4% larger for the 55 dB and the 65 dB contour area, respectively. In the year 2035, the Constrained Case's noise contour areas are already significantly larger than those of the Reference Case, where the 55 dB and 65 dB are by 10% and, respectively, 15% larger. For the year 2040, the differences found grow further. The Constrained Case's noise contour areas compared to the Reference Case are by 27% larger for the 55 dB contours, and by even 45% for the 65 dB contours.

The observed influence of airport capacity constraints on airport noise contour area can be explained from Fig. 4-8. Through the shifting of aircraft movements, flights may be shifted to hours during evening or night times. As introduced in Section 2.1.2, the DEN metric penalises flights during the periods 'evening' and 'night' by 5 dB and 10 dB, respectively. Hence, flights shifted from 'day' to 'evening' or 'night', or from 'evening' to 'night' increase the resulting DEN. In the year 2030 of the Constrained Case, as can be seen from Fig. 4-8, less than ten flights are shifted beyond their original period of time[129]. On the contrary, in 2040, about 220 flights are shifted beyond their original period of time.

As seen, the negative impact of airport capacity constraints on the DEN can be perceived with increasing intensity from the year 2030. By the year 2040, the impact is tremendous

[128] That is, in the baseline flight plan the maximum hourly aircraft movements is not yet reached. Note that the baseline flight plan is a representative day based on a year's averaged flight schedule.
[129] The reader is reminded that the period 'day' is defined from 7 am to 7 pm, 'evening' from 7 pm to 11 pm, and 'night' from 11 pm to 7 am (see Section 2.1.2).

and the resulting DEN noise contours increase severely by two-digit growth numbers. At this point it is important to consider the methodical approach and assumptions of the Airport Capacity Module. As introduced in Section 3.2.8, the approach assumes all aircraft movements exceeding the maximum throughput to be entirely transferred to other times of the day. In reality, yet, at a capacity-constrained airport it is probable that not all original traffic demand exceeding the airport's capacity would be operated at other times of the day. Instead, a certain proportion of the excess demand would likely not be met[130]. The Constrained Case's airport noise results, as discussed in Section 3.2.8, therefore may be regarded as a worst-case[131] baseline in the quantification of future airport noise. Furthermore, the Constrained Case demonstrates the FFDT's capabilities to consider noise-relevant effects of airport capacity constraints on future airport noise exposure.

4.5 One Operating Direction Case

The following section presents a *One Operating Direction Case*, in which the airport is entirely operated in one of the airport's two possible operating directions. The objective of this case is to assess the influence of the operating direction on airport noise exposure. A specific question, for instance, motivating this case is: Would it be beneficial if all the airport's flights were operated in the same operating direction?

4.5.1 Simulation Input

In order to reveal the dedicated impact of the operating direction on resulting airport noise exposure, only the definition of the route allocation input is changed compared to the previously shown Reference Case. All other input data is specified according to the Reference Case as presented in Section 4.3. The differing route allocation input is defined as followed.

All flights are assumed to be operated in one operating direction. Therein, two different cases are examined for the two operating directions of the airport. In a *Westerly Case*, 100% of the flights are operated in the direction 27, which in reality would be the preferred operating direction for wind from the west[132]. In an *Easterly Case*, 100% of the flights are operated in the direction 09, which would be the usual operating direction for wind from the east[133].

[130] In other words, a certain demand spill would occur. Furthermore, as discussed in Section 3.2.8, a stronger transfer to larger aircraft would be probable.
[131] The term "worst" applies to the resulting airport noise and thus reflects the point of view of airport residents. For aviation stakeholders, this "worst case" of maximised air traffic volume may be desirable.
[132] Which means that arrivals arrive from the eastern side of the airport and, thus, fly towards the west. Departures depart to the western side of the airport.
[133] Furthermore, as in the Reference Case (see Section 4.3), flights connected to the exit/entry point *North* are assigned to the northern runway, flights to the exit/entry point *South* to the southern runway, flights departing via the exit points *East* and *West* are distributed evenly over both runways.

4.5.2 Simulation Results

The simulation results of the One Operating Direction Case are presented in the following and compared to the results of the Reference Case.

Fleet Mix and Flight Plan Results

Using the input data specified in the previous section, the FFDT is used to model flight plans up to the year 2030. All fleet mix and flight plan results presented in the Reference Case (see Section 4.3.2) also apply for the One Operating Direction Case as all relevant input data are identical between the cases. The only difference in the resulting flight plans is found in the flight route distributions, which becomes apparent in the calculated airport noise exposure as shown in the following.

Airport-Level Noise Results

Based on the flight plan as modelled by the FFDT for the year 2030, airport noise is calculated using the AEDT. The resulting noise contours for the Easterly Case are presented in Fig. 4-11, the noise contours for the Westerly Case in Fig. 4-12. The figures present the noise contours from 45 dB to 70 dB in steps of 5 dB. It is obvious that the principle shape of the resulting noise contours is very different compared to the shape of the Reference Case 2030 (see Fig. 4-5), which is based on an operating direction share of 40% easterly to 60% westerly operations (see Section 4.3.1). In the Easterly Case and in the Westerly Case, respectively, the contour lobes corresponding to the curved western SIDs and the curved eastern SIDs, respectively, do not exist as no flights are assigned to those SIDs. In the same way, no contour lobes resulting from approaching aircraft are found for one of two airport's sides[134], because all approaching aircraft arrive from the opposite side. On the other hand, the two contour lobes corresponding to the remaining curved SIDs are larger compared to the Reference Case 2030 as the according SIDs are more frequently used in the One Operating Direction Case. For the same reason, the remaining contour lobe in the

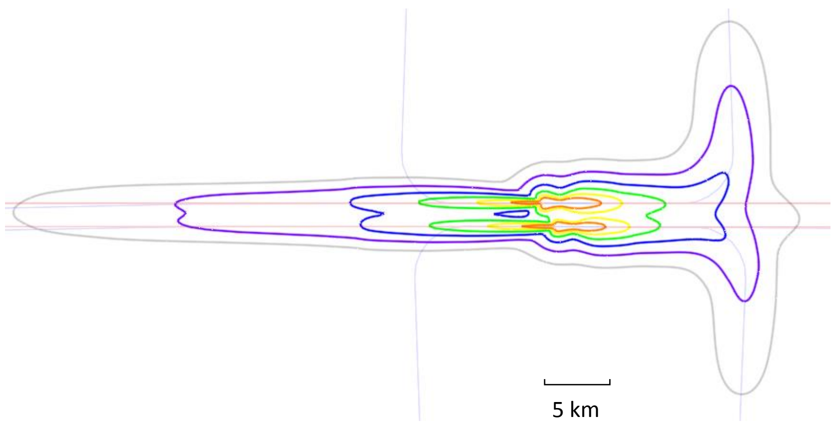

Fig. 4-11 Easterly Case (operating direction 09): DEN noise contours from 45 dB to 70 dB (in 5 dB steps)

[134] In the Easterly Case no contour lobe on the east of the runway system, in the Westerly Case no contour lobe to the west of the runway system exists.

direction of the runway system is larger compared to the corresponding contour lobe of the Reference Case 2030.

Although qualitatively the noise contour shapes are fundamentally different, quantitatively, the noise contour areas of the Easterly Case, the Westerly Case, and the Reference Case 2030 are found to be relatively similar. In numbers, the 55 dB DEN contour area is at about 104 km^2 for both the Easterly Case and the Westerly Case and thus slightly larger than for the Reference Case 2030 (ca. 101 km^2). The 65 dB DEN contour area measures approximately 16.4 km^2 for both the Easterly Case and the Westerly Case and is thus only marginally larger than for the Reference Case 2030 (ca. 16.2 km^2).

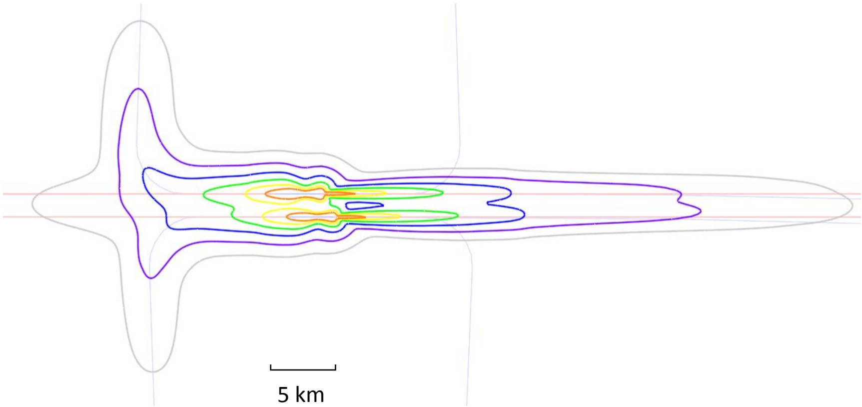

Fig. 4-12 Westerly Case (operating direction 27): DEN noise contours from 45 dB to 70 dB (in 5 dB steps)

Consequently, the results indicate that for the studied airport the operating direction only has a low impact on the resulting noise contour areas. The results indicate that a single operating direction applied to all the airport's flights leads to slightly larger noise contours than an airport operated from both directions[135]. However, it is important to note that unlike noise contour areas, local noise levels may strongly depend on the operating direction[136]. Besides this, the One Operating Direction Case demonstrates the FFDT's capabilities to consider differing route and runway allocation definitions on future airport noise exposure.

4.6 No Growth Case

In this section, a *No Growth Case* is presented to assess the influence of air traffic growth on future airport noise. For this purpose, the No Growth Case determines airport noise for the assumption of no further air traffic growth in the future. The question to be answered with this case therefore is: How would the airport noise exposure evolve in the future, if no further air traffic growth occurred?

[135] Obviously, the two operating directions are not used at the same time but in succession.

[136] This implies that for a real airport with a given specific population distribution, the operating direction may play a significant role on the resulting number of affected residents.

4.6.1 Simulation Input

As in previous cases, to assess the dedicated influence of air traffic growth on future airport noise only the traffic growth input rates are changed compared to the Reference Case. All other input data are specified according to the input data of the Reference Case (see Section 4.3). As only difference, the traffic growth rates are specified to 0% for all future years and all world region pairs.

4.6.2 Simulation Results

This section presents the No Growth Case's fleet mix and flight plan results, followed by the results of the airport noise calculations.

Fleet Mix and Flight Plan Results

The FFDT is used to model flight plans up to the year 2040 based on the input data of the previous section. Fig. 4-13 presents the modelled evolution of transport capacity (on the left) and of annual aircraft movements (on the right). The No Growth Case is depicted in dark blue, the Reference Case for comparison in lighter blue. As can be seen, due to the lacking traffic growth the No Growth Case's transport capacity remains constant at the level of the baseline year for all future years. As a result, by the year 2040 the modelled transport capacity is only about half of the Reference Case. Furthermore, as seen in Fig. 4-13 (right), the annual aircraft movement numbers show a continuous decrease from 2016 to 2040, dropping by about 14% within the modelled period. The reason for the decrease in aircraft movements is found in the increased average seat capacity of the aircraft fleet as detailed in the following.

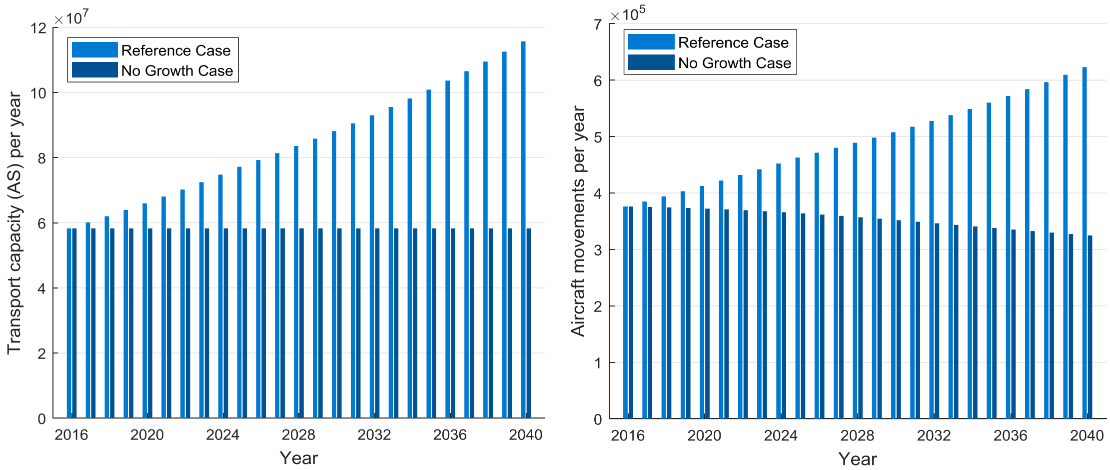

Fig. 4-13 No Growth Case: transport capacity (on the left), aircraft movements (on the right) (Will and Hornung, 2019)

Fig. 4-14 (on the left) presents the evolution of the modelled average aircraft seat capacity. Furthermore, Fig. 4-14 (on the right) illustrates the evolution of aircraft generation shares. As can be seen from the left, the average aircraft seat capacity of the entire fleet increases from 2016 to 2040. However, while the seat capacity development principally is similar to that of the Reference Case (see Fig. 4-4), the increase occurs somewhat slower. In 2040, the average seat capacity of the entire fleet has reached ca. 179 seats[137]. Similarly to the Reference Case, the seat capacity of the wide-body aircraft fleet does not grow significantly. Instead, the total fleet's increasing average aircraft seat capacity is driven by the narrow-body aircraft fleet, whose average seat capacity grows considerably.

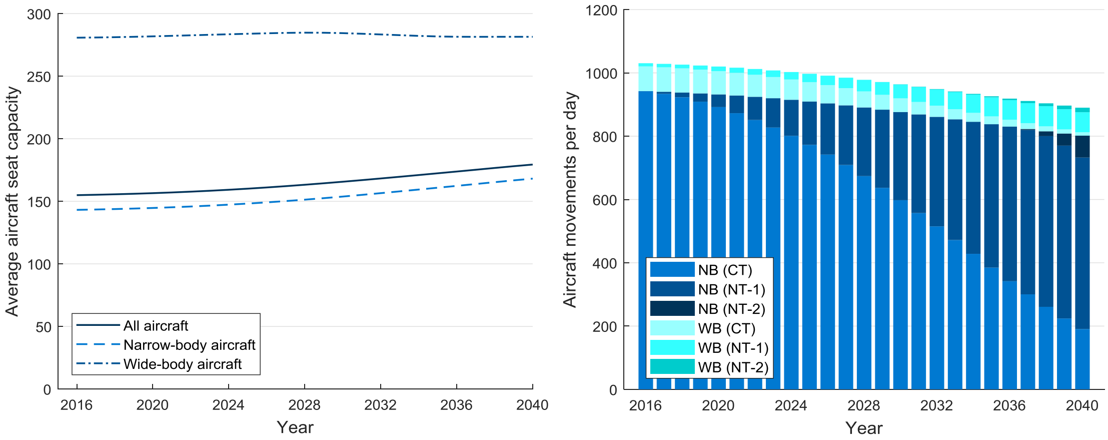

Fig. 4-14 No Growth Case: Modelled evolution of average aircraft seat capacity (on the left) and of aircraft generation shares for narrow-body (NB) and wide-body (WB) aircraft (on the right) (Will and Hornung, 2019)

The reason for the slower increase in average aircraft seat capacity lies in the fact that without air traffic growth, less aircraft are introduced to the fleet compared to the Reference Case. The aircraft added to the fleet only consist of replacement aircraft[138]. Hence, the proportion of older aircraft, which for narrow-body aircraft on average accommodate less seats, is larger. As a result, the average aircraft seat capacity for a given year is slightly lower compared to the Reference Case.

