Technische Universität München
TUM School of Engineering and Design

System Analysis of Long-haul Airline Market Dynamics

Marcia Urban

Vollständiger Abdruck der von der TUM School of Engineering and Design der Technischen Universität München zur Erlangung des akademischen Grades einer

Doktorin der Ingenieurwissenschaften (Dr.-Ing.)

genehmigten Dissertation.

Vorsitz:	Prof. Dr. Constantinos Antoniou
Prüfer der Dissertation:	1. Prof. Dr.-Ing. Mirko Hornung
	2. Prof. Dr. Andreas Größler

Die Dissertation wurde am 21.04.2022 bei der Technischen Universität München eingereicht und durch die TUM School of Engineering and Design am 14.12.2022 angenommen.

Acknowledgement

Many people have accompanied and supported me on this path of persistent endeavour during my doctorate.

First and foremost, I would like to thank my supervisor Prof. Dr.-Ing. Mirko Hornung for his constant support during my time at Bauhaus Luftfahrt e. V. and beyond in the final phase of my doctorate. I would also like to thank Prof. Dr. Andreas Größler for assessing my dissertation and Prof. Dr. Constantinos Antoniou for chairing the doctoral committee. My special thanks also go to Prof. Dr. Birgit Kopainsky for her mentorship in the last stages of my doctorate and to everyone I met in the System Dynamics Society and especially in the German Chapter.

I would like to thank my former colleagues at Bauhaus Luftfahrt e. V., especially Mara, Annika, Anne, Anna, Ulrike, Julia, Paul, Raoul, Toni, Arne, Sascha, Patrick, Michael, Uli, Michael, and Kay, who have become friends, enabled a very pleasant working environment, room for discussions and a nice time besides work to enjoy life.

Special thanks to my family, my parents, my brother, my grandparents and all other family members who believed in me and my abilities when I didn't, who always had my back and who made it possible for me to follow my path to become the person I am today.

Thank you to all my new friends in Munich as well as my old friends in my hometown and all across Germany and abroad. I especially thank Maren for her honesty and her perseverance in our long-distance friendship.

And last but not least, I thank you, Mathias, for your endless patience and companionship in life.

Marcia Urban

Munich, 27th March 2023

Abstract

The establishment of market deregulation and liberalisation in air transport markets paved the way for the rise of airline low-cost services. In contrast to short-haul markets, where low-cost airlines have gained and maintained significant market shares in the past decades, there are increasing efforts of low-cost airlines to extend their business approach to long-haul flight connections with the objective to exploit additional market segments. The scientific research community controversially discusses the market potential of long-haul low-cost air transport services. It remains questionable to which extend cost advantages of low-cost services can be transferred to long-haul markets and which market requirements are necessary for the successful low-cost service implementation.

This thesis investigates the market potential resulting from the low-cost service introduction to long-haul air transport markets to complement this discussion with research findings from the simulation of recent transatlantic low-cost operations. The scientific contribution comprises the provision of a dynamic model, developed and implemented with System Dynamics (SD), as an abstraction of the transatlantic market. Dynamics in the system, resulting from airline decisions and strategies as well as passenger decisions, drive its behaviour. SD was identified as a feasible methodology to enable the abstraction of complexity and provide the simulation capabilities required to represent interactions between demand and supply side in the air transport system. Previous SD research in this field focusses on key areas such as the airline profit cycle, airline competition in different markets following market liberalisation or operational aspects, e. g. the aircraft fleet development or airport operations. The simulation of the long-haul low-cost service market potential with the developed transatlantic air transport model (TATM) as well as the analysis and discussion of the simulation results from parameter variation and scenario studies, including recommendations for future research in the field, complement existing research.

Simulation results reveal a market share potential of 26.1 % for long-haul low-cost services in the transatlantic market in the baseline parameter setting. The long-haul low-cost market potential varies between 10 % and 30 %, depending on the setting of input parameters. The scenario studies, presented in this thesis, provide insights to the market development in case of different exogenous impacts. The introduction of a price for carbon emissions and resulting additional environmental costs affects the long-haul low-cost carrier (LHLCC) market share at environmental cost levels of 0.23 USD per passenger kilometre in 2030 to 0.31 USD per passenger kilometre in 2035 for the operation of a B787-800 aircraft type. The LHLCC market share increases to 37.6 % in this scenario due to effects from an increasing cost advantage over time and a resulting increasing attractiveness of the LHLCC for passengers. The demand shock simulation resulting from the Coronavirus SARS-CoV-2 (COVID-19) pandemic highlights that a lack of support measures and coping strategies such as governmental financial subsidies results in a market collapse.

The TATM, developed in this thesis, serves as an analysis framework for policy makers and other stakeholders within the market to gain insights into the dynamic transatlantic market behaviour facing exogenous impacts. It can be applicable to other long-distance market segments, depending on the data availability. However, it is crucial to define specific input parameters when investigating other market segments.

Contents

List of Figures

List of Tables

Nomenclature

List of Subscripts

c	Characteristic Type
i	Passenger Group
j	Airline Type
k	Ownership Option

List of Symbols

A	Attractiveness
n	Number of Observations
P	Passenger Choice Probability
r	Coefficient of Correlation
R^2	Coefficient of Determination
U	Utility
U^C	Unequal Covariation
U^M	Bias
U^S	Unequal Variation
ε	Preference Weight
W	Willingness to Consider Service
x	Service Characteristic

List of Acronyms

ASEAN	Association of the South East Asian Nations
ASK	Available Seat Kilometre
CLD	Causal Loop Diagram
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
COVID-19	Coronavirus SARS-CoV-2
FFP	Frequent Flyer Program
FSNC	Full-service Network Carrier
GDP	Gross Domestic Product
HUB	Hub Airport
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCC	Low-cost Carrier
LHLCC	Long-haul Low-cost Carrier
MAE	Mean Absolute Error
MAPE	Mean Absolute Percent Error
MTOW	Maximum Take-Off Weight
NHB	Non-Hub Airport
OAG	Official Airline Guide
OD	Origin-Destination
OECD	Organisation for Economic Co-operation and Development
RMSE	Root Mean Square Error
RPK	Revenue Passenger Kilometre
SD	System Dynamics
SLF	Seat Load Factor
TATM	Transatlantic Air Transport Model
TOC	Total Operating Cost
U.S.	United States
USD	US Dollar
VFR	Visiting Friends and Relatives

Chapter 1

Introduction

The implementation of low-cost air transport services after market deregulation and liberalisation has substantially shaped the landscape of the air transport system [1–3]. The pioneer of the low-cost carrier (LCC) business model was Southwest Airlines, which started its operations in North America in the 1970s [4]. Since its introduction, the LCC business model became widely established in air transport markets, especially in Europe, North America, and Asia [5–9]. In comparison to the differentiation strategy applied by a full-service network carrier (FSNC) with a focus on service and quality, the LCC business model gains its competitive advantage from a cost leadership strategy [10]. This business model type significantly influenced the development of the global air transport sector [11]. The market entry of LCCs resulted in lower ticket prices which increased the demand for air transport services, especially in the leisure market segment, and resulted in additional air transport capacity and flying became affordable for a broader group of customers [2, 12]. LCCs can offer flight services at lower ticket prices due to cost-saving potentials along the value chain of 50 % in short-haul markets [13] and a higher capacity utilisation. With this competitive advantage, the LCCs have achieved notable market shares [5–9, 14].

Today, the short-haul markets are mostly saturated by low-cost air transport services [13]. Thus, LCCs strive for new business opportunities in markets with longer distances [15]. Several LCC characteristics such as shorter turnaround times, higher density seating, and a homogeneous fleet are particularly suitable for generating cost advantages on short-haul routes [1]. Not all of these characteristics are transferable to long-haul operations [13, 16, 17]. For example, longer distances reduce the daily frequency of flights to a minimum and larger aircraft are operated on long-haul routes. Consequently, the competitive advantages of LCCs from higher daily utilisation due to shorter turnaround times and more daily flights diminish on longer distance routes. Quality and comfort characteristics such as seat pitch, meals served during the flight, and in-flight entertainment become more important with an increasing flight duration [11]. With a feasible business approach and a selection of routes in price-sensitive markets, LCCs are expected to still achieve a cost advantage per seat kilometre flown of about 20-25 % on long-haul routes [13, 18, 19]. This cost advantage is significantly lower compared to 50 % on short-haul routes [13]. Changing conditions in long-haul markets require the adaptation of the traditional LCC business model.

Several past attempts of airlines to operate a low-cost oriented business model in long-haul route markets were not successful in the long term [20]. But market conditions shifted in 2008 when the Open Skies Agreement between Europe and the United States of America became effective and paved the way for new market entrants because it enabled liberalised market structures [21]. Recent developments in this market provide evidence that LCC services are being introduced to several long-haul routes, mostly by LCCs affiliated to an FSNC. The question remains whether the LCC business model can be transferred to long-haul markets and established in the long term. Moreover, there is a need to investigate under which conditions the LCC business model can be maintained in these markets and which characteristics become important for LCCs to achieve a competitive advantage and to operate profitably.

Figure 1.1 presents the market share development of LCCs in terms of annual global seats offered on routes above 4,630 kilometres (2,500 nautical miles). Since 2006, market shares in long-haul market segments have increased continuously. Today, the largest share is gained on long-haul flights within the Asia-Pacific region, followed by the long-haul market between Europe and North America.[1] [14]

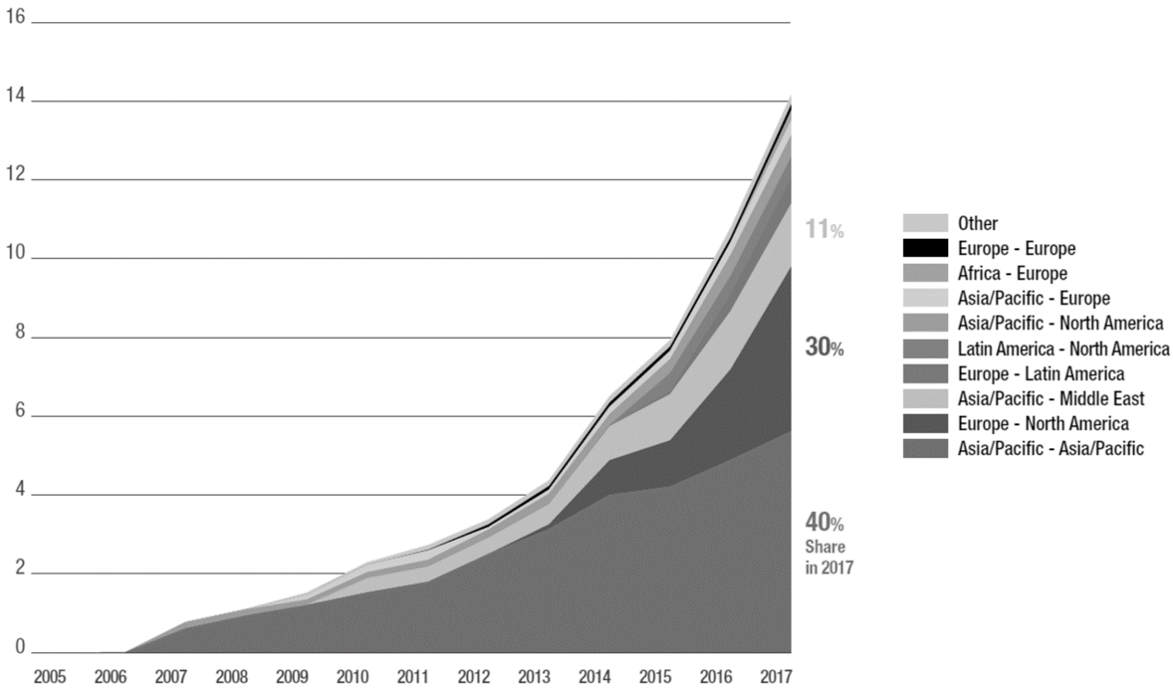

Figure 1.1: Number of global seats offered by LCCs on routes above 4,630 kilometres between 2005 and 2017 [million] ([14, p. 21])

[1] Eurocontrol (2005) defines long-haul flights as all flights with a distance above 4,000 kilometres. In this thesis, transatlantic long-haul flights are defined as all flights departing from one global region, i. e. Europe or North America, and arriving in the respective other region. Flights below 4,000 kilometres are not considered as long-haul flights. [22]

When considering only long-haul flights with distances above 4,630 kilometres (as represented in figure 1.1) which are operated between two different global regions, LCCs have achieved the largest share of 40 %, in terms of global seats offered by LCCs, within the Asia-Pacific region, followed with 30 % in the transatlantic air transport market and 11 % on connections between Asia-Pacific and the Middle East [14].

The Open Skies Agreement introduced unique conditions for an international market [21, 23] compared to other agreements present in the global air transport system. This level of market liberalisation does not exist at the same level in the Asia-Pacific market. The Association of the South East Asian Nations (ASEAN) agreed on a regional open skies area within all member states [2]. But the ASEAN open skies area focusses on a regional scope, comparable to the merger of the European countries to the European Union, and nearly 50 % of all operating airlines in Asia-Pacific were still state-owned by 2011 [24]. Hence, the transatlantic air transport market serves as a feasible case for investigation in this thesis because it represents a liberalised and deregulated international market.

Several external factors drive the growth of global air transport and cause dynamics in the global air transport markets because of the adaptation to these changes in demand [11]. Increasing demand for air transport combined with advancing liberalisation in this market confront airlines with rapidly changing market conditions. In addition, the demand for air transport does not only increase on a global scale but also accelerate in its development [25]. This is paired with an increasing individualisation of customer needs [25]. To respond to these changes, airlines continuously develop and adapt their business model [11]. This increasing level of airline business model innovation and individualisation results in an increasing gravitation of traditional business model types such as the FSNC and the LCC towards each other [26]. All of these developments and resulting impacts on airline operations need to be considered when investigating the transferability of the LCC business model to long-haul markets.

1.1 Motivation and definition of the problem

Mobility is a general need of society. This need is satisfied by a wide range of mobility services offered by various modes of transport. Air transport especially serves on long-distance routes overseas since it provides a global network of flight connections and it is unrivalled in terms of travel time compared to alternative modes of transport. Travelling around the world enables society to experience cultural exchange, to make and sustain lifelong friendships and to broaden the personal horizon. In addition, air transport services play a major role in the business world, especially if companies operate globally, since physical meetings between representatives are an important part of the business relationship. In result, air travel is expected to recover and build on pre-COVID-19 pandemic air traffic growth rates. [27]

An increasing operational and emission efficiency per passenger or tonne kilometre transported [27, 28] and the resulting lower costs, which also result from tendencies towards more liberalised markets [1, 2], made air travel available and attractive to an ever larger group of potential customers and, thus, created induced demand. The downside and main point of criticism is the environmental impact that results from the increasing traffic volumes despite the fact that fuel and operational efficiency continuously improve [2, 28, 29]. 2.1 % of all global anthropogenic carbon dioxide (CO_2) emissions resulted from fuel burn during air transport operations in 2019 [27]. International air transport accounts for about 60 % of all CO_2 emissions from this total global CO_2 emissions from air transport in 2017 [28]. In addition, air transport operations in the stratosphere generate water vapour emissions that substantially impact the climate [1]. To counteract these impacts, the European Commission has published the Flightpath 2050 vision in 2011 that includes environmental targets for the air transport sector to support carbon-neutral growth of air traffic beginning in 2020 and the reduction of CO_2 emissions of 50 % by 2050 [30]. To meet these ambitious targets, the air transport sector continuously investigates potential improvements in engine and aircraft technologies [27], operational improvements, and the introduction of economic measures such as taxes, emission trading and offsetting, to reduce the climate impact of aviation [1]. The relevance of aviation's climate impact affects the future development in international air transport markets due to the disproportionate share of CO_2 emissions.

This thesis investigates the introduction and future development of low-cost services in the transatlantic market in terms of its market potential. An introduction of low-cost services in the transatlantic and other long-haul markets increases air transport demand since especially price-sensitive customer target groups are addressed with these services, resulting in additional demand for international flights. Different airline types and passenger groups will be considered in this thesis. The air transport system can be characterised as a complex system with a multitude of interrelations between different stakeholders such as airports, airlines, passengers, aircraft manufacturers, air transport management service providers, and regulators [4]. The stakeholders' decisions and actions are affected by the behaviour of competitors as well as other stakeholders. Airlines take a crucial role in this system with providing flight services between airports, the network nodes of the air transport system [4]. They have a direct relation to their customers, the air passengers, which represent the demand side.

SD is introduced as a methodology to address the complex structure and the dynamics of the air transport system. The method will be applied to develop a model of the transatlantic air transport market. This model comprises elements to model decisions of passenger groups and different airline types as well as methods to include behaviour between the airline types. It provides capabilities for the simulation of the transatlantic air transport market and enables the identification of dynamics and system behaviour from the introduction of low-cost services as well as the investigation of different decision rules for LCCs competing with FSNCs in this market. Model simulation enables parameter studies and the analysis of potential policy scenarios in this market. Depending on data availability, the model can be transferred to other long-haul or short-haul markets to investigate competition between the two airline types considered.

1.2 Research questions

The transferability of low-cost services to long-haul markets impacts the global supply of air transport services. The effect of increasing competition in air transport markets combined with technological innovation, that led to declining ticket prices in the last decades [2], also applies in long-haul markets with the introduction of low-cost services. This results in a positive effect for the demand side. International flights become more attractive, especially for price-sensitive customers. However, the provision of these flight options for potential customers strongly depends on the market potential of long-haul low-cost services. Hence, this thesis complements existing research in the field of market dynamics from the introduction of low-cost services in long-haul markets and its implications on competitive dynamics between different airline types, i. e. LCCs and FSNCs.

Previous research in aeronautical economics on long-haul low-cost services and their market potential set priorities in the definition of business model characteristics and in the competitive advantage of low-cost services over FSNC operations [13, 17, 19, 20, 31–40] (see chapter 2). Major findings from this research reveal that not all competitive advantages of an LCC can be transferred from short-haul to long-haul routes. As a consequence, LHLCCs face more demanding barriers to market entry compared to the ones in short-haul markets. Studies on route-specific competitive advantages such as [38] provide valuable insights in the differences of revenue characteristics between LHLCCs and FSNCs. However, these studies focus on time-related snapshots of the markets investigated. To gain a better understanding of how low-cost services evolve over time and which endogenous dynamics drive the market potential, a novel approach is required. This thesis fills this research gap with the development of a dynamic model that provides simulation capabilities to investigate the endogenous dynamics in long-haul markets when low-cost services are introduced. Past research attempts of dynamic modelling in the field of aviation strongly focussed on airline profit cycles [41–48] and airline market competition [47, 49] (see chapter 3). However, as far as the author is aware, there is currently no existing dynamic model available that focusses on long-haul air transport operations with a detailed level of the airline market dynamics considering different airline types, different passenger groups, passenger choice, and willingness to consider low-cost services. With such a model, the endogenous development of low-cost services in long-haul air transport markets can be investigated and scenario studies with different decision rules for LHLCCs, that compete with FSNCs, can be carried out. To structure this novel approach towards the analysis of long-haul airline market dynamics, the following research questions are defined:

- **How did airline market structures evolve in the past and which key drivers influence their future development?**
- **Which methodological approach is feasible to investigate the introduction and operation of long-haul low-cost services?**
- **How can interrelations between airlines and other stakeholders in the air transport system be modelled?**

- **Which implications on low-cost airline operations can be derived from long-haul future airline market dynamics?**

The first research question addresses the past development as well as structural aspects of the air transport market. It is crucial for the analysis of market dynamics in long-haul air transport markets to understand the fundamental structures of a system and to collect information about characteristics and strategies of the entities to be modelled. In a second research question, a feasible methodological approach needs to be identified to connect the insights from the first research question. This selection defines the method for the development of a dynamic model to investigate the endogenous behaviour of airlines in long-haul air transport markets after the introduction of low-cost services. It is important to ensure that the selected method meets the requirements of time-varying endogenous modelling. After the selection of the modelling method, potential solutions need to be identified of how to model interrelations between airlines and other stakeholders in the air transport system. For this, the accumulated knowledge of market dynamics, airline business models, airline competition aspects, and specific characteristics of long-haul air transport markets needs to be conceptualised and implemented in a dynamic model. The developed dynamic model serves as a tool to analyse the behaviour of low-cost operations in long-haul airline markets. The model application to a use case and the execution of parameter variation and scenario studies serve to gain confidence in the model developed and to address the last research question.

1.3 Research scope and expected results

The research in this thesis complements previous modelling activities of the air transport system and applies a holistic approach with focus on airlines as one major air transport stakeholder. Previous economic studies on competition in the transatlantic market between LHLCC and FSNC apply econometric models to specific routes [17, 38, 50]. From a methodological perspective, existing literature contains initial models which represent short-haul air transport markets with two airlines and a distinction between different passenger groups. In this research, a simulation model is developed based on characteristics of the transatlantic air transport market as identified in previous econometric models to analyse this market from a macroscopic perspective. More specifically, two different airline types, representing the LHLCC and the FSNC business model, are implemented [51]. These two types cover the total flight capacity within the transatlantic market. Thus, single airlines are not considered in the model. Previous studies on defined city-pairs provide initial structures of a methodological approach to model airline competition. This thesis adds value to the existing research by considering the interaction and competition between two carrier types beyond specific city-pairs on the transatlantic market. As one major outcome, different airline approaches will be simulated and the resulting market share development will be investigated.

Research results from this thesis will comprise a statement on potential future developments of the transatlantic air transport market as a growth market in the air transport system with focus on the development of market shares of FSNC and LHLCC. In particular, the identification and analysis of market characteristics for a successful establishment of the LCC business approach in long-haul markets are addressed with this research. In addition, the simulation model allows for simulation of predefined scenarios regarding the future development for air transport or policy-related scenarios such as implications from the implementation of a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [52] and the impact of COVID-19 on the supply of transatlantic flight services. According implications will be derived from the simulation results and discussed.

1.4 Thesis structure

The thesis commences with an introduction to the historical development of the air transport market with focus on the transatlantic market, market strategies, and airline business models. Aspects, which will be integrated into the model, will be described in detail in chapter 2. Different airline business models will be introduced and a differentiation of key characteristics between the FSNC and the LCC business model will be highlighted. Based on these insights, potential challenges of the implementation of LCC services into long-haul markets, such as the transatlantic market, will be discussed in section 2.2.3.

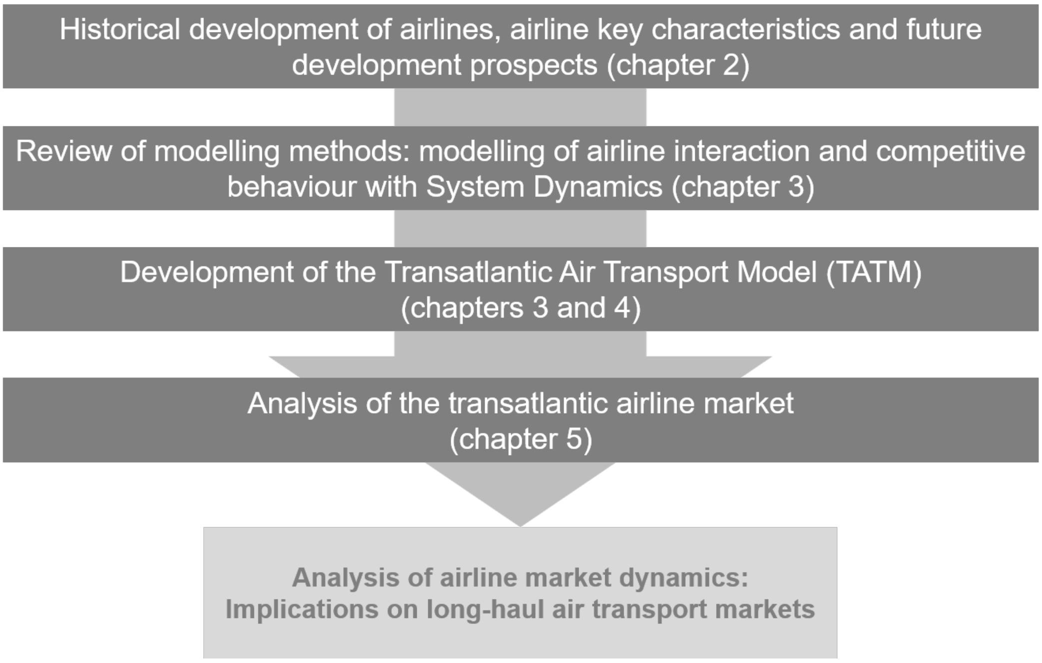

Figure 1.2: Thesis structure (own depiction)

The thesis continues with the selection of a feasible methodological approach to model the air transport system, followed by an introduction of the method selected, SD, in chapter 3. After this part, a review of existing research on modelling the air transport sector with focus on airlines as one major stakeholder as well as competitive behaviour with SD is provided. Subsequently, an SD model with focus on airline operations is developed, calibrated, and validated. This model will be applied to analyse the transatlantic air transport market regarding the development of airline market shares over time. The simulation model developed in this thesis is introduced in chapter 3 and validated in chapter 4. Model validation includes the model structure as well as model behaviour. For testing the model behaviour, simulation results are compared to historical behaviour that is derived from available data on the transatlantic air transport market. Parameter studies representing different airline strategies are investigated, i. e. ticket price policies or airline capacity policies in section 5.2. In addition, different scenarios of exogenous effects on the potential development of the transatlantic air transport market are defined and simulated in section 5.3.

Chapter 2

Review of airline strategies within air transport markets

Air transport is a complex system with a multitude of different actors and interactions [4]. Airlines take a crucial role in this system by providing a key resource: air transport services [4]. It is pivotal to gain a thorough understanding of the interactions between airlines and the other stakeholders in the air transport value chain [53, 54] to assess different airline market strategies and the impact of external influences on the development of airline strategies. A system-wide perspective is required for the analysis of changing airline strategies and business models in this framework to investigate which aspects influence dynamics in the system.

This chapter focusses on general aspects of airline strategy and according business models as well as on specific characteristics of long-haul air transport services to set the scene for the investigation of airline dynamics in these markets. Long-haul flight connections have been a market place where established FSNCs competed with airlines of the same business model type. With an increasing liberalisation of international air transport markets in general and the Open Skies Agreement between Europe and The United States of America in 2008 [21] in particular, these new market conditions capacitated low-cost airlines to enter these long-haul markets. Despite the success of low-cost services in short-haul markets, LHLCCs face remarkable challenges in the endeavour to establish their business model [13, 35]. The questions remain whether these challenges can be overcome and based on which framework requirements the low-cost business model might be successful in long-haul markets. To investigate these questions, some background information about the air transport market, airline business models and market strategies, and specific characteristics of the long-haul low-cost airline business model will be presented. Differences in airline business approaches and according strategies will be highlighted as a valuable source of information for the implementation of different airline types in the simulation model which will be described in chapter 3. Furthermore, specific characteristics of LCC services in long-haul markets will be discussed since this research focusses on the transfer of the LCC business model to a long-haul market. Chapter 2 addresses the first research question of this thesis:

- **How did airline market structures evolve in the past and which key drivers influence their future development?**

The extent of this research question comprises the past development of air transport markets, key characteristics describing the interaction between airlines and passengers, and an overview of different airline business model approaches. Furthermore, recent developments in the transatlantic air transport market such as the Open Skies Agreement between Europe and the United States of America and future prospects of this market such as the demand for long-haul flights will be presented in this chapter. All these aspects provide the foundation for the analysis of interactions and competition between airlines in the transatlantic market.

A summary of the major findings from chapter 2 include the following aspects:

- Open Skies Agreements between Europe and the United States of America as well as between Europe and Canada liberalised the transatlantic air transport market and enabled the introduction of airline business models other than the traditional FSNC.
- LCC and FSNC represent two generic airline business model types which span a continuum in which most of today's operating airlines place their operations, covering business model aspects from both models.
- Ticket price and flight frequency are key characteristics of the demand for air transport services and, thus, their adjustment majorly drives airline competition strategies.
- In recent attempts to establish low-cost services in long-haul markets, LCCs face challenges in transferring their business model characteristics to these markets and a resulting reduced cost advantage compared to short-haul markets.

2.1 The air transport market

The air transport market consists of a complex structure of interrelations among the different actors and entities [4]. Several system views exist on air transport, each one focussing on different key actors. Pompl [55] presents a visualisation where demand and supply, represented with air passengers and airlines, have a centred location whereas other actors, e. g. airports or aircraft manufacturers take a supportive role for the provision of flight services. An alternative representation is the aviation value chain as described in [53] and [54] (see figure 2.1). The aviation value chain is an idealised framework of structure and functionalities of the air transport system and contains all relevant stakeholders, independent from each other, for the provision of air transport services [53, 54]. Every participating entity provides crucial elements for air transport services such as airport infrastructure, air traffic management, aircraft, flight and cabin crew, ground staff, and distribution opportunities [53, 54]. The airlines as one major stakeholder within the value chain represent the interface to the demand side [53, 54]. Economic market mechanisms ensure the continuous alignment of supply and demand with the aim of achieving the highest possible degree of saturation of demand [3].

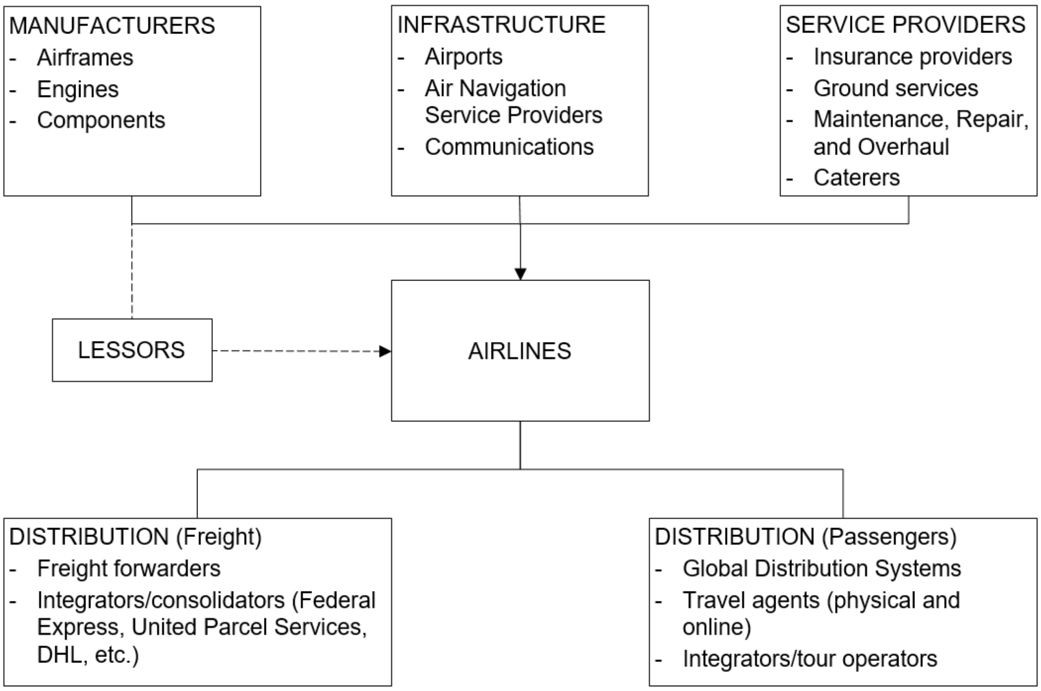

Figure 2.1: The aviation value chain (adapted from [53, p. 5, Fig. 1])

Within the aviation value chain (see figure 2.1) [53], manufacturers of the aircraft airframe, engines, and components provide the aircraft required for an airline to operate air transport services. Furthermore, entities that provide infrastructure resources such as airports, air traffic control, and communications as well as additional services such as insurance, ground handling services, maintenance, repair and overhaul services, and catering are mandatory elements [4, 53]. The airlines unite all these resources in their operations and build the interface to the demand side: the air transport service customer [4]. This includes not only air passengers but also freight transport services. When freight transport services are requested, freight forwarders and integrators represent the demand side. Airlines provide air transport services in various markets, depending on their network structure, fleet size and composition, and geographical location [56]. Each market consists of a multitude of distinct routes between two cities on which airlines compete with each other or where only one airline operates all flights in a monopolistic position within this specific route market.