These effects can also be observed in Fig. 4-14 (on the right). As can be seen, the share of CT aircraft continuously decreases over the modelled years for both wide-body and narrow-body aircraft. On the other hand, through the introduction of new aircraft, the share of NT-1 aircraft and for the last modelled years of NT-2 aircraft increases. Whereas the fleet renewal process principally is similar to the Reference Case (see Fig. 4-4), considerable differences in the specific fleet mix share of a given year can be found. Comparing Fig. 4-14 and Fig. 4-4, it is obvious that the No Growth Case has significantly higher shares of CT aircraft than the Reference Case. For instance, in the year 2030 from all aircraft movements the share of CT narrow-body aircraft is ca. 62% for the No Growth Case while only ca. 44% for the Reference Case.[139] By 2040, the CT narrow-body aircraft still make up for ca. 21% of aircraft movements for the No Growth Case, but only ca. 12% for the Reference Case.

[137] 186 seats for the Reference Case (see Section 4.3.2).
[138] The growth gap is zero for all modelled years. The total capacity gap to be filled by new aircraft solely consists of the retirement gap (see Fig. 3-5).
[139] In 2030, for instance, the share of NT-1 narrow-body aircraft movements has reached ca. 46% for the Reference Case, but only ca. 29% for the No Growth Case.

The presented results thereby illustrate the significant effect of air traffic growth on the composition of a future fleet mix. An increased air traffic demand additionally requires airlines to purchase and operate new aircraft, which leads to a younger aircraft fleet.

Airport-Level Noise Results

From the flight plans modelled by the FFDT, airport noise is simulated using the AEDT. The development of the resulting 55 dB DEN noise contour area is presented in Fig. 4-15 (in blue). For comparison, the according noise contour area of the Reference Case is shown (in grey). As can be seen, the noise contour area of the No Growth Case continuously decreases from 2016 to 2040. Relative to the baseline year the 55 dB noise contour area is at 90% by the year 2030, and at only 71% by the year 2040.

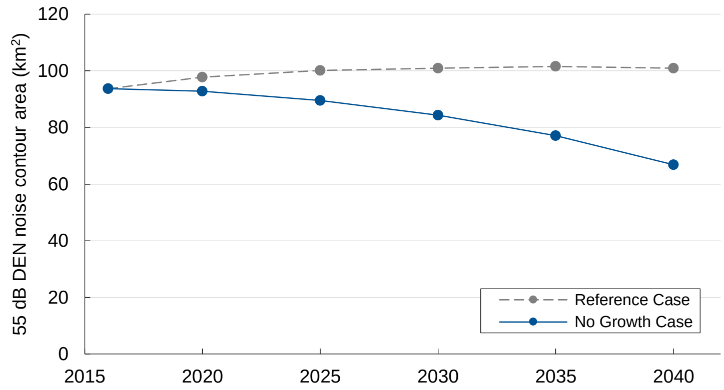

Fig. 4-15 No Growth Case: Evolution of the 55 dB DEN noise contour area

In the same way, the development of the resulting 65 dB noise contour area is depicted in Fig. 4-16. Similarly as the 55 dB noise contour, the 65 dB noise contour area continuously decreases from 2016 to 2040. The decreases in noise contour area are even larger as found for the 55 dB level. Relative to the baseline year the 65 dB noise contour area is at 84% by the year 2030, and at only 60% by the year 2040. The stronger reduction of the 65 dB noise contour compared to the 55 dB contour is caused by the effect already discussed in Section 4.3.2. In comparison to according CT aircraft types, the noise reduction of future aircraft types generally is larger for departure procedures than for approach procedures. Because the louder noise contours at an airport are mainly influenced by departures, these contours compared to quieter noise contours benefit more strongly from an increased share of NT-1 and NT-2 aircraft types.

As a result, the No Growth Case shows the tremendous effect of air traffic growth on future airport noise. If air traffic demand in the future remained at a constant level, the positive effects resulting from future aircraft fleet renewal would enable airport noise exposure to decrease strongly. In other words, the No Growth Case represents the situation of today's air traffic volume operated by an aircraft fleet of tomorrow. It hence presents the isolated benefit of a future fleet renewal process on airport noise contours. Thereby, the No Growth

Case not only reveals the tremendous effect of air traffic growth, but also of the aircraft technological progress on future airport noise exposure. Moreover, the No Growth Case demonstrates the FFDT's capabilities to consider varying air traffic growth scenarios on future airport noise exposure.

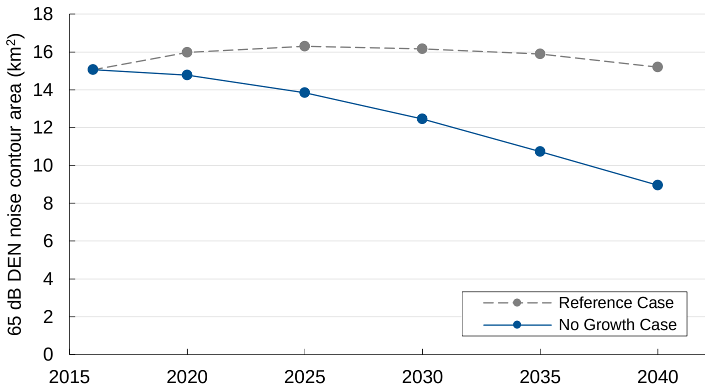

Fig. 4-16 No Growth Case: Evolution of the 65 dB DEN noise contour area

4.7 Old Technology Case

In this section, an *Old Technology Case* is presented, in which aircraft technology remains at the level of the baseline year for all future years. The purpose of the case is to project a "no action scenario" into the future[140]. In other words, this case poses the question: How would the airport noise exposure evolve in the future, if no new aircraft technology were introduced to the fleet?

4.7.1 Simulation Input

As in previous cases, compared to the Reference Case (see Section 4.3) all input data except the aircraft introduction input remains unchanged. The definition of the aircraft introduction input is detailed in the following.

In the Reference Case, as introduced by Section 4.3, the operating aircraft fleet is subject to a fleet renewal process, in which novel aircraft types replace older aircraft types.[141] In contrast to the Reference Case, the swap matrix[142] of the Old Technology Case is defined according to Tab. 4-1. Consequently a flight plan gap corresponding to a flight plan entry of an Airbus A320 is filled with 100% by the aircraft type A320 for all modelled years. In

[140] That is, the aviation industry does not take further action to renew the aircraft fleet with improved aircraft technology.

[141] Therein, as previously discussed, the share of aircraft types introduced to the fleet in future years is defined by the aircraft introduction reference scenario (see Section 3.2.10). In the first modelled years a mix of CT and NT-1 aircraft types is introduced to the fleet, followed by a period of introducing only NT-1 aircraft types. In the last modelled years, NT-2 aircraft types enter service and are subsequently added to the fleet.

[142] The reader is reminded that the swap matrix is the scenario-specific input of the Aircraft Introduction Module specifying the future aircraft introduction (see Section 3.2.7).

the same way, for instance, is a Boeing 747 flight plan gap always filled with a Boeing 747, and an Embraer 195 flight plan gap always with an Embraer 195. As a result, the FFDT fills a flight plan gap corresponding to a given aircraft type by the introduction of the same aircraft type for all future years to be modelled.

Tab. 4-1 Old Technology Case: Definition of the swap matrix as input of the Aircraft Introduction Module (extract)

Aircraft Type (flight plan gap)	*Aircraft Type (introduced)*	*Year 1*	*Year 2*	*Year 3*	*...*
Airbus A320	*Airbus A320*	*100%*	*100%*	*100%*	*...*
Boeing 747	*Boeing 747*	*100%*	*100%*	*100%*	*...*
Embraer 195	*Embraer 195*	*100%*	*100%*	*100%*	*...*
...	*...*	*...*	*...*	*...*	

4.7.2 Simulation Results

In the following, the Old Technology Case's fleet mix and flight plan results as well as the results of the subsequent airport noise simulations are presented.

Fleet Mix and Flight Plan Results

The FFDT is used to model future flight plans from 2016 to 2040 based on the input data specified by the previous section. The modelled evolution in transport capacity as well as the evolution in aircraft movement numbers is depicted in Fig. 4-17. The results of the Old Technology Case is shown in darker blue, the results of the Reference Case in lighter blue.

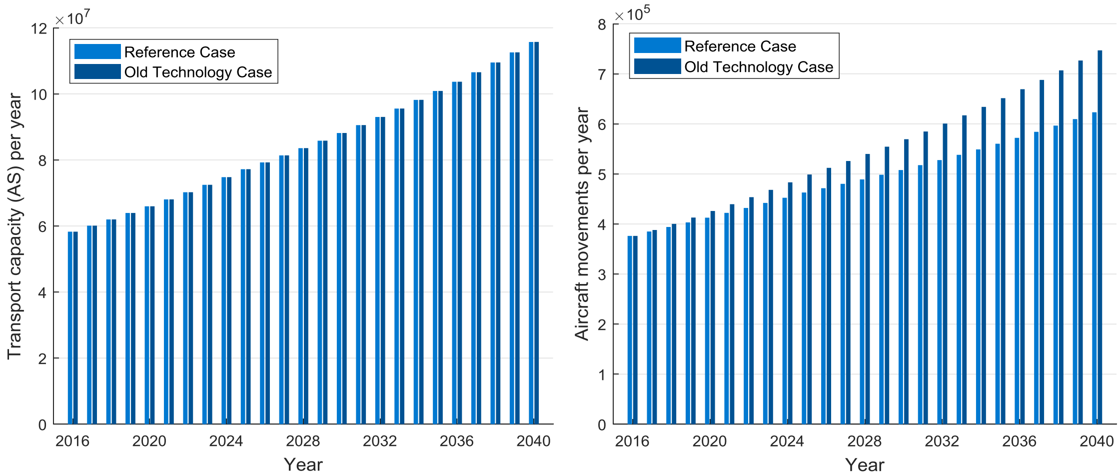

Fig. 4-17 Old Technology Case: Modelled evolution in transport capacity (on the left) and aircraft movement numbers (on the right) (Will and Hornung, 2019)

As can be seen from Fig. 4-17, the evolution of transport capacity (on the left) of the Old Technology Case is identical to the Reference Case since the same air traffic growth rates are used as model input. However, the evolution of aircraft movement numbers (on the right) differs between the two cases. Compared to the Reference Case, the Old Technology Case shows higher movement numbers. The reason for this development lies in the fact that in the Reference Case, with preceding time, an aircraft fleet with higher average aircraft seat capacity provides the given traffic demand. On the contrary, in the Old Technology Case, the average aircraft seat capacity does not increase as shown in the following.

The Old Technology Case's evolution of average aircraft seat capacity is depicted in Fig. 4-18 (on the left). As can be seen, for both narrow-body and wide-body aircraft, the average seat capacity remains unchanged at the level of the baseline year throughout all modelled years. Because each aircraft is replaced by the same aircraft type, the occurring fleet renewal process[143] does not modernise the fleet in terms of aircraft technology. This effect is illustrated by the evolution of aircraft generations as found in Fig. 4-18 (on the right). The shares of CT narrow-body aircraft, of CT wide-body aircraft, and of NT-1 wide-body aircraft[144] remain almost identical. Unlike in the Reference Case (see Fig. 4-4), neither the share of CT aircraft decreases over time, nor does the share of NT-1 aircraft increase. Instead, the aircraft fleet mix practically remains unchanged. Only a minor shift is found from narrow-body aircraft movements (2016/2040: 91/90%) to wide-body aircraft movements (2016/2040: 9/10%). This, as discussed before, is caused by the generally higher air traffic growth rates of world region-pairs connecting 'Western Europe' to distant world regions, which are usually served by wide-body aircraft.

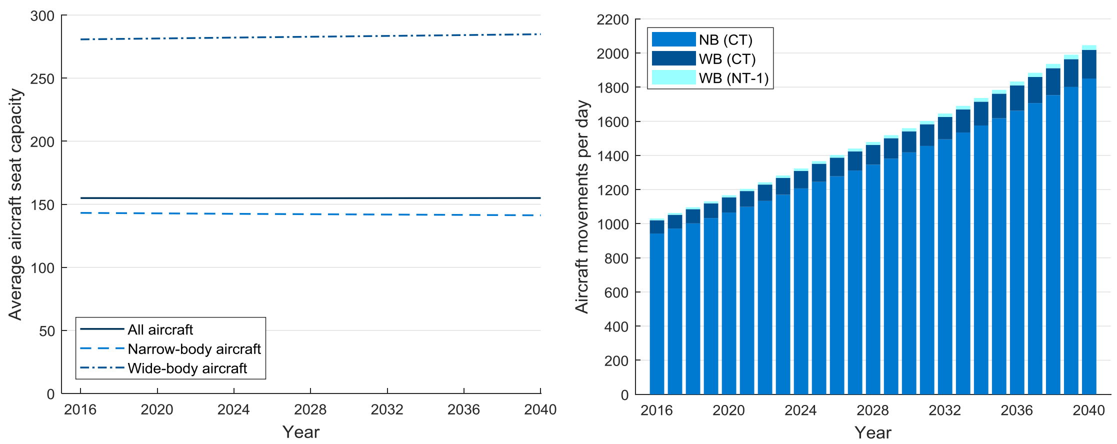

Fig. 4-18 Old Technology Case: Modelled evolution of average aircraft seat capacity (on the left) and of aircraft generation shares for narrow-body (NB) and wide-body (WB) aircraft (on the right) (Will and Hornung, 2019)

[143] Note that still a fleet renewal process is modelled by the Old Technology Case.
[144] Note that in 2016, already a small share of NT-1 wide-body aircraft is present in the baseline flight plan (the majority of which are of the aircraft type Airbus A380).

Airport-Level Noise Results

From the modelled future flight plans, the Old Technology Case's airport noise is calculated with the help of the AEDT. The evolution of the resulting 55 dB noise contour area is presented in Fig. 4-19 (in blue). For comparisons, the according results of the Reference Case are depicted, too (in grey). From 2016 to 2040, the noise contour area of the Old Technology Case continuously increases by an almost linear growth. Compared to the baseline year, the 55 dB noise contour area grows by 27% up to 2030 and by 50% in 2040.

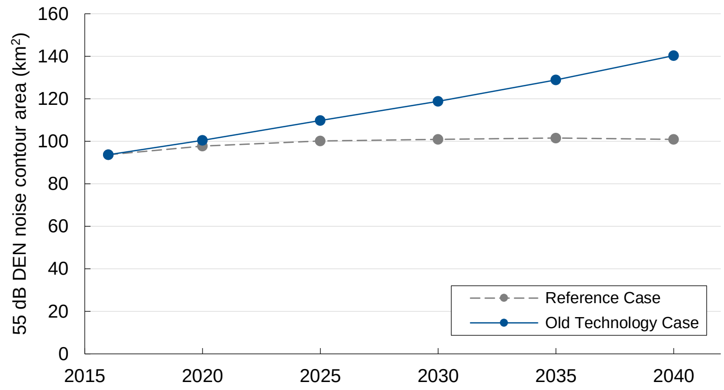

Fig. 4-19 Old Technology Case: Evolution of the 55 dB DEN noise contour area

The resulting evolution of the 65 dB noise contour area is presented in Fig. 4-20. In a similar way as the 55 dB noise contour, the noise contour area shows an almost linear growth between 2016 and 2040. The slope, yet, is even higher, with a relative growth compared to the baseline year's noise contour area of 45% up to 2030 and of even 87% up to 2040.