Airline markets pass through different phases of evolution or maturity (see figure 2.2) [24]. In each phase, the market is characterised differently. The first phase provides airline markets which are highly regulated and where there is proportionately little demand for air transport services. In these markets, ticket prices are high and efficiency and profitability are low. This changes through the second and third phase due to an increasing demand for air transport services and a decreasing level of regulation. As a result, prices decrease and efficiency and profitability are improved compared to the first phase. [24]

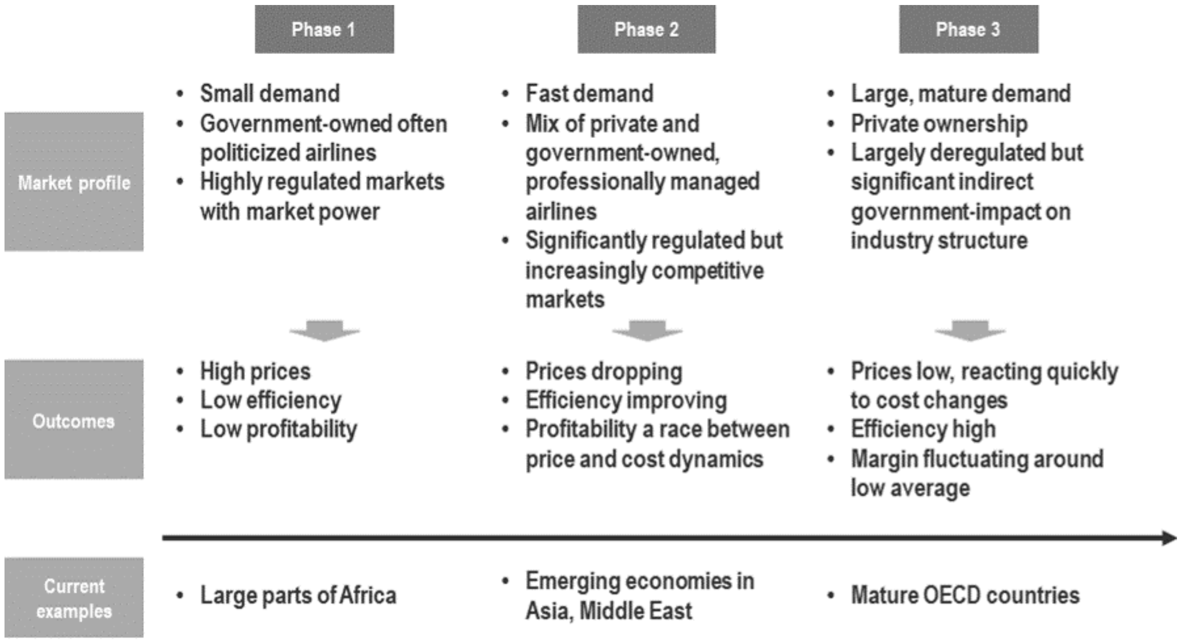

Figure 2.2: Airline market evolution (adapted from [24, p. 30, chart 33])

The representation in the International Air Transport Association (IATA) report Vision 2050 from 2011 [24] reveals structural differences in terms of market maturity in different global regions. Emerging economies such as Asia or the Middle East are categorised as having airline markets in the second phase and airline markets in the first phase can be found in African or Indian countries, where air transport is about to build up. Only fully developed countries, which are members of the Organisation for Economic Co-operation and Development (OECD), have reached the third phase of market maturity in 2011 according to the IATA report. [24]

2.1.1 Historical development of the air transport market

The first commercial flight by KLM Royal Dutch Airlines from London to Amsterdam in 1920 marks the beginning of civil aviation [11]. Between this first flight and the air transport system as it is today, various technological and economic developments as well as policy choices have shaped the system fundamentally. This includes the evolution of aircraft technology, the Chicago Convention in 1944, the market deregulation in 1978 in the United States of America and the subsequent market liberalisation in Europe in the 1990s as well as the implementation of the Open Skies Agreement between Europe and the United States of America in 2008 [1]. This agreement plays a major role in the development of the transatlantic air transport market [57–59]. In addition, Europe and Canada entered an Open Skies Agreement in late 2009 [2, 60]. Especially these two agreements have paved the way for new market entrants on routes between North America, Canada, and Europe [21].

Liberalisation and deregulation activities were key requirements for the development and introduction of airline business approaches other than the initial flag carriers which had operated most of the commercial flights before 1978 in North America and before 1990 in Europe respectively [2, 3]. The LCC business model originates from the resulting conditions of liberalisation and deregulation, when market entry barriers for LCCs levelled off, and its cost leadership strategy turned the LCC into a credible competitor for the established service-oriented airlines [1]. Southwest Airlines pioneered in its role as the first LCC in North America and started its operations in 1971 [2, 4]. Prior to the deregulation in the U. S. market, Southwest Airlines operated for the first years as an LCC only on flights within Texas; one of the two states besides California at that time, in which airlines were allowed to define their own prices without the requirement of a permission from the Civil Aeronautical Board [3]. In Europe, initial low-cost operations were provided by Ryanair after the market liberalisation in the mid 1990s [1, 2].

In the following decades, market concentration and consolidation activities dominated the markets in North America and Europe. Merger and acquisition activities as well as the introduction of various forms of cooperation ranging from bilateral code-share agreements to the foundation of airline alliances[1] have shaped the airline markets [1]. In terms of operational aspects, the hub-and-spoke system transformed into a proven concept for FSNCs to further develop their network. Regional carriers, affiliated to the global network airlines, started to provide feeder flights into a major hub airport (HUB) within the network system [12]. Main drivers of these developments towards more and more connected airline cooperation structures were advantages from economies of scale, scope, and density [4]. Governmental institutions responded to these developments with the establishment of certain barriers to prevent a critical level of market concentration, especially in North America and Europe where consolidation nowadays is well advanced compared to other global regions [12].

The rise of the internet induced an acceleration of distribution channels and adaptation of business model characteristics by certain airlines. Traditional travel offices were replaced to a large extent by online distribution and ticket selling which most of the LCCs implemented in their business structure [11]. But distribution channels were not the only business model characteristic which has evolved. The current status of the airline business model landscape represents a diverse situation with many airlines operating a hybrid business model where full-service network as well as low-cost characteristics are combined. This fact underlines an observed increasing convergence of airline business models [26].

Figure 2.3 provides an overview of the overall market capacity and the LCC market share development in the three largest domestic markets Europe, North America, and Asia between 2000 and 2016. The data is based on the Official Airline Guide (OAG) database for the years 2000, 2004, 2008, 2012, and 2016 and includes the number of annual total available seats as well as the share of available LCC seats from the total seat availability in percent in these three markets [5–9]. The domestic markets in Asia show a continuous growth in LCC market shares (dashed line indicates LCC market shares in per cent on right axis) with an increase

[1]The first global alliance was the Star Alliance, founded in 1997 by five airlines from North America, Europe, and Asia [1].

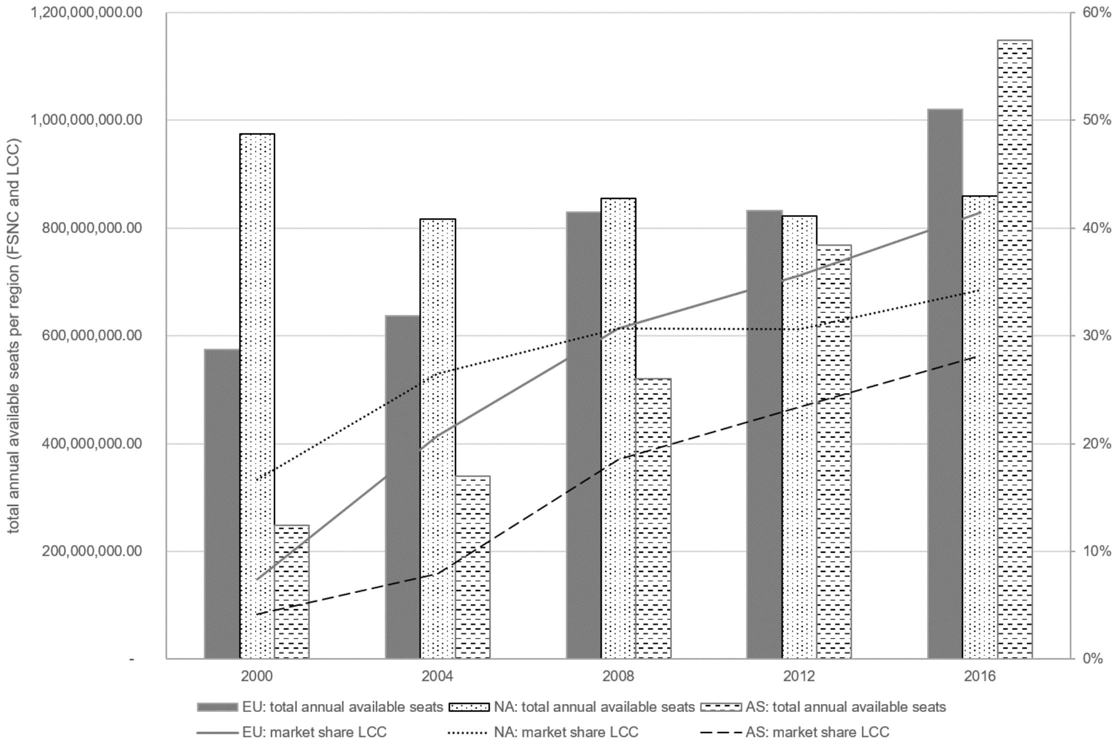

Figure 2.3: Total annual available total seats (FSNC and LCC) and LCC market shares in the three largest domestic markets Europe - EU, North America - NA, Asia - AS (own depiction, based on data from OAG, 2000, 2004, 2008, 2012, 2016 [5–9], long-range aircraft types excluded)

from 4 % to 28 % between 2000 and 2016. The overall domestic market in Asia, indicated as total available capacity from FSNC and LCC (dashed bar indicates total available seats on the left axis), grows by a factor of 4.6 over the period shown, which also indicates high growth rates for the FSNC. In contrast, the North American domestic market exhibits a declining development with slight growth trends between the years 2004 and 2008 and between 2012 and 2016 (dotted bar indicates total annual available seats on the left axis). The North American LCC market share increases in this period from 17 % in 2000 to a market share of 34 % in 2016 (dotted line indicates annual LCC market shares in per cent on right axis). It stagnates between the years 2008 and 2012. Hence, the LCC increases its market share despite the overall stagnating market development in the North American domestic market. In Europe, LCCs achieve the largest domestic market shares in comparison with North America and Asia with a value of 41 % in 2016 compared to an initial market share of 7 % in 2000 (solid grey line indicates annual LCC market shares in per cent on the right axis). Over the period shown, the LCC market share in Europe increases faster between 2000 and 2008 and, then, slightly flattens towards slower market share increase. The overall European domestic market constantly grows within the depicted time period (solid grey bar indicates total available seats on the left axis).

Nowadays, well-established LCCs have achieved saturated levels of market share. Since the LCC business model has its strategic foundation on growth [3], it can be expected and observed within many trial and error attempts that LCCs observe long-haul routes as new potential markets to be considered for the future strategic orientation of the airline. LCCs have shown several attempts in the past to transfer their business model to long-haul operations with Skytrain or Air Asia X and other airlines operating in long-haul markets [20].

2.1.2 The transatlantic air transport market

The Open Skies Agreement between Europe and the United States of America became effective in March 2008 [21]. With the allowance for European and American airlines to operate from any airport within Europe to an airport in the United States of America and vice versa[2], an increase in competition among airlines is expected resulting in an increase in overall flights in the transatlantic market due to lower ticket fares [58]. Since 60 % of the global air transport output is operated within and between Europe and the United States of America [59], the Open Skies Agreement for this air transport market has a significant global impact. It enables unrestricted fares and capacity for airlines from Europe as well as from the United States of America, allows access to all airports in each country, and establishes the fifth freedom rights [61]. The fifth freedom of the air constitutes that an airline can operate one flight leg between foreign countries when the origin or final destination airport is located in the airline's home country [59]. On the downside, an increase of airlines and according flight services in this market lead to an increasing demand due to reduced ticket prices [2, 12] which produces an increase in the environmental footprint of aviation in terms of CO_2 and other emissions. Hence, global solutions are required to reduce the impact of aviation on climate change as much as possible.

In 2009, the European Union and Canada signed an air transport agreement for air transport connections between these two air transport markets. This agreement complements the Open Skies agreement between Europe and the United States of America and has replaced bilateral agreements between Canada and European member states. With this, both partners hold privileges regarding liberal rights to operate flights from any point in Canada to any point in Europe and vice versa. [62]

One beneficiary for air passengers from these agreements was the emergence of LCCs who strive at the potential of cost-savings on long-haul operations in the transatlantic market [59]. This development was actually observed with the market entry of Norwegian Air Shuttle and Wow Air in the transatlantic market in 2014 respectively 2015 (based on Sabre data between 2010 and 2017) [63]. Before the market liberalisation agreements, capacity as well as prices were restricted in the transatlantic air transport market and several European member states could not operate to Canada or the United States of America since they did not have any bilateral air transport agreement [21, 62].

[2] Cabotage or the right for European airlines to operate flights within the United States of America or US airlines to offer connections within Europe is excluded from the Open Skies Agreement between Europe and the United States of America. Additionally, significant foreign airline ownership, e. g. a United States American airline owning a European network carrier, is prohibited in the agreement. [23]

Figure 2.4 depicts the trend in the development of origin-destination (OD) passengers between Europe and North America between 2010 and 2017 [51]. The analysis is based on data from the Sabre Data and Analytics Market Intelligence 5.15 database, including annual data of total OD passengers for all years between 2010 and 2017 [63]. OD passengers are defined as all passengers which start their air travel either in Europe or North America and have their final destination in the respective other region [51]. The figure only includes passengers which travel on routes with a total distance of above 4,000 kilometres. This includes all direct connections as well as connections with one or more intermediate stops.

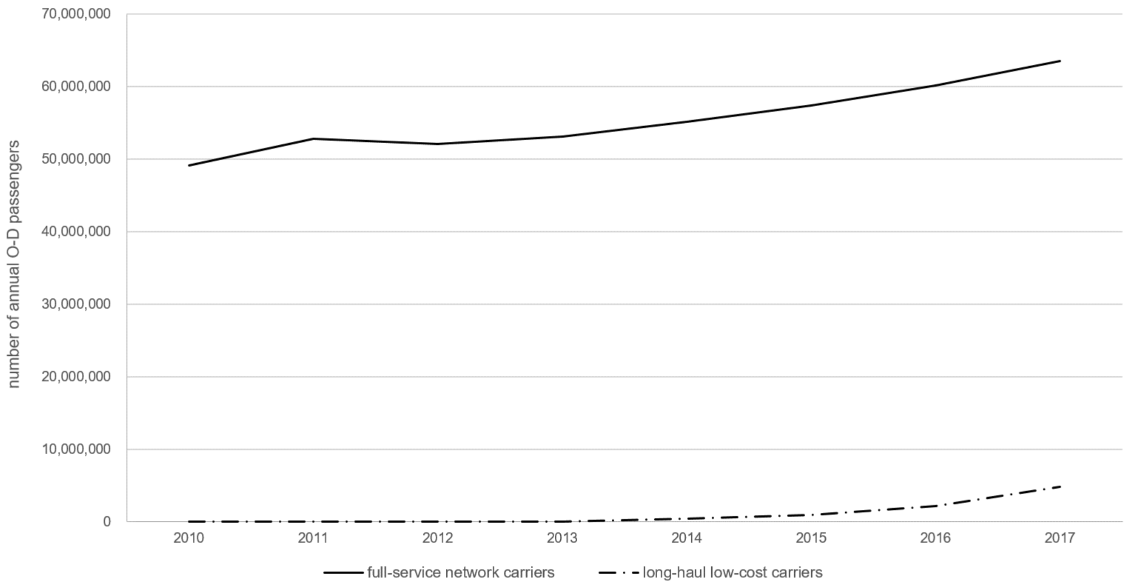

Figure 2.4: Annual OD passenger development between Europe and North America, flight distance above 4,000 kilometres ([51, p. 2, Fig. 1], based on data from Sabre Data & Analytics Market Intelligence 5.15, 2010-2017 [63])

The trend of the initial growth of the number of passengers which travel with an LHLCC increases up to a market share of 8 % of total transatlantic passengers transported by airlines classified as FSNC or LHLCC; other airline types are excluded (see figure 2.4) [51]. This development marks the beginning of a potential LHLCC market share growth between 2014 and 2016. However, lower market shares compared to the developments in the domestic markets (see figure 2.2) are expected since the implementation and operation of a cost leadership strategy, which is the selected strategy of airlines who operate an LCC business model, is more uncertain in long-haul markets since cost advantages over the competitors are more difficult to achieve [35–37].

2.2 Market strategies and airline business models

Market deregulation and liberalisation were the driving forces of the air transport market transformation towards its current state with different levels of a competitive market environment [2, 3]. This development allowed the entry of airlines which compete with market incumbents. New market entrants follow a different market strategy and operate different business models compared to its competitors. Hence, the increasing market liberalisation encouraged the emergence of new market strategies and according business models. Casadesus-Masanell and Ricart [64] define the relation between a strategy and a business model. In their words, the term "Business Model refers to the logic of the firm, the way it operates and how it creates value for its stakeholders" [64, p. 196] whereas the term "Strategy refers to the choice of business model through which the firm will compete in the marketplace" [64, p. 196]. Besides these two definitions, they introduce a third level, the tactics of an enterprise which comprise all choices of an enterprise on how to operate their business within a given business model framework [64].

The following sections provide an overview of different airline market strategies (see section 2.2.1) and according business models (see section 2.2.2). In addition, the phenomenon of airline business model convergence [26, 65] will be discussed. The focus in this overview lies on the comparison of two generic airline business model types: the FSNC and the LCC business model. Since the objective of this thesis is to investigate the transferability potential of LCC services to long-haul markets, it is crucial to identify major differences between the different market strategies of the long-haul market incumbent and the market entrant (see section 2.2.3).

2.2.1 Airline market strategies

Several influences within the airline industry enabled the formation and development of different strategies which airlines apply regarding their competitive positioning, marketing, and cost management aspects. Porter [10] specifies three different generic types of strategies for a competitive market situation: the cost leadership strategy, the differentiation strategy, and the focus strategy. An airline, that applies a cost leadership strategy, strongly focusses on cost-cutting measures to offer air transport services for rather price sensitive passengers [1]. A differentiation strategy, in turn, can be achieved if an airline implements a high quality standard and a unique customer experience [1]. According to Wensveen and Leick [34], airlines operating in long-haul markets will further diversify their strategy and focus on either niche markets with a high quality of the network and its connectivity or on a competitive ticket price offered [34]. Expressions of all three strategies, introduced by Porter [10], can be observed in long-haul air transport markets.

In general, the air transport market setting can be described with many passengers, a smaller number of airlines providing air transport services, and an increasing differentiation of air transport services [12]. In a simplified duopoly with two market actors, the incumbent faces several challenges in the entry of a low-cost service provider [12]. In turn, the market incumbent can react in different ways to a sustainable low-cost entry: match fares, establish a low-fare option or redefine and simplify the business model [12]. This thesis focusses on the analysis of the two different market strategies of established FSNCs and LCC market entrants.

Holloway [12] more specifically defines different approaches for market incumbents to deter other airlines from market entry. These include the reduction of prices in response to a market entrant as well as an increase of output and capacity. A price reduction decreases the potential difference in ticket price that can be achieved from a new market entrant. An increase in the market incumbents' capacity in a market reduces the share of available capacity in terms of slots at airports that a market entrant can introduce into the market. Other approaches are the provision of a Frequent Flyer Program (FFP), corporate contracts with business travellers and limiting the access for market entrants to distribution channels. However, the deterring-effect especially of the last approach is very limited due to the fact that, nowadays, many airlines utilise direct distribution channels such as ticket purchase via their websites. [12]

2.2.2 Airline business models

There are various definitions of a general business model [66]. In this thesis, the following definition is applied: a business model describes all elements and processes relevant for the operational performance and value generation for the customer [1, 66]. These elements include key partners and activities, key resources, value proposition, customers and relationships to the customer, revenue and costs, and distribution channels, as introduced in the Business Model Canvas framework developed by Osterwalder and Pigneur [67]. Scientific literature on the evolution and categorisation of airline business models differentiates between two to four types [1, 2, 68–70]. The two traditional airline business model types are the FSNC and the LCC [70]. Figure 2.5 depicts a ranking of the 10 largest airlines in 2015 in terms of the total annual passengers transported, differentiating between FSNC and LCC airlines [71].

In the ranking in figure 2.5 [71], three out of the ten largest global airlines in 2015 are LCCs (light grey bars in figure 2.5). This indicates that the LCC business model has been well established since its market entry in the 1970s and that LCCs are serious competitors for FSNCs nowadays. An according ranking of the annual traffic volume in terms of revenue passenger kilometre (RPK) would result in Southwest Airlines remaining among the 10 largest airlines in 2015 [71]. A ranking in terms of RPK weights traffic volumes by the distances flown. The ranking in figure 2.5 in terms of total annual passengers was selected to provide a more general view on the global airline market distinguishing between FSNCs and LCCs. Hence, the weighting of passenger volume by distance flown was neglected in this case.

Besides the FSNC and the LCC business model, scientific literature on airline business approaches introduces a charter and regional carrier business model [1, 69, 70]. Because regional and charter carriers provide proportionally lower traffic volumes and especially regional carriers focus on short-haul routes, these two airline types only take a minor role in the global air transport system. Especially on long-haul routes, FSNCs dominate the markets besides LCC attempts to enter these markets and some charter operations on selected routes. Regional carriers only operate small aircraft types with short-haul ranges [1]. A global airline ranking from 2017, illustrated in figure 2.5, underlines the importance of the FSNC and the LCC in terms of traffic volume, i. e. annual passengers transported [71]. Consequently, the focus in

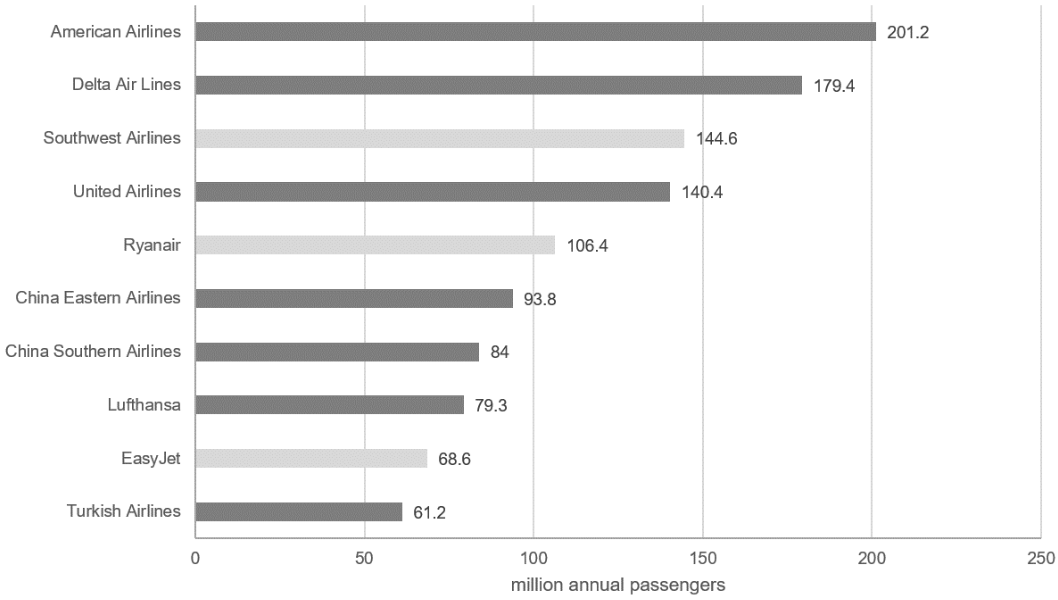

Figure 2.5: Ranking of global airlines in 2015 [million annual passengers] (own depiction, based on data from [71, p. 12], FSNCs depicted in dark grey bars, LCCs depicted in bright grey bars)

this thesis will be on FSNCs and LCCs who enter the long-haul markets. Regional and charter carriers will be neglected which is why these two business models will not be introduced in detail in the following. In addition, cargo transport and, thus, cargo airlines and their respective business models as well as business aviation are not considered in this research. The focus remains on scheduled air passenger transport. Bieger and Wittmer [68] define an airline business model as the strategy, or, in accordance with the definition by Casadesus-Masanell and Ricart [64], as the logic how airlines design and operate their networks. All business models have three dimensions in common: “the type of markets and production applied, the type of revenue and pricing systems applied, and the type of coordination of the value chain or network” [68, p. 95]. In the following, the two airline business model types will be briefly defined and cost-cutting measures of LCCs [72] will be highlighted. Subsequently, a specific literature review on the transferability of the LHLCC is presented to give an overview of specific characteristics of this business model derivative. These insights shed a light on the low-cost service market potential when introduced to long-haul air transport markets.

Full-service network carrier (FSNC)

FSNCs represent a traditional airline business model operated by a significant amount of former national carriers that have evolved towards large network carriers over time [1]. Connectivity and integrated products at comparably high quality characterise this type of airline. Different cabin classes as well as additional services before and after the actual flight such as the availability of lounges or other amenities throughout the check-in constitute this strong focus on quality and service [2]. FSNCs operate a heterogeneous aircraft fleet within a hub-and-spoke network [1, 2]. Smaller aircraft in the fleet provide feeder connections to the HUB, from which larger aircraft connect long-haul destinations [1]. The selection of a HUB takes a crucial role in a hub-and-spoke network [1]. According to Bieger and Agosti [73], FSNC success factors are HUB operation and a significant share of transfer flights, specific customer services, integrated technical departments and catering companies, and a complex network management.

FSNCs extend their connectivity within the network through various forms of cooperation [1, 2]. The current trend in the development of airline cooperation reveals an increasing consolidation and strengthening of airline alliances [1, 2]. Active participation in an alliance brings benefits for the individual airline as this participation substitutes merger activities [73], enables access to flight connections beyond the own network as well as an increase in economies of scale and scope, and a reduction of competition [1, 2]. Core airlines within an airline alliance, mostly large former flag carriers such as Lufthansa within Star Alliance, provide a strong brand, a strong and efficient HUB, intercontinental flight operations, and a competent network management [73].

Low-cost carrier (LCC)

The key characteristics of the LCC business model in comparison with the FSNC business model are an increased seat capacity per aircraft and a higher aircraft utilisation [2]. A high degree of fleet commonality reduces operating cost such as maintenance and crew training [1]. In line with this focus on low operating cost, LCCs offer a standardised service with no premium class on point-to-point connections, no seat assignment, and no frequent-flyer programs [2, 69]. Employees of the generic LCC business model are not organised within a labour union [69]. Thus, these employees have less power to act against lower wages. From the LCC perspective, lower wages and less restrictive work rules allow higher operational productivity [69]. Another source of cost reduction potential is to only distribute tickets directly and not to use distribution channels which require commission fee payment [69].

LCCs depend on efficient and lean production processes that include short turnover times, low airport charges, simple network structures with point-to-point shuttle services, and very often low salary structures as well as cheap leasing rates [2, 73]. In comparison to that, charter airlines focus on lean and efficient processes, low salary structures, comparably good or reasonable service, reputation, and integration into a tour operator system and regional carriers establish lean and efficient processes and low complexity, access to regional markets, and technical skills or specialities in the sense of ability to serve small airports with very often difficult approach conditions and short runways as major success factors [73].

According to Budd and Ison [72], LCCs can implement several measures to reduce their operating cost. The following list gives an overview of potential cost-cutting measures [72]:

- homogenous aircraft fleet to reduce maintenance costs, training costs, and cost of spares inventory, to streamline scheduling and to bulk purchase discount potential from airframe and engine manufacturers
- aircraft utilisation at high levels to increase short-haul operations to up to 12 operational aircraft hours per day
- short-haul point-to-point flight operations without flight interlining to reduce baggage handling expenses, decrease turnaround times, and operate multiple flight cycles per aircraft per day
- operation from secondary airports to reduce operational costs and engage in partnerships with airports towards the operation of dedicated low-cost terminals
- operation of a uniform all-economy class cabin to utilise the maximum aircraft cabin seat capacity and to reduce cabin services to a required minimum
- fast turnaround times of around 30 minutes to increase daily flight cycles and, therefore, the utilisation of the aircraft
- ancillary revenue generation to charge all additional services separately (no FFPs offered)
- utilisation of online reservation and sophisticated revenue management systems
- high level of subcontracts to increase competition between providers of e. g. ground handling services and, thus, decrease prices and operational costs for these services
- increased labour productivity and less staff per passenger to reduce labour and training costs to a minimum
- horizontal strategic partnerships across the travel value chain to engage in cooperation with accommodation providers, car rental firms and credit card companies
- strong focus on short-term tactical advertising to sell additional tickets shortly prior to the actual flight and to increase the seat load factor (SLF)

These listed cost-cutting measures apply to the traditional markets of LCCs, the short-haul markets. However, some of these measures can be transferred to long-haul markets. This aspect will be discussed in more detail in section 2.2.3.

Airline Business Model Convergence

Today, several airline business model categorisations exist. Recent studies claim that airline business models tend to gravitate towards each other [26, 65]. Thus, airline clustering, based on business model characteristics, originates new categories that are more specific compared to the well-established full-service network and the low-cost model [26, 74].

A transformation of airline business models and their performance can be observed over time. Key success factors of an FSNC are the operation of a HUB, inducing big shares of transfer traffic, integrated technical departments, catering companies, a complex network management, and specific customer services that can form an integrated travel product, i. e. lounges or mileage programs [73].

Trends in the airline business model transition seem to develop towards an increasing share in low-cost characteristics, a strong erosion of traditional business models, primarily with charter airlines, and the fact that the regional business model seems to reach its limits. Future strategic success factors for airlines rely on the customer service contact that includes individualised service packages, passenger-specific care and attention, market access, the travel itself (experience, safety), and the airport infrastructure [73]. On long-haul flights, the adoption of ancillary services such as checked-in baggage, catering, priority boarding, seat selection or the availability of internet access during the flight by LHLCCs can be observed [75].

2.2.3 Long-haul low-cost characteristics

The transformation of the LCC business model to long-haul operations is not a novel approach. First attempts to implement low-cost air transport services to long-haul markets go back to the efforts of Laker Airways in 1977 [1, 32]. However, the Open Skies Agreement in 2008 [21] accelerated these attempts. LHLCCs operate a decentral point-to-point network in which feeder traffic is not explicitly scheduled [37]. The example of the airline Norwegian underlines this due to the fact that this airline focusses on selected, dense routes in the transatlantic market [76]. A significant share of passengers up to 60 % book a long-haul connection with one or more stopovers[3]. The pricing scheme of an LHLCC is expected to be a sum-of-sector concept if connecting flights are offered [37]. Potential target groups include visiting friends and relatives (VFR) groups as well as price sensitive business passengers [37].

The major difference between the short-haul and the long-haul LCCs is how they compete with the other airlines. Short-haul LCCs operate more efficiently than their competitors whereas long-haul LCCs optimise the yields based on the given aircraft capacities they operate with a small share of premium seats subsidising the operating cost of the highly discounted economy seats [34]. Yield optimisation can be achieved by more seats offered per available flight capacity [38] compared to the FSNC competitor. Operational efficiency advantages on short-haul routes can be generated through a decrease in the turnaround time and resulting additional flights per day compared to an FSNC [1]. Due to longer flight times, this advantage cannot be leveraged on long-haul routes [31, 33]. Furthermore, a reduction of cabin personnel can be utilised more effectively on short-haul than on long-haul routes. A maximisation of yield on long-haul routes is realised through high density seating [34]. This is connected with less cabin comfort since high density seating reduces the space offered to each passenger. The degree to which passengers accept less comfort on long-haul routes at a lower price compared to a competitor is difficult to define and only applicable to specific markets in terms of city-pair markets [34]. The success of low-cost services in long-haul markets strongly depends on

[3]Key figure calculated from OD Sabre data [63] for 2014 between Europe and North America and distances flown above 4,000 kilometres.

a feasible business plan that enables a sustainable competitive advantage, a long-term vision developed and applied by a well-functioning management team, flexibility, and steady and moderate growth [34].

A study on the transferability of the low-cost business model to long-haul routes reveals that not all competitive advantage measures, presented in the previous subsection, are suitable for long-haul markets [51]. The results from this study, conducted by the author of this thesis, are discussed in this section 2.2.3 in the following. Table 2.1 gives an overview of existing studies on the LCC transferability to long-haul markets from [51]. A structured literature review revealed a list of journals and complementary conference papers on the topic which were published between 2007 and 2019 [51]. The according journals were selected from a ranking list from the Scimago Journal & Country Rank (based on the Scopus database[4]) [51]. No consistent opinion exists on the potential of long-haul low-cost air transport services [51]. The findings of the structured literature review comprise three aspects: operating cost advantage, competitive advantage measures, and potential markets [51].

The range of the operating cost advantage in long-haul markets is lower compared to an operating cost advantage of 40 % to 50 % in short-haul markets [13, 18, 78]. The existing research literature, as summarised in table 2.1, indicates an LCC operating cost advantage between 10 % and much lower than 50 % to 60 % in long-haul markets [13, 18, 19, 32, 35, 37]. Five publications from table 2.1 do not quantify the operating cost advantage [20, 31, 38–40]. Soyk et al. [37] find that only a share of 24 % from the overall 33 % cost-saving potential can be characterised as sustainable for a longer term and that this share is further split into 11 % resulting from business model differences and 13 % resulting from higher seating density in the aircraft operated. Overall, there is a mutual agreement among researchers that the low-cost business approach has a certain potential in long-haul markets [51]. However, the range of this potential turns out to be broad, with a tendency of cost advantages between 20 % and 25 % (see table 2.1), and linked to several requirements that need to be fulfilled in a respective long-haul market [51].

The potential for an LCC to reduce its operating cost on long-haul flights results from several characteristics in the airline type's strategy and resulting business model [64]. These characteristics relate to the list of measures to save operational cost in short-haul markets, listed in the previous section 2.2.2 as cost-cutting measures [72]. The study on the transferability of low-cost services to long-haul markets identifies competitive advantage measures of which some relate to the objective to cutting costs [51]. These measures are compared to the generic cost-cutting measures from [72] and discussed in the following.

One competitive advantage measure for LCCs on short-haul routes is the higher utilisation of the aircraft fleet [1, 72]. Due to shorter turnaround process times, LCCs can operate more flights during a day and, thus, increase the utilisation of their aircraft fleet compared to their FSNC competitors [54]. This competitive advantage is reduced on long-haul routes due to longer flight times and distances which is why higher aircraft fleet utilisation is difficult to transfer to long-haul markets [31, 33]. LHLCCs can compensate for that reduced utilisation

[4]Scimago Journal & The following selection was made: Country Rank: 'all subject categories': Transportation, year: 2018 [77].

Table 2.1: Overview of research literature on the transferability of low-cost air transport services to long-haul markets ([51, pp. 4-5, Table 1])

Author(s), Year	**Markets of Observation**	**Type of Research**	**Operating Cost Advantage**	**Competitive Advantage Measures**	**Potential Markets**
Francis et al. (2007) [13]	transatlantic	quantitative analysis of potential cost differentials	20 %	• "no frills" concept limited due to longer flight times, FFPs, and belly cargo more important revenue source • higher load factors on long-haul flights, in general, limiting the LHLCC utilisation advantage • highest potential in labour cost reduction and a lean central administration	• pure leisure markets, VFR • dense point-to-point markets from secondary airports • cost and risk involved in building up a critical mass
Pels (2008) [31]	*no specification*	network competition analysis	*not quantified*	• competitive advantage in terms of utilisation difficult to generate due to longer distances and flight times • scheduled long-haul low-cost services strongly dependent on continuous demand	• picking of profitable point-to-point routes and opening new markets from secondary airports
Morrell (2008) [32]	transatlantic	evaluation of cost and other competitive advantages	much lower than 50-60 %	• limited potential for increased aircraft productivity due to longer flight times and higher average SLFs on long-haul routes • highest potential for reduced passenger services ("frills") and reduced passenger handling fees from secondary airport operations	• focus on point-to-point markets

Table 2.1 continued: Overview of research literature on the transferability of low-cost air transport services to long-haul markets ([51, pp. 4-5, Table 1])

Author(s), Year	Markets of Observation	Type of Research	Operating Cost Advantage	Competitive Advantage Measures	Potential Markets
Gross/ Schroeder (2008) [33]	transpacific, transatlantic	qualitative long-haul low-cost business model analysis	20 % ([13])	• aircraft utilisation of legacy carriers already very high on long-haul routes • cost reduction due to second-hand, less-fully equipped aircraft • outsourcing of ground handling operations	• high volume markets with large point-to-point share / secondary airports • high share of business travellers; pure leisure markets (focus on VFR)
Wensveen/ Leick (2009) [34]	*no specification*	long-haul low-cost business model analysis	20-25 % ([18])	• yield optimisation from available aircraft capacities (dense seating) • new aircraft technologies, young cabin staff, and direct internet distribution	• high density markets with legacy competition
Moreira et al. (2011) [19]	*no specification*	cost simulation for B767-300 platform	10 % (SLF levels > 85 %)	• limited potential from reduced on-board catering, internet distribution of tickets and lean admin. structure, a young cabin crew and new aircraft • aircraft utilisation: strong impact from load factors on airline profitability	• niche VFR/leisure-oriented markets (underserved by legacy carriers) • best prospects in Asia
Daft/ Albers (2012) [20]	EU-based airline perspective	long-haul low-cost profitability analysis	*not quantified*	• belly cargo additional revenue source, esp. on flights with lower SLFs • homogeneous aircraft fleet with new aircraft types • generation and absorbing of price sensitive demand	• existing point-to-point routes without required feeder traffic • operations from secondary airports

Table 2.1 continued: Overview of research literature on the transferability of low-cost air transport services to long-haul markets ([51, pp. 4-5, Table 1])

Author(s), Year	**Markets of Observation**	**Type of Research**	**Operating Cost Advantage**	**Competitive Advantage Measures**	**Potential Markets**
Poret et al. (2015) [17]	transatlantic	financial assessment of transatlantic low-cost operations	20-25 % ([13], [18])	• essential to expand revenue sources (cargo, ancillary revenues) • potential benefit from short-haul network if short-haul LCCs expand their markets • crew cost & airport charges provide potential areas to save operating cost	• point-to-point routes with sufficient potential leisure or feeder traffic sources at both ends of the routes operated
Whyte/ Lohmann (2015) [35]	Europe (UK) - Australia	case study: cost simulation on routes between Melbourne and London	13-17 %	• increase of fleet utilisation • minimisation of crew rest times and wages to reduce labour cost • reduction of overhead cost through outsourcing of services • minimisation of distribution cost through a strong focus on direct online booking services	• limited potential point-to-point between Australia and the UK, even with newest, fuel-efficient aircraft technology
Wilken et al. (2016) [36]	inter-continental from Europe	gravity model: air transport demand on intercontinental routes	10-20 % ([13], [19])	• high aircraft utilisation with 150 to 200 seat capacity per aircraft and high load factors required • potential for market entry and subsequent increase of flight frequency, routes served through "hubbing" and "self-hubbing"	• OD (point-to-point) routes between 4,000 kilometres and 12,000 kilometres distance

Table 2.1 continued: Overview of research literature on the transferability of low-cost air transport services to long-haul markets ([51, pp. 4-5, Table 1])

Author(s), Year	**Markets of Observation**	**Type of Research**	**Operating Cost Advantage**	**Competitive Advantage Measures**	**Potential Markets**
Soyk et al. (2017) [37]	transatlantic	cluster analysis	33 % (24 % sustainable on longer term: business model differences (11 %) // higher seating density (13 %))	• strong focus on low complexity (reduction of overhead and operational processes) and low cost	• dense long-haul point-to-point routes • coincidental feeder traffic from short-haul LCC operations at secondary airports
Soyk et al. (2018) [38]	transatlantic	profitability analysis	*not quantified*	• larger seat capacity per aircraft (19 %) and higher SLFs (14 %) compared to FSNC • lower yields partly offset by higher ancillary revenues, lower passenger taxes, and a higher load factor	• direct point-to-point routes, partially from secondary airports
Gualini et al. (2019) [39]	transatlantic	regression analysis: LHLCC presence, airline alliances impact on airfares	*not quantified*	• competition with two or more alliance competitors not manageable with lower ticket prices	• focus on tourist-oriented routes • avoiding routes with two or more alliance competitors present
Hunt/ Truong (2019) [40]	transatlantic	survey on factors affecting passenger choice of LHLCC	*not quantified*	• airfare most important factor, followed by comfort, service, and flight schedule • operation of new aircraft technologies (passengers associate increased comfort with new aircraft)	• markets with price sensitive customers and non-stop/ point-to-point flights

advantage with higher SLFs compared to their competitors [36, 38]. However, airlines already operate with higher average SLFs in long-haul markets [32]. Hence, this competitive advantage cannot be fully exploited in these markets for LHLCCs. Another competitive advantage measure results from the operation of a homogeneous fleet [1, 72]. Whereas FSNCs operate a broad diversity of short-haul and long-haul aircraft within their network, LCCs focus to reduce operating cost and increase flexibility through the operation of a single aircraft type [1]. Since LHLCCs operate a smaller aircraft fleet during their market entry [79], the cost reduction effect from fleet homogeneity is limited. But operating a homogeneous fleet can be advantageous for LHLCCs since FSNCs mostly do not have the opportunity to change their fleet composition towards a more homogeneous fleet because they operate a heterogeneous network with a wide range of different routes [1]. These routes require different aircraft types to optimise the respective operating cost on a specific route.

In terms of the selection of aircraft type, the literature review findings in table 2.1 reveal a heterogeneous opinion [51]. Several studies conclude that new aircraft technologies such as the Airbus A350 or the Boeing B787 are the advantageous choice that offers economic and environmentally efficient operations [34, 35, 40]. These aircraft types have the potential to attract passengers since they offer a high quality standard within the cabin in terms of noise and overall furnishing [51]. However, the acquisition of these new aircraft types is cost-intensive and this fact can create a market entry barrier for new LHLCCs [51]. As an alternative, second-hand aircraft can be purchased for the entry into long-haul markets, such as the Airbus A330, at relatively low prices compared to the new aircraft types [33].

Operational costs in terms of labour, ground handling services or maintenance as well as overhead costs resulting from administrative structures show potential from competitive advantage measures [13, 16, 17, 19, 33, 35]. For example, ground handling services can be outsourced to external providers [33, 54]. However, FSNCs also facilitate external ground handling service providers at the majority of the airports within their network which reduces the cost-advantage of the LHLCCs over the FSNCs. Besides, it is questionable whether these services can be outsourced cost-efficiently at secondary airports where there might be only one provider available. Labour costs can be reduced by employing a young cabin crew and by reducing the crew rests abroad to decrease costs for crew accommodation [16, 17, 19]. LHLCCs can further operate their flights with a minimum crew factor [20] which can have a negative impact on the service standard. A strong focus on online ticket distribution can further decrease operational costs [34, 35]. FSNCs today also rely on these distribution channels and continuously improve the transparency of the ticket purchase process [19]. Thus, the cost advantage for LHLCCs from online ticket distribution is limited [19].

Operational costs can be further reduced with flight operations from secondary airports that offer lower airport and ground handling charges [13, 20, 31–33, 37, 38]. But long-haul operations imply airport requirements that not all potential secondary airports can fulfil such as minimum runway lengths (and width) for large aircraft or flexible opening hours to align with a long-haul flight schedule. In addition, ancillary revenues gain importance for LHLCCs operating on long-haul routes to cover the reduced operational cost advantage [51]. These ancillary revenues can be generated from cargo transport in the lower aircraft deck [13, 17, 20] and the unbundling of services for additional charges besides the basic flight services included in the ticket price [13, 17, 19, 37, 38, 80].

The summary of research on the transferability of low-cost services to long-haul markets in table 2.1 highlights that niche routes with a price sensitive OD demand and passengers who primarily want to VFR are the most promising potential markets [13, 19, 31, 33, 40]. There is a heterogeneous opinion about feeder traffic as a requirement to generate sufficient OD demand [51]. On the one hand, LHLCCs should select routes with a robust continuous demand in the airport catchment area to avoid a dependence on short-haul feeder traffic [20, 31]. This would mean operating flights primarily from secondary airports. On the other hand, coincidental flight connections [37] or the concept of self-hubbing [81, 82] might arise, especially applied by price sensitive passengers. In addition to these literature findings, two recent studies investigate the effects of the LHLCCs market entry on ticket prices of market incumbents [76, 83].

Expected contributions

This thesis will extend the research on competition in long-haul air transport markets and the long-haul market potential of low-cost services through the development of a simulation model that will address the question whether low-cost services can be transferred to long-haul markets or not and which market potential might result from this implication. The model will provide capabilities to investigate the dynamics in the transatlantic air transport market and especially the uptake of passenger demand for LHLCC services and its effects on the airline market, represented with two generic airline types, the FSNC and the LHLCC [51]. The following aspects highlight the contribution of this thesis:

- This thesis provides a simulation model which supports the analysis of market dynamics in competitive long-haul air transport markets resulting from the introduction of low-cost services.
- With this model, different market conditions and development scenarios are simulated and the market potential of low-cost services in long-haul markets is analysed.
- The model will be applied to the transatlantic air transport market to investigate passenger demand development for LHLCC services and market competition between FSNCs and LHLCCs.

The following chapter 3 will select a feasible methodological approach to model the air transport system and introduce a simulation model to investigate the LHLCC market potential and to address the research objective on the transferability of low-cost services to long-haul markets and the resulting market potential in this thesis. Subsequently, the model development steps and the model structure are explained in detail. The model is based on previous modelling activities of air transport applications with the simulation methodology selected and is aligned to the specific problem definition.

Chapter 3

Methodological approach for transatlantic air transport assessment

The previous chapter 2 provided an overview of specific market potential characteristics of low-cost services in long-haul markets. The following chapter 3 introduces SD as a feasible methodology for the investigation of the research question on the future development of different airline business models in the transatlantic market. This model will be defined as the TATM and will be utilised to investigate the transferability of low-cost services to long-haul markets through the implementation with SD. For this, the following two research questions regarding the method selection and modelling of airline interrelations will be addressed in this chapter:

- **Which methodological approach is feasible to investigate the introduction and operation of long-haul low-cost services?**
- **How can interrelations between airlines and other stakeholders in the air transport system be modelled?**

The chapter provides a detailed description of the TATM and its different model elements covering demand generation, passenger decision, and airline decision and operation. Modelling approaches of the air transport system from previous research serve as a valuable source to gain insights and to highlight the novel aspects of the TATM.

A summary of the major findings from this chapter includes the following aspects:

- SD is identified as a feasible methodology to represent the various dynamics between the selected airline business model types LHLCC and FSNC in the transatlantic air transport market.
- This method enables the investigation of dynamics within a system which arise through feedback loops that represent the interactions between the demand and the supply side as well as strategic decisions of the airlines.

- The TATM development complements the existing research with a first transatlantic SD model that represents interactions of airlines and passengers in this long-haul market.
- The model includes specific aspects such as ticket price development and capacity development in terms of available seats as major effects on passenger choice to analyse the market potential of low-cost services in the transatlantic market, including passenger consideration and passenger choice.

The chapter begins with the selection and introduction of SD as methodology applied in this thesis to model and simulate the transatlantic air transport market. In addition, an overview of previous SD research in air transport system modelling is presented. After that, the model with its problem definition, reference mode, and model boundary chart is explained in detail. A basic model concept depiction and a causal loop diagram (CLD) provide further insights in the structure of as well as the interactions within the TATM that drive its behaviour.

3.1 Selection of a methodological approach to model the air transport system

Several basic simulation methodologies to model a complex system are discussed in scientific literature. A simulation is based on a mathematical formulation and represents the essential interdependencies and effect structures of a real system [84–86]. Kieckhäfer [87] introduces a categorisation for simulation models for market simulation, based on existing literature [84, 88–92] in the field of simulation models, that differentiates between contrary characteristics such as static or dynamic, stochastic or deterministic, continuous or event-discrete, and microscopic or macroscopic models. Static models simulate the market at a specific point in time whereas dynamic models represent the market behaviour over time. Stochastic simulation models observe random events in the system. In a deterministic simulation, input parameters define the events within the system modelled. Continuous simulation models map the development of the system over time and event-discrete simulation models focus on changes in the system at discrete time steps or events. Microscopic models provide a very detailed view of the respective system to be observed whereas macroscopic simulation aggregates the level of detail of the system. [87]

The characteristics can be applied to describe different basic simulation methodologies. The following list comprises different types of simulation approaches to model complex systems (compiled from [84, 87]):

- Discrete-Event simulation
- Monte-Carlo simulation
- Continuous simulation
- Agent-based simulation

Discrete-Event simulation focusses on the modelling of a specific state of a dynamic complex system at a defined event or time step [84]. The dynamic in this simulation methodology results from discrete changes of this state [93]. Discrete-Event methodology is often used to investigate and improve the underlying process of a system [84, 94]. The Monte-Carlo simulation methodology enables a static, stochastic analysis of a set of input parameters to a complex system and the resulting system behaviour [84, 93]. Different input settings are defined and simulated in random sample simulations [84]. Interrelations within the system are investigated by simulation repetition and analysis of the set of input parameters and the according simulation results [84]. Continuous simulation methodology is applied to macroscopic, dynamic systems based on differential equations with continuously changing state variables over time [84, 86]. The use of differential equations is the reason for a comparably high degree of abstraction [87]. SD is one representative of continuous simulation methodologies [84, 86]. Feedback loops modelled within the complex system drive the system behaviour over time [86]. A set of input parameters and time-series data determines the framework conditions of the simulation. Agent-based simulation methodology provides continuous microscopic models where agents with specific characteristics, that interact with each other, are introduced [90]. System behaviour is generated through the mutually conditioned agent decision-making behaviour in the system [84, 87]. Conclusions on functional relationships between the actions of the individual agents and the resulting system behaviour cannot be derived; the system behaviour rather indirectly results from the individual decisions and actions of the agents [84].

The scope of this thesis is to provide a dynamic model that represents a macroscopic perspective on the transatlantic air transport market interactions via key elements such as ticket price and capacity development. From this, requirements can be derived for the simulation methodology to be selected. The object of investigation is the market share potential of the long-haul low-cost service. The transatlantic market is characterised by several basic conditions such as e. g. an average flight distance, suitable aircraft types to be operated, or operating cost structures that determine the system to be modelled. The resulting market share potential develops over time as a result of continuous interactions and feedbacks between the demand and supply side. The supply side is constituted by different airline types that compete with each other. The demand side represents potential passengers for long-haul air transport services in the transatlantic market. Hence, the required simulation methodology has to enable continuous simulations over time where different market stakeholders interact with each other within framework conditions defining the system. The demand and the supply side respond to each other's decisions with delay, i. e. the supply side offers a novel, low-cost service, passengers notice this new service and include this option in their decision process. In turn, airlines on the supply side have to manage changes in passengers' decisions that lead to changes in seat capacities required to operate economically.

Concluding the requirements discussed above such as depicting the dynamic behaviour of a complex system from a macroscopic perspective considering interactions between different entities involved in the system, SD is selected as a feasible methodology for the model development in this thesis as it satisfies these requirements. The SD methodology allows for continuous simulation over time and focusses on the dynamics within a system that arise from market interaction between the demand and the supply side and according feedback from a macroscopic perspective to reduce complexity and include the major elements and effect mechanisms of the system to be investigated [86]. SD will be introduced in the following section in more detail.

3.2 Systems Thinking and System Dynamics

SD is a well-established methodology to model complex systems and the prevalent interrelations and dynamics within a system of interest [86]. In the 1950s and 1960s, this methodology has been developed by Jay W. Forrester at the Massachusetts Institute of Technology [95]. The objective of SD is to provide a framework that enables structuring a complex system and, therefore, enabling an understanding of the dynamic complexity within the system [86]. SD models focus on the endogenous behaviour of a system [87]. The modelling process includes five essential steps which are conducted in an iterative manner. These five steps comprise: the problem articulation (boundary selection), the definition of a dynamic hypothesis, the model formulation, the model testing, and the policy formulation and evaluation [86]. Figure 3.1 comprises all five steps of the SD modelling process [86].

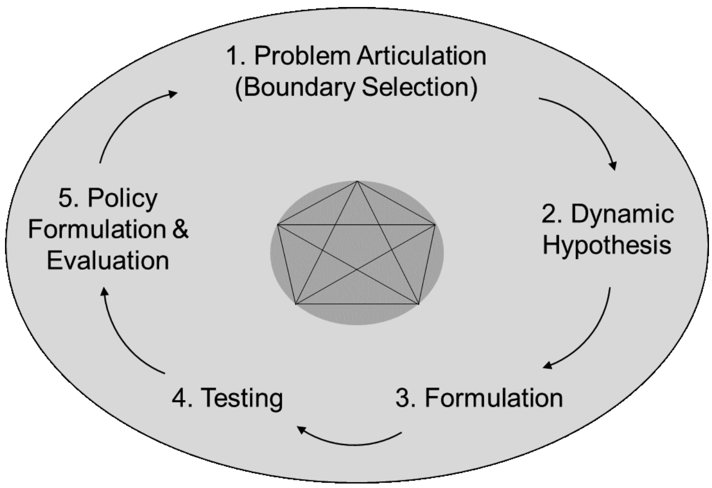

Figure 3.1: SD modelling process (adapted from [86, p. 87, Figure 3-1])

Steps one and two constitute the basis for the research with SD: the definition of a concrete research question to be answered with an SD model and a hypothesis on the model's behaviour in interaction with different assumptions and policies [86]. The subsequent step is the actual formulation of the model [86]. This can be subdivided in a qualitative model of a system, which is conceptualised with a CLD, and the quantification with the actual development of a quantitative model using a stock and flow logic [96]. After the formulation of the model, several structure and behaviour tests need to be compiled with the model to gain confidence in it [97–99]. The final step is the formulation and simulation of policy scenarios with the developed model and the subsequent evaluation of the simulation results [86].

A CLD is based on different elements and arrows not only connecting two of these elements but also indicating the direction of influence [86]. Additionally, a positive influence of one element to another can be accentuated with an addition operator next to the arrow whereas a negative influence is marked with a subtraction operator [86]. A CLD includes feedback loops as soon as interactions between several elements feed back to an initial element [86]. Feedback loops can be negative, i. e. balancing or self-correcting, or positive, i. e. self-reinforcing [96]. Figure 3.2 provides a generic CLD of the population development.

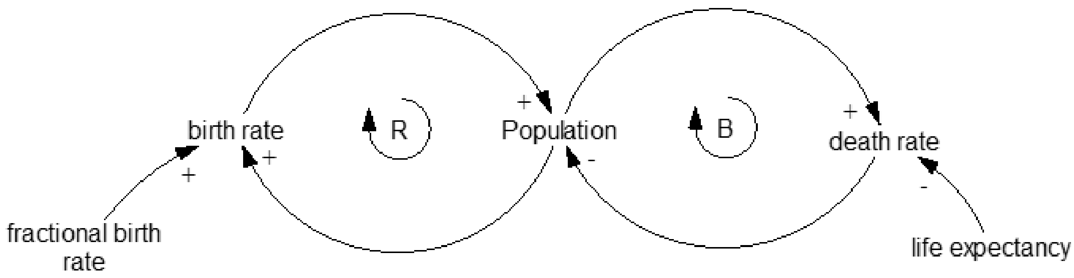

Figure 3.2: CLD population development example ([51, p. 7, Fig.2], adapted from [86, p. 138, Figure 5-1])

The CLD example in figure 3.2 contains causal relations between a population and a birth and death rate which both influence the population development over time. In general, positive feedback loops result in amplified growth or increase whereas negative feedback loops counteract change and result in a balancing goal-seeking growth or decline [86, 96, 100]. Transferred to the population example, this means that an increase in the population leads to an increase in the birth rate which, in turn, results in a larger population. This relation can be characterised as a reinforcing loop. In comparison to that, a growing population causes a higher death rate, which, in turn, decreases the overall population within a balancing or self-correcting feedback loop. The population would be reduced to zero if the balancing death-rate loop was the only effect on the population development. The fractional birth rate defines an average number of births per time unit to be expected and the life expectancy defines the death rate per time unit. [86]

From this basic example, the population development can be expanded arbitrarily with several aspects that have an impact on the population development such as scarce resources impacting a required level of food to provide for the population or effects from migration as an additional source for an increasing population. A CLD visualisation of an SD model allows to highlight major feedback loops. These feedback loops drive the dynamics within the system [86]. Such systems can be characterised as path dependent indicating that a single event at a specific time can determine the further course of the overall system [86].

Based on the structure of a qualitative CLD, modellers can quantify the model structure and implement input data such as initial figures, decision parameter figures, and formal equations.

Two basic elements of such a quantitative SD model are stocks and flows. Stocks represent a cumulative figure of a state variable and flows can be either inflows which increase the level of this state variable or outflows which decrease the level [86]. An initial value can be assigned to the stock. In case of the population example, this initial value would represent the population at the beginning of the simulation time t_0. Figure 3.3 depicts these two basic elements.

Figure 3.3: Basic stock and flow logic in SD (adapted from [86, p. 193, Figure 6-1])

The mathematical expressions for the stock is [86]:

$$Stock(t) = \int_{t_0}^{t} [inflow\,(s) - outflow\,(s)]ds + Stock\,(t_0) \tag{3.1}$$

And the differential equation resulting from this integral equation is [86]:

$$\frac{d\,(Stock)}{dt} = net\ change\ in\ stock = inflow(t) - outflow(t) \tag{3.2}$$

The level of a stock can be expressed as an accumulation of inflows over time t reduced by respective outflows. In- and outflows are determined by different concurrent or opposite trends and always represent values per time unit, whereas the level of a stock is expressed in an absolute value at a specific time t. [86]

The alternate notation of a stock as used in Sterman [86] represents that the stock accumulates all inflows reduced by the outflows considering an initial level of the stock at t_0 which can be expressed alternately to equation 3.1 as follows using the $INTEGRAL()$ function:

$$Stock = INTEGRAL(inflow - outflow, Stock(t_0)) \tag{3.3}$$

The actual dynamics of a system arise with reinforcing and balancing feedback loops [86]. An exponential accumulation of a stock results from reinforcing feedback loops whereas a stock level can either grow asymptotically or decrease from balancing feedback loops [96, 100]. Since stocks representing resource levels, e. g. people, money or inventory, cannot usually be negative, it is good modelling practice to implement outflows with a negative feedback loop (first-order control) [86]. First-order control deactivates the outflow when the stock level is zero. According model formulations that prevent stock non-negativity have to be implemented in the model. Effects from a feedback loop can be delayed [86]. Examples for such delays are manufacturing times of a product or time it takes to make a purchase decision. In general, SD provides continuous models whereas econometric modelling techniques operate with discrete time intervals [86].

3.3 Previous System Dynamics research in air transport system modelling

The SD methodology has been applied to several research questions related to the air transport system in the past. It is classified as part of the group of structural modelling approaches [100]. Its application aims to achieve research findings that support the development of transport policy recommendations [96, 100]. The following section 3.3 highlights two summarising studies on SD applications in transport modelling followed by an overview of major SD modelling activities regarding different aspects of the air transport system.

The application of the SD methodology to transport modelling has been evaluated within a review study by Abbas and Bell [100]. In their research, they derived a list of twelve advantages of SD in transport modelling compared to established traditional transport modelling approaches. Two major steps of SD modelling are defined: the qualitative and quantitative formulation of a model, which represents a problem to be investigated, and the development and collection of methods and techniques which are required to solve the problem defined. They conclude that the SD methodology can feasibly complement existing methods in transport modelling, especially with focus on strategic analyses in policy and decision-making processes. Many SD studies in the field of transport, summarised in Abbas and Bell [100], exhibit highly aggregated models from which qualitative implications can be drawn as result including policy impacts and development trends of the main system variables over time. Five explicit studies are listed in the review of SD applicability to transport system problems. The authors mention that the focus of their study is on the applicability of SD as a modelling method for research in transport systems rather than an exhaustive literature review of existing studies in this field. [100]

Shepherd [96] follows up with the rather qualitative introduction to SD applications in transport modelling in [100] and presents an extensive literature review of peer-reviewed publications between 1994 and 2014. These cover various research fields such as the reduction of environmental impacts through the introduction of novel transport vehicles, supply chain management applications in logistics, maintenance of transport infrastructure, airport operations and capacities, and the airline profit cycle [96]. Ten out of all 54 journal papers identified relate to an application case on airline or airport related aspects [96]. They include publications on the analysis of the airline profit cycle [41, 45, 101] and the investigation of airport capacity development [102–107]. The studies incorporate qualitative assessment with a CLD as well as quantitative modelling within a stock and flow structure in equal shares.

Table 3.1 summarises previous studies that apply the SD methodology to model different aspects of the air transport system. These aspects include the airline profit cycle, aircraft manufacturer processes, airport operations, and airline competition. The summary highlights the focus of each modelling approach, key variables implemented, and the respective application case.

Table 3.1: Overview of studies applying the SD methodology to the air transport system (own depiction)

Author(s)	Focus	Key Variables	Application Case
Lyneis (2000) [101]	• commercial jet aircraft industry	• air transport demand • ticket fare • operating aircraft fleet • manufacturing capacity • order backlog	• identification of important structural changes to avoid unnecessary capacity expansion • strategies to overcome business downturn
Liehr et al. (2001) [41]	• airline profit cycle • airline capacity management	• revenue passengers • aircraft orders • fleet capacity	• airline-manufacturer interaction
Pfaender (2006) [108]	• aircraft manufacturer perspective	• two aircraft types • demand for aircraft types • attractiveness for airline types • aircraft characteristics	• competition analysis of two aircraft types • application of scenarios defining macro-economic market conditions (fuel price)
Sgouridis (2007) [42]	• business cycles in the aviation sector	• air passenger demand • demand for aircraft • aircraft production capacity	• analysis of cyclic behaviour of demand and supply in aviation
Behrens et al. (2008) [43]	• airline profit cycle	• passenger development • industry cycle modelling • market potential	• simulation and analysis of passenger development airline companies • analysis of effects of entry and exit on routes between two airports
Kleer et al. (2008) [49]	• airline market development • airline competition	• passenger demand • airline attractiveness • demand distribution • airline configuration and policy	• analysis of strategic airline movements using the example of Lufthansa and Germania
Suryani et al. (2010) [104]	• air passenger demand forecasting	• air passenger demand • average number of flights • runway utilisation • congestion	• air passenger demand forecast for airport capacity (terminal and runway) • application of policy scenarios
Pierson (2011) [44]	• airline profit cycle	• demand, pricing, and other feedbacks • endogenous capacity expansion • yield management	• behavioural dynamic airline industry model

Table 3.1 continued: Overview of studies applying the SD methodology to the air transport system

Author(s)	Focus	Key Variables	Application Case
Suryani et al. (2012) [105]	• demand forecasting of air cargo	• air cargo demand • terminal capacity and utilisation	• air cargo terminal capacity planning • application of policy scenarios
Pierson/ Sterman (2013) [45]	• airline profit cycle	• endogenous capacity expansion • passenger demand • pricing • yield management	• behavioural dynamic model of the airline industry
Csala/ Sgouridis (2013) [109]	• aircraft manufacturer perspective	• aircraft production capacities • aircraft characteristics	• analysis of impact of technology innovation on environment and economy • competition between two aircraft manufacturers
von Beuningen (2014) [46]	• airline competition	• ticket price • fleet development	• competition between airlines from Germany to Asia
Bießlich et al. (2014) [110]	• airport operations	• passenger demand • terminal capacity • runway capacity	• link of operational aspects of an airport with economic development • single airport perspective
Qin (2016) [111]	• airport revenue structure	• airport revenues/ charges • airport demand • airport flight volumes	• impact of airport-airline relations on airport revenues
Urban et al. (2017) [112]	• air transport system behaviour	• passenger demand • fleet development • airport capacities • ticket price	• analysis of European air transport system
Shepherd/Orta (2017) [47]	• open skies agreement • airline competition	• passenger demand • ticket price • market share • net income	• analysis of airline competition on a route
Cronrath (2018) [48]	• airline profit cycle	• demand • supply • fleet development (incl. aircraft leasing) • revenue management	• analysis of airline cyclical profit dynamics
Mayrhofer (2019) [113]	• airport operations	• runway capacity • revenue structure • airport charges	• analysis of airport capacity management and revenues

Several publications address cyclical behaviour patterns in the air transport market [41–45, 48, 101]. Lyneis [101] applies the SD methodology to investigate the cyclical global demand for aircraft. This demand has fluctuated in the past. To analyse this cyclical behaviour and to forecast the future development of global aircraft demand, Lyneis [101] introduces a dynamic structure with several major variables such as demand, ticket price, manufacturing capacity, order backlog, and operating aircraft fleet [101]. Demand is driven by changes in ticket fares, flight frequency, traffic congestion, and passenger experience with the airline and aircraft fleet development depends on projected demand and traffic congestion [101]. In contrast to this forecast study, Liehr et al. [41] introduce an airline market model to analyse cyclical behaviour of capacity in the air transport market, applied to Lufthansa German Airlines. Aspects with potential to reduce cyclicality in the system are identified, including aircraft order process, airline network planning, aircraft leasing and retirement decisions, and the level of capacity adaptation flexibility [41]. They conclude that business cycles do not result from the exogenous impact from the gross domestic product (GDP) development [41]. Sgouridis [42] builds on the model structure of [101] and presents a model that provides the elements demand generation, airline competition, and airframe supply competition. The functionalities of airlines in this model range from demand forecasting to capacity management to ticket price adjustment [42]. With this model set up, Sgouridis [42] investigates the cyclical behaviour in commercial aviation and according strategies to reduce the effects of this cyclicality.