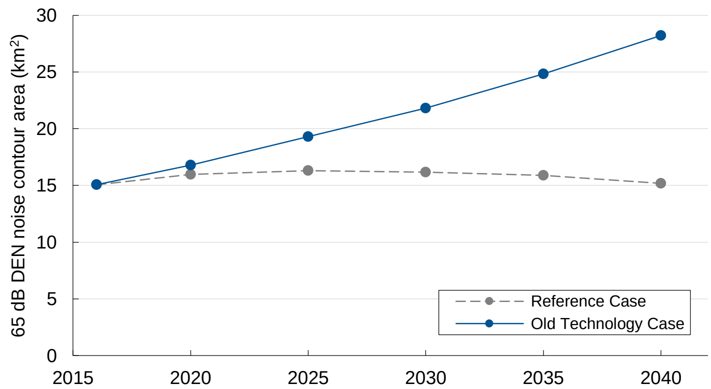

Fig. 4-20 Old Technology Case: Evolution of the 65 dB DEN noise contour area

The differences in noise contour areas between the Reference Case and the Old Technology Case can be fully attributed to the two case's differing aircraft fleets, as other characteristics are identical. While from 2016 to 2020, the slope in noise contour growth between the two cases is quite similar, the difference in noise contour growth increases considerably with preceding years (see Fig. 4-19 and Fig. 4-20). This relies on the different aircraft introduction and, hence, fleet mix of the two cases. In the Old Technology Case, mainly CT aircraft types are introduced to the fleet throughout all modelled years. In the Reference Case, between 2016 and 2020, next to NT-1 aircraft, still a significant share of CT aircraft types enter service, which explains the two case's similarity in noise contour evolution up to 2020. Between 2020 and 2035, mainly NT-1 aircraft types are added to the fleet by the Reference Case, leading to growing noise benefits compared to the Old Technology Case[145]. In the years prior to 2040 already a small, yet noticeable share of NT-2 is added to the fleet by the Reference Case, which further increases the noise benefits relative to the Old Technology Case.

As a result, the comparison of Old Technology Case and Reference Case underlines the tremendous influence of the introduction of new aircraft technology on future airport noise. As a "no action scenario" the Old Technology Case may be interpreted as a worst-case scenario in terms of aircraft technology. As seen, noise contours would grow strongly in the future if the aircraft fleet mix remained at a level of the baseline year. Furthermore, the Old Technology Case demonstrates the FFDT's capabilities to consider differing scenarios in terms of future aircraft introduction behaviour on airport noise exposure.

4.8 Low Noise Future Aircraft Case

In this section, a *Low Noise Future Aircraft Case* is presented. Therein, a future low-noise narrow-body study aircraft is assumed to enter service. The question posed by this case is: How would airport noise evolve in the future, if a particularly quiet narrow-body aircraft entered the fleet? Altogether, four different scenarios in the aircraft's noise reduction levels are assessed. Furthermore, two different entry into service years of the study aircraft are examined.

4.8.1 Simulation Input

In order to be able to assess the isolated influence of the noise-reduced study aircraft, the input data of the Low-Noise Future Aircraft Case is based on the input data of the Reference Case. Besides the aircraft introduction input and the additionally specified study aircraft, all other input data is identical to the input of the Reference Case (see Section 4.3.1). The aircraft introduction input and the assessed noise-reduced study aircraft are specified in the following.

[145] Which between 2020 and 2035, in the same way as in previous years, still mainly adds CT aircraft to the fleet.

Definition of the noise-reduced study aircraft:

An overview of the major characteristics of the studied future aircraft type is given in Fig. 4-21. The aircraft to enter service in future years is a twin-engine narrow-body aircraft type based on the Airbus A320.[146] Its assumed seat capacity is specified to 190 seats. In a first series of simulations, the aircraft's entry into service is specified to the year 2035. In a second series, the entry into service is assumed already five years earlier in 2030. In terms of noise reduction, four different scenarios are assessed with differing noise reduction levels as detailed in the following.

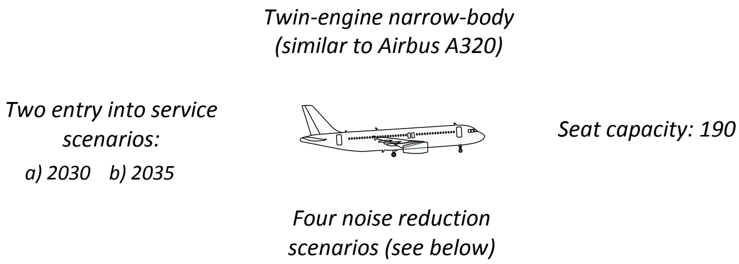

Fig. 4-21 Low Noise Future Aircraft Case: Specifications of the noise-reduced study aircraft

The assumed noise reduction levels of the four study aircraft are listed in Tab. 4-2. Compared to the A320-232, the least noise-reduced study aircraft features a noise reduction of 2.5 dB for approach operations, and 5 dB for departure operations. Three further study aircraft are assumed with further noise reductions of each 2.5 dB for both approach and departure. The noise specification of the most noise-reduced study aircraft thus is 10 dB below the A320 for approach, and 12.5 dB for departure. The noise reduction levels of the study aircraft are larger for departure operations than for approach operations because noise reductions in future aircraft are expected to be stronger for departure operations.[147] The resulting cumulative noise margins[148] respective the Chapter 4 noise limits reach from 21.5 dB up to 44 dB for the four study aircraft.[149]

Aircraft introduction input:

The aircraft introduction input of the Low Noise Future Aircraft Case is based on the Reference Case's aircraft introduction scenario (see Section 3.2.10). For wide-body aircraft, the aircraft introduction input remains identical to the Reference Case throughout all years. For narrow-body aircraft, prior to the entry into service of the study aircraft, the aircraft introduction input is also identical to the Reference Case. However, from the specified

[146] The Airbus A320-232 serves as surrogate model of the study aircraft. The according aircraft-level noise modelling follows the method suggested by Section 3.3.
[147] As previously discussed (see, for instance, Footnote 125).
[148] *Cumulative noise* refers to the sum in noise levels at the three noise certification points. The *margin* describes the difference in measured noise levels to the maximum noise levels allowed by Annex 16. Note that, according to the noise certification process, two departure noise levels („take-off" and „flyover") are included in the cumulative noise levels (see also Section 2.2.2).
[149] For comparison, the Airbus A320-232 has a cumulative noise margin of 9 dB respective the Chapter 4 noise levels. The Airbus A320neo has an according cumulative noise margin of 19 dB.

entry into service year the study aircraft is assumed to be produced and, hence, introduced to the fleet. For all narrow-body aircraft types, the swap factors of the study aircraft is set to 50%. The remaining 50% are defined according to the original aircraft introduction reference scenario, whose swap factors are halved. As a result, after the study aircraft's ramp-up[150], a gap in flight plan of a narrow-body aircraft type is filled with 50% by the study aircraft. An illustration of the resulting swap factors is presented in the Appendix E.[151]

Tab. 4-2 Noise reduction levels of the four study aircraft respective the aircraft type Airbus A320-232

Aircraft	*Approach*	*Departure*	*Cumulative margin (resp. Chapter 4)*
Reduced Noise Study Aircraft	*-2.5 dB*	*-5.0 dB*	*-21.5 dB*
Low Noise Study Aircraft	*-5.0 dB*	*-7.5 dB*	*-29.0 dB*
Very-Low Noise Study Aircraft	*-7.5 dB*	*-10.0 dB*	*-36.5 dB*
Ultra-Low Noise Study Aircraft	*-10.0 dB*	*-12.5 dB*	*-44.0 dB*

4.8.2 Simulation Results

In the following, the flight plan and fleet mix results of the Low Noise Future Aircraft Case as well as the results of the subsequent airport noise calculations are presented.

Fleet Mix and Flight Plan Results

The FFDT is applied to model future flight plans up to the year 2040. The evolution in transport capacity and in aircraft movement numbers is shown in Fig. 4-22. Therein, the Low Noise Future Aircraft Case is presented in dark blue for an entry into service of the study aircraft in 2035; the Reference Case is depicted in darker blue.

As can be seen, the transport capacity behaviour of the two cases is identical because the corresponding air traffic growth input is identical. The resulting aircraft movement numbers of the two compared cases are relatively similar, too. From 2035, yet, the aircraft movement numbers of the Low Noise Future Aircraft Case show a marginally slower growth rate compared to the Reference Case. The reason for this is a marginally stronger increase in the average aircraft seat capacity caused by the introduction of the study aircraft, which is assumed with a seat capacity of 190 (see Fig. 4-21).

[150] To account for the ramp-up in production, the same three-year period as suggested by the aircraft introduction reference scenario is used (see Section 3.2.10).
[151] On the top for narrow-body aircraft, below for wide-body aircraft. The noise-reduced study aircraft is represented by the light blue colour.

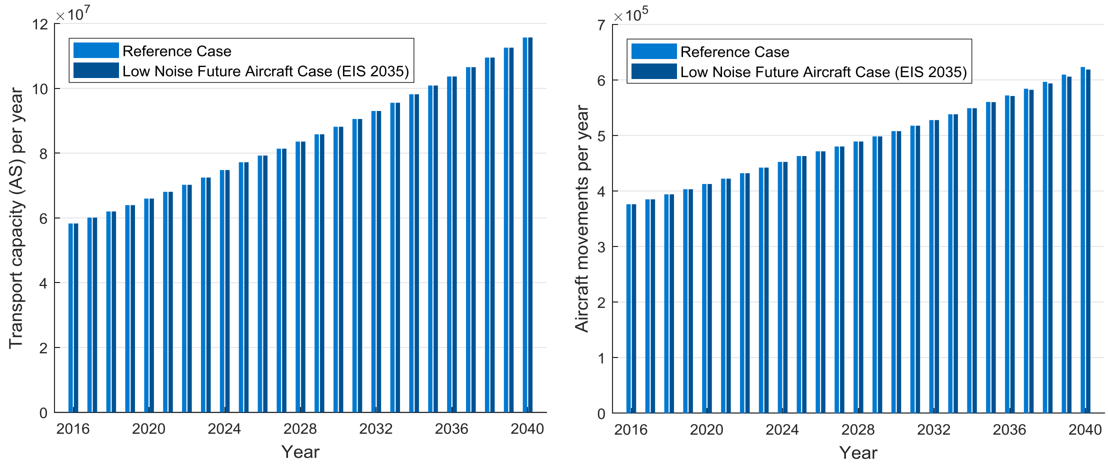

Fig. 4-22 Low Noise Future Aircraft Case: Modelled evolution in transport capacity (on the left) and aircraft movement numbers (on the right)

The evolution of the average aircraft seat capacity in the Low Noise Future Aircraft Case for a 2035 entry into service is presented in Fig. 4-23. The observed differences compared to the Reference Case are minor (see Fig. 4-4). Whereas the developement of the wide-body aircraft fleet is identical to the Reference Case, the seat capacity of the narrow-body aircraft is somewhat different: By 2040, the average seat capacity of the narrow-body aircraft has reached ca. 173 in the Reference Case, and ca. 174.5 in the Low Noise Future Aircraft Case.

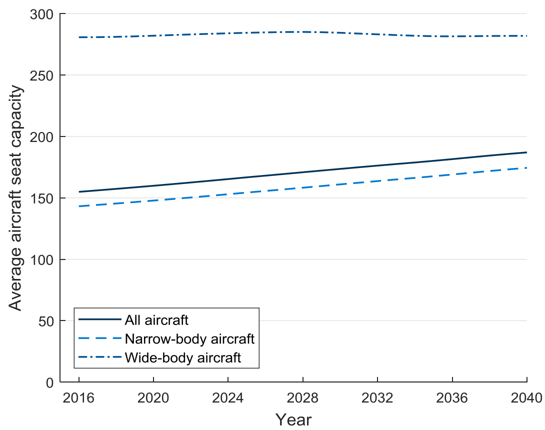

Fig. 4-23 Low Noise Future Aircraft Case (EIS 2035): Modelled evolution of average aircraft seat capacity

Of more interest for the Low Noise Future Aircraft Case is the evolution of aircraft generations as presented in Fig. 4-24. The left chart shows the FFDT results based on the study aircraft's entry into service in 2035, the right figure based on the study aircraft's entry into service in 2030. The evolution of the study aircraft's movement share is depicted in dark grey. As can be seen, following the according entry into service year, the study aircraft's share significantly rises. By 2040, the study aircraft's share increases to ca. 12% for a 2035 entry into service and to ca. 24% for the 2030 entry into service. The aircraft's share increases at a considerable rate, because after ramp-up one in two narrow-body aircraft entering the fleet is of the study aircraft type.[152] Compared to the Reference Case (Fig. 4-4), the study aircraft's share comes at the cost of lower shares of other narrow-body aircraft types. The wide-body aircraft shares evolve in the same way as for the Reference Case, since the according aircraft introduction input is identical.[153]

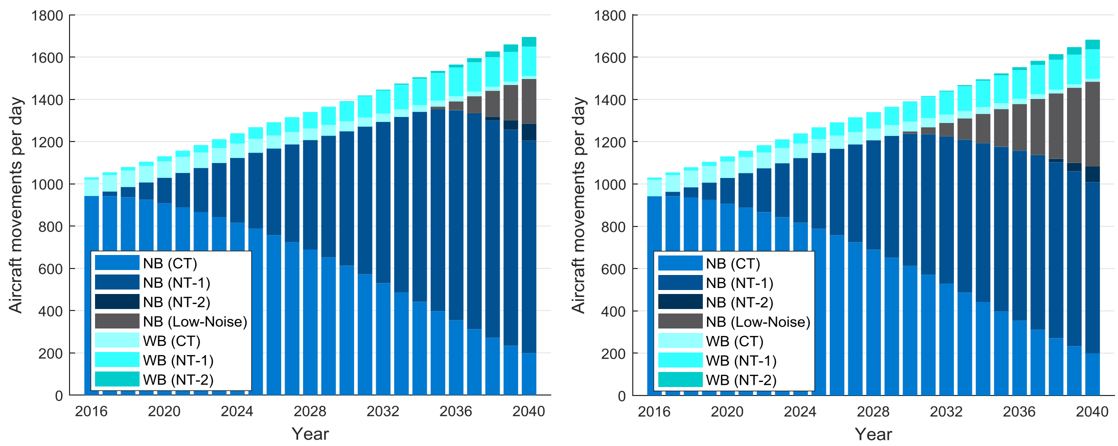

Fig. 4-24 Low Noise Future Aircraft Case: Modelled evolution of aircraft generations for different entry into service years of the low-noise study aircraft: 2035 (on the left) and 2030 (on the right) (Will and Hornung, 2019)

Airport-Level Noise Results

From the modelled future flight plans, airport noise is calculated for the various scenarios defined by Section 4.8.1. Simulations are run considering the study aircraft with each of the four different aircraft-level noise reductions (see Tab. 4-2). The resulting evolution of the 55 dB DEN noise contour area is presented in Fig. 4-25. The results corresponding to the least noise reduced study aircraft are depicted in red, those of the most noise reduced study aircraft in green. Furthermore, simulation results are presented for an assumed entry into service of the study aircraft of 2030 and 2035. For comparisons, the results of the Reference Case are given in grey (dotted line).