Pierson [44] and Pierson and Sterman [45] present an industry level model of the airline profit cycle with endogenous effects from capacity, pricing, demand, costs, profit, and salaries. They introduce yield management in their model and find that extensive yield management can increase the cyclical behaviour whereas delays in the capacity adjustment, i. e. aircraft purchase, have no significant impact [44, 45]. Several model parameters are estimated with a Makrov Monte Carlo simulation during the calibration process [44, 45]. Cronrath [48] further extends the modelling activities with an industry level model to investigate the airline profit cycle. Her model includes four different modules covering demand, supply, costs, and ticket price development [48]. Cronrath [48] concludes with a similar finding as Pierson [44] and Pierson and Sterman [45] to focus on long-term profitability when setting ticket prices and to reduce short-term yield management activities since these highly influence the cyclical airline profit behaviour.

Behrens et al. [43] introduce a Bass diffusion model which is commonly used to model the diffusion process of novel products in a given market [86, 114]. Another application of this model is presented in the analysis of the market entry of EasyJet as a LCC into the Great Britain market [115]. In this case, a variation of the Bass diffusion model is implemented to analyse the market diffusion of low-cost services from EasyJet within this market.

Specific airport related SD modelling and simulation activities cover passenger as well as cargo capacity management (terminal and runway), airport charges, and revenue development [104, 105, 110, 111, 113]. In terms of forecasting airport capacities for cargo, the GDP development takes a crucial role in the future development as compared to limited impact of other factors such as import and transit growth [105]. Passenger demand forecast for airports is driven by the development of the ticket price, the level of service (provided by airlines and perceived by passengers), GDP, population, infrastructure, airport revenues, and the dwell time of passengers at airports [104, 110].

Other modelling attempts focus on the interaction between different stakeholders within the air transport system, including relations between passengers and their preferred airline type, relations between aircraft manufacturers and airlines as part of the aircraft ordering and capacity development process, and airline competition [46, 47, 49, 101, 108, 109, 112]. Some of these studies focus on airline competition and include either one or different passenger groups in their model structure [46, 47, 49].

The introduction of new products or services such as low-cost flights in long-haul air transport markets can be compared to the introduction of novel vehicles with alternative powertrains in the road transport sector. SD models exist where this introduction is implemented considering the consumer choice as well as passengers' willingness to consider a certain new product or service [116, 117]. These SD approaches from the road transport sector serve as a basis for the development of the model part addressing demand distribution.

This thesis complements the existing research with an SD model that focusses on long-haul air transport markets and the competition of two different airline types, the FSNC and the LHLCC considering passenger choice and passenger consideration. None of the existing studies applying SD methodology to the air transport system focusses on long-haul markets considering two airline types and two passenger groups. The TATM combines existing modelling approaches from the field of air transport as well as the automotive market, which creates a new model, and applies it to the transatlantic market. Airline structures such as the ticket price and the aircraft capacity development are derived from [48]. The passenger demand is retrieved from the passenger decision structure in [49] and [86] and complemented by a passenger consideration structure as applied in the road transport sector [116–119] and adapted to air transport to model the market introduction and diffusion of the LHLCC air transport service. The resulting dynamic model will provide simulation capabilities to investigate market dynamics in long-haul airline markets that result from the introduction of long-haul services and the subsequent shifts in passenger choice and aircraft capacity as a reaction to changing demand.

3.4 Definition of the model scope

The first step in the SD modelling process is to define the purpose of the model and to formulate the specific research question that the SD model addresses [86]. The objective of the research in this thesis is to model the introduction of low-cost air transport services to long-haul markets. The model has to provide simulation capabilities to investigate to which extent low-cost services can be transferred to these markets.

The transatlantic air transport market is equipped with unique conditions on market liberalisation and deregulation in the aftermath of the Open Skies Agreement between Europe and the United States of America [21, 23] and a comparable agreement between Europe and Canada [2, 60]. In addition, Dobruszkes et al. [120] state that "Europe and the US can be considered as the only two mature LCC markets." [120, p. 52], referring to short-haul markets and arguing that these two markets are broadly developed compared to, for example, the air transport market in Asia-Pacific or the Middle East where future annual growth rates for air transport demand range between 5.4 % and 5.6 % and, thus, are higher than in Europe or North America [121]. It is expected that global regions with a mature LCC market structure have a higher probability of LCC efforts to enter new markets, i. e. long-haul markets due to a higher degree of deregulation [24]. The question remains, at which stage of the market diffusion of LHLCC operations the transatlantic air transport market can be classified currently and what market potential in terms of market shares can be gained from long-haul low-cost services in the future.

Every SD model is characterised by a dynamic problem definition which describes the object of investigation [86]. As mentioned earlier, the object of investigation in this thesis is the market potential of long-haul low-cost services. As defined in previous studies on the market potential of long-haul low-cost services (see table 3.1), it is expected that long-haul low-cost services achieve a certain market share level after their introduction due to moderate cost advantages between 10 % and 33 % [13, 18, 19, 32, 35, 37]. This level of market share, as well as the mid- to long-term market potential of this airline business approach, will strongly depend on the overall market development and on the competition with market incumbents.

The following sections 3.4.1 and 3.4.2 introduce the problem which is targeted with the presented SD model and give an overview of the reference mode. The reference mode dynamically describes the problem development over time [86]. In this thesis, the reference mode will focus on the past development of the low-cost business model in short-haul markets. An overview of the actual TATM input figures is provided during calibration in section 4.2.2.

3.4.1 Problem definition

The definition of the problem to be investigated is an integral part of the first step in the SD modelling process [86]. In this thesis, the research problem covers the market potential of low-cost services in the transatlantic air transport market which arise from interactions of the market participants on the demand and the supply side. In order to be able to make statements about the market potential, it is crucial to identify and map the essential interactions under investigation, the transatlantic market, between the relevant actors in the system. The demand side is represented by passengers for air transport services. This group is typically divided into two passenger groups, leisure and business passengers [2]. Airlines constitute the supply side. Two different airline types need to be considered in the analysis: the market incumbent, FSNC, and the new market entrant, LHLCC, which compete with each other. To provide insights to which extend LHLCC characteristics identified such as an operating cost advantage, the selection of potential markets, and other competitive advantage measures (see section 2.2.3) are beneficial when competing with FSNCs, these characteristics need to be considered for the model development. Hence, all major features required to model the competition between the two airline types as well as the interaction between demand for a specific transport service and supply of transport capacities need to be addressed to solve the research problem. The interaction needs to focus on decision-making processes on both, the demand and the supply side, and the dynamic behaviour of the transatlantic market over time where passenger decisions on the choice of air transport services follow airline decisions on capacity, ticket price, and flight frequency development and vice versa. The next step is the definition of a reference mode.

3.4.2 Reference mode

A reference mode is defined as a dynamic characterisation of the problem which is investigated [86]. This is represented as a set of data and graphs which describe the behaviour of a system over time [86]. The thesis focusses on the transatlantic market and its development towards the transition of LCC services to this long-haul segment. However, historical data reveals that LHLCC services have only been operated irregularly since the first flight of Laker Airways in 1977 [1, 32] which can be seen as the first long-haul low-cost service in the transatlantic market. Thus, the LCC development on the short-haul market within Europe will be selected as a reference mode [51] since it represents a mature market with an LCC market share that is developing towards a saturated level [24]. The historical development of LCC services in this market will serve as an approximation of how LCC services might evolve after being transitioned to the long-haul transatlantic market [51] (see figure 3.4).

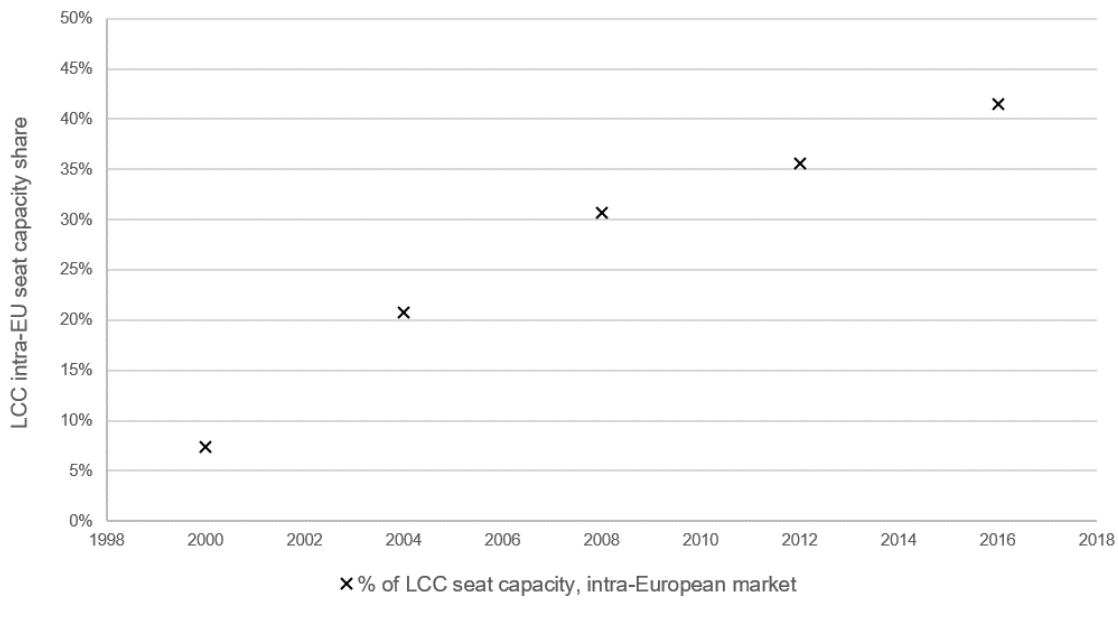

Figure 3.4: LCC share of annual seat capacity between 2000 and 2016 on intra-European flights ([51, p. 8, Fig. 3], based on OAG flight schedule data (2000, 2004, 2008, 2012, 2016), long-range aircraft types excluded [5–9])

Figure 3.4 depicts the market share development of LCCs within Europe in terms of annual airline seat capacity share between 2000 and 2016 [51]. The overview of the historical development of the global air transport markets in section 2.1.1 underlined the key requirements, i. e.

market liberalisation and deregulation, for the market entry and establishment of the LCC airline business model in short-haul markets [2, 3]. As depicted in figure 2.3, LCCs in Europe exhibit the highest market shares in terms of total annual available seats compared to the other two large domestic markets Asia and North America. The system behaviour between 2000 and 2016, as represented in figure 3.4, is reminiscent of the rear part of sigmoid-shaped growth [114, 115] where annual market share growth rates gradually decline. However, a saturated level cannot be derived from this development up to 2016. For long-haul low-cost services, a similar behaviour of the market share but with lower absolute levels of market saturation is assumed. Hence, lower LHLCC market shares are expected compared to short-haul markets, as concluded from the literature review on long-haul low-cost characteristics in section 2.2.3 (see table 2.1). The reference mode selected for the TATM, representing the ramp-up of LCC market shares in the European short-haul market, can therefore be considered relatively in terms of the sigmoid-shaped course of market diffusion of LCC flight services but not absolutely in terms of the LHLCC market potential. For this purpose, the developed TATM is used to simulate the absolute LHLCC market potential.

3.5 Overview of the Transatlantic Air Transport Model

The scope of this research is to develop a model that provides insights into the development of market shares in a defined air transport market. Existing studies on the performance of the low-cost airline business model on long-haul routes investigate parameters such as profitability on route level [20, 37, 38]. In this previous research, a market is defined on a route level, a specific connection between two airports or two cities. In contrast, the transatlantic long-haul air transport market in the TATM comprises all OD flight connections between Europe and North America. Market shares of LCCs entering the long-haul segment cover a wider scope. Route distances as well as the aircraft types operated between two global regions are represented with average values. Thus, the focus of this research is on the dynamics within the overall transatlantic air transport market rather than on a detailed analysis of distinct routes between Europe and North America or competition between single airlines.

As mentioned earlier, the airline market is abstracted and represented by two competing different airline types, FSNC and LHLCC airlines. Aircraft production capacities are considered for one representative aircraft type for each of the two airline types: LHLCCs operate a Boeing B787-800 and FSNCs an Airbus A330-300 aircraft type [51]. These two representative aircraft types were derived from OAG data as the statistical modus[1] for the years 2014, 2016, and 2018 [9, 123, 124] to cover the calibration period [51], applied in chapter 4. For this, the number of total annual scheduled flights, represented in the sum of annual flight frequencies, between Europe and North America on distances above 4,000 kilometres[2] was selected per specific aircraft type for each of the three OAG datasets [51]. The TATM will be applied to

[1] The statistical modus equals the most frequent value of a sample [122].

[2] Flights above 4,000 kilometres define the system boundary for long-haul air transport services in the transatlantic market in consideration in this thesis. Air transport services below this boundary are not considered in the simulation model.

the transatlantic air transport market to investigate its future development of market shares of the two different airline types FSNC and LHLCC and to gain a better understanding of the LHLCC market potential.

Figure 3.5 depicts the basic model concept and highlights major interactions between the demand and the supply side that generate market shares. The model comprises one module for demand generation (demand side), two modules that cover the passengers' general willingness to consider transatlantic flight services and passenger choice of selecting one airline type (demand side), and one module covering all relevant aspects of the airline market (supply side). These include capacity management to develop the aircraft fleet, ticket price and frequency development representing two major drivers for passenger choice, aircraft utilisation in terms of the SLF, and the development of airline revenues and profits. Hence, all major features of the two airline types considered, the FSNC and the LHLCC, are included.

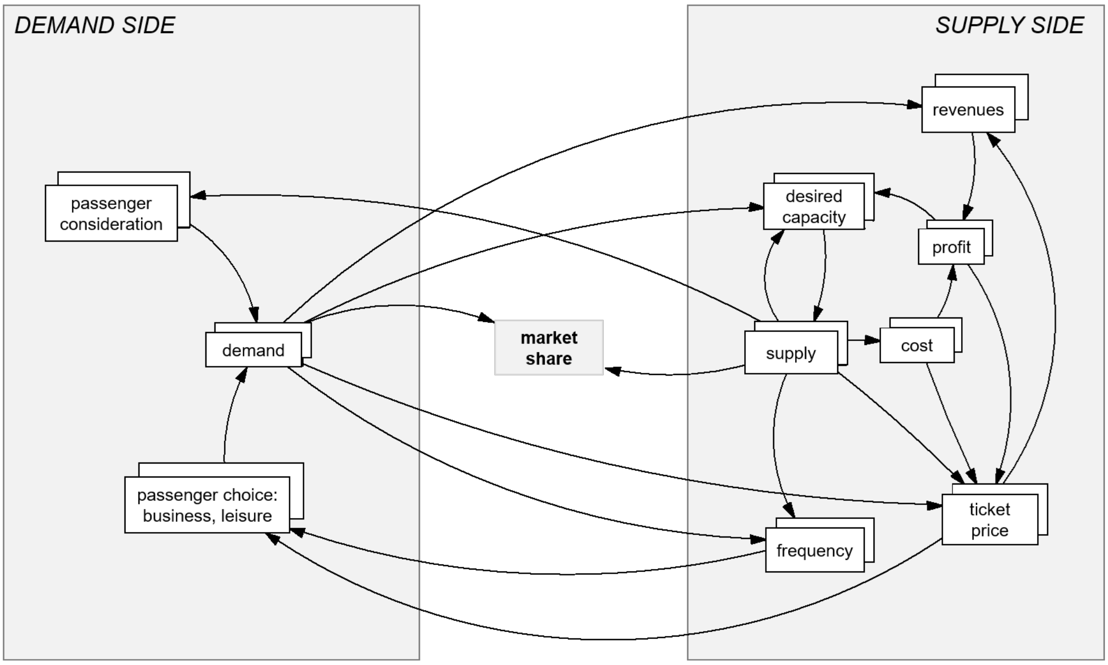

Figure 3.5: Basic model concept (own depiction)

Competition between these two airline types can be represented in the dynamic development of demand in terms of passengers' decisions and supply, represented as dynamic capacity management. The model structure is equal for both airline types. However, the operational requirements resulting from the representative airline type operated as well as decisions on how to populate aircraft capacity and passenger decision parameters such as ticket price and frequency vary between the two airline types. The equal structure is depicted in figure 3.5 through the two overlapping boxes for each variable shown.

Introducing low-cost services in long-haul markets will have an impact on the market behaviour of passengers as well as airlines. The LHLCC market entrant will introduce a flight service that changes the set of passenger choice and passengers will take the additional, new flight option into account in their decision process. The passenger decision process will be driven by choice parameters such as the ticket price and the flight frequency offered. As a consequence, demand share for the different flight service options, i. e. FSNC and LHLCC flights, in the transatlantic market change over time. The FSNC market incumbent will react to this development and adapt his supply in terms of available seats. This decision is driven by changes in the revenue and according profit as well as in the utilisation that results from demand changes that lead to a new desired capacity. The LHLCC market entrant will also respond to an expected increasing utilisation of its capacity during the ramp-up of this new flight service and increase its capacity. Changes on the capacity supplied and subsequent changes in the operating costs impact the passenger decision parameters, ticket price and flight frequency. This results in changes in demand as a feedback from capacity changes. A more detailed explanation of the model structure and major feedback loops will be provided in the CLD (figure 3.6).

Table 3.2 represents the model boundary chart of the TATM which is created in the second step of the SD modelling process. In a model boundary chart, exogenous model elements are segregated as input from endogenous elements which develop over time in dependence of the dynamics in the system [86]. In addition, aspects, which are not included in the model, are listed in the model boundary chart and highlight the limitations of the model [86]. In the case of the TATM, excluded aspects are the education influence on the development of demand for air transport and the fleet composition since only one representative aircraft type per airline type is introduced with a more dense seating in the LHLCC aircraft type compared to the FSNC aircraft type [51]. The TATM does also not consider dynamic aircraft production capacities for a specific aircraft type. Aircraft production capacities are rather derived from average values neglecting production capacities of a specific aircraft type. In addition, the influence of fuel price changes on the operating cost, effects of ticket price changes on the overall transatlantic demand in terms of price elasticity of demand, and airline yield management are not included in the TATM.

Exogenous elements of the TATM are included as input parameters. They have an impact on the demand generation for transatlantic flights as well as the corresponding fleet capacity, ticket price, and frequency development on the supply side. The passenger choice of one airline type is influenced by the attractiveness of each airline type on the two passenger groups considered, business and leisure passengers, representing the two major general passenger groups [2]. Exogenous ticket price and flight frequency preferences per passenger group as well as availability of a FFP shape the attractiveness of an airline type. In addition, the passengers' willingness to consider a flight service is influenced endogenously by the market presence of an airline type, represented in the total number of available seats, besides the exogenous effects of airline marketing and word of mouth. On the supply side, airline profits as well as capacity utilisation, i. e. SLFs, influence the ticket price and capacity development for both airline types. In terms of capacity, airlines can steer their available seat capacity by adjusting aircraft orders to achieve the desired fleet capacity. Aircraft production capacities are introduced as exogenous parameters for both aircraft types.

Data on airport capacity and airport charges result from a previous SD modelling study on airport dynamics with focus on airside capacity and airport charges development [113].

Table 3.2: Model boundary chart (further developed from [51, p. 8, Table 2])

Endogenous	**Exogenous**	**Excluded from the Model**
aircraft fleet (LHLCC, FSNC)	airport capacity (HUB, non-hub airport (NHB))	dynamic aircraft production capacities
aircraft orders (LHLCC, FSNC)	FFP availability (LHLCC, FSNC)	fleet composition (only one representative aircraft type considered for capacity)
desired fleet (LHLCC, FSNC)	passenger ticket price and frequency preferences (business, leisure) (LHLCC, FSNC)	influence of education on demand for air transport
airline revenues (LHLCC, FSNC)	marketing effort (LHLCC, FSNC)	influence of fuel price changes on operating cost
airline profits (LHLCC, FSNC)	word of mouth effect (LHLCC, FSNC)	influence of ticket price changes on overall transatlantic demand
market share (LHLCC, FSNC)	aircraft production capacity (LHLCC, FSNC)	airline revenue management
passenger willingness to consider service (LHLCC, FSNC)	initial revenue passengers (transatlantic)	
airline attractiveness (LHLCC, FSNC)	passenger demand growth rate (transatlantic)	
passenger choice (LHLCC, FSNC)	unit cost (TOC per seat kilometre) (A330-300, B787-800)	
ticket price (LHLCC, FSNC)		
target ticket price (LHLCC, FSNC)		
flight frequency (LHLCC, FSNC)		
target flight frequency (LHLCC, FSNC)		
airline profitability (LHLCC, FSNC)		
seat load factor (SLF) (LHLCC, FSNC)		

The unit cost components per available seat kilometre (ASK) for the two representative aircraft types A330-300 and B787-800 are introduced exogenously to the TATM and result from cost calculations with a smart reference costing model [125]. In addition, the initial number of transatlantic revenue passengers as well as the demand growth rate for transatlantic air transport services are both deduced exogenously from the Sabre database [63] for the calibration time scope and defined by expected future growth rates from forecast studies [121, 126].

The CLD represents the major elements and feedback loops of the transport system implemented in the TATM, including endogenous generation of supply and demand per airline type as well as passenger choice of transport service. Figure 3.6 depicts the CLD of the TATM. At the beginning of the iterative development process of the CLD, elements from [48] and [49] were taken into account for the passenger decision process and airline dynamics. The number of potential transatlantic air transport passengers develops over time on the left side of figure 3.6. The resulting transatlantic demand is separated into demand for FSNC and for LHLCC flights. This separation represents passenger choice and is driven by the ticket price offered, the flight frequency, and the availability of a FFP from both airline types. These three variables affect the potential air passenger choice and resemble the passenger choice module of the TATM. The supply in terms of ASK as well as the exogenous parameters, airline marketing effort and the word of mouth effect, have an impact on the passengers' willingness to consider to choose a flight service at all. To constantly provide flight capacity in terms of an aircraft fleet and flight frequency at reasonable ticket prices, basic dynamics of an airline are constructed and adjusted to the different characteristics of the two airline types. This part of the TATM is defined as the airline market module. It includes a stock and flow structure for the major variables: aircraft orders and airline fleet development, airline ticket price, and flight frequency [51]. Major feedback loops, driving the dynamics within the system, are highlighted with bold arrows in the CLD. Circular arrows around a letter B indicate balancing feedback loops and reinforcing feedback loops are marked with an R in a circular arrow (see figure 3.2). The stocks with a great influence on the dynamic behaviour of the system are depicted with a box in the CLD. Additionally, exogenous parameters such as maximum frequency, minimum ticket price, airport capacity, and aircraft production capacity or coefficients for the word of mouth, the marketing effect, passenger ticket price and frequency preferences, and the monthly transatlantic demand growth rate are highlighted in italic blue in the CLD in figure 3.6.

To describe the major dynamics within the transatlantic market, decision rules are implemented in the model that represent the behaviour of the actors [86] in the model, i. e. business passengers, leisure passengers, FSNC, and LHLCC airlines. One of these rules is relevant for the demand allocation to the two airline types, implemented as a logit model [127] where each demand share is given by its attractiveness. This passenger choice module considers the ticket price and frequency development as well as the availability of FFPs as attributes affecting the passenger decision for an airline type [51]. Another decision rule determines the airline ticket price development which is strongly tied to the demand and supply balance, expressed as the SLF, and the profit development. A third decision rule steers the fleet development

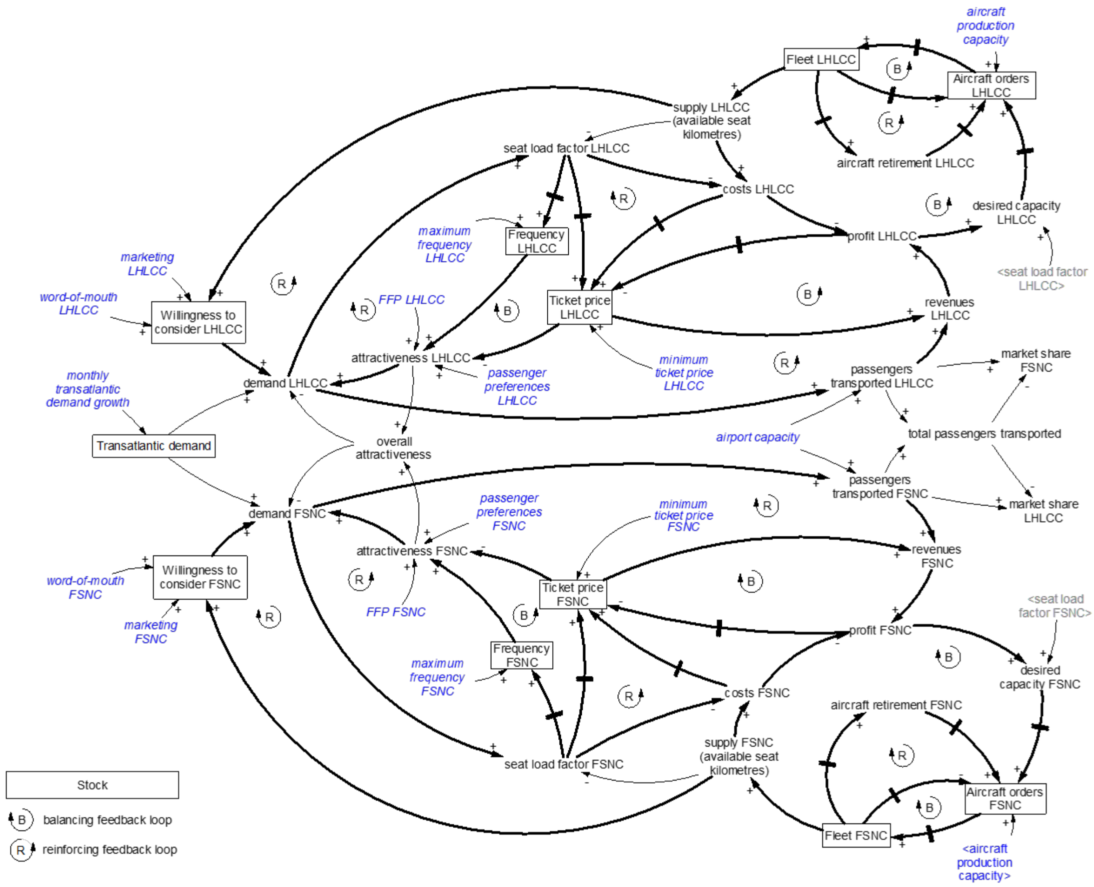

Figure 3.6: CLD of the TATM (further developed from [51, p. 9, Fig. 4])

of an airline type and, therefore, the capacity management. In general, the two airline types can manage their capacity through a delayed increase or decrease of their aircraft fleet size and through an increase or decrease of their flight frequencies that is linked to the demand development. It is crucial to differentiate between the immediate and the delayed option. The extend of forecasted change in demand might lead the decision whether an airline type adapts flight frequency when possible, depending on slot allocation procedures [128], or changes its aircraft fleet size with a delay of at least aircraft production and delivery duration. Fleet development results from changes in the desired capacity which are influenced by the profit development as well as the utilisation, i. e. SLF, and the expected demand supply balance. The latter initially drives the capacity ramp-up when entering the market in case of the new market entrant, the LHLCC.

The model is implemented and simulated with Anylogic, a simulation software with capabilities for SD, agent-based, and dicrete-event modelling as well as multi method modelling when combining two or more of the three methods [129]. The simulation time steps are set to one month as airline as well as passenger decisions can be represented feasibly in such time steps whereas yearly time steps would be too inaccurate and daily time steps are very difficult to be supported with available data. Monthly data is available from the major data sources [63] and [9, 123, 124].

3.5.1 Passenger demand generation

The demand for air transport services is an exogenous input extracted from the Sabre database [63]. It is modelled as a stock and flow structure with the number of the potential transatlantic air transport passengers *PotPAXTA* represented as a stock that changes its level through its inflow, the monthly growth rate of potential transatlantic air transport passengers *potPAXGrowthTA*. The monthly growth rate results from the input table function *potPAXGrowthRateTATF* with the monthly growth rates over time. In general, the growth rate can be both positive or negative and, thus, increase or decrease the level of the stock, i. e. the total number of potential transatlantic air transport passengers per month.

$$PotPAXTA = INTEGRAL\,(potPAXGrowthTA, initialPotPAXTA(t_0)) \tag{3.4}$$

with

$$potPAXGrowthTA = (PotPAXTA * potPAXGrowthRateTA) \tag{3.5}$$

and

$$potPAXGrowthRateTA = potPAXGrowthRateTATF.get(time()) \tag{3.6}$$

The initial number of potential transatlantic air transport passengers as well as the monthly growth rates for air transport demand in the transatlantic market during the calibration period (July 2014 - December 2017) are exogenous model input. For scenario simulation in chapter 5, abrupt decline of the number of potential passengers is introduced to represent a demand shock.

3.5.2 Passenger decision

The market development depends on the demand for air transport services and this demand is affected by passenger behaviour and passenger purchase decisions. Hence, it is crucial to investigate the effects on the passenger decision process to gain a better understanding of the development of demand over time. The passenger decision process comprises passenger choice, implemented as a choice model, and passenger consideration, implemented as a Bass diffusion model [86, 114]. Passengers choice is based on choice parameters such as ticket price, flight frequency, and the availability of FFPs [51]. Passenger consideration of flight services results from the level of how aware passengers are of a service, depending on the presence of an airline in the market as well as marketing activities, and a word of mouth effect about available air transport services. The two elements passenger choice and passenger consideration of airline services will be described separately in detail in the following.

Passenger choice

The passenger choice model is based on a multinomial logit model [127] which provides choice probabilities based on different utilities for each passenger choice and adapted from [49, 130]. It is assumed that passengers select a preferred airline type for their long-haul journey. Passengers pick their preferred airline type based on several attributes. In this model, these passenger choice attributes are ticket price, frequency, and the availability of a FFP [51]. The utilities resulting from a specific airline characteristic are implemented according to the Fishbein model [131]. The basic assumption in the Fishbein model is the existence of a relation between the way in which an individual is attuned to a selected object and how a consumer cognitively evaluates a product [132]. For this, utilities for different airline types for a leisure or a business passenger are calculated as follows.

$$U_{i,j} = \sum_{c} \epsilon_{c,i} * x_{c,j} \tag{3.7}$$

for $\epsilon_{c,i}$= *preference weight,* $x_{c,j}$ = *service characteristic,* c = *characteristic type* (ticket price, frequency, FFP availability) i = *passenger group* (Business, Leisure), and j = *airline type* (FSNC, LHLCC)

The preference weights $\epsilon_{c,i}$ are adopted from a study that analyses the customer loyalty of air passengers [130]. These preference weights were already implemented by Kleer et al. [49] in their model to investigate strategic movements of airlines. In the initial survey in [130], participants were asked to rate a selection of four flight factors on a ten-point constant sum where the sum of all preference weights per participant sums up to ten. Three of these four factors were selected for implementation in the TATM: schedule convenience (frequency), price of ticket (ticket price), and FFP (availability of FFPs) [51]. The sum of the three selected preference weights results to 8.6. Recent passenger surveys on airline choice reveal that the top three decision factors are the ticket price, the flight schedule, and airline reputation [2]. The first two aspects are included in the TATM. Airline reputation is partly covered with the FFP availability [2]. The reason for neglecting additional aspects that represent airline reputation stems from the absence of reliable data on these choice parameter aspects to model its impact. Since two of the remaining choice parameters ticket price and flight frequency are modelled endogenously in the TATM, another possibility is to include the airline reputation impact in the same way. However, data on safety performance, branding or the use of digital technology would be required for airlines operating in the transatlantic market to feasibly measure airline reputation [2]. This is the reason why endogenous airline reputation effects were neglected in the TATM. Future research leaves room for conducting a specified passenger survey for the market segment investigated in this thesis to enable a consideration of additional passenger choice parameters besides the ones chosen for the TATM. Table 3.3 provides the preference weights for ticket price, frequency, and the availability of a FFP for both airline types FSNC and LHLCC [130].

Table 3.3: Passenger preference weights $\epsilon_{c,i}$ (based on [130, p. 106, Table 5])

	Business Passengers	**Leisure Passengers**
ticket price	2.1	3.9
frequency	4.5	3.2
availability of FFPs	2.0	1.5

The utilities for each passenger group and airline type combination refer to the following three service characteristics (adapted from [49]).

$$x_{ticketprice,j} = 1 - \left(\frac{TicketPrice_j}{maxTicketPrice}\right) \tag{3.8}$$

$$x_{frequency,j} = frequencyUtility = frequencyUtilityTF.get\left(\frac{Frequency_j}{maxFrequency}\right) \tag{3.9}$$

$$x_{FFPavailability,j} = \begin{cases} \mathit{0,\ if\ a\ FFP\ is\ not\ available\ (LHLCC)} \\ \mathit{1,\ if\ a\ FFP\ is\ available\ (FSNC)} \end{cases} \tag{3.10}$$

for j = *airline type* (FSNC, LHLCC)

The ticket price service characteristic $x_{ticketprice,j}$ is normalised by a maximum ticket price value for both airline types. This value is set to the maximum ticket price offered by the LHLCC in the transatlantic market at the beginning of the calibration time scope in 2014, extracted from the Sabre database [63]. FSNCs serve transatlantic market flights with ticket prices significantly above this level. However, LHLCCs do not directly compete with FSNCs in these market segments which is why ticket prices above the maximum ticket price offered by the LHLCC for a premium economy seat only affect passenger segments that do not consider LHLCC services as an alternate option to the FSNC offer. The focus in this thesis is on average ticket prices in the transatlantic market in which FSNCs and LHLCCs compete with each other.

The relation between frequency and frequency utility to calculate $x_{frequency,j}$ from equation 3.9 is defined with a table function (see figure 3.7). Table functions represent non-linear relationships, expressed with a functional equation [86]. The frequency utility is normalised between 0 and 1 and the frequency is divided by the maximum frequency of 60 flights per month and per aircraft. The minimum and the maximum utility values are applied from [49] and the slope is adapted to long-haul flight operations. The frequency utility steeply increases up to a frequency of 30 flights per month per aircraft that represents one flight connection in one-way flights between Europe and North America. Between 30 and 60 flight frequencies (0.5 and 1.0 of frequency-max frequency quotient), it increases more slowly up to a frequency utility level of 0.95. The frequency utility increases more slowly between 30 and 60 flights per aircraft, representing a decrease of the marginal utility from an increase in flight frequency. The maximum frequency *maxFrequency* of 60 flights per aircraft equals one return trip between Europe and North America due to the longer distances in this long-haul market. The slower utility increase after 30 flights per month and aircraft was defined to resemble a lower utility increase for passengers from a return flight with the same aircraft as compared to the utility of at least one flight connection per day or 30 flights per month. The same relation between frequency and frequency utility is applied for both airline types. Differences in the overall frequency utility result from different passenger group weights for frequency. For business passengers, a higher flight frequency level with a higher utility is more important than for leisure passengers [1].

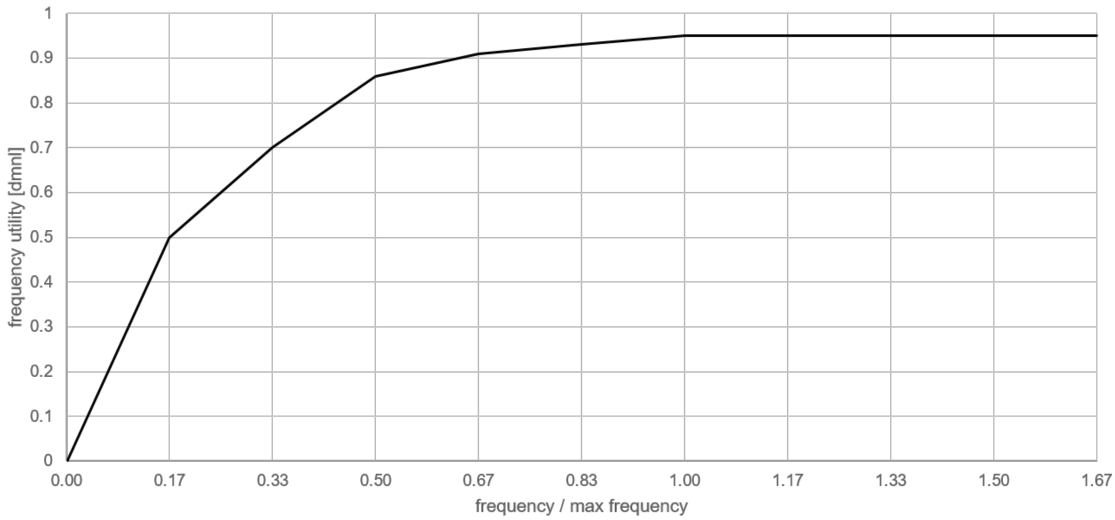

Figure 3.7: Table function: relation between flight frequency and frequency utility (adapted from [49, p. 9, Figure 7])

The attractiveness $A_{i,j}$ for the two passenger groups to choose an airline type results from the exponential equation 3.11, including the utilities for each passenger-airline type combination (see equation 3.7). In contrast to the procedure in [49] where the price-performance ratio is expressed in the attractiveness by dividing the utilities in the exponential equation by the price, the airline attractiveness in the TATM does not consider this ratio to avoid disproportionate influence of the ticket price on the passenger choice. Hence, a standard multinomial logit framework [127] is applied as it can be found in several SD applications including choice modelling [116, 133, 134].

$$A_{i,j} = e^{U_{i,j}} \tag{3.11}$$

for i = *passenger group* (Business, Leisure) and j = *airline type* (FSNC, LHLCC)

The probability $P_{i,j}$ that customers from passenger group i choose airline type j results from the attractiveness for this passenger group and airline type combination divided by the sum of attractiveness figures from all passenger group and airline type combinations possible [127].

$$P_{i,j} = \frac{A_{i,j}}{\sum_{i,j} A_{i,j}} \tag{3.12}$$

for i = *passenger group* (Business, Leisure) and j = *airline type* (FSNC, LHLCC)

The passenger choice model uses normalised airline characteristics multipliers between 0 and 1 which is why some components of an airline's attractiveness are set in relation to a maximum value, i. e. for the ticket price and the frequency.

Passenger consideration

Besides passenger choice where potential passengers evaluate an air transport service based on service attributes and preference weights as described above, the purchase decision is also affected by passengers' willingness to consider a service or passenger consideration. According to Struben and Sterman [116], the concept of willingness to consider comprises social, cognitive, and emotional processes which enable a potential customer to gain a thorough understanding of the offered service as well as information, and a certain emotional attachment. On an individual scope, the consideration expresses the probability that a customer, i. e. a passenger, is aware of a specific service, i. e. the air transport service, and willing to consider this service as a possible alternative in the decision-making process [117]. In the TATM, the passenger consideration is aggregated and, thus, represents the share of passengers that are willing to consider an offered air transport service in their choice set. Passenger consideration is implemented as a Bass diffusion model [114] in a stock and flow structure where the flow adoption rate changes the level of the stock willingness to consider a flight service, adapted from [116–118]. A Bass diffusion model [114] is a commonly applied model for the introduction and diffusion of novel services or products in a market [115]. Passenger consideration is affected by marketing and advertisement as well as word of mouth in the respective direct environment, and the presence of an airline type.

$$\begin{aligned} adoptionRate_j = (&coefficientOfMarketing_j \\ +&coefficientOfWordOfMouth_j * WillingnessToConsiderService_j) \\ *&(maxWillingnessToConsiderService_j - WillingnessToConsiderService_j) \end{aligned} \tag{3.13}$$

for j = *airline type* (FSNC, LHLCC)

Equation 3.13 represents the diffusion process as applied in [117], derived from [119]. In this equation, the actual *coefficientOfWordOfMouth*$_j$ parameter is implemented as a weight to the willingness of a passenger to consider a service. The reinforcing loop of an increasing consideration results from an increasing supply of available seats. It is driven by an increasing demand and a number of passengers transported that results in an increasing revenue and profit for the LHLCC as well as a higher level of utilisation, and, hence, an increase in available seats. Both coefficients $coefficientOfWordOfMouth_j$ and $coefficientOfMarketing_j$ are implemented exogenously (see table 4.2).

The variable $maxWillingnessToConsiderService_j$ results from the presence of the airlines in the market and represents the potential to which extent potential passengers are aware of and willing to choose an airline service. As a proxy for this market presence, the number of total seats offered is selected. This concept is derived from Walther et al. [119], as applied in [117], where the market introduction of alternative power trains is investigated and the purchase decision for alternative power train vehicles depends on the available charging infrastructure. The shape of the table function in [117, p. 14, Fig. 5] is transferred to the table function for the willingness to consider an airline service. The maximum number of passenger seats, where the maximum passengers' willingness to consider is 1, is estimated as a share of 45 % of the total number of seats offered at time step t_0. This represents the order of magnitude of the LCC seat capacity share in the reference mode, the short-haul intra-European market, which exhibits a high level of low-cost market saturation (see figure 3.4 in section 3.4.2).

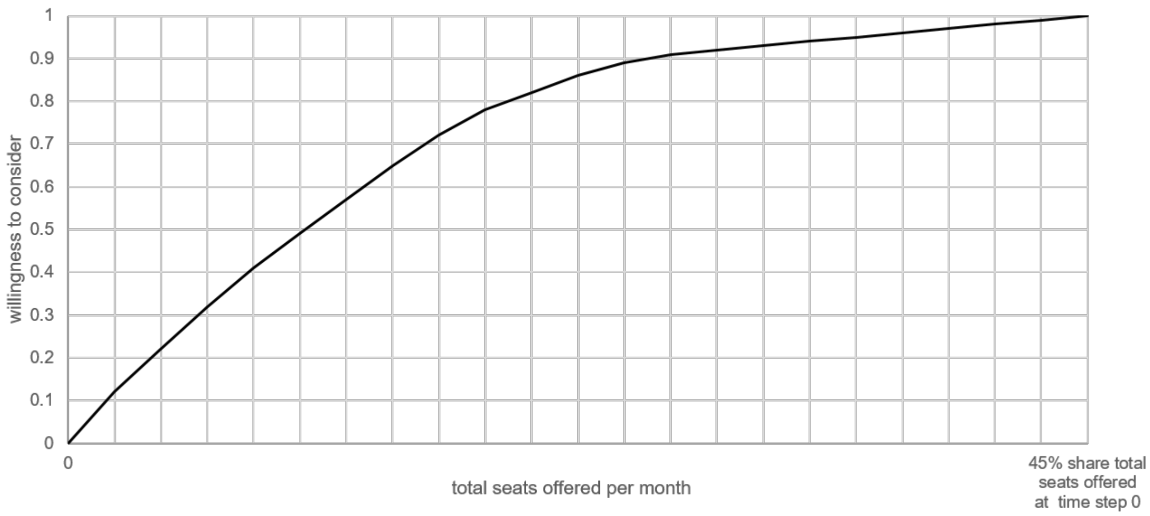

Figure 3.8: Table function: relation between available seats and willingness to consider a flight service (adapted from [117, p. 14, Fig. 5])

The following equation describes the functional relation resulting from the table function in figure 3.8.

$$\begin{aligned} maxWillingnessToConsiderService_j = \\ willingnessToConsiderTF.get\,(totalSeatsPerMonth_j) \end{aligned} \tag{3.14}$$

for j = *airline type* (FSNC, LHLCC)

The actual level of *WillingnessToConsiderService*$_j$ of an offered flight service, represented as a stock, changes over time by the adoption rate. A negative adoption rate indicates that the level of willingness to consider a flight service declines. This results from a dominant effect of decay when potential passengers are exposed to the offered air transport services infrequently, e. g. when marketing does not reach them or they do not exchange information about the service with other people [116].

$$\begin{aligned} WillingnessToConsiderService_j = W_j = INTEGRAL(&adoptionRate_j, \\ &initialWillingnessToConsiderService_j(t_0)) \end{aligned} \tag{3.15}$$

for j = *airline type* (FSNC, LHLCC)

Passenger choice and passenger consideration are combined and included in the calculation of demand as passenger decision probability. The probability that one passenger group chooses an airline type is calculated in accordance with [118] as follows.

$$choiceProbability_{i,j} = \frac{W_j * A_{i,j}}{\sum_{i,j} W_j * A_{i,j}} \tag{3.16}$$

for i = *passenger group* (Business, Leisure) and j = *airline type* (FSNC, LHLCC)

The resulting number of passenger demand and the actual revenue passengers transported are introduced in the following.

Resulting revenue passengers and airline market shares

The total number of potential transatlantic air passengers *potPAXTA*, which results from the demand generation module, splits up into demand for FSNC and demand for LHLCC flights. For this, the shares of business and leisure passengers that wish to fly with either the FSNC or the LHLCC aircraft type are calculated with the respective probabilities of one customer type choosing one airline type (see equation (3.12)). The demand for the two airline types results as follows.

$$demand_j = potPAXTA * \sum_i choiceProbability_{i,j} \tag{3.17}$$

for i = *passenger group* (Business, Leisure) and j = *airline type* (FSNC, LHLCC)

The resulting *revenuePassengers*$_j$ are limited by the maximum possible consumption at the current supply level [48], i. e. the number of available seats per month for each airline type multiplied by the maximum SLF (equal to 1, see table 4.2).

$$revenuePassengers_j = min(demand_j, maxConsumptionAtCurrentSupply_j) \tag{3.18}$$

$$marketShare_j = \frac{revenuePassengers_j}{\sum_j revenuePassengers_j} \tag{3.19}$$

for j = *airline type* (FSNC, LHLCC)

The market share of each airline type, which represents the major model variable to investigate the market potential of low-cost services in the transatlantic air transport market, results from the *revenuePassengers*$_j$ (see equation 3.19). Thus, it can be compared to revenue passenger data from the Sabre database in the model validation (see chapter 4).

3.5.3 Airline dynamics

The TATM incorporates airline dynamics considered within the airline market module. These dynamics are the development of capacity and an according price structure. Capacity is represented as the aircraft fleet of an airline type and the monthly flight frequency per aircraft. Both parameters as well as the airline ticket price are implemented as a stock. The fleet development over time is included as an ageing chain structure with an additional stock of airlines on order that feeds into the fleet stock. The frequency and the ticket price are represented for each airline type as a stock and flow hill-climbing structure [86] where target frequencies and ticket prices are defined and the actual frequency and ticket price are adjusted to the target values over time. Within the airline market module, the two different airline business model types, the FSNC and the LCC, are introduced [51]. They have the same structure. However, different parameters and other input values differentiate between the two business model types. An airline can influence its profit development to a certain extent by aligning its capacity provided to the market, i. e. fleet size and number of flights offered per month. In case of revenue losses, capacity needs to be decreased to reduce the operating cost. In the short-term, an airline realises this through immediate reduction of flights offered per month. In addition, the airline does not order any additional aircraft for a certain mid-term to long-term period, depending on the forecast of demand for air transport services and profit anticipations. The following paragraphs give an overview of the airline cost and revenue structure and highlight the model implementation of the airline ticket price development, the flight frequency development, and capacity development within the airline fleet planning process.

Airline cost and revenue structure

The cost structure of an airline comprises non-operating and operating cost [2, 12]. For non-operating costs, there is no direct connection to the actual airline service operation [2, 12]. This cost category includes taxes or state subsidies, costs from interest payments from loans, and all losses and profits from the business activities of an airline and its subsidies, including foreign exchange and property retirement [2]. This cost category can have a significant impact on the overall financial performance of an airline [12] detached from the core business which is why this cost component is neglected for the development of the TATM in this thesis. The second cost category, the operating cost, can be further divided into direct and indirect operating cost [2, 12]. Direct operating cost comprise all activities required to operate the aircraft fleet such as fuel costs, crew costs for the cockpit and cabin crew, including training, airport and air transport navigation charges, insurance cost, and leasing cost in case of the operation of leased aircraft [2, 12]. Besides, maintenance and overhaul expenses and costs for depreciation if the equipment required for the airline core business belong to the direct operating cost [2]. Indirect operating cost comprise costs for ground operations at the airport besides charges and landing fees, costs for passenger services and ticket sales and promotion activities, and system-related administration and general costs that cannot be allocated to a specific function within an airline [2, 12]. Air transport demand is affected by the airline operating costs. In turn, airline costs depend on demand for air transport services to a certain extent. The type of aircraft operated on a specific route determines the unit cost of an airline. General exogenous influences on airline's operational costs are the price for jet fuel, airport, and en-route facility charges (passenger- and aircraft-related), and commission payments for sales and distribution [2]. Figure 3.9 presents one exogenous influence, the fuel price development.

Figure 3.9: Development of U.S. Gulf Coast Kerosene-Type Jet Fuel Spot Price [Dollars per Litres] (own depiction, based on data from [135])

One major operating cost component is the share of fuel expenditure. This component accounts for 20-30 % of the total operating cost (TOC) [2]. Fuel costs are directly impacted by the fuel price development. Figure 3.9 shows the historical development of the Jet Fuel Spot Price in United States (U.S.) Dollars per gallon per month between January 2000 and September 2020 [135]. A large majority of the major airlines apply jet fuel hedging to reduce volatility in their fuel cost and, thus, in their operating cost [11]. Permanent fuel hedging activities do not have long-term effects on profits but on cost and resulting revenue volatility in the event of an unexpected fuel price change [80].

Exogenous effects on operating costs are not included in baseline model setup of the TATM but will be taken into account in the scenario simulation in section 5.3 with the introduction of CORSIA to international markets. The airline cost structure in the TATM only considers operating costs and comprises variable and fixed cost components. Variable cost components are linked to the ASKs and the average distance and fixed cost components refer to the number of aircraft within the fleet [2]. The total operating unit costs $unitTOC_j$ are calculated as follows.

$$\begin{aligned} unitTOC_j = (fixedCostPerASK_j + variableCostPerASK_j) \\ *costRecoveryFactor_j \end{aligned} \tag{3.20}$$

for j = *airline type* (FSNC, LHLCC)

The $fixedCostPerASK_j$ component includes the elements cost of ownership, maintenance, and overhead cost. Cost of ownership refer to all costs for loans, equipment leasing rates, and other forms of credit including interest rates [11]. Maintenance cost comprise all costs related to maintenance and overhaul activities of the aircraft fleet operated [12]. Overhead cost summarise all other fixed cost components resulting from administrative and management-related airline activities [1]. Fixed cost per ASKs operated are directly linked to the costs resulting from the aircraft fleet if no flights are operated.

$$\begin{aligned} fixedCostPerASK_j = costOfOwnershipPerASK_j \\ +maintenanceCostPerASK_j \\ +overheadCostPerASK_j \end{aligned} \tag{3.21}$$

for j = *airline type* (FSNC, LHLCC)

The $variableCostPerASK_j$ component includes fuel and labour cost as well as airport, ground handling, and navigation charges for airport operations. Additionally, environmental cost including local noise and emission charges, and costs for the European emission trading scheme [1].

$$\begin{aligned} variableCostPerASK_j = fuelCostPerASK_j \\ +labourCostPerASK_j \\ +airportChargesPerASK_j \\ +GHNavChargesPerASK_j \\ +addOperatingCostPerASK_j \end{aligned} \tag{3.22}$$

for j = *airline type* (FSNC, LHLCC)

Variable cost per ASKs operated are directly linked to the available seats per aircraft, operated by an airline type, and the average transatlantic flight distance. The $totalOperatingCost_j$ result from the sum of fixed cost per ASK and variable cost per ASK multiplied by total seats offered per month and average flight distance.

$$\begin{aligned} totalOperatingCost_j = (fixedCostPerASK_j + variableCostPerASK_j) \\ *totalSeatsPerMonth_j * averageDistancekm_j * costRecoveryFactor_j \end{aligned} \tag{3.23}$$

with

$$\begin{aligned} totalSeatsPerMonth_j &= flightsPerMonth_j * averageSeatsPerAircraft_j \\ &= min(Frequency_j * (Fleet_{purchase} + Fleet_{lease}), totalRWYCapacity_{HUB/NHB}) \\ &\quad *averageSeatsPerAircraft_j \end{aligned} \tag{3.24}$$

and

$$averageDistancekm_j = avgDistkmTAOD_jTF.get(time()) \tag{3.25}$$

for j = *airline type* (FSNC, LHLCC)

The $totalSeatsPerMonth_j$ result from multiplying the number of flights per month with the number of seats per representative aircraft type. The flights result from the product of the frequency and the total number of aircraft in the fleet, comprising purchased and lease aircraft. For FSNC flights, airport capacity from HUBs is considered whereas for LHLCC flights, NHB capacity is considered. The $averageDistancekm_j$ is implemented as an exogenous input, calculated separately for both airline types [63] (see table 4.1). A $costRecoveryFactor_j$ with a default value of 1 is introduced in the model structure and the $unitTOC_j$ and the *totalOperatingCost*$_j$ are multiplied with it. This factor becomes important during the calibration process of the model since especially the new market entrant, the LHLCC, might implement a strategy where not all operating costs are covered during the ramp-up of services in a new market with the expectation to increase revenues and cover the initial cost surplus, especially if the LHLCC is established as a subsidiary of a FSNC to add low-cost services to the existing portfolio to create a hybrid service offer [15, 136].

The *revenue*$_j$ is generated from the ticket sales to all revenue passengers transported within one month. And the profits result when deducting the TOC from the revenue. This is implemented in the TATM as follows.

$$revenue_j = revenuePassengers_j * TicketPrice_j \tag{3.26}$$

$$profit_j = revenue_j - totalOperatingCost_j \tag{3.27}$$

for j = *airline type* (FSNC, LHLCC)

The *profit*$_j$, that each airline type generates, feeds into a TATM module that represents a stock and flow structure for the anticipation of future profitability trends and an according perceived profitability [48]. To cover the operating costs incurred and generate profits, an airline has to define a ticket price for a transatlantic flight. The following section describes in detail how the ticket price development over time is implemented in the TATM.

Ticket price

The ticket price, or fare for a flight between an origin and a destination airport selected, comprises all costs per one passenger arising from this service and an additional yield component per passenger. The yield component per passenger can be positive or negative, depending on the utilisation of an aircraft [12]. Airlines calculate with a break-even load factor describing the utilisation of an aircraft at which revenues equal costs and yield per passenger equals zero [1]. When a specific flight is operated at a SLF level above the break-even equivalent, the airline generates positive profits per passenger on this flight [1, 137]. FSNCs and LCCs strongly differ in the way they practice price setting. FSNCs focus on a general differentiation market strategy offering different seat classes [1]. The according ticket prices follow this differentiation [12] (see also section 2.2). Mostly, return flights are automatically offered. In contrast, an LCC provides a simple fare for single flights where additional services such as catering, baggage handling, or seating selection are billed additionally following a price leadership market strategy [1]. The following two equations 3.28 and 3.29 define the airline ticket price modelling in the TATM. The *TicketPrice*$_j$ is integrated as a stock which gets adjusted to a target ticket price over time. The target ticket price is affected by the TOC development, the aircraft utilisation in terms of the SLF, and the profit development.

$$\begin{aligned} TicketPrice_j = INTEGRAL\left((targetTicketPrice_j - TicketPrice_j)\right. \\ \left./adjTimeTicketPrice_j, initialTicketPrice_j\left(t_0\right)\right) \end{aligned} \tag{3.28}$$

for j = *airline type* (FSNC, LHLCC)

The *targetTicketPrice*$_j$ for both airline types results from the development of aircraft utilisation in terms of the SLF, the airline profit development, and an airline type specific sensitivity with regard to the development of the TOC. A minimum ticket price that covers all operating costs is defined as a lower boundary for the ticket price.

$$\begin{aligned} targetTicketPrice_j = \\ max(minimumTicketPrice_j, \\ TicketPrice_j \\ *effectOfTOCOnTargetTicketPrice_j \\ *effectOfSLFOnTargetTicketPrice_j \\ *effectOfProfitOnTargetTicketPrice_j) \end{aligned} \tag{3.29}$$

with

$$\begin{aligned} minimumTicketPrice_j = unitTOC_j * averageDistancekm_j \\ /seatLoadFactor_j \end{aligned} \tag{3.30}$$

for j = *airline type* (FSNC, LHLCC)

The minimum ticket price describes a lower boundary to cover the *unitTOC*$_j$. The impact of the TOC is implemented with a fixed ticket price sensitivity to cost changes *sensitivityTOC*$_j$. This sensitivity is higher for the LHLCC (0.3, see also table 4.2 in section 4.2.2) compared to the FSNC (0.2, see also table 4.2 in section 4.2.2), since the LHLCC airline type has a stronger focus on cost reduction [1]. Thus, a higher ticket price sensitivity increases the cost changes impact to the ticket price setting process. In general, this sensitivity increases with an increase in competition in a particular air transport market [138]. The effect of the TOC on the ticket price is adapted from [48] and defined as follows.

$$\begin{aligned} effectOfTOCOnTargetTicketPrice_j = \\ 1 + sensitivityTOC_j * ((unitTOC_j/seatLoadFactor_j/yield_j) - 1) \end{aligned} \tag{3.31}$$

for j = *airline type* (FSNC, LHLCC)

The effect of the SLF development is implemented with a table function that relates the quotient of SLF to reference SLF to the ticket price. This effect as well as the SLF are implemented as follows.

$$\begin{aligned} &effectOfSLFOnTargetTicketPrice_j = \\ &effectOfSLFOnTargetTicketPrice_jTF.get \\ &(seatLoadFactor_j/refSeatLoadFactor_j) \end{aligned} \tag{3.32}$$

$$\begin{aligned} &seatLoadFactor_j = \\ &min(1, revenuePassengers_j/totalSeatsPerMonth_j) \end{aligned} \tag{3.33}$$

for j = *airline type* (FSNC, LHLCC)

Figures 3.10 and 3.11 represent the effect of the relation between SLF and a reference SLF on the target ticket price for both airline types.

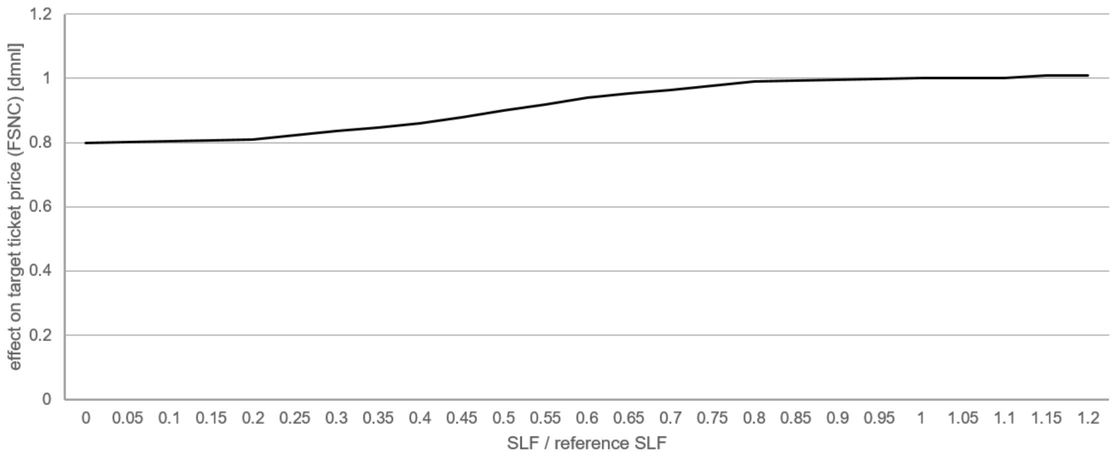

Figure 3.10: Table function: relation between SLF and a reference SLF and its effect on the FSNC target ticket price (own estimation)

When the current SLF equals the reference SLF, the effect on the target ticket price is 1. The target ticket price is reduced when the SLF is below the reference SLF to attract more potential passengers. In case of a SLF above the reference, the resulting effect increases the ticket price to regain the target level of 1 by increasing the ticket price and, thus, reducing demand. The LHLCC airline type offers lower ticket prices than an FSNC competitor [11]. When utilisation in terms of SLFs is low, the LHLCC airline type will address potential passengers with significantly lower ticket prices to stimulate demand. Hence, the effect of the SLF on the ticket price is more pronounced for the LHLCC than for the FSNC airline type, especially as long as the SLF is below the targeted reference. However, the minimum effect of the SLF development on the target ticket price reaches 0.8 for the FSNC and 0.6 for the LHLCC. Airlines will not reduce this effect to 0 since the operation of aircraft capacity at low

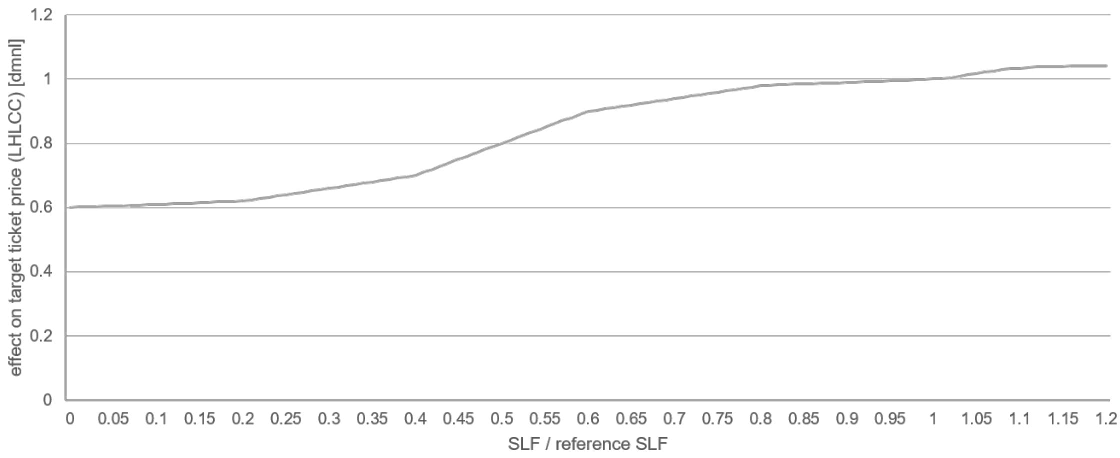

Figure 3.11: Table function: relation between SLF and a reference SLF and its effect on the LHLCC target ticket price (own estimation)

SLF levels requires to cover at least a share of the resulting operating cost. The maximum value of the quotient of SLF and its according reference is 1.2 for the FSNC and 1.16 for the LHLCC due to a higher LHLCC reference of 0.86 ([139]: average SLF between Europe and North America in 2015) compared to the FSNC reference SLF of 0.8216 (derived from [139]). These maximum values correspond to a resulting effect on the ticket price of 1.01 for the FSNC and 1.04 for the LHLCC.