According to Fig. 4-25, the 55 dB noise contour area of all simulated scenarios shows a bend from the study aircraft's specified entry into service year. As a result, for the years following the entry into service, all noise contour areas lie below the Reference Case. It can thus be followed that for all four assumed noise reduction levels and for both entry into service years the introduction of the study aircraft is beneficial in terms of airport noise exposure. The extent of the observed benefits, yet, varies between the studied scenarios. For an entry into service in 2035, depending on the aircraft-level noise reduction, the noise contour area decreases by ca. 3% (arrival -2.5 dB/departure -5 dB) to ca. 5% (-10

[152] As defined by to the aircraft introduction input (see Section 4.8.1).
[153] Note that the presented flight plan and fleet mix results in the same way apply for all assessed study aircraft independent from the specific noise reductions. As mentioned, the corresponding scenarios only differ in the study aircraft's noise reduction levels.

dB/-12.5 dB) in 2040 compared to the Reference Case. For an entry into service in 2030, the noise contour area shrinks by ca. 6% (-2.5 dB/-5 dB) to ca. 11% (-10 dB/-12.5 dB). For an entry into service in 2030, three of the four study aircraft noise reduction levels allow the resulting noise contour area by 2040 to be below the level of the baseline year.[154]

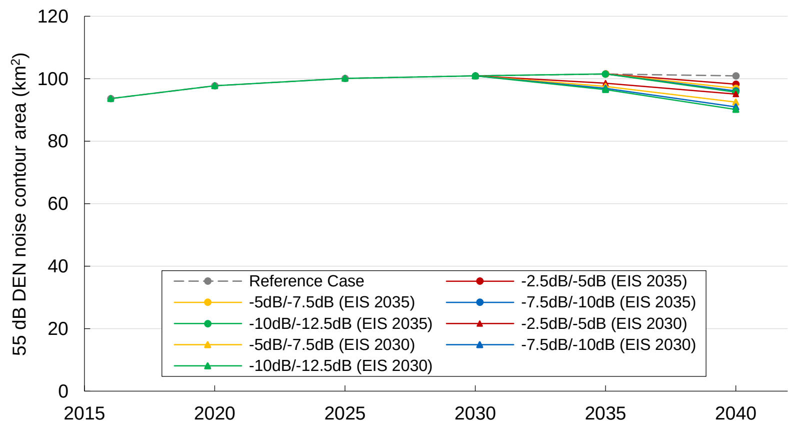

Fig. 4-25 Low Noise Future Aircraft Case: Evolution of the 55 dB DEN noise contour area (Will and Hornung, 2019)

The modelled evolution of the 65 dB noise contour area is shown in Fig. 4-26. Similarly to the 55 dB noise contours, all cases reveal a bend in noise contour area from the respective entry into service year on. The relative decrease as compared to the Reference Case is somewhat larger than for the 55 dB noise contours.[155] For an entry into service of the study aircraft in 2035, by the year 2040 the noise contours are by ca. 3% (-2.5 dB/-5 dB) to ca. 7% (-10 dB/-12.5 dB) lower than the Reference Case. For an entry into service of the study aircraft in 2030, compared to the Reference Case the noise contour areas in 2040 decrease by even ca. 7% (-2.5 dB/-5 dB) to ca. 15% (-10 dB/-12.5 dB). Even for the study aircraft's later entry into service in 2035, the noise contour areas of all assessed cases by 2040 can be reduced below the level of the baseline year.

A further relevant effect is found in a more detailed comparison of the simulation results for different aircraft-level noise reductions of the study aircraft. As can be seen from both Fig. 4-25 and Fig. 4-26, additional noise reductions of the study aircraft by 2.5 dB do not manifest in an equivalently strong noise contour area reduction. In fact, increasing the aircraft-level noise reduction from 2.5 dB/5 dB to 5 dB/7.5 dB has a larger airport-level benefit than the same additional noise reduction of 2.5 dB from 5 dB/7.5 dB to 7.5 dB/10 dB. A further aircraft-level noise reduction to 10 dB/12.5 dB shows to reduce noise contour area only marginally. This saturation effect is caused by the fact that metrics

[154] For an entry into service in 2035, the noise contour areas by 2040 are still slightly above the level of the baseline year.
[155] This, as previously discussed, is caused by the higher noise reduction levels of the study aircraft for departure operations than for approach operations.

based on the equivalent continuous sound level, such as the DEN, are particularly determined by the louder noise events.[156] As a result, the potential of an ever-increasing noise reduction of the study aircraft to reduce airport noise exposure is limited as long as other aircraft still emit significantly louder noise levels.[157]

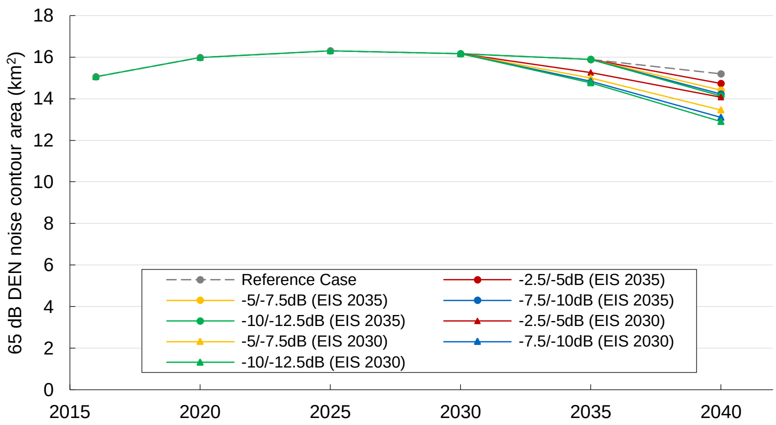

Fig. 4-26 Low Noise Future Aircraft Case: Evolution of the 65 dB DEN noise contour area (Will and Hornung, 2019)

In summary, the introduction of the study aircraft proves to be significant in all simulated scenarios. As seen, the extent of the benefit increases, firstly, with higher aircraft-level noise reductions of the study aircraft and, secondly, with an earlier entry into service of the study aircraft. Furthermore, the results allow a comparison between the effect of aircraft-level noise reduction and the effect of the entry into service year. For the input assumptions[158] of the Low Noise Future Aircraft Case the results show that in 2040 a five year's difference in the study aircraft's entry into service is more significant to airport noise than an additional 7.5 dB noise reduction.[159] In other words, if the aviation industry were to decide, on the one hand, between a future narrow-body aircraft with given noise reductions and given entry into service, and, on the other hand, the aircraft entering service five years earlier, yet with 7.5 dB lower noise reductions, the latter may be more effective for noise mitigation. Finally, the Low Noise Future Aircraft Case demonstrates the framework's capabilities to model the impact of future aircraft entering service on airport noise.

4.9 Discussion and Summary of Scenario-Specific Findings

In the previous sections, multiple scenarios have been modelled for the purpose of demonstrating the general capabilities of the developed FANAM approach. In this section, firstly,

[156] For instance, a single noise event of 90 dB is equivalent to ten noise events of 80 dB.
[157] Such as CT/NT-1 narrow-body aircraft or wide-body aircraft.
[158] Most importantly, a 50% share of the study aircraft from all narrow-body aircraft to enter service. Before reaching "full production" a three-year ramp-up period of the study aircraft is assumed (see Section 4.8.1).
[159] The least noise-reduced study aircraft compared to the most noise-reduced study aircraft is reduced by a further 7.5 dB in noise emissions for both approach and departure operations (see Tab. 4-2).

a comparison of the Reference Case with related studies found in the literature is presented. Then, a number of relevant scenario-specific findings as result of the undertaken simulations are summarised.

It is helpful to compare the results of the Reference Case[160] (see Section 4.3) with the results of future airport noise studies found in the literature. It is to mention, though, that these results are only comparable to a limited extent, e.g. due to different modelled periods of time or different air traffic growth assumptions. A further difficulty in the comparison of the results arises from the fact that the methods and assumptions are not always clearly stated by the available reports. However, due to a lack of data with higher comparability, the results of these studies are presented in order to provide some reference for the results of the Reference Case. The results of the seven studies presented in Section 2.3 are briefly discussed in the following.

1. The study by ANOTEC projects the accumulated noise exposure of 53 European airports into the future (ANOTEC Consulting, 2003). From a baseline year in 2002 airport noise is projected for the years 2007 and 2015. The estimations result in an expected moderate growth in accumulated airport noise exposure within the studied period of 13 years.[161]
2. The study by the ERCD/CAA estimates airport noise of Heathrow Airport from a baseline year in 2002 for the years 2015, 2020, and 2030 (Rhodes and Beaton, 2007). Compared to the year 2002 the study estimates airport noise to decrease slightly by 2015 and to decrease significantly by 2030.
3. The report by the ICAO includes estimations on the future aircraft noise exposure at a global level (International Civil Aviation Organization, 2010). Starting from 2006, the accumulated airport noise is projected for the years 2016, 2026, and 2036. The report indicates that the global noise exposure will moderately grow within the modelled time period, yet “at a rate far slower than the demand for air travel” (International Civil Aviation Organization, 2010, p. 24).[162]
4. The report by Sustainable Aviation examines the accumulated future airport noise exposure of the combined UK airports (Sustainable Aviation, 2013). From a baseline year in 2010, future airport noise is projected up to the year 2050. The results suggest airport noise to remain at a constant level until 2025. From the year 2025 up to 2050, a continuous reduction in airport noise is estimated.
5. The study by Bernardo et al. examines the design space of future fleet-level noise from the simulations of eight generic airports (Bernardo et al., 2016). Whereas the baseline year is not explicitly stated[163], the target year of the simulations is 2030. The mean of

[160] Which, from all cases of the application case may be regarded as the most plausible scenario.
[161] Note that the studied period entirely lies before the time period examined in this thesis (which is from 2016 to 2040).
[162] Note that global air traffic is generally expected to grow stronger than European air traffic.
[163] Possibly the year 2014.

the simulated scenarios estimates fleet-level noise to slightly grow within the assessed period of time.

6. The study by Torija et al. estimates the evolution of future UK airport noise for different aircraft-level noise reduction scenarios (Torija et al., 2016). With a baseline year in 2010, airport noise is projected up to 2050. The results present a slight increase in airport noise until 2025, when new aircraft types are assumed to enter service. From 2025, depending on the assumed aircraft-level noise reductions, airport noise contours by 2050 lie within the range of a slight increase to a considerable decrease with respect to the year 2010.
7. The study by LeVine et al. projects fleet-level noise from the simulations of eight generic airports (LeVine et al., 2018). From a baseline year in 2015, results are modelled up to 2050. The paper states that with increased air traffic the projected cumulated noise remains "relatively static" (LeVine et al., 2018, p. 18) over the assessed time period; in other words, no significant decrease or increase is estimated.

The general trend of the seven studies does not present an entirely homogenous picture. This is not surprising given the variations in the scope and the underlying methodologies. However, it can be stated that the studies neither expect airport noise to drastically worsen nor to drastically improve in the future. In addition, the modelled reductions in airport noise tend to be expected mainly on the medium- and long-term rather than on the short-term. Keeping in mind that the study airport of this thesis is assumed to lie in Western Europe[164], the Reference Case (see Fig. 4-27) lies well within the range of the studies found in literature. The general picture of the related airport noise studies thus underlines the plausibility of the modelled Reference Case.

At this point, it is to mention that the uncertainty concerning future air traffic growth is likely to be larger than the uncertainty regarding the future fleet turnover.[165] As demonstrated by the No Growth Case, the air traffic growth has a strong influence on future airport noise. For this reason, the accuracy of the Reference Case strongly depends on the accuracy of the air traffic growth assumptions, which rely on the growth rates of the Airbus GMF. Significant over- or underestimations by the Airbus GMF will therefore lead to significant over- or underestimations of the Reference Case's resulting airport noise.

As a summary, Fig. 4-27 presents different projections of the evolution in airport noise modelled by the application case. On the one hand, the No Growth Case leads to significant reductions in airport noise as result of the modelled fleet renewal process. On the other hand, the Old Technology Case is subject to a significant increase in airport noise due to its increased air traffic. The trend of the Reference Case, which includes both the effect of future air traffic growth and the effect of future fleet renewal, lies between the

[164] With lower expected traffic growth compared to the global air traffic.

[165] At least on the short- and medium-term. On the long-term, the aircraft types available at the market and, hence, the future aircraft introduction must be considered as highly uncertain, too.

former two. Furthermore, Fig. 4-27 depicts the Low Noise Future Aircraft Case corresponding to the study aircraft reduced by -5 dB/-7.5 dB.[166] As can be seen, the introduction of the study aircraft, though obviously not in the range of the two extreme cases, is able to reduce airport noise noticeably.

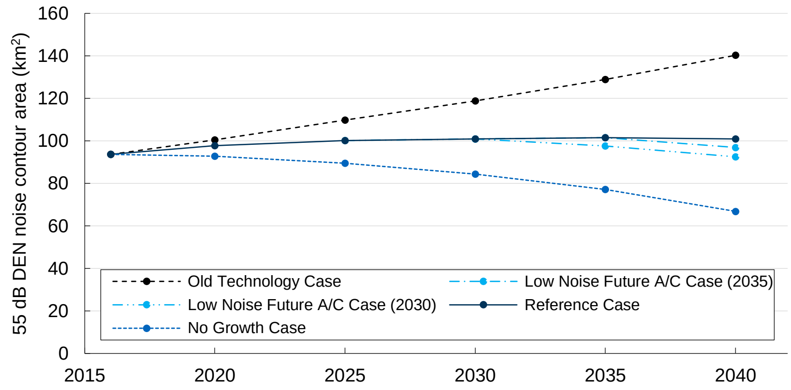

Fig. 4-27 Summary of the modelled evolution in 55 dB noise contour area of different scenarios. The Low Noise Future Aircraft Case features the -5 dB/-7.5 dB (arrival/departure) reduced study aircraft as modified from Will and Hornung (2019)

Altogether, from the evaluation of the different scenarios assessed by the application case, the following key findings can be summarised:

1. As a major result, according to the Reference Case, which follows the traffic growth assumptions of the Airbus Global Market Forecast, airport noise exposure at the study airport will marginally increase on the short-term, then level off[167], and approaching the year 2040 marginally decrease[168].
2. The Constrained Case suggests that at the study airport, negative effects from airport capacity constraints on the resulting DEN levels become relevant starting from 2030.[169] With proceeding years, the negative effects will grow and lead to severe deteriorations by the year 2040.
3. The One Operating Direction Case reveals that the operating direction at the studied airport only has a marginal influence on noise contour areas. No significant advantage is found if the airport is entirely operated in either direction of the runway system. However, for local noise levels the operating direction can be of crucial importance.
4. The No Growth Case and the Old Technology Case show that both the future air traffic growth and the future fleet renewal process have a strong influence on future airport noise. The relatively constant development of future airport noise in

[166] Originally, four different noise reduction scenarios have been assessed by the Low Noise Future Aircraft Case (see Section 4.8).
[167] With a maximum between 2025 and 2035 depending on the assessed noise level.
[168] In particular, for louder noise levels (65 dB).
[169] Assessing a representative day based on averaging the flight plan of an entire year.

the Reference Case implies that the positive impact resulting from the aircraft fleet modernisation is in the same order of magnitude as the negative impact resulting from the increased air traffic.