The third impact results from the profit development. Cronrath [48] provides a conceptualisation of the effect of profit maximisation on the ticket price in a detailed SD model of the airline profit cycle. Depending on the profitability trend and the perceived profitability, an airline defines the *profitabilityPerfGap*$_j$ and adapts the ticket price to this gap to steer its profits [48]. This relation structure is integrated into the ticket price development process in the TATM with a stronger focus of FSNCs on profit generation. The following equations formulate this functionality based on [48].

$$\begin{aligned} PerceivedProfitability_j = \\ INTEGRAL\left(\left(\left(profit_j/totalOperatingCost_j\right) - PerceivedProfitability_j\right)\right. \\ \left./adjTimePerceivedProfitability_j, initialPerceivedProfitability_j\left(t_0\right)\right) \end{aligned} \tag{3.34}$$

$$\begin{aligned} ProfitabilityTrend_j = \\ INTEGRAL\left(\left(\left(profit_j/totalOperatingCost_j\right) - ProfitabilityTrend_j\right)\right. \\ \left./adjTimeProfitabilityTrend_j, initialProfitabilityTrend_j\left(t_0\right)\right) \end{aligned} \tag{3.35}$$

for j = *airline type* (FSNC, LHLCC)

A *profitabilityPerfGap$_j$* results from the difference of the perceived profitability and the profitability trend of the airline type. With this gap, the effect of profits on the ticket price development is calculated as an exponential function with a ticket price sensitivity on profit pressure as the exponent. [48]

$$\begin{aligned} profitabilityPerfGap_{\mathrm{j}} = {} & PerceivedProfitability_{\mathrm{j}} \\ & - max\left(0, \left(ProfitabilityTrend_j + stretchGoal_{\mathrm{j}}\right)\right) \end{aligned} \tag{3.36}$$

$$\begin{aligned} effectOfProfitOnTargetTicketPrice_{\mathrm{j}} = {} & (1 + max\,(0, \\ & profitabilityPerfGap_{\mathrm{j}} * (-1)))^{sensPPP_{\mathrm{j}}} \end{aligned} \tag{3.37}$$

for j = *airline type* (FSNC, LHLCC)
and $sensPPP_j$ = $sensitivityPriceOnProfitPressure_j$

The airline ticket price is one of the three drivers of passenger choice besides the frequency and the availability of a FFP. Thus, it is an important characteristic of the competition between FSNCs and LHLCCs in the transatlantic market. Another competitive attribute is the monthly flight frequency offered. It will be introduced in the following section.

Frequency

Flight frequency is a key characteristic of an airline operation as it represents a level of schedule based service quality [2]. In short-haul markets, a flight schedule with more than one connection between an origin and a destination airport especially attracts time sensitive customers, i. e. business travellers who usually book a flight at short notice. Thus, a high number of frequencies in a flight schedule of an airline improves its competitiveness since it increases the probability to offer services close to the passengers preferred departure times [54]. In turn, an airline, which operates high frequencies, can increase the utilisation of flight crews and the aircraft [2]. This also pays off on long-haul routes. An increase in frequencies on long-haul routes can reduce the duration, and, thus, the costs of crew layover at destinations other than the home base [2].

The *Frequency$_j$* is implemented similarly to the *TicketPrice$_j$* formulation with the actual flight frequency at time step t as a stock that gets adjusted to a target flight frequency. The aircraft utilisation in terms of the SLF determines the development of the target frequency over time. An adaptation of the flight frequency is a short-term measure for an airline to adapt the provided capacity to the dynamic demand development [1, 12].

$$\begin{aligned} Frequency_j = INTEGRAL\,((targetFrequency_j - Frequency_j) \\ /adjTimeFrequency_j, initialFrequency_j(t_0)) \end{aligned} \tag{3.38}$$

for j = *airline type* (FSNC, LHLCC)

The *targetFrequency*$_j$ is formulated as a hill-climbing adjustment [86] of the flight frequency to react to changes in the aircraft utilisation, expressed with the SLF, at short notice.

$$\begin{aligned} targetFrequency_j = min\,(maxFrequency_j, \\ Frequency_j * effectOfSLFOnFrequency_j) \end{aligned} \tag{3.39}$$

with

$$\begin{aligned} effectOfSLFOnFrequency_j = \\ effectOfSLFOnFrequency_jTF.get \\ (seatLoadFactor_j/refSeatLoadFactor_j) \end{aligned} \tag{3.40}$$

for j = *airline type* (FSNC, LHLCC)

The table functions in figures 3.12 and 3.13 indicate the relation between the SLF development and its effect on the flight frequency. The figures depict one relation for each airline type FSNC and LHLCC.

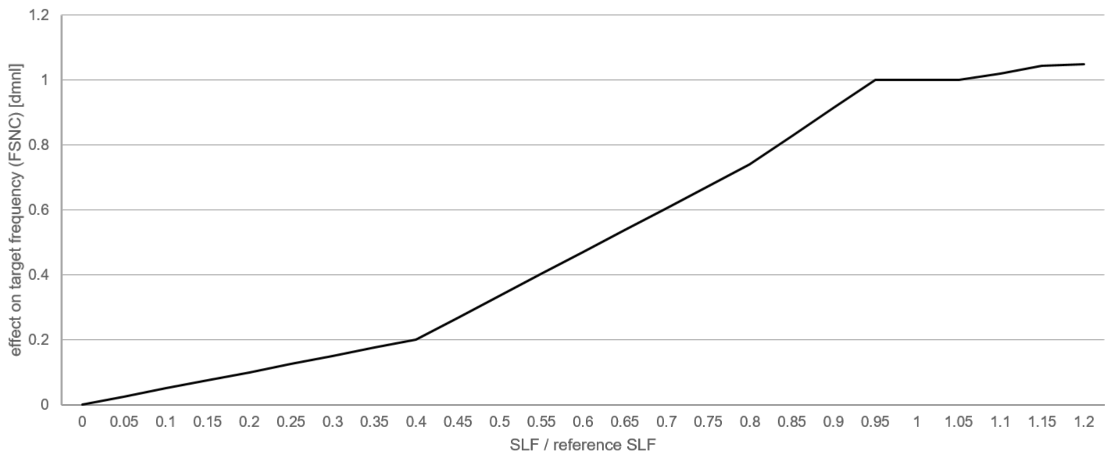

Figure 3.12: Table function: relation between SLF and its effect on the FSNC flight frequency (own estimation)

The table functions of the effects of the SLF on the flight frequency follow an s-shaped development with a range of +/- 5 % around the point where the SLF equals its reference and the resulting effect on frequency is 0. At SLF values below the reference, the effect on the frequency decreases to 0 when no passengers are transported. In case of SLF values above the reference, the resulting effect increases up to a value of 1.05. Hence, airlines react more strongly to capacity utilisation decrease with the reduction of flight services per month. The two relations for the FSNC and the LHLCC only differ in the ratio between SLF and reference SLF: 1.2 for the FSNC and 1.16 for the LHLCC. This has an impact on the slope of the resulting effect on the target frequency. The effect increases faster for the LHLCC than for the FSNC since the LHLCC is more sensitive to SLF changes above the reference SLF compared to the FSNC. Due to the fact that the resulting effect on target frequency ranges between 0 and 1 below a ratio of 1 and only between 1 and 1.05 above that ratio, the differences between the two relations in the latter range in figure 3.12 and figure 3.13 are not recognisable in one figure depicting both table functions for a SLF-reference SLF ratio range between 0 an 1.2, which is why the two relations are each shown in a separate diagram.

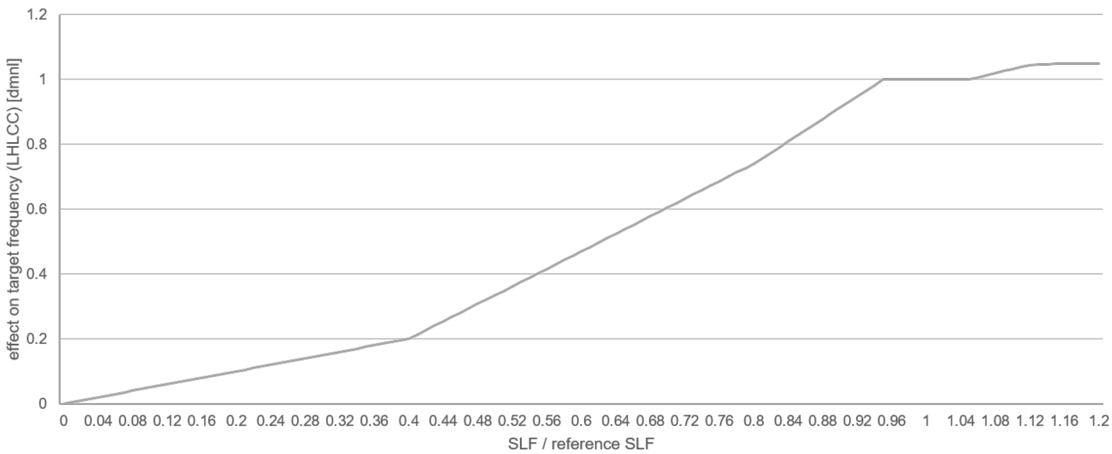

Figure 3.13: Table function: relation between SLF and its effect on the LHLCC flight frequency (own estimation)

The average frequency feeds into the calculation of total available seats per airline type. Airlines can adjust their flight frequency within six months. The $adjTimeFrequency_j$ indicates this flexibility in short-term capacity changes, compared to long-term capacity changes such as aircraft lease or purchase.

Airline fleet planning

Compared to the short-term capacity flexibility that airlines can achieve by adapting flight frequencies, the fleet development process with the options to either purchase or lease aircraft concerns long-term planning and investment decisions. According to Clark [128], this long-term scope has several reasons. Providing future capacities requires information from demand forecasts and depends on the existing route network and its future development [128]. Aircraft purchase decisions are also linked to the business plan of an airline since these decisions influence the airline's market behaviour in terms of the aircraft allocation to routes within the network [128]. Another impact on fleet planning results from changing environmental and technological regulations from which requirements for aircraft performance can be derived [128].

Within the TATM, the fleet development over time is conceptualised in two steps, the actual decision to change the aircraft fleet capacity of an airline and the decision to order aircraft, according to [47, 48]. The airline fleet development over time is modelled as an ageing chain structure [86] with two stocks: the $AircraftOnOrder_{j,k}$, i. e. the number of aircraft which are ordered at manufacturers at a specific time, and the $Fleet_{j,k}$, i. e. the number of aircraft actively operated within the fleet of a representative airline type. The airline fleet comprises purchased as well as leased aircraft in the TATM. The fleet development structure for both airline types is implemented as an array indicating the same structure for both purchased and leased aircraft. Aircraft leasing allows airlines to react more quickly to fluctuations in demand than when purchasing aircraft. Also, this option requires less financial liquidity which is why it is preferred by new market entrants such as the LHLCCs in the transatlantic market. The model structure of the leasing option resembles the purchase option structure but with the difference in duration until a leased aircraft is available ($aircraftProductionTime_{j,k}$), the opportunity to phase out leased aircraft on shorter notice than purchased aircraft if required by the market conditions ($adjTimeAircraftLifetime_{j,k}$), the initial number of aircraft leased within the fleet ($initialFleet_{j,k}$), and the initial number of aircraft ordered for leasing ($initialAircraftOnOrder_{j,k}$). The effects on the desired capacity affect purchased and leased aircraft in the same way. The two stocks are implemented in the TATM as follows.

$$\begin{aligned} AircraftOnOrder_{j,k} = INTEGRAL\,((aircraftOrderRate_{j,k} \\ -aircraftDeliveryRate_{j,k}\,)\,, initialAircraftOnOrder_{j,k}\,(t_0)) \end{aligned} \tag{3.41}$$

$$\begin{aligned} Fleet_{j,k} = INTEGRAL\,((aircraftDeliveryRate_{j,k} - retirementRate_{j,k}\,)\,, \\ initialFleet_{j,k}\,(t_0)) \end{aligned} \tag{3.42}$$

for j = *airline type* (FSNC, LHLCC) and k = *ownership option* (purchase, lease)

The inflows and outflows of this stock and flow structure link the number of aircraft ordered with the aircraft fleet. The *aircraftOrderRate*$_{j,k}$ increases the number of ordered aircraft whereas the *aircraftDeliveryRate*$_{j,k}$ reduces it. In turn, the *aircraftDeliveryRate*$_{j,k}$ increases the number of aircraft within the airline fleet and the *retirementRate*$_{j,k}$ reduces the fleet size. These three flows are implemented in the TATM as follows (*aircraftOrderRate*$_{j,k}$ and *retirementRate*$_{j,k}$ developed based on [41, 42, 47, 48]).

$$aircraftOrderRate_{j,k} = max(0, orderAdjustment_{j,k}) \tag{3.43}$$

$$\begin{aligned} aircraftDeliveryRate_{j,k} = max\,(0, min\,(&deliveryPerMonth_{j,k}\,, \\ &AircraftOnOrder_{j,k}\,/aircraftProductionTime_{j,k}\,)) \end{aligned} \tag{3.44}$$

$$retirementRate_{j,k} = Fleet_{j,k}\,/adjTimeAircraftLifetime_{j,k} \tag{3.45}$$

for j = *airline type* (FSNC, LHLCC) and k = *ownership option* (purchase, lease)

The following equations comprise the two decision steps with the capacity and the order adjustment. The adjustment of the fleet capacities and aircraft orders is implemented as a stock control formulation with a non-linear smoothing structure [86] (*capacityAdjustment*$_{j,k}$ adapted from [48]).

$$\begin{aligned} capacityAdjustment_{j,k} = (&desiredCapacity_{j,k} - Fleet_{j,k}\,) \\ &/adjTimeFleetCapacity_{j,k} \end{aligned} \tag{3.46}$$

with

$$\begin{aligned} desiredCapacity_{j,k} = Fleet_{j,k} &* effectOfSLFOnDesiredCapa_j \\ &* effectOfProfitabilityOnDesiredCapa_j \\ &* effectOfExpectedDSGapOnDesiredCapa_j \end{aligned} \tag{3.47}$$

for j = *airline type* (FSNC, LHLCC) and k = *ownership option* (purchase, lease)

The three effects on the desired capacity are implemented with table functions in the TATM. These table functions represent the functional relations between SLF and desired capacity (3.14, 3.15), profitability and desired capacity (3.16), and expected demand-supply gap and desired capacity (3.17). The table functions differ for the two airline types. The effect of the SLF is represented in two figures, one for each airline type. The two figures include two curves, one representing the table function for the FSNC (black line) and one for the LHLCC (grey line). The SLF effect on the desired capacity is implemented as follows.

$$\begin{aligned} effectOfSLFOnDesiredCapa_j = \\ effectOfSLFOnDesiredCapa_jTF.get \\ (seatLoadFactor_j/refSeatLoadFactor_j) \end{aligned} \tag{3.48}$$

for j = *airline type* (FSNC, LHLCC)

The effects of the quotient of SLF divided by a reference SLF (see table 4.2) on the desired capacity are represented in an s-shaped curve. When the actual SLF equals the reference SLF, the resulting effect on the desired fleet capacity is 1. In case of actual SLFs below the reference, the resulting effect decreases the desired capacity. When the SLF is higher than the according reference, the effects on desired capacity strongly increase up to a maximum of 4 (FSNC) and 6 (LHLCC) respectively. Airlines have the objective to increase their aircraft fleet capacity in case of a high level of utilisation.

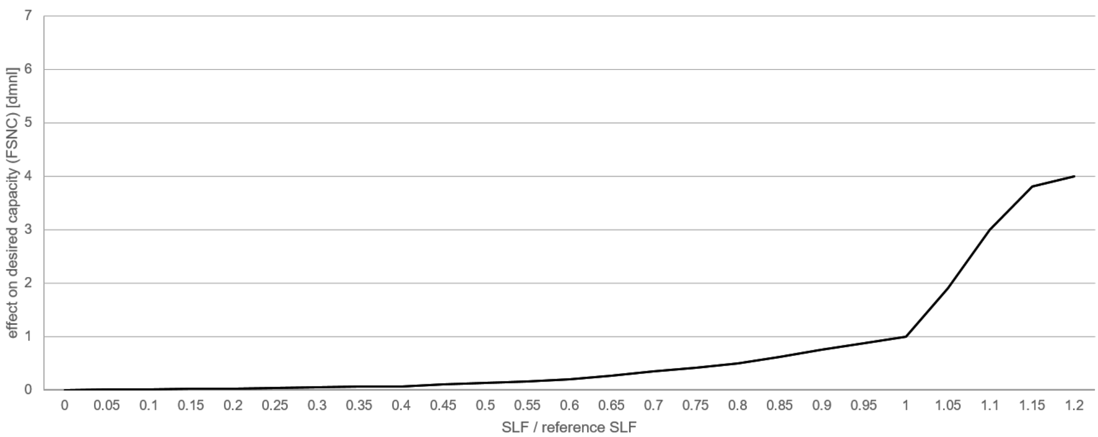

Figure 3.14: Table function: relation between SLF and its effect on the desired FSNC fleet capacity (own estimation)

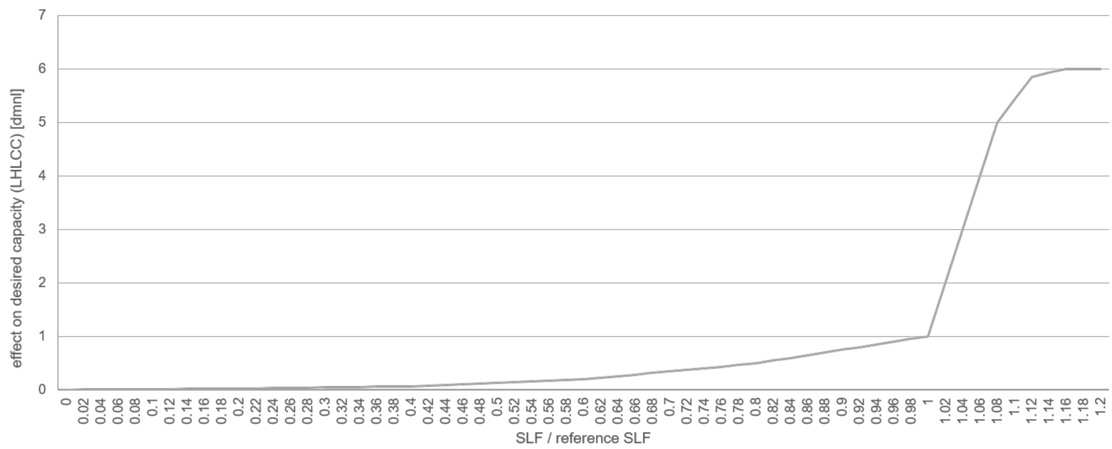

Figure 3.15: Table function: relation between SLF and its effect on the desired LHLCC fleet capacity (own estimation)

For the relation between profitability and desired capacity, the airline's expected profitability is calculated adapted from [48] as follows[3].

$$\begin{aligned} profitability_j = ZIDZ(yield_j - \\ ZIDZ(unitTOC_j, seatLoadFactor_j) \\ , yield_j) \end{aligned} \tag{3.49}$$

with

$$yield_j = TicketPrice_j / averageDistancekm_j \tag{3.50}$$

for j = *airline type* (FSNC, LHLCC)

The resulting effect of the profitability on the desired capacity is implemented as follows.

$$\begin{aligned} effectOfProfitabilityOnDesiredCapa_j = \\ effectOfProfitabilityOnDesiredCapa_jTF.get \\ (Profitability_j) \end{aligned} \tag{3.51}$$

for j = *airline type* (FSNC, LHLCC)

The table functions of the profitability effect on the desired capacity are applied for the FSNC from [48]. The LHLCC table function equals the one from [48] for the negative profitability part.

[3]The formula ZIDZ divides the first value before the decimal point by the value after the decimal point in Anylogic. If divided by 0, the formula generates a return value of 0.

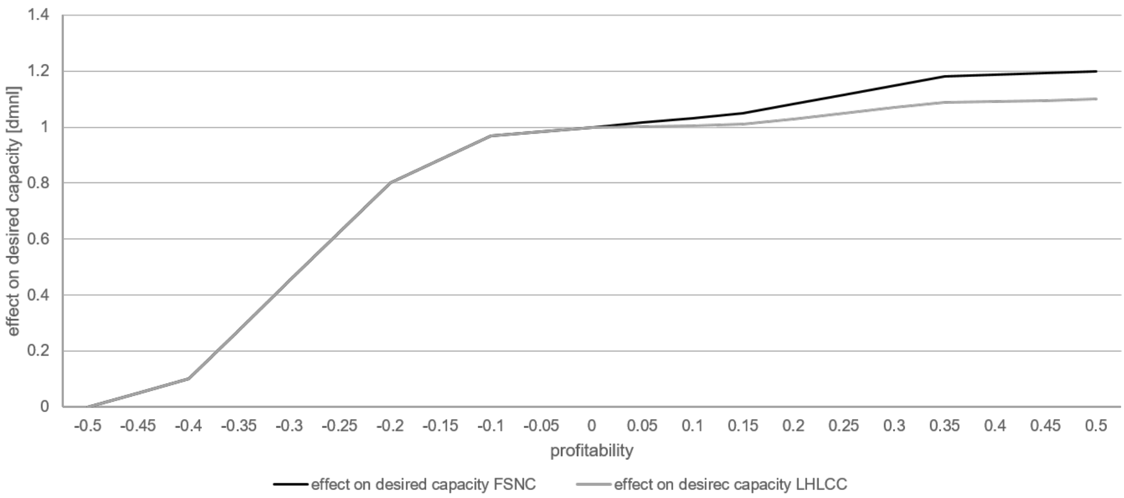

Figure 3.16: Table function: relation between profitability and its effect on the desired fleet capacity (adapted from [48, p. 116])

According to [48], established market incumbents will be more willing to invest in additional capacity in case of positive profitability compared to new market entrants such as the LHLCC. Hence, the maximum effect on desired capacity is lower for the LHLCC (1.1) compared to the FSNC (1.2). At the maximum values, potential market limits for acquisition of new capacity are reached which is why both table functions have an s-shaped form for the part where profitability is positive [48]. When the profitability is negative, airlines do not immediately reduce their capacity but wait until pressure from a continuing negative development trend of profitability increases before fleet capacity is downsized which explains the s-shape of the table function when profitability is negative [48].

The effect from the expected demand-supply gap on the desired capacity is implemented as follows.

$$\begin{aligned} &effectOfExpectedDSGapOnDesiredCapa_j = \\ &effectOfExpectedDSGapOnDesiredCapa_jTF.get \\ &(expectedDSGap_j/refSeatLoadFactor_j) \end{aligned} \tag{3.52}$$

with

$$\begin{aligned} &expectedDSGap_j = \\ &forecast(demand_j/totalSeatsPerMonth_j, 1, 1) \end{aligned} \tag{3.53}$$

for j = *airline type* (FSNC, LHLCC)

The effect of the expected gap between demand and supply on the desired capacity has an additional effect to ramp-up capacity besides the effect from the SLF, especially when an airline enters the market and expects a high level of demand compared to its supply offered. The expected demand-supply-gap is defined as the forecasted value of the quotient of demand and supply with a forecast time horizon of 1 month. The effect is higher for the LHLCC airline type since the LHLCC will ramp-up capacities faster than the FSNC airline type expecting a steeper ramp-up of demand due to lower ticket prices, especially when price sensitive passenger groups were not addressed until LHLCC services are introduced to the long-haul market.

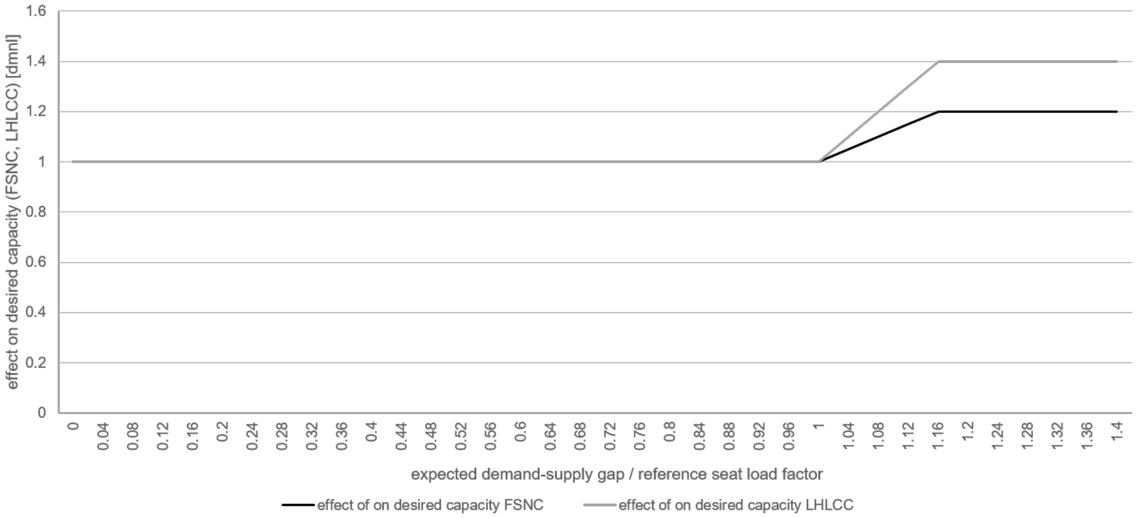

Figure 3.17: Table function: relation between demand-supply gap and its effect on the desired fleet capacity (own estimation)

Within the order adjustment step, the number of desired orders reduced by the number of actual orders which are already placed at that time step, is adapted over a minimum time to adjust (adapted from [48]).

$$\begin{aligned} orderAdjustment_{j,k} &= desiredOrders_{j,k} \\ &- (AircraftOnOrder_{j,k} / adjTimeFleetCapacity_{j,k}) \end{aligned} \tag{3.54}$$

with

$$\begin{aligned} desiredOrders_{j,k} &= \\ capacityAdjustment_{j,k} + retiredAircraft_{j,k} &= \\ capacityAdjustment_{j,k} + retirementRate_{j,k} \end{aligned} \tag{3.55}$$

for j = *airline type* (FSNC, LHLCC)

A documentation of the basic TATM implemented with the simulation software Anylogic can be accessed via the link in appendix A. The following chapter 4 gives an overview of the time series and parameter data applied to the baseline simulation and the model calibration as well as results from the model calibration and validation process. The TATM is calibrated for the years between 2014 and 2017 where another wave of low-cost services was observed in the transatlantic market. Because of this short time frame, additional parameter variation studies are performed to gain a better understanding of the model behaviour besides the calibration statistics. The parameter variation studies are presented in chapter 5.

Chapter 4

Validation and model testing

According to Forrester and Senge [97], the process of validating an SD model means gaining and improving confidence in its usability and ability to generate sound results. To achieve this, Sterman [86] recommends an iterative application of model testing throughout the model development process to constantly improve the model. Step four of the SD modelling process, the model testing (see figure 3.1 in section 3.2) comprises all activities related to model calibration and validation [86]. The following chapter 4 addresses the validation and model testing of the TATM to gain confidence in the model and its functionalities. The TATM will be calibrated using revenue data which represents the historical transatlantic air transport market behaviour between 2014 and 2017 [63]. This revenue data is applied as reference data for the calibration. Besides this reference dataset, the model calibration requires an input dataset of all time series data, fixed parameters, and initial values for the initial model starting date t_0, that is set to July 2014.[1] The validation of the model comprises different testing levels: model structure and model behaviour testing. A generally applicable procedure to test the model structure is not elaborated. However, several procedures to test the structure address boundary adequacy, structure assessment, and dimensional consistency among others [86]. One well-established approach is the partial model testing [99]. Statistical tests are commonly used for behavioural model testing [98].

A model can always only represent a simplification of a system in reality [85, 86]. Especially, SD models are developed to address a specific question and to provide a better understanding of the development of this system over time [86]. The TATM represents a simplification of the transatlantic air transport market to analyse low-cost service introduction and potential. The dynamics within the model result from feedback loops and decision rules which describe the major dynamics within the transatlantic market. Chapter 4 introduces some best practices for model testing in SD, provides an overview of model input and reference data, required to calibrate the model and to test its behaviour, and highlights results from several complementary model structure and behaviour tests such as dimensional consistency

[1] The reference dataset comprises data between 2010 and 2017, based on the Sabre database [63]. t_0 is set to this month since it is the first month in which flight operations from LHLCC were observed in the transatlantic air transport market with distances above 4,000 kilometres between 2010 and 2017.

and integration error testing. Parameter variation and sensitivity analyses will be presented in the subsequent chapter.

The major finding from this chapter includes the following:

- Results from the model behaviour testing reveal that the TATM reproduces the market share development in the transatlantic air transport market between 2014 and 2017 for the simplification of the two basic airline types FSNC and LHLCC.

4.1 System Dynamics approaches for validation and model testing

Model validation in SD is a dynamic and comprehensive process that is performed iteratively during the entire model development process [86]. SD models are associated to the group of design-oriented models [98]. This model type describes not only the behaviour but also the structure of a real system [98]. Thus, not only model behaviour but also model structure need to be tested. Forrester and Senge [97] introduce a list of validation tests to build confidence in an SD model. They also add a third component for model testing: tests for policy implications [95]. Especially, model structure tests are already implemented at an early stage of the model development process when defining the model boundary and developing the CLD and stock-and-flow structure of the model. Model structure tests include structure verification, parameter verification, extreme conditions testing, boundary adequacy, and dimensional consistency [95]. Barlas [98] introduces a procedure with a fixed sequence of the various tests. He further divides the model structure testing into direct structure tests regarding structure and parameter confirmation as well as dimensional consistency, and structure-oriented behaviour tests that focus on extreme model inputs, a feasible definition of the model boundary, and model sensitivity. For Barlas [98], the overall objective is to gain confidence in the structure of the model which is why he emphasizes a strong focus on structure over behaviour testing, which should be carried out after the structural tests. Sterman [86] claims that “All models are wrong, so no models are valid or verifiable in the sense of establishing their truth.” [86, p. 890]. Thus, models can only be validated based on the confidence they create with the simulation results. Sterman [86] highlights the aspects on which modellers should focus when developing an SD model, i. e. purpose, suitability and boundary of an SD model, its physical as well as decision-making structure, and the sensitivity and robustness when applying extreme conditions. Furthermore, he complements the list of tests with integration error tests, behaviour reproduction and anomaly tests, family member tests, surprise behaviour tests and system improvement tests [86]. The following sections address model structure as well as model behaviour tests with a selection of best practice tests applied from the previous literature sources.

4.2 Validation of the Transatlantic Air Transport Model

The validation of the TATM combines a selection of different tests to verify the structure as well as the behaviour of the model. Besides, the model input data and the reference data applied for the calibration time scope between 2014 and 2017 is presented in this chapter. This data forms the basis to reproduce a simplification of the historical behaviour of the transatlantic air transport market with two airline types. The following list summarises the validation effort in terms of model structure, model behaviour, and model fit testing.

Model structure

- model structure and adequacy of the model boundary is tested with insights from the available scientific literature on the introduction of low-cost services to long-haul markets (see also chapter 2)
- dimensional consistency is performed to check model units
- integration error testing is applied for time scope adjustment from months to days and years

Model behaviour

- model behaviour is tested with the comparison of simulation results with historical behaviour, complemented with model fit statistics
- parameter variation and sensitivity studies (see chapter 5) complement the validation of the model behaviour

The validation commences with model structure testing in section 4.2.1. After an overview of the model reference data and model input data required for the model behaviour analysis in section 4.2.2, results from the behaviour reproduction test simulation of the transatlantic air transport market between 2014 and 2017 is presented in section 4.2.3.

4.2.1 Validation of the model structure

The TATM structure was validated based on scientific literature on the general relations and stakeholders (see section 2.2) in the airline market and previous SD modelling activities and publications (see section 3.3). Besides the fundamental requirement to develop a demand and corresponding supply structure, the focus of the model development was on a feasible representation of the major system elements and feedback loops of the transatlantic air transport market with the differentiation of two generic airline types, the FSNC and the competing LHLCC market entrant. The choice behaviour of two generic passenger groups, leisure and business, was developed on the demand side to conceptualise the feedback from changing airline key variables such as the ticket price or the capacity. To validate the model structure with recommended tests in accordance with [86, 97, 98], dimensional consistency analysis and integration error testing were conducted with the TATM baseline simulation model.