5. The Low Noise Future Aircraft Case suggests that the introduction of a hypothetical low-noise narrow-body aircraft may allow noticeable airport-level noise reductions. The airport noise exposure benefits from increasing aircraft-level noise reductions and from an earlier entry into service of the study aircraft. The results point out that, generally speaking, an earlier entry into service of the study aircraft can be more effective than significantly increased aircraft-level noise reductions.
6. Furthermore, the Low Noise Future Aircraft Case reveals saturation effects regarding airport-level noise for increasing noise reductions of the study aircraft. This demonstrates that the airport-level benefit of increased vehicle-level noise reductions of only a share of the entire fleet is limited as long as louder aircraft are still present in the fleet.[170]

4.10 Review and Evaluation of the Developed Framework

The previous section has focused on an evaluation of the simulation results of the particular scenarios examined by the application case. This section is dedicated to a review of the developed framework itself. In the following, the major capabilities and limitations of the FANAM approach are summarised.

Major capabilities of the approach

- FANAM may be applied to arbitrary airports. This includes the ability to study arbitrary geometries with respect to runway system layout and flight routes (SIDs/STARs). The high flexibility in the assessment of different airport geometries is enabled by the modelling capabilities of the AEDT.[171] Moreover, arbitrary baseline flight plans may be processed by FANAM, which is enabled by a flexible structure of the developed FFDT. As a result, FANAM may principally be applied to any given airport.
- At a specific airport, the developed FFDT allows a user to consider multiple noise-relevant effects in the study of future airport noise. In detail, the FFDT is able to model the impact of the following effects on future flight plans and, hence, on future airport noise.

[170] Due to the fact that continuous sound pressure levels are strongly determined by the loudest noise events.
[171] Note that, as presented in Section 2.3, some related studies found in the literature have developed own airport-level noise modelling capabilities, which, notwithstanding possible advantages, may be less flexible than the AEDT in modelling relevant airport geometries (e.g. restricted to single-runway airports or to straight-in/straight-out flight routes).

- Future air traffic growth:
  Air traffic growth rates may be defined at an annual basis. Furthermore, air traffic growth rates may be differentiated according to world regions.[172]
- Future aircraft retirement:
  The modelled aircraft retirement is determined through retirement curves, which quantify an aircraft type's percentage of survival as a function of aircraft age. In this thesis, the FFDT's default retirement curves are used as derived in previous research. If desired, yet, the default retirement curves may be replaced with other user-defined retirement curves.
- Future aircraft introduction:
  The future aircraft introduction may be defined at an annual basis, too. This, amongst others, allows a user to specify any modelled year for a certain future aircraft type to enter service. The FFDT principally allows the specification of individual aircraft introduction rules for each aircraft type to be replaced.[173] In the definition of aircraft introduction rules for a specific aircraft type to be replaced, arbitrary combinations of other aircraft types may be specified.
- Airport capacity constraints:
  Airport capacity constraints are defined through the specification of the airport's maximum hourly throughput. In this, any value may be defined corresponding to the specific airport under consideration.
- Flight route (SID/STAR) distribution:
  The flights of a modelled future flight plan may be arbitrarily distributed onto the airport's different flight routes. In this, user-defined entry/exit points may be defined and assigned to each origin/destination airport.[174] Moreover, for each entry/exit point the user may define the distribution of flights onto the different SIDs/STARs leading to the airport. Through this, the user can also specify the runway usage of a scenario.[175]

- FANAM relies on an iterative modelling of the future fleet mix depending on scenario-specific inputs, rather than applying a-priori assumptions on the future fleet mix of a future year.[176] The particular fleet mix of a simulation results from the baseline flight plan and the input specifications concerning air traffic growth, air-

[172] Different air traffic growth rates may be defined for different world region pairs, which describe air traffic between two regions of the world.
[173] In the application case of this thesis, aircraft-type specific introduction rules were not applied. Instead, the same aircraft introduction rules were applied for all narrow-body aircraft, and the same introduction rules for all wide-body aircraft.
[174] Realistically, this should not be regarded as a free scenario input. To minimise flight distances, an entry/exit point in the direction of the corresponding origin/destination airport should be chosen.
[175] That is, which runways are used to what proportion (for arrivals as well as for departures).
[176] As found in some of the related studies (see Section 2.3).

craft retirement, and aircraft introduction. Furthermore, in the FFDT's determination of a future fleet mix, the average aircraft seat capacity is a non-predetermined degree of freedom.[177]

- As result of the FFDT's iterative modelling based on individual years, the user may principally select any desired target year.[178]
- In the consideration of the various aircraft types of a fleet, FANAM describes the fleet at an aircraft-type level.[179] FANAM abstains from high-level fleet simplifications and, hence, from possibly resulting inaccuracies.
- As of aircraft-level noise modelling, FANAM applies the well-accepted modelling procedures proposed by ECAC Doc. 29. The particular aircraft models are used as published by Eurocontrol in its aircraft noise and performance database.
- FANAM offers a high level of automation in the execution of airport-level noise studies. Based on the user-defined input data, the FFDT automatically creates an entire AEDT Standard Input File that can subsequently be loaded into the AEDT. This generated file fully defines an airport noise simulation, which leads to low set-up times of different scenarios at a given airport.

Major limitations of the approach

As mentioned earlier, it is the nature of any model to make assumptions and simplifications. The major limitations of the proposed FANAM approach are listed in the following:

- FANAM is limited to noise emissions from airliners. The current method does not consider flight operations of non-airliners, such as cargo aircraft, general aviation aircraft, or helicopters. Furthermore, FANAM does not consider ground noise, such as from taxiing aircraft or from APU noise.[180]
- The FFDT assumes one "world airline" to operate all flights at a studied airport. Therefore, airport-specific fleet effects concerning the retirement and introduction of aircraft as result of individual airlines' strategies are not considered by the method.
- The FFDT is limited in the modelling of negative air traffic growth rates. For sufficiently large negative growth rates, the current version of the FFDT introduces errors.
- The retirement modelling applied by the FFDT relies on statistical, static retirement curves. As a result, aircraft are retired in the same manner independently

[177] Depending on the scenario-specific input. This capability is enabled through the FFDT modelling future air traffic at a passenger transport level (in AS) rather than at an aircraft movement level.
[178] Rather than being able to select target years only from larger intervals (e.g. of 5 years). Obviously, for later target years the required input data and, hence, the FANAM results are expected to become less accurate.
[179] In accordance with the applied OAG database, which applies IATA codes in the description of aircraft types. This aircraft type-level consideration stands in contrast to a possible substitution of the fleet with a smaller number of representative aircraft types.
[180] Noise emitted by departing/arriving aircraft on the runway are not counted as ground noise and are therefore considered by FANAM.

from other effects; for instance, the same retirement behaviour is modelled during times of recession and during periods of strong traffic growth.[181]

- In the modelling of the effect of airport capacity constraints, all flights exceeding the hourly throughput are shifted to the nearest free hours of a day. In reality, a certain share of the shifted flights might not actually be operated, which can be interpreted as a demand spill.[182]
- In order to consider future aircraft types without a given aircraft model, FANAM relies on a surrogate aircraft approach. As a result, FANAM does not explicitly model new flight procedures of future aircraft types.[183] This limitation is assumed to be particularly relevant if unconventional aircraft configurations with significantly different flight trajectories[184] are to be considered by FANAM.

[181] In reality, airlines may delay planned retirements during years of unexpectedly strong traffic growth.
[182] Consequently, FANAM's consideration of airport capacity constraints may be regarded as a worst-case estimation in terms of the resulting airport noise.
[183] However, improved flight procedures are implicitly considered through the consideration of noise certification levels. Noise certification levels benefit from both the effect of source noise reduction and from the effect of improved flight procedures.
[184] Compared to current tube-and-wing aircraft concepts.

5 Conclusions

5.1 Summary

In this thesis, a novel and comprehensive method for the assessment of future airport noise has been presented. Since aircraft noise is a significant challenge for the aviation industry, effective measures are required to mitigate airport noise in the future. The developed method offers versatile modelling capabilities to gain insight into the future development of airport noise, which can help define the right noise-mitigation strategies.

Two primary goals have been achieved by the presented research. Firstly, a theoretical method was defined for impact assessments of future airport noise. Secondly, the developed method was implemented in a framework that allows a user to efficiently conduct future airport noise studies.

In short, the method estimates future airport noise from the modelling of future flight plans and the modelling of aircraft noise at the vehicle level. Future flight plans are modelled based on a flight plan of a baseline year considering the assumed future evolution of multiple noise-relevant effects. The aircraft-level noise modelling applies an approach suggested by the European Civil Aviation Conference. The airport-level noise modelling capabilities are provided by the FAA's Aviation Environmental Design Tool (AEDT), which is the successor to the Integrated Noise Model. This thesis evaluates DEN levels, as suggested by the European Union; however, the AEDT is able to assess other noise metrics, too.

The resulting framework may be applied to arbitrary airports. At a given airport, a user may study a wide range of future scenarios considering the effects of air traffic growth, aircraft retirement, the fleet mix of aircraft entering service, airport capacity (maximum throughput) and route distribution (SID/STAR). For example, in terms of aircraft introduction, the user is able to examine the effect of a future aircraft type entering service in a user-defined year according to user-specified aircraft-level noise reductions.

A main advantage of the method lies in the dynamic flight plan and fleet mix modelling, which allows very flexible scenario definitions based on the annually defined user input. A further advantage is that future air traffic is modelled at a passenger transport level, which leaves aircraft seat capacity a degree of freedom. An additional advantage is the framework's significant degree of automation. For a given airport and based on the user's scenario input, the implemented Future Flight Plan Development Tool automatically generates a single XML file that entirely defines an airport noise simulation.

An important limitation of the method is found in the surrogate aircraft approach that is applied in the modelling of future aircraft. As a result, future aircraft types are assumed to have the same flight performances and trajectories as its surrogate aircraft type. This approach is a significant drawback if radical aircraft concepts, such as blended wing body configurations, are to be considered by the method.

Furthermore, this thesis assumes ATM rules will remain constant in the future. The current method applies the approach and departure procedures of the baseline year for all future years to be modelled. In reality, future changes in ATM rules may allow further noise reductions. As an example, continuous descent approaches or steeper glide slope angles may mitigate aircraft noise during approach. Operational improvements were not in the scope of this thesis.

With regards to validation, the flight plan modelling has been validated through simulations of historic developments at Munich Airport. The simulations revealed that the aircraft movement numbers were moderately overestimated by the model as in reality, the growth in average aircraft seat capacity at Munich Airport was unexpectedly strong during the modelled period from 2008 to 2016. Generally, the validation of the flight plan modelling showed expected and plausible results. A validation of the airport-level noise modelling was not necessary as the framework uses the FAA's Aviation Environmental Design Tool. A validation of the ECAC's widely accepted aircraft-level noise modelling approach and of the applied aircraft models provided by Eurocontrol was not required, either.

To demonstrate the different capabilities of the method, the developed framework was used to study several relevant scenarios from the example of a two-runway airport. In a first unconstrained Reference Scenario, a plausible development of future airport noise was estimated starting from a baseline year in 2016. Air traffic growth was assumed according to the Airbus Global Market Forecast, aircraft retirement curves according to previous research at the Institute of Aircraft Design, and aircraft introduction based on the analysis of OEMs' open aircraft orders. On the middle and long term, future aircraft types were postulated according to the noise reduction goals published by the ICAO's Committee on Aviation Environmental Protection (CAEP). It was found that airport noise at the study airport would slightly increase on the short term, then level off and slightly decrease until 2040, during which time passenger traffic demand would approximately double. A comparison of the Reference Case with the results of related studies found in the literature revealed good agreement with the generally projected trends concerning future airport noise.

In a second scenario, the impact of airport capacity constraints on airport noise exposure was assessed. For this, the maximum throughput at the study airport was limited to 90 movements per hour for all future years. The results showed that due to flights being shifted to less frequented hours of the day, the DEN levels increase starting from around 2030 with significant negative effect by 2040.

In a third scenario, the impact of the operating direction on airport noise was assessed, assuming the study airport to be entirely operated in an easterly or westerly direction. Compared to a 40% to 60% (easterly/westerly) operation, none of the two extreme cases showed a significant difference in noise contour area.

In a fourth scenario, the development of future airport noise was examined if air traffic demand remained at the level of the baseline year for all future years. As a result of the isolated effect of aircraft fleet turnover, airport noise improves strongly until 2040.

In a fifth scenario, the aircraft fleet was kept unchanged for all future years, while air traffic growth was assumed according to the Airbus Global Market Forecast. With this "frozen" aircraft fleet, airport noise was shown to increasingly worsen with strong effects by 2040.

In a last scenario, a noise-reduced narrow-body study aircraft was assumed to enter the fleet in the future. The aircraft type, which would make up 50% of all narrow-body aircraft entering service, was assessed for four different noise reduction levels and for two different entry into service years. In all cases, a positive effect on airport noise was noticeable with an increasing influence of earlier entry into services and stronger vehicle-level noise reductions. However, the results also showed that the ability of a single noise-reduced aircraft type to reduce overall airport noise is limited. Noise reductions of subsets of the entire fleet lead to saturation effects at the airport level because loud noise events dominate the resulting continuous sound levels. In the specific simulations, it was further found that in 2040 an entry into service of the study aircraft five years earlier is more beneficial to airport noise than a 7.5 dB reduction in the aircraft's noise emission. As a relevant result, the assessed scenarios confirm the importance of the aviation industry's efforts to reduce future airport noise through the introduction of new aircraft technology.

In this thesis, the influence of psychoacoustic effects was not regarded. However, it is well known that individuals may react quite differently to the same noise events. In this, the subjective annoyance perceived by humans significantly relies on factors that go beyond physical sound levels. For instance, it is debatable how well continuous sound levels, as used in this thesis, reflect the negative effects of aircraft noise on residents who live in the vicinity of an airport. Although it is common to quantify airport-level noise by continuous sound levels, residents may suggest that the actual amount of noise events (overflights) is of higher relevance than continuous sound levels. Number above threshold (NAT) criteria, which count the noise events above a specified noise threshold, were not assessed within the thesis.

Altogether, this thesis has proposed a novel method that offers a wide range of future airport noise assessments. The implemented framework allows an efficient application of the method in the actual calculation of different scenarios. The simulation results may then provide important insights to help various aviation stakeholders in the definition of effective aircraft-level, airport-level and fleet-level noise mitigation strategies.

5.2 Outlook

In the following, multiple recommendations for future work are discussed. Both possible improvements to the developed framework itself as well as possible research questions to be assessed in greater detail are suggested.

First of all, the developed flight plan modelling approach, as previously discussed, is currently limited to positive traffic growth rates due to the strict statistical retirement approach, which does not retire additional aircraft in years of strong negative traffic growth. This limitation could be addressed in order to correctly model negative air traffic growth in the future.

Furthermore, more detailed focus could be laid on the airport capacity modelling. Due to the approach of shifting excess aircraft movements entirely to the nearest free hours, the capacity module currently quantifies a worst-case scenario in terms of airport noise. Future work could assess how precisely the shifting approach represents the reality, especially if air traffic demand strongly exceeds the airport capacity. In addition, night-time restrictions could be implemented into the airport capacity modelling to prohibit a shifting of operations to specified restricted hours during the night.

The probably most laborious possibility for future work is to fundamentally question the applied surrogate aircraft approach in the modelling of future aircraft. One goal could be to develop a novel aircraft-level noise modelling approach that is able to describe the flight procedures and the noise emissions of future aircraft concepts. This would require, among other things, sufficiently precise thrust and trajectory modelling based on the limited knowledge of future aircraft.

Further future work is recommended in the analysis of the various impacts considered by the developed method. As a first suggestion, the impact of aircraft retirement behaviour could be analysed using the method, for instance the effect of a significantly accelerated (or decelerated) aircraft retirement behaviour. Moreover, with the method the impact of decoupling aircraft movement growth from passenger traffic growth could be further examined. In this, the effect of increased passenger capacity allowing for decreased movement numbers at the cost of possibly larger and, hence, usually louder aircraft could be studied in detail.

Furthermore, the method could be applied within technology evaluation of future aircraft. Usually, research and industry evaluate the noise emission of new aircraft concepts at the vehicle level. However, the impact of the noise reduction of a future aircraft concept could also be evaluated at the airport- or fleet level. This impact could be analysed depending on the entry into service year and the share of the aircraft type of all aircraft to enter service. In a similar way, with the method the impact of the noise emission reduction of different aircraft segments, e.g. the large narrow-body aircraft segment, on overall airport noise could be assessed. According studies may provide useful suggestions to aviation stakeholders on how to focus future aircraft noise research to the most effective scope.

Next to these high-level developments further questions might be of particular interest in the assessment of local airport situations. At a given airport, the framework would allow quick assessments of various operational scenarios with respect to route distributions and runway usage. For airports operating close to the airport's maximum capacity, a significant question to be answered by the method is the impact of an additional runway on future airport noise.

It is important to highlight that the answers to the above-mentioned questions will not be identical for different airports. Therefore, further research might address the difference of the modelled airport-level noise trends at different airport types. This also points to another fact worth mentioning. All of the proposed research questions could be answered at two different levels of detail. Firstly, the questions could be studied at a strategic or system level, for example from a set of representative airports. This would provide the aviation industry with high-level suggestions for the general definition of noise mitigation strategies. Secondly, the discussed questions could also be assessed at a local level, that is, at a specific real airport. This would allow the local stakeholders of a given airport to analyse and decide on airport-specific measures.

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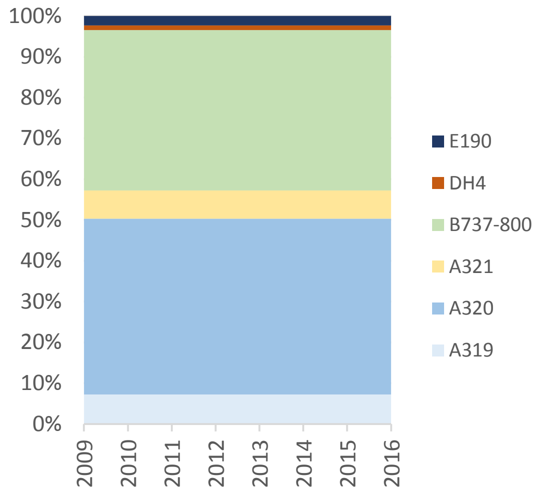
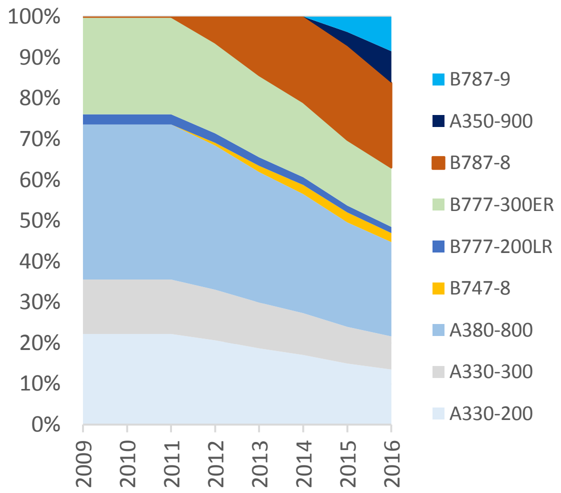
Appendix

A Aircraft Introduction Input of the Validation Case





B Overview of Aircraft Types Considered by the Application Case

Aircraft Type	IATA / FFDT Aircraft Code	Manufacturer	Aircraft Category	Aircraft Generation	Retirement Cluster	Aircraft-Level Noise Modelling Approach	Surrogate/Substitution Aircraft Type	ANP / AEDT Aircraft Code	Aircraft Introduction Reference Scenario: Aircraft Introduced	Aircraft Introduction Reference Scenario: Entry Into Service Year	Aircraft Introduction Reference Scenario: End of Production Year
100	*100*	*Fokker*	*NB*	*CT*	*4*	*ANP*		*F10065*	*NO*		
146-200	*142*	*British Aerospace*	*NB*	*CT*	*4*	*ANP*		*BAE146*	*NO*		
146-300	*143*	*British Aerospace*	*NB*	*CT*	*4*	*ANP*		*BAE300*	*NO*		
2000	*S20*	*Saab*	*NB*	*CT*	*6*	*ANP*		*HS748A*	*NO*		
328JET	*FRJ*	*Dornier*	*NB*	*CT*	*4*	*ANP*		*CNA750*	*NO*		
50	*F50*	*Fokker*	*NB*	*CT*	*4*	*ANP*		*HS748A*	*NO*		
70	*F70*	*Fokker*	*NB*	*CT*	*4*	*ANP*		*F10062*	*NO*		
A310	*310*	*Airbus*	*WB*	*CT*	*7*	*ANP*		*A310-304*	*NO*		
A318	*318*	*Airbus*	*NB*	*CT*	*4*	*ANP*		*A319-131*	*NO*		
A318/319 /320/321	*32S*	*Airbus*	*NB*	*CT*	*9*	*ANP*		*A320-211*	*NO*		
A319	*319*	*Airbus*	*NB*	*CT*	*9*	*ANP*		*A319-131*	*NO*		
A320	*320*	*Airbus*	*NB*	*CT*	*9*	*ANP*		*A320-211*	*YES*		*2018*
A320-200 (Sharklets)	*32A*	*Airbus*	*NB*	*CT*	*9*	*ANP*		*A320-211*	*NO*		
A320neo	*320NEO*	*Airbus*	*NB*	*NT-1*	*9*	*NRV-Method*	*A320*	*Airbus A320NEO FW*	*YES*	*2016*	
A321	*321*	*Airbus*	*NB*	*CT*	*9*	*ANP*		*A321-232*	*YES*		*2019*
A321-200 (Sharklets)	*32B*	*Airbus*	*NB*	*CT*	*9*	*ANP*		*A321-232*	*NO*		

A321neo	321NEO	Airbus	NB	NT-1	9	NRV-Method	A321	Airbus A321NEO FW	YES	2017	
A330	330	Airbus	WB	CT	7	ANP		A330-301	NO		
A330-200	332	Airbus	WB	CT	8	ANP		A330-343	YES		2020
A330-300	333	Airbus	WB	CT	7	ANP		A330-301	YES		2020
A330-800neo	338	Airbus	WB	NT-1	8	Substitution	B787-9	B787-9 FW	YES	2018	
A330-900neo	339	Airbus	WB	NT-1	7	Substitution	B787-9	B787-9 FW	YES	2018	
A340-300	343	Airbus	WB	CT	8	ANP		A340-211	NO		
A340-500	345	Airbus	WB	CT	8	ANP		A340-642	NO		
A340-600	346	Airbus	WB	CT	8	ANP		A340-642	NO		
A350-1000	351	Airbus	WB	NT-1	2	NRV-Method	A330-200	A350-1000 FW	YES	2017	
A350-900	359	Airbus	WB	NT-1	8	NRV-Method	A330-200	A350-941 FW	YES	2014	
A380-800	388	Airbus	WB	NT-1	2	ANP		A380-841	YES	2007	
B717	717	Boeing	NB	CT	9	ANP		717200	NO		
B737	737	Boeing	NB	CT	9	ANP		737800	NO		
B737-300	733	Boeing	NB	CT	9	ANP		737300	NO		
B737-300 (Winglets)	73C	Boeing	NB	CT	9	ANP		737300	NO		
B737-400	734	Boeing	NB	CT	9	ANP		737400	NO		
B737-500	735	Boeing	NB	CT	9	ANP		737500	NO		
B737-600	736	Boeing	NB	CT	9	ANP		737700	NO		
B737-700	73G	Boeing	NB	CT	9	ANP		737700	NO		
B737-700 (Winglets)	73W	Boeing	NB	CT	9	ANP		737700	NO		
B737-700 Combi	73R	Boeing	NB	CT	9	ANP		737700	NO		
B737-800	738	Boeing	NB	CT	9	ANP		737800	YES		2019
B737-800 (Winglets)	73H	Boeing	NB	CT	9	ANP		737800	NO		
B737-900	739	Boeing	NB	CT	9	ANP		737800	YES		2020
B737-900 (Winglets)	73J	Boeing	NB	CT	9	ANP		737800	NO		
B737-MAX8	737MAX8	Boeing	NB	NT-1	9	NRV-Method	B737-800	B737-MAX8 FW	YES	2017	

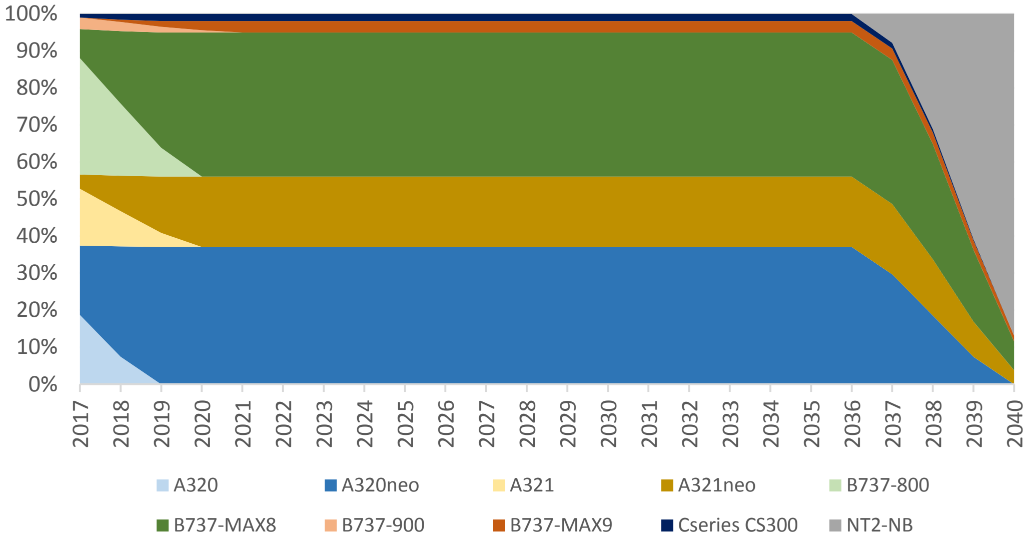
B737-MAX9	*737MAX9*	*Boeing*	*NB*	*NT-1*	*9*	*Substitution*	*B737-MAX8*	*B737-MAX8 FW*	*YES*	*2018*	
B747	*747*	*Boeing*	*WB*	*CT*	*2*	*ANP*		*747400*	*NO*		
B747-400	*744*	*Boeing*	*WB*	*CT*	*2*	*ANP*		*747400*	*NO*		
B757	*757*	*Boeing*	*NB*	*CT*	*7*	*ANP*		*757300*	*NO*		
B757-200	*752*	*Boeing*	*NB*	*CT*	*7*	*ANP*		*757PW*	*NO*		
B757-200 (Winglets)	*75W*	*Boeing*	*NB*	*CT*	*7*	*ANP*		*757PW*	*NO*		
B757-300	*753*	*Boeing*	*NB*	*CT*	*7*	*ANP*		*757300*	*NO*		
B757-300 (Winglets)	*75T*	*Boeing*	*NB*	*CT*	*7*	*ANP*		*757300*	*NO*		
B767	*767*	*Boeing*	*WB*	*CT*	*7*	*ANP*		*767300*	*NO*		
B767-300 / 300ER	*763*	*Boeing*	*WB*	*CT*	*7*	*ANP*		*767300*	*NO*		
B767-300 / 300ER (Winglets)	*76W*	*Boeing*	*WB*	*CT*	*7*	*ANP*		*767300*	*NO*		
B767-400ER	*764*	*Boeing*	*WB*	*CT*	*8*	*ANP*		*767400*	*NO*		
B777	*777*	*Boeing*	*WB*	*CT*	*8*	*ANP*		*777200*	*NO*		
B777-200	*772*	*Boeing*	*WB*	*CT*	*8*	*ANP*		*777200*	*NO*		
B777-200LR	*77L*	*Boeing*	*WB*	*CT*	*8*	*ANP*		*777300*	*NO*		
B777-300ER	*77W*	*Boeing*	*WB*	*CT*	*8*	*ANP*		*7773ER*	*YES*		*2022*
B777X	*77X*	*Boeing*	*WB*	*NT-1*	*8*	*Substitution*	*A350-1000*	*A350-1000 FW*	*YES*	*2020*	
B787-10	*781*	*Boeing*	*WB*	*NT-1*	*2*	*Substitution*	*B787-9*	*B787-9 FW*	*YES*	*2018*	
B787-8	*788*	*Boeing*	*WB*	*NT-1*	*7*	*ANP*		*7878R*	*YES*	*2011*	
B787-9	*789*	*Boeing*	*WB*	*NT-1*	*7*	*NRV-Method*	*B787-8*	*B787-9 FW*	*YES*	*2014*	
CRJ200	*CR2*	*Bombardier*	*NB*	*CT*	*4*	*ANP*		*CRJ9-ER*	*NO*		
CRJ700	*CR7*	*Bombardier*	*NB*	*CT*	*4*	*ANP*		*CRJ9-ER*	*NO*		
CRJ900	*CR9*	*Bombardier*	*NB*	*CT*	*4*	*ANP*		*CRJ9-ER*	*NO*		
CS100	*CS1*	*Bombardier*	*NB*	*NT-1*	*4*	*NRV-Method*	*E195*	*Bombardier CS-100 FW*	*NO*		
CS300	*CS3*	*Bombardier*	*NB*	*NT-1*	*4*	*NRV-Method*	*E195*	*Bombardier CS-300 FW*	*YES*	*2016*	
DH4	*DH4*	*Bombardier*	*NB*	*CT*	*6*	*ANP*		*CVR580*	*NO*		