Dimensional consistency testing allows to identify potential unit errors that might arise from a wrong understanding of the structure or decisions implemented in an SD model [86]. In addition, arbitrary scaling factors can be identified with this technique [86]. It is conducted in the TATM with an Anylogic functionality at the beginning of each model validation iteration and repeated every time that changes are implemented in the model. After the final model unit check, the TATM exhibits no dimensional errors.

Model simulation results should not show sensitive behaviour to changes of the selected time step or the method of integration [86]. The integration error testing is performed by simulating the model for the calibration period with the two different time steps years and days besides the initial time step months. Calibration simulation reveals that the model structure generates the same results for all time step settings. A switch of the numerical integration method for differential equations from Euler to fourth-order Runge Kutta in the TATM leads to the same results in the calibration simulation run between 2014 and 2017.[2]

4.2.2 Reference and input data for model behaviour testing

The required reference and input data for building confidence in the model behaviour is available for different periods, all covering the years from 2014 to 2017. The revenue data from the Sabre database [63] reveals that airlines, classified as a LHLCC in this thesis (see appendix B, based on [79, 140]), started operations in the transatlantic air transport market in July 2014. According to a report from [79], five airlines characterised as LHLCC were operating at that time between North America and Europe: Air Canada Rouge, Norwegian Air Shuttle, Norwegian Air International, WestJet, and Wow Air [51]. Additional input data on demand growth rates, average flight distances, and airport capacities for the calibration period from 2014 to 2017 is included in appendix C. The model reference and input data is applied for the range between 2014 and 2017 to calibrate the model. The simulation model only considers OD flights from the Sabre database [63] above 4,000 kilometres as defined as system boundary for long-haul air transport services in the transatlantic market in section 3.5. Since the purpose of the TATM is to investigate the market development rather than the cyclical nature in this market, the focus is on monthly data adjusted for annual cyclical behaviour that results from the varying demand for air transport services in the transatlantic market during the different times of the year. This is achieved by applying average monthly demand growth rates calculated from the OD passenger dataset of the Sabre database. The two tables 4.1 and 4.2 introduce the input data implemented in the TATM, comprising all input datasets, initial values, and parameter values. The reference data will be provided with the model behaviour testing in section 4.2.3.

[2]Both methods, Euler and fourth-order Runge Kutta, are applied to numerically compute the stock levels at each time step. The Euler integration method assumes constant inflow and outflow rates between two subsequent time steps and the fourth-order Runge Kutta method considers variable time step changes which makes it more accurate [86]. If no significant changes occur when switching the numerical integration method, the modelling time steps are selected accurately [86].

Table 4.1: Available time series input data implemented for the TATM calibration (own depiction)

TATM module	Time Series Data	Metric	Years of Observation	Source
demand generation	demand growth rates	rate per month	2010-2017	calculated from Sabre database [63]
demand generation	demand growth rates	rate per month	2018-2035	derived from average annual RPK growth rate based on data from [141]
airline market	runway capacities (HUB, NHB)	flights	2010-2017	OAG database [7–9, 123, 124]
airline market	runway capacities (HUB, NHB)	flights	2018-2035	simulation base case airport model [113], capacities kept constant at 2030 value for 2031-2035
airline market	average flight distance FSNC	km	2014-2035	calculated from Sabre database [63]: FSNC airline flights only, flights $\geq$ 4,000 kilometres, distance kept constant at 2017 value for 2017-2035
airline market	average flight distance LHLCC	km	2014-2035	calculated from Sabre database [63]: LHLCC airline flights only, flights $\geq$ 4,000 kilometres, distance kept constant at 2017 value for 2017-2035

For the model input, the collection and analysis of data is required to conceptualise, populate, and calibrate the model components. Two major data sources are used for the model: revenue data from the Sabre database and flight schedule data from OAG [8, 9, 63] between the two regions Europe and North America. 46 countries are defined as European countries and North America comprises two countries, Canada and the United States of America (see appendix D). Time series data is available for different years of observation but it is only applied for the calibration period between 2014 and 2017. Parameter and initial stock value input data results from literature, other model approaches (see table 3.1), and own estimations.

Airport related input data, i. e. passenger and runway capacities up to 2017, result from the OAG database. Future values for these two parameters are applied from an SD modelling study of dynamics in airport charges and capacity developments [113]. The parameter values for the passenger choice module are taken from a study on customer loyalty and service quality in the commercial airline industry [142]. The data was also applied in [49]. However, this data does not specifically address passengers' preferences in the long-haul market segment. Thus, parameter variation studies are conducted in chapter 5 to investigate the sensitivity of the market share development to feasible changes in these parameters. The variable and fixed cost components per ASK are calculated with a smart reference costing model [125] for the A330-300 and the B787-800. The average seat capacity for the reference aircraft for both airline types is derived from data of scheduled average seats per aircraft type between 2014 and 2018 [9, 123, 124]. For the FSNC reference aircraft A330-300, this data differs by two seats with the data used for the operating cost calculation with the smart reference costing model [125]. To analyse whether this discrepancy has an effect on the model results, a TATM baseline simulation (2014-2017) was conducted one time with the operating cost calculations based on an FSNC seat capacity of 277 and the average seats per FSNC aircraft of 279 and then again with a seat capacity of 277 for both cost calculation and average seat parameter of 277 for the FSNC in the TATM. Results reveal that this discrepancy in the seating baseline for the cost calculation and the average seat parameter does not affect the results of the TATM for the baseline simulation. Hence, the seating capacity operating cost calculation for the FSNC is kept at 279 seats per aircraft [125]. For the LHLCC reference aircraft B787-800, the OAG data analysis reveals that this aircraft type is operated with 291 seats on average. This number of average seats is within the range of the smart reference costing model of 242 seats at typical seating and 381 seats for high seating. Thus, the TOC are adapted within a linear interpolation to represent a cost level that matches the operation with 291 seats for the TATM calibration simulation. The cost calculation with the smart reference costing model [125] is based on the assumption that the FSNC reference aircraft A330-300 has a maximum take-off weight (MTOW) of 212 tons and changes due to technological renewals of this aircraft type [143] are not considered. The according MTOW of the LHLCC aircraft type B787-800 accounts for 227.93 tons. One major airport and navigation charges driver is the MTOW [128] which is why these two charges per ASK are lower for the FSNC than for the LHLCC airline type (see table 4.2).

Table 4.2 comprises all exogenous parameter values included in the different TATM modules. The parameter values are partly derived from the scientific literature or calculated based on available data sources. Some parameter values are estimated or result from the model calibration.

Table 4.2: Available initial values and parameter data implemented for the TATM calibration (own depiction)

TATM module	**Variable/ Parameter**	**Extracted Data**	**Metric**	**Source**
demand generation	*initialPotPAXTA*	4,631,177	passengers	calculated from Sabre database [63]
demand generation	*maxSeatLoadFactorFSNC*	1	dmnl	own estimation
demand generation	*maxSeatLoadFactorLHLCC*	1	dmnl	own estimation
passenger choice	*maxTicketPrice*	5,000	USD per passenger	own estimation: based on Sabre database [63] (max. LHLCC ticket price)
passenger choice	*maxFrequency*	60	flights / aircraft	own estimation: max. 2 long-distance flights per a/c per day

Table 4.2 continued: Available initial values and parameter data implemented for the TATM calibration (own depiction)

TATM module	Variable/ Parameter	Extracted Data	Metric	Source
passenger choice	$preferenceTicketPrice_{Business}$	2.1	dmnl	adapted from [130] as applied in [49]
passenger choice	$preferenceTicketPrice_{Leisure}$	3.9	dmnl	adapted from [130] as applied in [49]
passenger choice	$preferenceFrequency_{Business}$	4.5	dmnl	adapted from [130] as applied in [49]
passenger choice	$preferenceFrequency_{Leisure}$	3.2	dmnl	adapted from [130] as applied in [49]
passenger choice	$preferenceFFP_{Business}$	2	dmnl	adapted from [130] as applied in [49]
passenger choice	$preferenceFFP_{Leisure}$	1.5	dmnl	adapted from [130] as applied in [49]
passenger choice	$availabilityFFP_{FSNC}$	1	binary	adapted from [130] as applied in [49]
passenger choice	$availabilityFFP_{LHLCC}$	0	binary	adapted from [130] as applied in [49]
passenger considera-tion	$initialWillingness\text{-}ToConsiderService_{FSNC}$	1	dmnl	own estimation: FSNC well established and potential passengers fully aware of FSNC service
passenger considera-tion	$initialWillingness\text{-}ToConsiderService_{LHLCC}$	0.03	dmnl	own estimation, derived from LHLCC share of revenue passengers at t_0 ([63])
passenger considera-tion	$coefficientOfMarketing_{FSNC}$	0.025	dmnl	[116]
passenger considera-tion	$coefficientOfMarketing_{LHLCC}$	0.026	dmnl	derived from [116]
passenger considera-tion	$coefficientOfWordOfMouth_{FSNC}$	0.25	dmnl	[116]
passenger considera-tion	$coefficientOfWordOfMouth_{LHLCC}$	0.26	dmnl	derived from [116]
airline market	$averageSeatsPerAircraft_{FSNC}$	279	seats/ aircraft	calculated from OAG data 2014, 2016, 2018 [9, 123, 124] (A330-300)
airline market	$averageSeatsPerAircraft_{LHLCC}$	291	seats/ aircraft	calculated from OAG data 2014, 2016, 2018 [9, 123, 124] (B787-800)

Table 4.2 continued: Available initial values and parameter data implemented for the TATM calibration (own depiction)

TATM module	Variable/ Parameter	Extracted Data	Metric	Source
airline market	$initialFleet_{FSNC(purchase,\ lease)}$	(601, 401)	no. of aircraft	calculated average based on OAG database 2014 [123])
airline market	$initialFleet_{LHLCC(purchase,\ lease)}$	(4, 3)	no. of aircraft	calculated average based on OAG database 2014 [123])
airline market	$initialAircraftOnOrder_{FSNC(purchase,\ lease)}$	(90, 70)	no. of aircraft	own estimation
airline market	$initialAircraftOnOrder_{LHLCC\ (purchase,\ lease)}$	(5, 3)	no. of aircraft	own estimation
airline market	$adjTimeFleetCapacity_{FSNC(purchase,\ lease)}$	(12, 12)	months	[48]
airline market	$adjTimeFleetCapacity_{FSNC(purchase,\ lease)}$	(12, 12)	months	[48]
airline market	$aircraftProductionTime_{FSNC(purchase,\ lease)}$	(24, 12)	months	[48]
airline market	$aircraftProductionTime_{LHLCC(purchase,\ lease)}$	(24, 12)	months	[48]
airline market	$deliveryPerMonth_{FSNC(purchase,\ lease)}$	(25.324, 25.324)	no. of aircraft	derived from [144] for purchase and applied accordingly to lease option
airline market	$deliveryPerMonth_{LHLCC(purchase,\ lease)}$	(25.324, 25.324)	no. of aircraft	derived from [144] for purchase and applied accordingly to lease option
airline market	$adjTimeAircraftLifetime_{FSNC(purchase,\ lease)}$	(300, 60)	months	[48]
airline market	$adjTimeAircraftLifetime_{LHLCC(purchase,\ lease)}$	(300, 60)	months	[48]
airline market	$refSeatLoadFactor_{FSNC}$	0.8216	dmnl	[139]: average SLF EU-NA in 2015
airline market	$refSeatLoadFactor_{LHLCC}$	0.86	dmnl	own estimation
airline market	$initialFrequency_{FSNC}$	20	flights/ month	derived from [145]
airline market	$initialFrequency_{LHLCC}$	25	flights/ month	derived from [145]
airline market	$adjTimeFrequency_{FSNC}$	6	months	own estimation
airline market	$adjTimeFrequency_{LHLCC}$	6	months	own estimation

Table 4.2 continued: Available initial values and parameter data implemented for the TATM calibration (own depiction)

TATM module	Variable/ Parameter	Extracted Data	Metric	Source
airline market	$maxFrequency_{FSNC}$	60	flights/ month	own estimation: max. 2 long-distance flights per a/c per day
airline market	$maxFrequency_{LHLCC}$	60	flights/ month	own estimation: max. 2 long-distance flights per a/c per day
airline market	$sensitivityPriceOnProfitPressure_{FSNC}$	0.4	dmnl	[48]
airline market	$sensitivityPriceOnProfitPressure_{LHLCC}$	0.2	dmnl	own estimation
airline market	$stretchGoal_{FSNC}$	0.01	dmnl	[48]
airline market	$stretchGoal_{LHLCC}$	0.01	dmnl	[48]
airline market	$adjTimePerceivedProfitability_{FSNC}$	3	dmnl	[48]
airline market	$adjTimePerceivedProfitability_{LHLCC}$	3	dmnl	[48]
airline market	$adjTimeProfitabilityTrend_{FSNC}$	12	dmnl	[48]
airline market	$adjTimeProfitabilityTrend_{LHLCC}$	12	dmnl	[48]
airline market	$initialPerceivedProfitability_{FSNC}$	0.05	dmnl	own estimation
airline market	$initialPerceivedProfitability_{LHLCC}$	0.025	dmnl	own estimation
airline market	$initialProfitabilityTrend_{FSNC}$	0.05	dmnl	[48]
airline market	$initialProfitabilityTrend_{LHLCC}$	0.02	dmnl	own estimation
airline market	$sensitivityTOC_{FSNC}$	0.2	dmnl	[48]
airline market	$sensitivityTOC_{LHLCC}$	0.3	dmnl	own estimation
airline market	$adjTimeTicketPrice_{FSNC}$	12	months	own estimation
airline market	$adjTimeTicketPrice_{LHLCC}$	3	months	own estimation

Table 4.2 continued: Available initial values and parameter data implemented for the TATM calibration (own depiction)

TATM module	Variable/ Parameter	Extracted Data	Metric	Source
airline market	$initialTicketPrice_{FSNC}$	1,285.24	USD per passenger	calculated from Sabre database [63] (OD data)
airline market	$initialTicketPrice_{LHLCC}$	910.22	USD per passenger	calculated from Sabre database [63] (OD data)
airline market	$costRecoveryFactor_{FSNC}$	1	dmnl	own estimation
airline market	$costRecoveryFactor_{LHLCC}$	0.7	dmnl	own estimation
airline market	$fuelCostPerASK_{FSNC}$	0.03551	USD per ASK	smart reference costing model [125]
airline market	$fuelCostPerASK_{LHLCC}$	0.03021	USD per ASK	interpolated from smart reference costing model [125]
airline market	$labourCostPerASK_{FSNC}$	0.00817	USD per ASK	smart reference costing model [125]
airline market	$labourCostPerASK_{LHLCC}$	0.00815	USD per ASK	interpolated from smart reference costing model [125]
airline market	$maintenanceCostPerASK_{FSNC}$	0.0112	USD per ASK	smart reference costing model [125]
airline market	$maintenanceCostPerASK_{LHLCC}$	0.00739	USD per ASK	interpolated from smart reference costing model [125]
airline market	$costOfOwnershipPerASK_{FSNC}$	0.00344	USD per ASK	smart reference costing model [125]
airline market	$costOfOwnershipPerASK_{LHLCC}$	0.00785	USD per ASK	interpolated from smart reference costing model [125]
airline market	$overheadCostPerASK_{FSNC}$	0.03767	USD per ASK	smart reference costing model [125]
airline market	$overheadCostPerASK_{LHLCC}$	0.03658	USD per ASK	interpolated from smart reference costing model [125]
airline market	$airportChargesPerASK_{FSNC}$	0.01395	USD per ASK	smart reference costing model [125]
airline market	$airportChargesPerASK_{LHLCC}$	0.01452	USD per ASK	interpolated from smart reference costing model [125]
airline market	$GHNavChargesPerASK_{FSNC}$	0.0036	USD per ASK	smart reference costing model [125]
airline market	$GHNavChargesPerASK_{LHLCC}$	0.00373	USD per ASK	interpolated from smart reference costing model [125]
airline market	$addOperatingCostPerASK_{FSNC}$	0.00053	USD per ASK	smart reference costing model [125]
airline market	$addOperatingCostPerASK_{LHLCC}$	0.00029	USD per ASK	interpolated from smart reference costing model [125]

4.2.3 Comparison to historical behaviour

The model behaviour validation is conducted with the reproduction of historical data of the transatlantic air transport market between July 2014 and December 2017 and complemented with model fit statistics of the simulation results for this time scope. Parameter sensitivity studies in chapter 5 will extend the validation of the model behaviour. The following table gives an overview of the model fit statistics [86] that are calculated from the historical model run simulation results.

Table 4.3: Model fit statistics (own calculation)

	$\mathbf{R^2}$	**r**	**MAPE**	**MAE/ mean**	**RMSE**	**Theil's Inequality Statistics**			**n**
						Bias $\mathbf{U^M}$	**Unequal Vari- ation $\mathbf{U^S}$**	**Unequal Co- variation $\mathbf{U^C}$**	
market share FSNC	0.949	0.974	1 %	1 %	7.50E-03	0.0248	0.3664	0.6088	42
market share LHLCC	0.949	0.974	29 %	14 %	7.50E-03	0.0248	0.3664	0.6088	42
ticket price FSNC	0.433	0.658	5 %	5 %	7.00E+01	0.4740	0.2435	0.2825	37
ticket price LHLCC	0.972	0.986	2 %	2 %	1.78E+01	0.0005	0.4144	0.5851	37
revenue passen- gers FSNC	0.997	0.998	0 %	0 %	1.21E+04	0.0458	0.0249	0.9293	37
revenue passen- gers LHLCC	0.990	0.995	5 %	6 %	1.21E+04	0.2057	0.0076	0.7867	37
average fleet size FSNC	0.996	0.998	0 %	0 %	2.74E+00	0.0421	0.0092	0.9487	37
average fleet size LHLCC	0.991	0.995	5 %	6 %	1.85E+00	0.2893	0.0007	0.7100	37

The coefficient of correlation r, as well as the coefficient of determination R^2 are both expressions of the goodness of fit of the simulation results to the historical data [86]. Values close to 1 represent a high degree of goodness of fit [86]. The mean absolute percent error (MAPE), the mean absolute error as percent of the mean (MAE/mean), and the root mean square error (RMSE) are three statistical measures that can be applied to evaluate the error between simulation results and historical data [86]. The calibration objective is to minimise the error measures. The Theil's Inequality Statistics provide an inequality measure which, unlike the Gini coefficient, can be broken down into different parts [146]. According to Sterman [86], the error of the model simulation in comparison with the historical values is insignificant if the Theil's Inequality Statistics values are concentrated in the unequal covariation U_C.

The figures 4.1 until 4.8 present the comparison of the TATM baseline simulation results and the reference data for the time between 2014 and 2017 of the market shares, the ticket price development, the development of revenue passengers over time, and the fleet development, all for both airline types. The calibration results are presented and discussed in more detail in the following.

Figures 4.1 and 4.2 exhibit the market share development in terms of the share of revenue passengers of one airline type, FSNC or LHLCC, from the total number of monthly revenue passengers. The solid lines represent the historical data of market shares and the dashed lines provide the data from the model simulation. The FSNC airline type is represented with black lines and the LHLCC airline type is marked with grey lines.

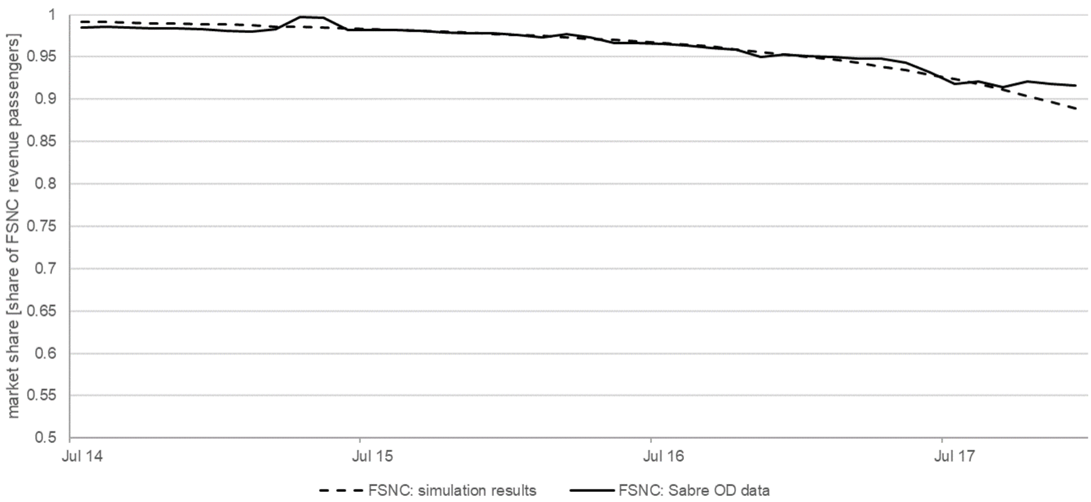

Figure 4.1: Calibration results: FSNC market shares (own depiction)

The market share development of both airline types is the major variable of investigation since the research objective is to analyse the transferability and potential of low-cost services in the transatlantic air transport market. The simulation results for the market shares are compared to historical data calculated from the Sabre database [63]. This database provides two different data: annual OD data and monthly leg data of all flight movements between Europe and North America. Since the leg data also includes flights that can be part of connections with more than one flight originating or arriving in a global region other than Europe or North America, the sum of revenue passengers from this dataset is bigger than the sum of all transatlantic OD passengers, i. e. all OD passengers are included in the leg passengers. To derive historical data for the market share calculation, monthly OD revenue passengers between Europe and North America are calculated from the available monthly leg data by multiplying the leg data by the annual share of OD flights per airline type. The share varies between 0.82 and 0.87 for the FSNC and between 0.97 and 1.0 for the LHLCC. The resulting monthly revenue passenger data includes seasonal cycles. However, the market share is calculated from this cyclical revenue passenger data. Since both airline types are exposed to the same seasonal cycle and the market share is expressed as the ratio of an airline type's share of the overall revenue passengers, the cyclical behaviour does not affect the resulting monthly market share significantly. The objective was to use data from the Sabre database [63] which is processed as little as possible to calibrate the model behaviour to the historical development, at least for the major variable of investigation: the market share.

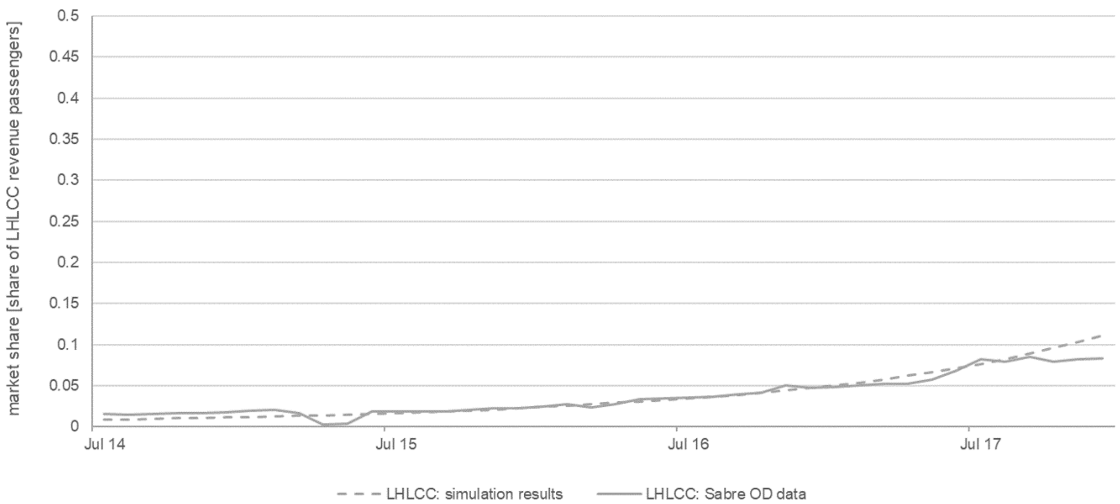

Figure 4.2: Calibration results: LHLCC market shares (own depiction)

As the model fit statistics indicate, the model resembles the historical behaviour of the market shares to a high degree of statistical significance for both airline types. Both, the coefficient of correlation r as well as the coefficient of determination R^2 show high values close to the target value for these two coefficients which is 1. The error measures exhibit a low error level between the simulation results and the historical calibration data. Only the MAPE for the LHLCC market share indicates an error level of 29 %. In case of historical data close to 0, Sterman [86] recommends to complement the error measures with the MAE/mean measure. This value indicates an error level of 14 % for the LHLCC market share. Additionally, the Theil's Inequality Statistics reveal a large share of unequal covariation (0.6088). The existence of systematic errors is indicated by specific settings of these three parts of the Theil Inequality Statistics [86]. In case of the TATM calibration, cycles in the model development are neglected. Hence, a concentration of calibration results in the unequal covariation indicates the presence of a large share of unsystematic errors [86] which is a targeted outcome for the model calibration. However, a value of 0.3664 of the unequal variation indicates that the calibration result tends to have a different trend compared to the historical data. In figures

4.1 and 4.2, the simulated market shares declines steeper for the FSNC and increases steeper for the LHLCC which can cause the model statistics value in the unequal variation.

Figures 4.3 and 4.4 provide the simulation results for the historical behaviour of the ticket prices. For ticket price, only average monthly values are available between July 2014 and December 2017. These average monthly values are calculated with interpolation from annual values available for the ticket price from the Sabre database [63]. The annual values are set for each according July within the calibration period and marked as crosses in figures 4.3 and 4.4. The interpolated values are considered for calculation of the model fit statistics but not depicted in the figures. As already indicated by the model fit statistics in table 4.3, these simulation results do resemble the historical data well for the LHLCC ticket price. The coefficient of correlation r as well as the coefficient of determination R^2 provide values close to the target value of 1, the error measures exhibit low levels (MAPE and MAE/mean at 2 %), and the Theil's Inequality Statistics show a tendency towards a concentration in the unequal covariation value (0.5851) as objected for the LHLCC ticket price.

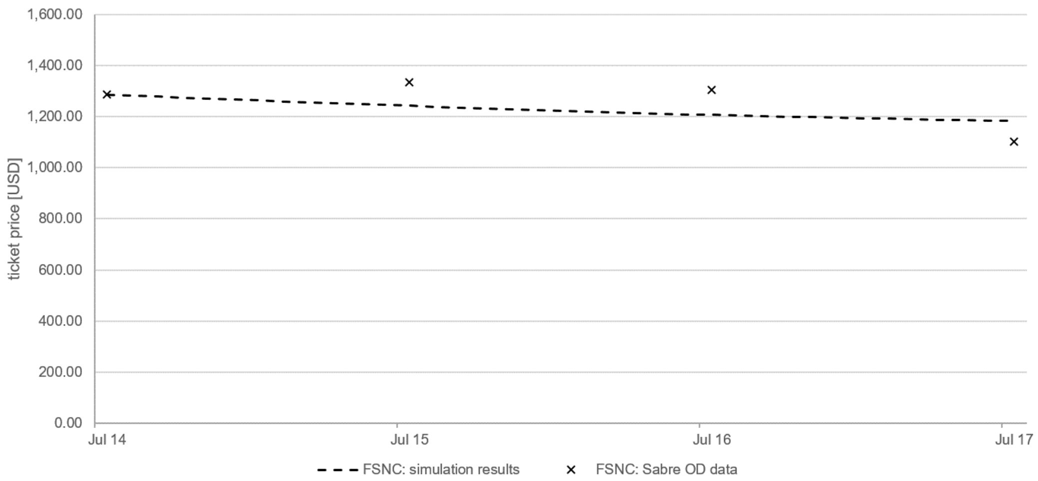

Figure 4.3: Calibration results: FSNC ticket price (own depiction)

The FSNC ticket price from the TATM baseline simulation does not resemble the historical behaviour with a ticket price increase in 2015 and 2016 followed by a decrease to an average of 1,100 US dollar (USD) as accurate as expected. In general, a concentration in the bias of the Theil's Inequality Statistics indicate a systematic error. The bias for the FSNC ticket price is 0.4740. The calibration is limited to a rather short period of time of only four years. The increase in FSNC ticket price between 2015 and 2016 might result from an overlapping of additional short-term effect besides the expected reaction to reduce the ticket price as soon as a competitor enters the market [12]. This short-term effect that results in an increase of ticket price in the historical behaviour from 2014 to 2015 is excluded from the TATM structure since the overall trend of a decreasing FSNC ticket price is sufficient to reflect the long-term behaviour on the transatlantic market. Hence, the general tendency towards a decrease of the FSNC ticket price from the historical data is represented in the TATM structure reasonably. The ticket price adjustment time is higher for the FSNC than for the LHLCC resembling the

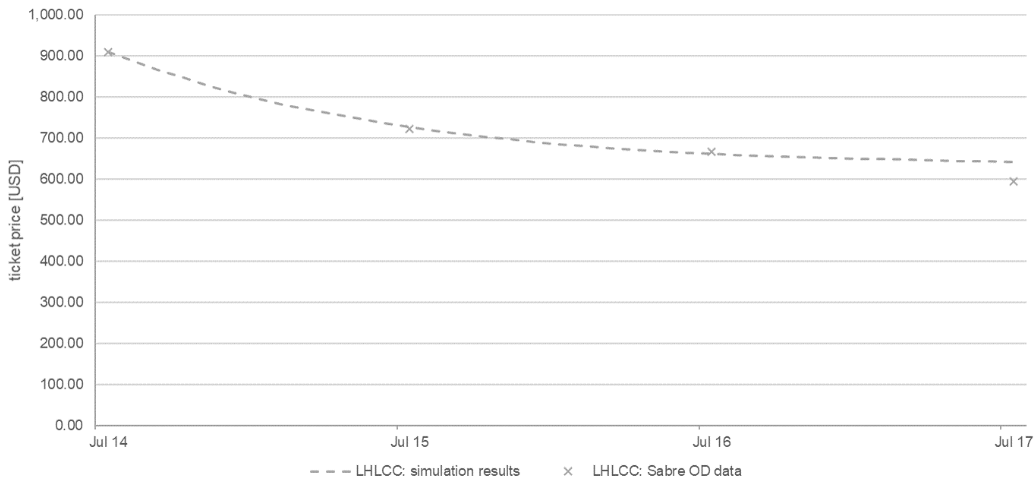

Figure 4.4: Calibration results: LHLCC ticket price (own depiction)

fact that FSNCs might wait and see how the LHLCC service is evolving in the market before directly reacting to the competitor with a lower FSNC ticket price.

The historical data for the monthly OD revenue passengers is calculated with interpolation from annual values available from the Sabre database [63] since the monthly OD revenue passenger data, as applied for the historical market share data calculation, includes seasonal cycles and the TATM neglects these cycles in the simulation which is why average monthly OD revenue passenger data is required for the calibration. Average monthly OD revenue passengers are calculated from the annual OD data available and set to each July per year within the calibration period. The remaining average monthly values are calculated from interpolation. The average monthly OD revenue passengers calculated are depicted with a cross in figures 4.5 and 4.6. The interpolated data is not depicted in the figures but applied for model fit statistics calculation.