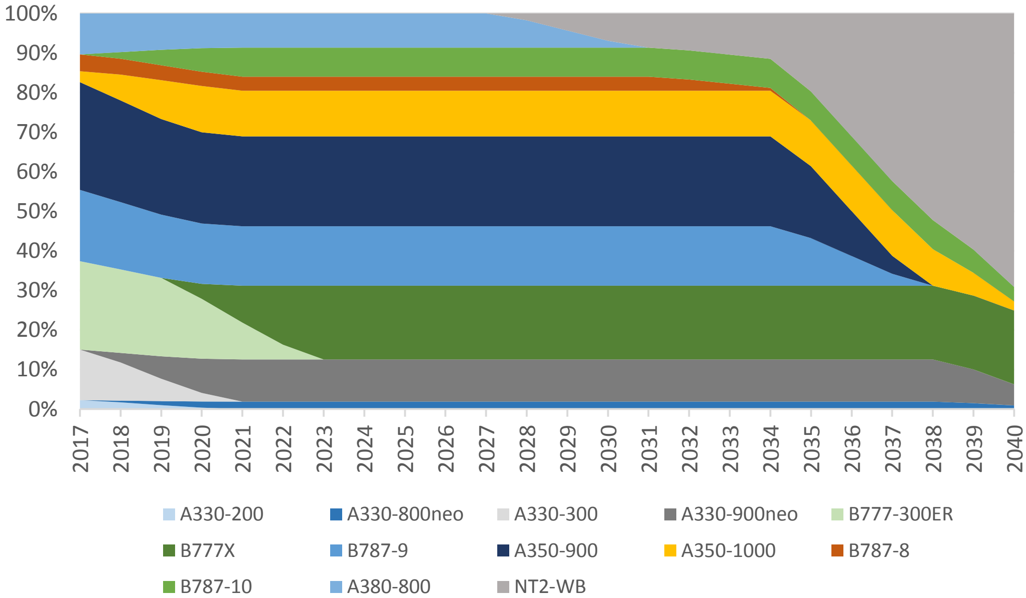
Do 328	*D38*	*Dornier*	*NB*	*CT*	*6*	*ANP*	*DO328*	*NO*
E170	*E70*	*Embraer*	*NB*	*CT*	*4*	*ANP*	*EMB170*	*NO*
E175	*E75*	*Embraer*	*NB*	*CT*	*4*	*ANP*	*EMB175*	*NO*
E190	*E90*	*Embraer*	*NB*	*CT*	*4*	*ANP*	*EMB190*	*NO*
E195	*E95*	*Embraer*	*NB*	*CT*	*4*	*ANP*	*EMB195*	*NO*
ERJ135	*ER3*	*Embraer*	*NB*	*CT*	*4*	*ANP*	*EMB145*	*NO*
ERJ145	*ER4*	*Embraer*	*NB*	*CT*	*4*	*ANP*	*EMB145*	*NO*
MD-88	*M88*	*McDonnell Douglas*	*NB*	*CT*	*9*	*ANP*	*MD83*	*NO*
MD-90	*M90*	*McDonnell Douglas*	*NB*	*CT*	*9*	*ANP*	*MD9025*	*NO*
RJ100 Avroliner	*AR1*	*British Aerospace*	*NB*	*CT*	*4*	*ANP*	*BAE146*	*NO*

C Air Traffic Growth Input of the Reference Case according to Airbus (2017b)

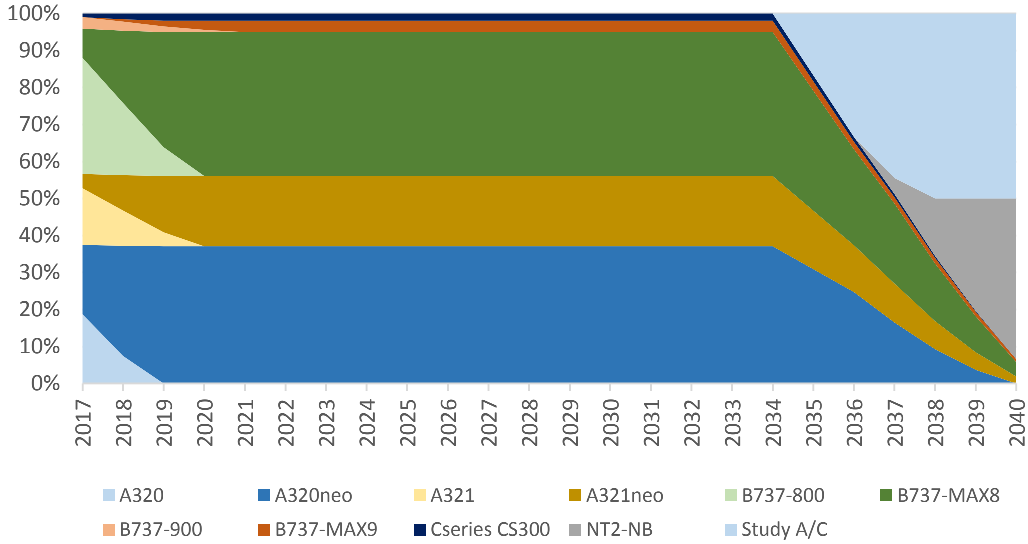
Traffic between Western Europe and …	*2017-2026*	*2027-2036*
North Africa	*4.6%*	*4.1%*
Domestic Western Europe	*2.1%*	*1.8%*
Africa Sub Sahara	*3.3%*	*3.1%*
South Africa	*2.2%*	*3.8%*
South America	*3.5%*	*3.4%*
Central Europe	*5.5%*	*4.4%*
PRC (People's Republic of China)	*4.6%*	*3.6%*
Russia	*3.8%*	*3.7%*
Asia Advanced	*2.9%*	*2.3%*
CIS (Commonwealth of Independent States)	*4.7%*	*3.9%*
Japan	*2.9%*	*2.3%*
Middle East	*4.9%*	*4.3%*
Asia Emerging	*3.2%*	*2.1%*
Indian Sub Continent	*4.1%*	*3.3%*
USA (United States of America)	*3.0%*	*2.8%*
Central America	*3.8%*	*3.4%*
Caribbean	*3.0%*	*2.5%*
Canada	*2.9%*	*2.3%*
Pacific	*2.9%*	*2.3%*
Western Europe (Intra)	*2.8%*	*2.2%*

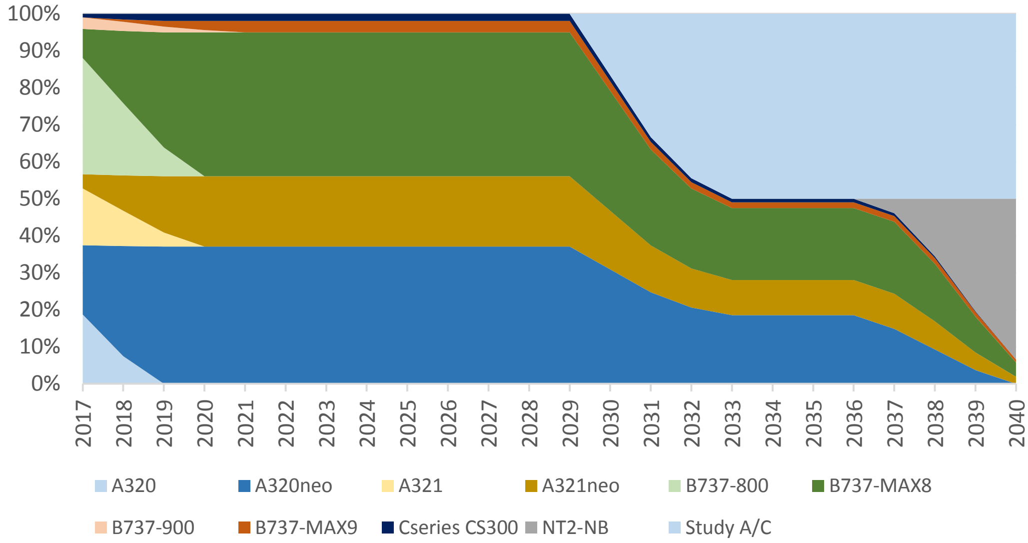
D Aircraft Introduction Input of the Reference Case





E Aircraft Introduction Input of the Low Noise Future Aircraft Case for Narrow-Body Aircraft (Two Entry-Into-Service Years)





F Applied Assignment of Destination Airports to World Regions and Exit Points at the Study Airport

Airport Code	*Destination Airport Name*	*World Region*	*Exit Point*
AAL	*Aalborg*	*Western Europe*	*N*
ACE	*Lanzarote*	*Western Europe*	*W*
ADA	*Adana*	*Middle East*	*E*
ADB	*Izmir Adnan Menderes Apt*	*Middle East*	*S*
AER	*Sotschi*	*Russia*	*N*
AGA	*Agadir*	*North Africa*	*W*
AGP	*Malaga*	*Western Europe*	*W*
AJR	*Arvidsjaur*	*Western Europe*	*N*
ALC	*Alicante*	*Western Europe*	*E*
AMM	*Amman Queen Alia International Apt*	*Middle East*	*S*
AMS	*Amsterdam*	*Western Europe*	*N*
ANR	*Antwerpen International Airport*	*Western Europe*	*W*
AOI	*Ancona*	*Western Europe*	*S*
AOK	*Karpathos*	*Western Europe*	*S*
ARN	*Stockholm Arlanda Apt*	*Western Europe*	*N*
ASR	*Kayseri*	*Middle East*	*E*
ASW	*Aswan*	*North Africa*	*S*
ATH	*Athens (GR)*	*Western Europe*	*S*
ATL	*Atlanta Hartsfield-jackson Intl Apt*	*USA*	*W*
AUH	*Abu Dhabi International Apt*	*Middle East*	*E*
AYT	*Antalya*	*Middle East*	*S*
BCN	*Barcelona Apt*	*Western Europe*	*S*
BDS	*Brindisi*	*Western Europe*	*S*
BEG	*Belgrade*	*Central Europe*	*S*
BEY	*Rafic-Hairi-Airport Beirut*	*Middle East*	*S*
BGI	*Grantley Adams International Airport Barbados*	*Caribbean*	*W*
BGY	*Milan Bergamo/orio al Serio Apt*	*Western Europe*	*S*
BHX	*Birmingham Airport*	*Western Europe*	*N*
BIA	*Bastia*	*Western Europe*	*S*
BIO	*Bilbao*	*Western Europe*	*W*
BJV	*Bodrum Milas Airport*	*Middle East*	*S*
BKK	*Bangkok Suvarnabhumi International Apt*	*Asia Emerging*	*E*
BLL	*Billund*	*Western Europe*	*N*
BLQ	*Bologna*	*Western Europe*	*S*
BOD	*Bordeaux Merignac Apt*	*Western Europe*	*W*
BOJ	*Burgas*	*Central Europe*	*S*
BOM	*Mumbai*	*Indian Sub Continent*	*E*
BOO	*Bodo*	*Western Europe*	*N*
BOS	*Boston Logan International Apt*	*USA*	*W*
BRE	*Bremen*	*Domestic Western Europe*	*N*
BRI	*Bari*	*Western Europe*	*S*

BRN	*Berne Belp*	*Western Europe*	*W*
BRQ	*Letiště Brno-Tuřany*	*Central Europe*	*N*
BRS	*Bristol*	*Western Europe*	*N*
BRU	*Brussels Airport*	*Western Europe*	*N*
BSL	*Basel*	*Western Europe*	*W*
BTS	*Bratislava*	*Central Europe*	*E*
BUD	*Budapest*	*Central Europe*	*E*
BVC	*Boa Vista Island*	*Africa Sub Sahara*	*W*
CAG	*Cagliari*	*Western Europe*	*S*
CAI	*Cairo*	*North Africa*	*S*
CDG	*Paris Charles de Gaulle Apt*	*Western Europe*	*W*
CEK	*Chelyabinsk*	*Russia*	*N*
CFU	*Kerkyra*	*Western Europe*	*S*
CGN	*Cologne/Bonn Apt*	*Domestic Western Europe*	*N*
CHQ	*Chania*	*Western Europe*	*S*
CLJ	*Cluj-Napoca*	*Central Europe*	*E*
CLT	*Charlotte*	*USA*	*W*
CMN	*Casablanca Mohammed V Apt*	*North Africa*	*W*
CPH	*Copenhagen Kastrup Apt*	*Western Europe*	*N*
CPT	*Cape Town*	*South Africa*	*S*
CTA	*Catania*	*Western Europe*	*S*
CUN	*Cancun*	*Central America*	*W*
CWL	*Cardiff*	*Western Europe*	*N*
DBV	*Dubrovnik*	*Central Europe*	*S*
DEB	*Debrecen*	*Central Europe*	*S*
DEL	*Delhi*	*Indian Sub Continent*	*E*
DEN	*Denver*	*USA*	*W*
DJE	*Djerba*	*North Africa*	*S*
DLM	*Dalaman*	*Middle East*	*S*
DME	*Moscow Domodedovo Apt*	*Russia*	*N*
DOH	*Doha*	*Middle East*	*E*
DOK	*Donetsk*	*CIS*	*E*
DRS	*Dresden*	*Domestic Western Europe*	*N*
DTM	*Dortmund*	*Domestic Western Europe*	*N*
DTW	*Detroit*	*USA*	*W*
DUB	*Dublin*	*Western Europe*	*N*
DUS	*Duesseldorf International Airport*	*Domestic Western Europe*	*N*
DXB	*Dubai International*	*Middle East*	*E*
EBA	*Elba Island*	*Western Europe*	*S*
EBL	*Erbil*	*Middle East*	*N*
EDI	*Edinburgh*	*Western Europe*	*N*
EGO	*Belgorod*	*Russia*	*E*
EIN	*Eindhoven*	*Western Europe*	*W*
ESB	*Ankara Esenboga Apt*	*Middle East*	*E*
EVE	*Harstad-Narvik*	*Western Europe*	*N*
EWR	*Newark Liberty International Apt*	*USA*	*W*

FAO	*Faro*	*Western Europe*	*W*
FCO	*Rome Fiumicino Apt*	*Western Europe*	*S*
FKB	*Karlsruhe*	*Domestic Western Europe*	*W*
FLR	*Florence (IT)*	*Western Europe*	*S*
FMO	*Muenster/Osnabrueck*	*Domestic Western Europe*	*N*
FNC	*Funchal*	*Western Europe*	*W*
FRA	*Frankfurt International Apt*	*Domestic Western Europe*	*N*
FUE	*Fuerteventura*	*Western Europe*	*W*
GDN	*Gdansk*	*Central Europe*	*N*
GIG	*Rio de Janeiro International Apt*	*South America*	*W*
GLA	*Glasgow*	*Western Europe*	*W*
GOA	*Genoa*	*Western Europe*	*S*
GOI	*Goa*	*Indian Sub Continent*	*E*
GOT	*Goteborg Landvetter Apt*	*Western Europe*	*N*
GPA	*Patrai*	*Western Europe*	*S*
GRU	*Sao Paulo Guarulhos Intl Apt*	*South America*	*W*
GRZ	*Graz*	*Western Europe*	*E*
GVA	*Geneva*	*Western Europe*	*W*
GWT	*Westerland*	*Domestic Western Europe*	*N*
HAJ	*Hannover*	*Domestic Western Europe*	*N*
HAM	*Hamburg Airport*	*Domestic Western Europe*	*N*
HAV	*Havanna*	*Caribbean*	*W*
HDF	*Heringsdorf*	*Domestic Western Europe*	*N*
HEL	*Helsinki-Vantaa*	*Western Europe*	*N*
HER	*Irakleion*	*Western Europe*	*S*
HHN	*Frankfurt Hahn*	*Domestic Western Europe*	*W*
HKG	*Hong Kong International Apt*	*Asia Advanced*	*N*
HND	*Tokyo Intl (Haneda)*	*Japan*	*N*
HOG	*Holguin Kuba*	*Caribbean*	*W*
HRG	*Hurghada*	*North Africa*	*S*
IAD	*Washington Dulles International Apt*	*USA*	*W*
IAH	*Houston George Bush Intercontinental Ap*	*USA*	*N*
IAS	*Iasi*	*Central Europe*	*S*
IBZ	*Ibiza*	*Western Europe*	*W*
ICN	*Seoul Incheon International Airport*	*Asia Advanced*	*N*
IKA	*Tehran Imam Khomeini International Apt*	*Middle East*	*E*
INN	*Innsbruck*	*Western Europe*	*S*
IST	*Istanbul Ataturk Airport*	*Middle East*	*S*
ISU	*Sulaymaniyah*	*Middle East*	*E*
JED	*Jeddah*	*Middle East*	*S*
JER	*Jersey*	*Western Europe*	*W*
JFK	*New York J F Kennedy International Apt*	*USA*	*W*
JMK	*Mykonos*	*Western Europe*	*S*
JNB	*Johannesburg O.r. Tambo International*	*South Africa*	*S*
JSI	*Skiathos*	*Western Europe*	*S*
JTR	*Thira*	*Western Europe*	*S*

KBP	*Kiev Borispol Intl Apt*	*CIS*	*E*
KEF	*Reykjavik Keflavik International Apt*	*Western Europe*	*N*
KGS	*Kos*	*Western Europe*	*S*
KIV	*Chisinau*	*CIS*	*E*
KLX	*Kalamata*	*Western Europe*	*S*
KRK	*Krakow*	*Central Europe*	*E*
KRR	*Krasnodar*	*Russia*	*E*
KSU	*Kristiansund*	*Western Europe*	*N*
KTT	*Kittila*	*Western Europe*	*N*
KUF	*Samara*	*Russia*	*N*
KVA	*Kavala*	*Western Europe*	*S*
KWI	*Kuwait*	*Middle East*	*S*
LAX	*Los Angeles International Apt*	*USA*	*N*
LBA	*Leeds Bradford*	*Western Europe*	*N*
LCA	*Larnaca*	*Western Europe*	*S*
LCJ	*Lodz*	*Central Europe*	*E*
LED	*St Petersburg Pulkovo Apt*	*Russia*	*N*
LEI	*Almeria*	*Western Europe*	*W*
LEJ	*Leipzig/Halle*	*Domestic Western Europe*	*N*
LGG	*Lüttich*	*Western Europe*	*W*
LGW	*London Gatwick Apt*	*Western Europe*	*N*
LHR	*London Heathrow Apt*	*Western Europe*	*N*
LIN	*Mailand Linate*	*Western Europe*	*W*
LIS	*Lisbon*	*Western Europe*	*W*
LJU	*Ljubljana*	*Central Europe*	*S*
LNZ	*Linz*	*Western Europe*	*E*
LPA	*Gran Canaria*	*Western Europe*	*W*
LPL	*Liverpool*	*Western Europe*	*W*
LRM	*La Romana*	*Caribbean*	*W*
LTN	*London Luton Apt*	*Western Europe*	*N*
LUX	*Luxembourg*	*Western Europe*	*N*
LWO	*Lviv*	*CIS*	*E*
LXR	*Luxor*	*North Africa*	*S*
LYS	*Lyon St-exupery Apt*	*Western Europe*	*W*
MAD	*Madrid Adolfo Suarez-Barajas Apt*	*Western Europe*	*W*
MAH	*Menorca*	*Western Europe*	*S*
MAN	*Manchester (GB)*	*Western Europe*	*N*
MBA	*Mombasa*	*Africa Sub Sahara*	*S*
MBJ	*Montego Bay*	*Caribbean*	*W*
MCT	*Muscat*	*Middle East*	*E*
MED	*Medin*	*Middle East*	*S*
MEX	*Mexico City Juarez International Apt*	*Central America*	*N*
MIA	*Miami International Apt*	*USA*	*W*
MJT	*Mytilini*	*Western Europe*	*S*
MLA	*Malta*	*Western Europe*	*S*
MPL	*Montpellier Mediterranee Apt*	*Western Europe*	*W*

MQF	*Magnitogorsk*	*Russia*	*N*
MRS	*Marseille Provence Apt*	*Western Europe*	*W*
MRU	*Mauritius*	*Africa Sub Sahara*	*S*
MSP	*Minneapolis*	*USA*	*W*
MST	*Maastricht/Aachen*	*Western Europe*	*N*
MXP	*Milan Malpensa Apt*	*Western Europe*	*S*
NAP	*Naples Capodichino Apt*	*Western Europe*	*S*
NBE	*Enfidha*	*North Africa*	*S*
NCE	*Nice*	*Western Europe*	*S*
NCL	*Newcastle*	*Western Europe*	*N*
NRK	*Norrkoping*	*Western Europe*	*N*
NRT	*Tokyo Narita Intl*	*Japan*	*N*
NTE	*Nantes Atlantique Airport*	*Western Europe*	*W*
NUE	*Nuremberg*	*Domestic Western Europe*	*N*
ODS	*Odesa*	*CIS*	*E*
OLB	*Olbia*	*Western Europe*	*S*
OMS	*Omsk*	*Russia*	*N*
OPO	*Porto*	*Western Europe*	*W*
ORD	*Chicago O'Hare International Apt*	*USA*	*N*
ORK	*Cork*	*Western Europe*	*W*
ORY	*Paris-Orly*	*Western Europe*	*W*
OSL	*Oslo Gardermoen Airport*	*Western Europe*	*N*
OTP	*Bucharest Henri Coanda Apt*	*Central Europe*	*E*
OVB	*Novosibirsk*	*Russia*	*N*
PAD	*Paderborn/Lippstadt*	*Domestic Western Europe*	*N*
PDL	*Ponta Delgada*	*Western Europe*	*W*
PEG	*Perugia*	*Western Europe*	*W*
PEK	*Beijing Capital Intl Apt*	*PRC*	*N*
PHL	*Philadelphia International Apt*	*USA*	*W*
PMI	*Palma de Mallorca*	*Western Europe*	*W*
PMO	*Palermo*	*Western Europe*	*S*
POP	*Puerto Plata*	*Caribbean*	*W*
POZ	*Poznan*	*Central Europe*	*N*
PRG	*Prague Ruzyne*	*Central Europe*	*N*
PRN	*Pristina*	*Central Europe*	*S*
PSA	*Pisa*	*Western Europe*	*S*
PTP	*Pointe-a-Pitre*	*Caribbean*	*W*
PUJ	*Punta Cana*	*Caribbean*	*W*
PUS	*Busan*	*Asia Advanced*	*N*
PUY	*Pula*	*Central Europe*	*S*
PVG	*Shanghai Pudong International Apt*	*PRC*	*N*
PVK	*Preveza/Lefkada*	*Western Europe*	*S*
RAK	*Marrakech*	*North Africa*	*E*
RHO	*Rhodes*	*Western Europe*	*S*
RIX	*Riga*	*Central Europe*	*N*
RJK	*Rijeka*	*Western Europe*	*S*

RLG	*Rostock*	*Domestic Western Europe*	*N*
RMF	*Marsa Alam*	*North Africa*	*S*
ROV	*Rostov*	*Russia*	*N*
RRR	*Raroia*	*Pacific*	*W*
RTM	*Rotterdam Apt*	*Western Europe*	*N*
RUH	*Riyadh*	*Middle East*	*S*
RZE	*Jasionka*	*Central Europe*	*N*
SAW	*Istanbul Sabiha Gokcen Apt*	*Middle East*	*S*
SBZ	*Sibiu*	*Central Europe*	*E*
SCN	*Saarbruecken Airport*	*Domestic Western Europe*	*N*
SCQ	*Santiago de Compostela*	*Western Europe*	*W*
SDQ	*Santo Domingo*	*Caribbean*	*W*
SFO	*San Francisco International Apt*	*USA*	*N*
SID	*Sal Island*	*Africa Sub Sahara*	*W*
SIN	*Singapore Changi Apt*	*Asia Advanced*	*E*
SJJ	*Sarajevo*	*Central Europe*	*S*
SJO	*San José*	*Caribbean*	*W*
SKG	*Thessaloniki*	*Western Europe*	*S*
SMI	*Samos*	*Western Europe*	*S*
SNU	*Santa Clara*	*Caribbean*	*W*
SOF	*Sofia*	*Central Europe*	*S*
SOU	*Southhampton*	*Western Europe*	*W*
SPC	*Santa Cruz de la Palma*	*Western Europe*	*W*
SPU	*Split*	*Central Europe*	*S*
SSH	*Sharm El-Sheikh*	*North Africa*	*S*
STN	*London Stansted Apt*	*Western Europe*	*N*
STR	*Stuttgart Airport*	*Domestic Western Europe*	*W*
SUF	*Lamezia Terme*	*Western Europe*	*S*
SVO	*Moscow Sheremetyevo International Apt*	*Russia*	*N*
SVQ	*Sevilla*	*Western Europe*	*W*
SVX	*Yekaterinburg*	*Russia*	*N*
SXB	*Straßburg*	*Western Europe*	*W*
SXF	*Berlin Schönefeld*	*Domestic Western Europe*	*N*
SZF	*Carsamba*	*Middle East*	*E*
SZG	*Salzburg*	*Western Europe*	*S*
SZY	*Szczytno*	*Central Europe*	*N*
TAB	*Tobago*	*Caribbean*	*W*
TBS	*Tbilisi*	*CIS*	*E*
TFS	*Tenerife Sur Apt*	*Western Europe*	*W*
TIA	*Tirana*	*Central Europe*	*S*
TIV	*Tivat*	*Central Europe*	*S*
TJM	*Tyumen*	*Russia*	*W*
TLL	*Tallinn*	*Central Europe*	*N*
TLS	*Toulouse*	*Western Europe*	*W*
TLV	*Tel Aviv-yafo Ben Gurion International*	*Western Europe*	*S*
TOS	*Tromso*	*Western Europe*	*N*

TRN	*Turin Caselle Airport*	*Western Europe*	*S*
TRS	*Trieste*	*Western Europe*	*S*
TSR	*Timisoara*	*Central Europe*	*E*
TUN	*Tunis*	*North Africa*	*S*
TXL	*Berlin Tegel Apt*	*Domestic Western Europe*	*N*
VAR	*Varna*	*Central Europe*	*S*
VCE	*Venice Marco Polo Apt*	*Western Europe*	*S*
VIE	*Vienna*	*Western Europe*	*E*
VLC	*Valencia (ES)*	*Western Europe*	*W*
VNO	*Vilnius*	*Central Europe*	*N*
VOL	*Volos*	*Western Europe*	*S*
VOZ	*Voronezh*	*Russia*	*N*
VRA	*Juan G Gomez Intl*	*Caribbean*	*W*
VRN	*Verona Villafranca Airport*	*Western Europe*	*S*
WAW	*Warsaw*	*Central Europe*	*N*
WDH	*Windhoek*	*Africa Sub Sahara*	*S*
WRO	*Wroclaw*	*Central Europe*	*N*
XRY	*Jerez*	*Western Europe*	*W*
YHZ	*Halifax*	*USA*	*W*
YUL	*Montreal Pierre Elliott Trudeau Int Apt*	*Canada*	*N*
YVR	*Vancouver International Apt*	*Canada*	*N*
YYZ	*Lester B Pearson Intl*	*Canada*	*N*
ZAD	*Zadar*	*Central Europe*	*S*
ZAG	*Zagreb*	*Central Europe*	*S*
ZAZ	*Zaragoza*	*Western Europe*	*W*
ZNZ	*Sansibar*	*Africa Sub Sahara*	*S*
ZQW	*Zweibruecken Airport*	*Domestic Western Europe*	*N*
ZRH	*Zurich Airport*	*Western Europe*	*W*
ZTH	*Zakinthos Island*	*Western Europe*	*S*

G List of student theses supervised

Kalsi, H.: Development and analysis of aircraft noise-mitigating departure and approach profiles at an international hub airport, Bachelor's Thesis, LS-BA 14/09

Leser, R.: Analyse und Vergleich fluglärmreduzierender Maßnahmen sowie Entwicklung einer Methodik für deren Bewertung, Term Thesis, LS-SA 14/10

Iñaki González Cabeza, J.: Design and Evaluation of an Aircraft Noise Index of a large, European Hub-and-Spoke Airport, Diploma Thesis, LS-DA 14/08

Beierke, F.: Analyse aktuell angewandter fluglärmreduzierender Verfahren am Beispiel eines internationalen Drehkreuz-Flughafens, Bachelor's Thesis, LS-BA 15/05

Jentzsch, S.: Analyse fluglärmreduzierender Maßnahmen und ihrer realen Umsetzung an internationalen Flughäfen, Bachelor's Thesis, LS-BA 15/06

Mirwald, J.: Analyse der Umsetzbarkeit lärmreduzierender Maßnahmen am realen Flughafen, Bachelor's Thesis, LS-BA 15/09

Qasem, J.: Untersuchung der Variation des Anflugwinkels ziviler Flugzeuge, Bachelor's Thesis, LS-BA 15/10

Dryancour, A.: Bewertung der Umsetzbarkeit lärmreduzierender Maßnahmen an einem realen Drehkreuz-Flughafen, Master's Thesis, LS-MA 15/07

Theobald, M.: Kombinierte Flughafen Lärm-/Kapazitätsuntersuchungen, Bachelor's Thesis, LS-BA 16/09

Brath, K.: Analyse des Fluglärmreduktionspotentials an einem zukünftigen Innenstadtflughafen, Term Thesis, LS-SA 16/09

Bauer, D.: Untersuchung lärmreduzierender Verfahren am Beispiel eines realen Hub-and-Spoke Flughafens, Master's Thesis, LS-MA 16/12

Engelke, C.: Entwicklung eines Simulationsmodells zur Einflussanalyse neuer Flugzeugtechnologien in zukünftigen Flugzeugflotten auf die Lärmimmission an Flughäfen, Master's Thesis, LS-MA 16/18

Wunderlich, T.-O.: Validation and Improvement of a Model to Analyse Impacts on Noise Immissions at Airports in Future Aircraft Fleets, Bachelor's Thesis, LS-BA 17/07

Batschkus, D.: Entwicklung einer Methodik zur Analyse zukünftiger Fluglärmimmissionen an zivilen Flughäfen, Bachelor's Thesis, LS-BA 17/11

Mayrhofer, A.: Improvement and Application of Methods for Impact Assessments of Future Airport Noise Situations, Term Thesis, LS-SA 17/24

Knoll, S.: Validierung der Fluglärm-Quellenmodelle des Programms "Eurofighter Noise Footprint" anhand von Flugversuchsdaten, Master's Thesis, LS-MA 17/01-EX

Stadler, F.: Analysis and Evaluation of Influences on Future Noise Situations at Civil Airports, Master's Thesis, LS-MA 18/01

Kalsi, H.: The Effect of the Fleet Development on Future Noise Immission and the Resulting Aircraft Top-Level Requirements - a Factorial Analysis, Master's Thesis, LS-MA 18/10