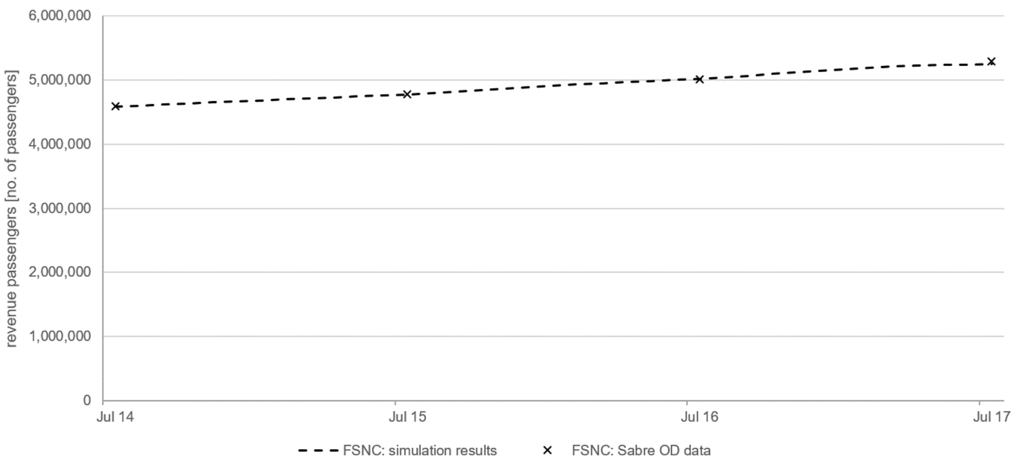

Figure 4.5: Calibration results: FSNC revenue passengers (own depiction)

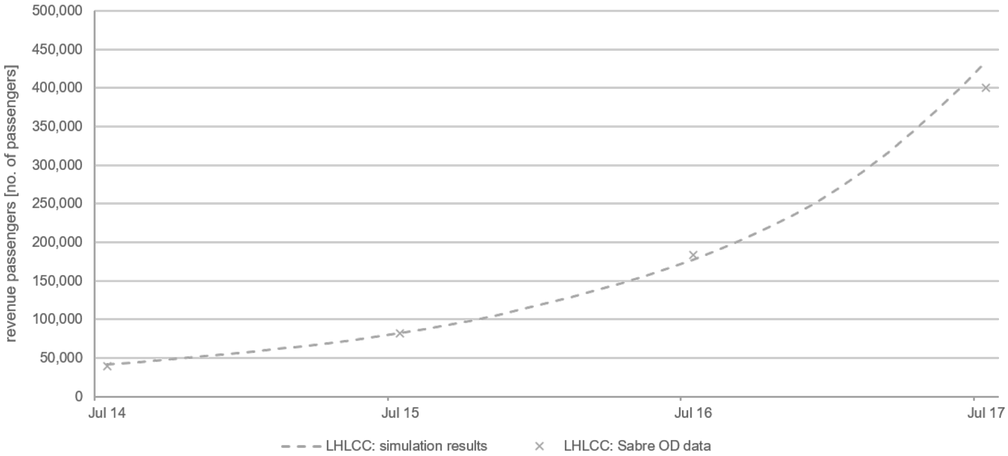

Figure 4.6: Calibration results: LHLCC revenue passengers (own depiction)

The results for the monthly revenue passengers are strongly related to the market share development since the market shares are calculated from the revenue passenger shares of each airline type. Thus, similar simulation results for the FSNC revenue passengers in comparison with the historical data is expected with a slight undershoot of the simulation results compared to the historical data in figure 4.5 in accordance with the lower simulated FSNC market share compared to the historical development. Following this explanation, the LHLCC revenue passengers reach a higher level compared to the historical value at the end of the calibration time period in 2017. This observation results from differences in the derived fleet size from the OAG database [123] with average seats and one aircraft type and its differences to the actual fleet operated by FSNC and LHLCC airlines in the transatlantic market as indicated in the historical values. The calibration results for both variables, the FSNC and the LHLCC revenue passengers, reach high values for the coefficient of determination R^2 and for the coefficient of correlation r. The error measures reveal low levels of 0 % for the FSNC and 5 % respectively 6 % for the LHLCC. The Theil's Inequality Statistics are concentrated in the unequal covariation U_C with a value of 0.9293 for the FSNC and a value of 0.7867 for the LHLCC.

The initial fleet of both airline types is derived from a representative aircraft type with an average number of seats derived from the OAG database (FSNC: 279, LHLCC: 291, [9, 123, 124]), an average initial flight frequency, and the average SLF in the transatlantic market (FSNC [139]: 82.16 %, LHLCC: 86 %). The simulation results from this aircraft capacity are compared to average monthly available seats per airline type, derived from the historical revenue passengers from the Sabre database [63], divided by average flight frequency, average seats per representative aircraft type, and transatlantic SLF per airline type. The results are shown in the following two figures 4.7 and 4.8.

The initial number of aircraft orders is derived from the expected fleet development with a percentage share of aircraft leased of 40 % [11]. The size of the FSNC fleet, derived from the average aircraft type, increases between mid 2014 until 2018 from 1,002 up to 1,142 aircraft.

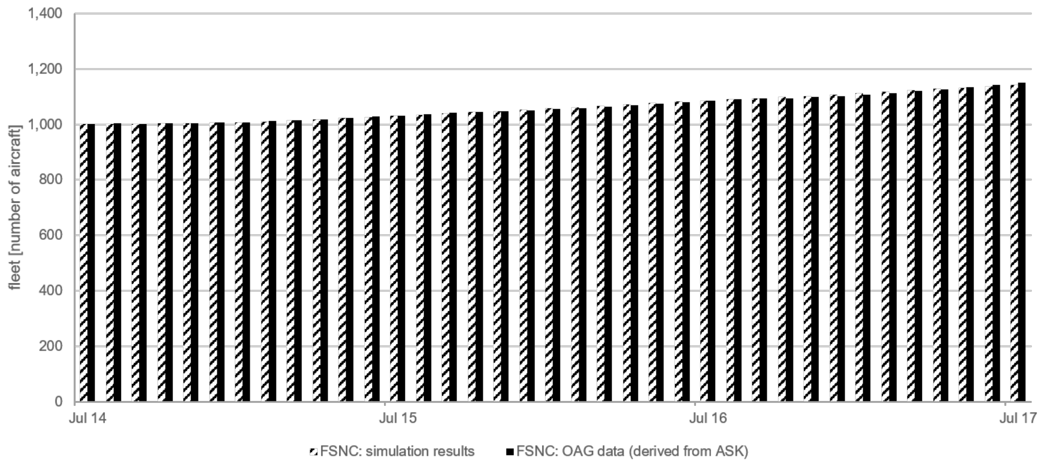

Figure 4.7: Calibration results: FSNC fleet size (own depiction)

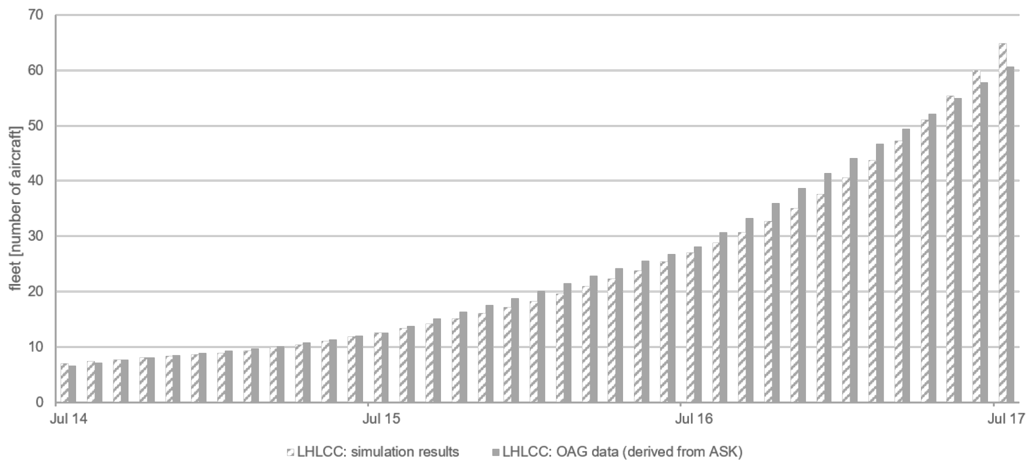

Figure 4.8: Calibration results: LHLCC fleet size (own depiction)

This increase results from the rising demand for transatlantic air transport services. In turn, the LHLCC fleet grows exponentially from an initial fleet of 7 aircraft in 2014 up to 65 aircraft in 2017. The model fit statistics for the fleet development provide similar results compared to the revenue passenger development for both airline types. The coefficient of correlation r as well as the coefficient of determination R^2 reach levels close to the target value of 1. The error measures are comparably low for the fleet and the revenue passenger development. The simulation results for the Theil's Inequality Statistics reach high values of 0.9487 for the FSNC and 0.7100 for the LHLCC fleet figures in the unequal covariation U_C.

The following chapter provides further studies to gain confidence in the model behaviour, including parameter variations and variations of the operating cost advantage as well as the aircraft capacity setting. Parameter variation studies are applied on the passenger choice module to further investigate effects of varying passenger utilities. In addition, the cost advantage of the LHLCC, the LHLCC cost coverage factor, and the aircraft availability in terms of delivery times for purchased or leased aircraft are varied to validate the model behaviour. After these parameter variation studies, scenario simulations are performed to investigate the impact of exogenous effects such as impacts on ticket prices or unexpected changes in demand on the potential of long-haul low-cost services in the transatlantic air transport market.

Chapter 5

Simulation of transatlantic air transport scenarios

After the development and the validation of the TATM, a parameter variation of the passenger choice modelling factors, the operating cost advantage, the LHLCC cost recovery factor, and the availability of aircraft are applied to gain a better understanding of the resulting model dynamics from varying passenger utility parameters (see table 5.1), operating cost (see table 5.2), and aircraft production and delivery times (see table 5.3). The LHLCC cost recovery factor is set to 1.0 as a variation of the calibration value of 0.7. These parameter variation studies are followed by the simulation of different scenarios for a feasible future simulation period between 2014 and 2035 to observe the model behaviour (see section 5.3). These include a scenario covering the introduction of the CORSIA scheme in 2021 (see section 5.3.1) and a scenario resembling the recent demand shock in global aviation due to the uprising of the COVID-19 pandemic (see section 5.3.2).

This chapter comprises the simulation of transatlantic air transport studies and addresses the following research question:

- **Which implications on low-cost airline operations can be derived from long-haul future airline market dynamics?**

The parameter variation studies in this chapter address this research question by investigating different potential airline strategies in terms of target cost advantage or selection of an aircraft type to operate. In addition, the scenario studies introduce different exogenous future impacts on the transatlantic air transport market such as the implementation of CORSIA and the occurrence of demand shocks such as the COVID-19 pandemic. A summary of the major findings from this chapter include the following aspects:

- The market share of the LHLCC airline type in the baseline simulation (*B-00*) up to 2035 reaches a level of 26.1 % in terms of transatlantic revenue passengers.

- A summary of parameter variation studies of passenger choice parameters (2014-2035) (*BPAX-01 - BPAX-04*), operational cost advantage (2014-2035) (*BCOST-01 - BCOST-02*), cost recovery factor (*BCOST-03*), and the aircraft availability (2014-2035) (*BAC-01, BAC-02*) result in a range for the LHLCC market potential of 10 % to 30 %.

- An introduction of environmental cost to internalise the environmental impact from aviation (CORSIA scheme, 2014-2035) in the scenarios (*B-00-CORSIA-01, B-00-CORSIA-02, B-00-IPCC-2.0, B-00-IPCC-1.5*) only affects the LHLCC market share development in the transatlantic market if levels of environmental costs of 0.23 USD per passenger kilometre in 2030 to 0.31 USD per passenger kilometre in 2035 for the operation of a B787-800 aircraft type are introduced. In this case, the LHLCC market share increases to 37.6 % in this scenario due to effects from an increasing cost advantage over time and a resulting increasing attractiveness of the LHLCC for passengers.

- The analysis of economic impact scenarios such as the demand shock resulting from the COVID-19 pandemic (2014-2035) (*B-00-COVID-01, B-00-COVID-02*) reveals that the transatlantic air transport market collapses if no coping strategies and support measures such as governmental financial subsidies are installed on short notice.

The results of this chapter are twofold. On the one hand, the extended baseline simulations with parameter variations and future simulations with a time scope up to 2035 provide insights into the model functionalities and dynamics and reveal the potential of the LHLCC business model for the transatlantic market under consideration of the given parameter settings. On the other hand, scenario simulations of external impacts on the system sketch the resilience of the transatlantic air transport system in a simplified model setting with two representative airline types, average capacities, and no consideration of a route network structure against extreme conditions. The scientific contribution of this thesis beyond existing modelling attempts and econometric studies on the transatlantic air transport system is to deliver results of the LHLCC market potential from dynamic developments within the system in the light of different exogenous effects.

5.1 Application case

The TATM, introduced in the two previous chapters 3 and 4, is calibrated with data of the transatlantic air transport market between Europe and North America for the time period between 2014 and 2017. Framework conditions such as the Open Skies Agreement [21] have contributed significantly to opening up the market for new airlines. Since LHLCCs such as Norwegian Air Shuttle [79] have established long-haul flight operations in this market recently, the performance of this airline business model as well as the behaviour of well-established FSNCs in response to the entry of LHLCCs in the transatlantic market can be analysed.

Future projections resulting from simulations beyond 2017, such as the following baseline as well as the parameter and scenario studies, do not indicate a most feasible forecast scenario of the market development. They rather reflect the market potential for long-haul low-cost air transport services in the transatlantic market based on the given parameter setting. Especially, the parameters for passenger choice are expected to have a significant effect on the market potential. The parameter studies in this chapter extend the calibration activities and provide additional results of the market dynamics within the modelled system in the TATM. From these results, the parameters with the largest impact on the model behaviour can be identified. Implications for LHLCCs can be derived from the behaviour of these high impact parameters to improve the market potential. The scenario studies, in turn, investigate exogenous effects and their impact on the market potential of long-haul low-cost services. In 2016, long-haul air traffic accounted for about 10 % of the total traffic which translates into about 35 % of CO_2 emissions from these flights (based on [9] and the Eurocontrol Base of Aircraft Data tool [147], also described in [148]). The introduction of a LHLCC is expected to stimulate the demand for long-haul air transport services such that a proportion of induced demand arises from LHLCC operations. The question remains whether policies such as the introduction of a carbon off-setting and reduction scheme for international aviation, CORSIA [52, 149], or other measures are capable of counteracting this additional demand to ensure a sustainable growth of global air transport.

Baseline

The baseline simulation run *B-00* of the calibrated model is set until 2035. Within this time scope, the LHLCC market entrant establishes its services within the transatlantic air transport market up to its market potential. The time scope covers short- and longer-term effects in the different scenarios, for example the introduction of the CORSIA scheme which will be carried out between 2020 and 2035 [52, 149]. The simulation results represent the baseline model run which serves as a starting point for parameter variation and scenario studies in the following two sections.

In a monopolistic market setting, the FSNC market share remains at 100 % since no competing airline type enters the market to gain market shares from the FSNC. The introduction of LHLCC transport services transfers the transatlantic market into a duopolistic structure. Figure 5.1 provides results of the baseline simulations in a duopolistic market setting for the time period between 2014 and 2035. The market share development of the LHLCC resembles a sigmoid-shaped growth and reaches a maximum value of 26.1 % within five years. This market share reflects the total market potential of the LHLCC in the transatlantic air transport market for the given baseline input parameter setting. Since the total number of passengers is split over the two different airline types in the model structure, the FSNC market share reduces by the same portion that the LHLCC market share increases. After the LHLCC has reached the maximum market share of 26.1 %, an equilibrium or market balance is established. In the subsequent scenario simulations, this equilibrium will be affected from exogenous factors to investigate the resulting changes in the LHLCC market share.

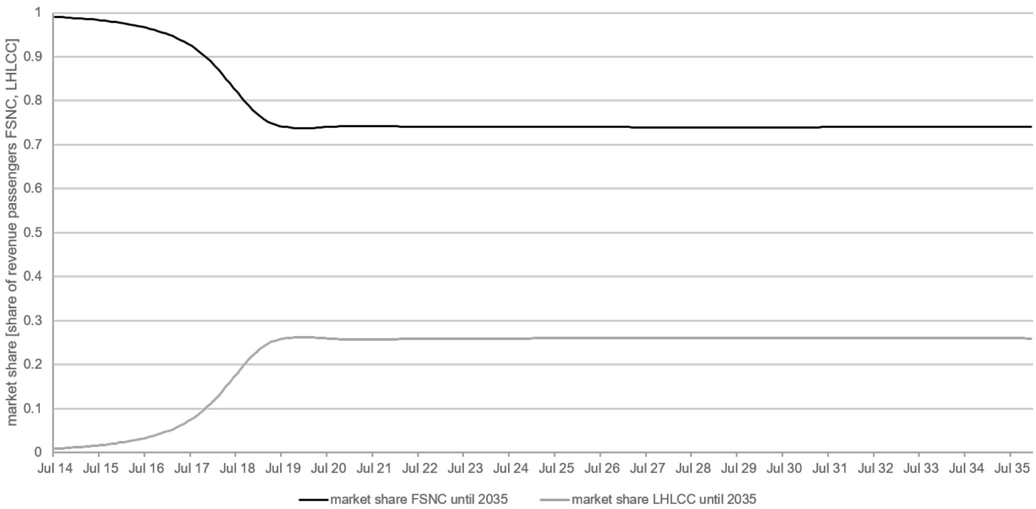

Figure 5.1: *B-00*: baseline simulation until 2035 (own depiction)

The LHLCC capacity ramp-up and demand development is depicted in figure 5.2. The capacity increases exponentially up to mid 2019 when the market share in figure 5.1 reaches its maximum and subsequent equilibrium level. At this point, a delay in the aircraft supply induces an overshoot in capacity which is reduced to a lower equilibrium level by mid 2021 with about 2 million passenger seats and about 1.72 million revenue passengers. This relation leads to a SLF approaching the target value of 0.86.

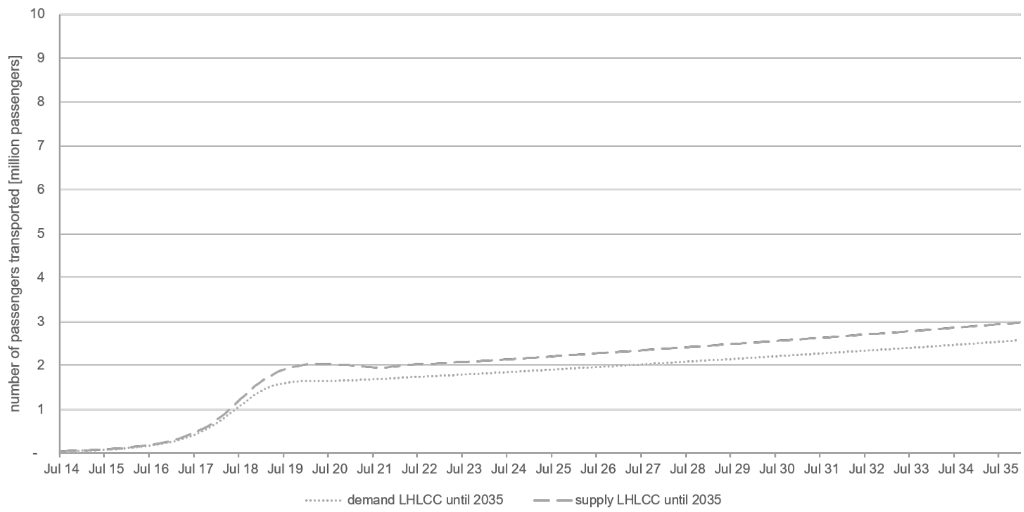

Figure 5.2: *B-00*: demand-supply-comparison LHLCC until 2035 (own depiction)

The demand and supply development of the FSNC airline type until 2035 is depicted in figure 5.3. The FSNC demand and supply follows an increasing development path in equilibrium until 2017 where the LHLCC capacity growth rates increase exponentially and passenger demand for FSNC services drops to a lower level. The supply side adapts to this demand

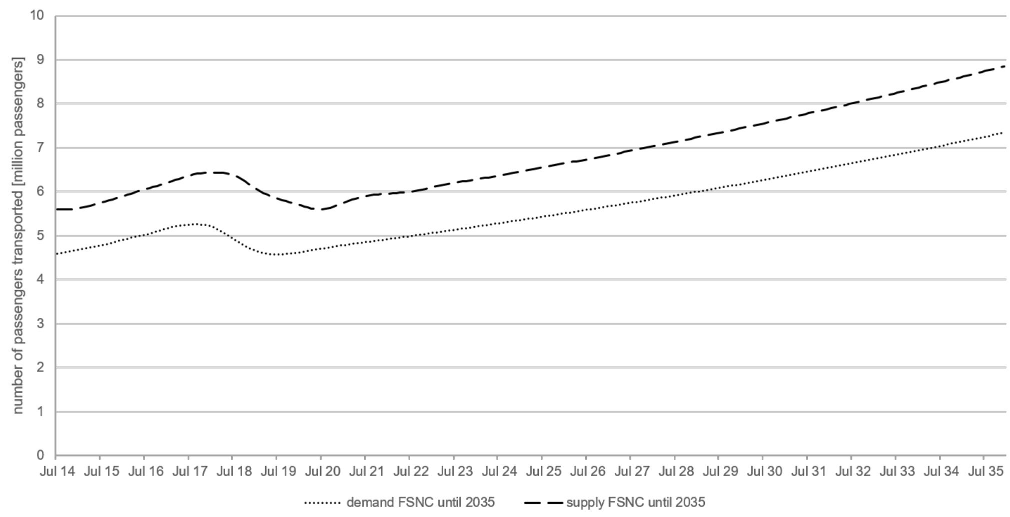

Figure 5.3: *B-00*: demand-supply-comparison FSNC until 2035 (own depiction)

drop with a time delay and transfers to a new state of equilibrium from 2021 onwards. The resulting SLF reaches a level of 0.83 which is lower compared to the according LHLCC value.

The baseline simulation *B-00* will be applied as a reference and compared to the parameter variation and scenario simulation results. The focus of this comparison will be on the market share development but in some cases, other TATM variables such as the aircraft fleet will be used for simulation results comparison and analysis.

5.2 Parameter variations

Parameter variation studies serve to investigate the sensitivity of the model to changes of the input. With this approach, high-leverage parameters of the system can be identified [116]. Since the TATM is set up with parameter values from different sources for the baseline calibration and simulation, sensitivity studies with variation of parameter values foster the understanding of the dynamics implemented in the model and the confidence in the simulation results [86].

The following parameter variation simulations complement the subsequent analysis of the model structure in chapter 4. The focus is on parameters that are integrated into the passenger choice model part as well as on competition aspects between FSNC and LHLCC such as available capacities, a competitive cost structure resulting in a cost advantage for the LHLCC airline type, and the analysis of the LHLCC cost coverage factor.

- variations of passenger preferences (*BPAX-01 - BPAX-04*)
- variations of the long-haul low-cost operating cost advantage (*BCOST-01 - BCOST-02*)
- variations of the LHLCC cost coverage factor (*BCOST-03*)

- variations of aircraft availability (production and delivery durations) (*BAC-01 - BAC-02*)

This section will introduce the variation of model parameters in the baseline simulation model run. The parameter confirmation test refers to the structural validity of a model in terms of both aspects, structurally and numerically [97]. The validation and model testing in the previous chapter 4 is extended with a set of parameter variation simulations of the baseline simulation in this chapter. The parameter variation simulations complement the analysis of the model behaviour.

5.2.1 Variations of passenger preferences

The passenger choice module is based on a parameter setting of business and leisure passenger preferences for low-cost or full-service network services in traditional short-haul markets [130] due to a lack of available equivalent data from preference studies in specific long-haul markets. On long-haul routes, price-sensitivity is expected to become less important due to the longer flight distances despite the fact that especially VFR passengers remain price sensitive and become important customer groups for LHLCCs [13, 19, 31, 33, 40]. To address this issue and to further investigate the sensitivity of the TATM to these passenger choice parameters, the dimensionless preference values of leisure passengers for the ticket price and the flight frequency are varied in a "less price focus" (*BPAX-01*) and a "more price focus" (*BPAX-02*) simulation as well as in a "less frequency focus" (*BPAX-03*) and a "more frequency focus" (*BPAX-04*) simulation and compared to the baseline setting from [130] (see also table 5.1). Leisure passengers represent the priority customer group of the LHLCC airline type [37] which is why the preference values of this customer group are varied to investigate the sensitivity of the LHLCC market share to changing leisure passenger preferences. The availability of a FFP is implemented in the TATM as a binary variable which is set to 1 for the FSNC and to 0 for the LHLCC by default. Hence, the LHLCC is implemented with characteristic low-cost features and focusses on operating parameters, especially during the market entry phase. The literature review in section 2.2.3 did not reveal a FFP to be a key feature for new market entrants to gain and maintain competitive advantage in long-haul markets. In general, passenger surveys indicate that FFPs become less important [2]. Such reward programs usually make sense when an airline has already build up a certain customer base. The generic LHLCC airline type in the model needs to focus on developing such a customer base in the first place before offering reward programs such as a FFP. The maximum ticket price is set to the maximum LHLCC ticket price of 5,000 USD offered in 2014 [63]. This ticket price equals the maximum ticket price of the LHLCCs competing with the FSNCs in the transatlantic air transport market.

The parameter variations are simulated between 2014 and 2035 to cover the ramp-up phase of the LHLCC market share. Table 5.1 presents the parameter variation settings for the different simulations. The baseline simulation reveals a market share potential of 26.1 %, reached after approximately five years. The market share of the LHLCC airline type reaches an equilibrium at this stage in the baseline simulation (see 5.1). Besides the baseline simulation, based on

Table 5.1: Overview of parameter variation: passenger choice analysis (own depiction)

Parameter [dmnl]	**Baseline Value**	**"less price focus" Parameter Setting**	**"more price focus" Parameter Setting**	**"less frequency focus" Parameter Setting**	**"more frequency focus" Parameter Setting**
Simulation	*B-00*	*BPAX-01*	*BPAX-02*	*BPAX-03*	*BPAX-04*
$preferenceTicketPrice_{Business}$	2.1	2.1	2.1	2.1	2.1
$preferenceTicketPrice_{Leisure}$	3.9	3.2	5.0	3.9	3.9
$prefrenceFrequency_{Business}$	4.5	4.5	4.5	4.5	4.5
$preferenceFrequency_{Leisure}$	3.2	3.2	3.2	2.6	3.8
$preferenceFFP_{Business}$	2.0	2.0	2.0	2.0	2.0
$preferenceFFP_{Leisure}$	1.5	1.5	1.5	1.5	1.5

[130], two different ticket price preference parameter variation simulations are defined, a "less price focus" parameter setting (*BPAX-01*) and a "more price focus" parameter setting (*BPAX-02*). The "less" and the "more" parameter variations, depicted in the following two figures 5.4 and 5.5, are simulated for the same time period as the baseline simulation run.

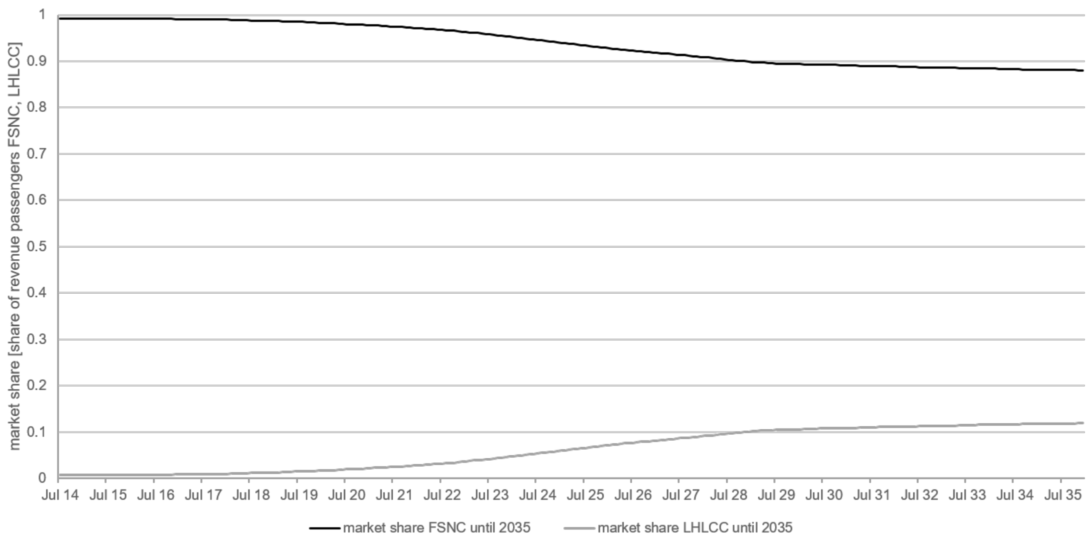

Figure 5.4: *BPAX-01*: "less price focus" simulation and its impact on LHLCC market share (own depiction)

In the more realistic "less price focus" *BPAX-01* parameter setting, potential leisure passengers are less price sensitive. The preference weight setting for the FSNC is kept constant during the parameter variations. In addition, the preference weights of business and leisure passengers converge. As a result, the market share potential of the LHLCC airline type decreases to 12 % and the market share ramp-up extends towards a time period of about

15 years (see figure 5.4). This behaviour is more realistic for long-haul markets since price-elasticities of both business and leisure passengers are observed to be reduced on long-haul international trips compared to short-haul trips [12, 150].

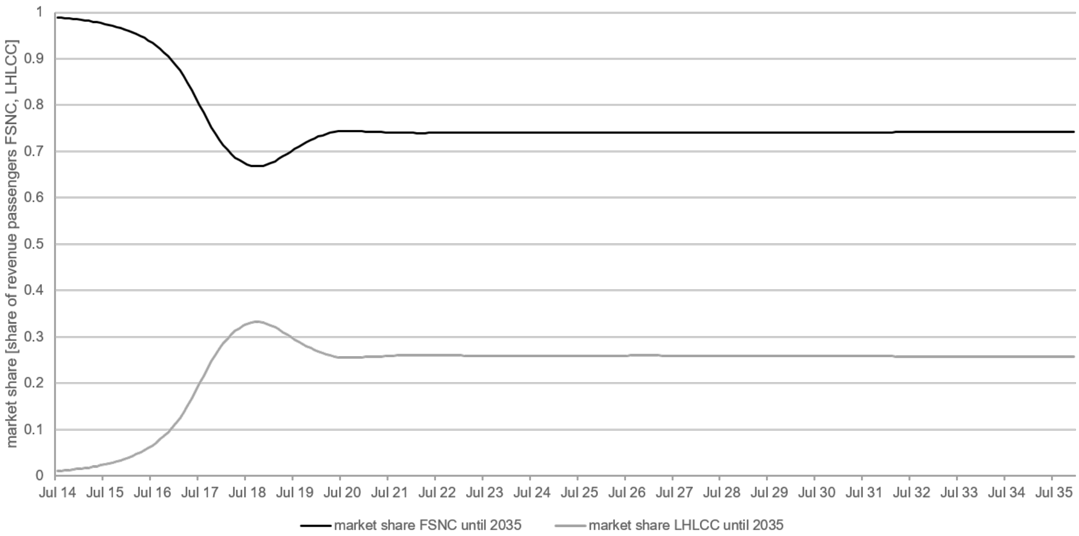

Figure 5.5: *BPAX-02*: "more price focus" simulation and its impact on LHLCC market share (own depiction)

The second parameter variation "more price focus" *BPAX-02* replicates a behaviour where leisure passengers become more price sensitive. In this simulation, the differences in preference weights for ticket price and frequency diverge between the business and the leisure passenger types compared to the baseline parameter setting. It was selected as a theoretical setting to investigate the effect of an increase in price-sensitivity. However, this behaviour is not expected to appear in long-haul markets in the upcoming years. The market share potential of the LHLCC airline type from this simulation slightly increases as expected and reaches a level of 26 % after an overshoot to up to 33 % in August 2018. This stems from a steep increase in capacity between 2014 and 2018 that exceeds the passenger demand for LHLCC services according to the preference setting in this simulation. This capacity increase induces an increase of the ticket price as a divergent effect.

The following two figures 5.6 and 5.7 provide an overview of the variation of passengers preferences on flight frequency and the resulting market shares. The maximum flight frequency per aircraft is defined as 60 flights per month which is equivalent to one return flight per day per aircraft. The "less frequency focus" simulation *BPAX-03* reduces the resulting overall leisure passenger preference. This leads to a maximum market share of 19.7 %. The ramp-up phase of the market share is less steep than in the baseline simulation and the equilibrium market share level is reached at a later point in time between 2022 and 2035. Compared to the "less price focus" simulation *BPAX-01*, the "less frequency focus" simulation *BPAX-03* results in a higher market share level. This observation is based on the difference in absolute change between the specific simulation parameter setting and the according baseline parameter setting. Whereas the ticket price preference is reduced by 0.7 in simulation *BPAX-01*, the frequency preference is reduced by 0.6 in simulation *BPAX-03*. This observation will be further analysed in the following parameter sensitivity studies (see figures 5.8 - 5.11).

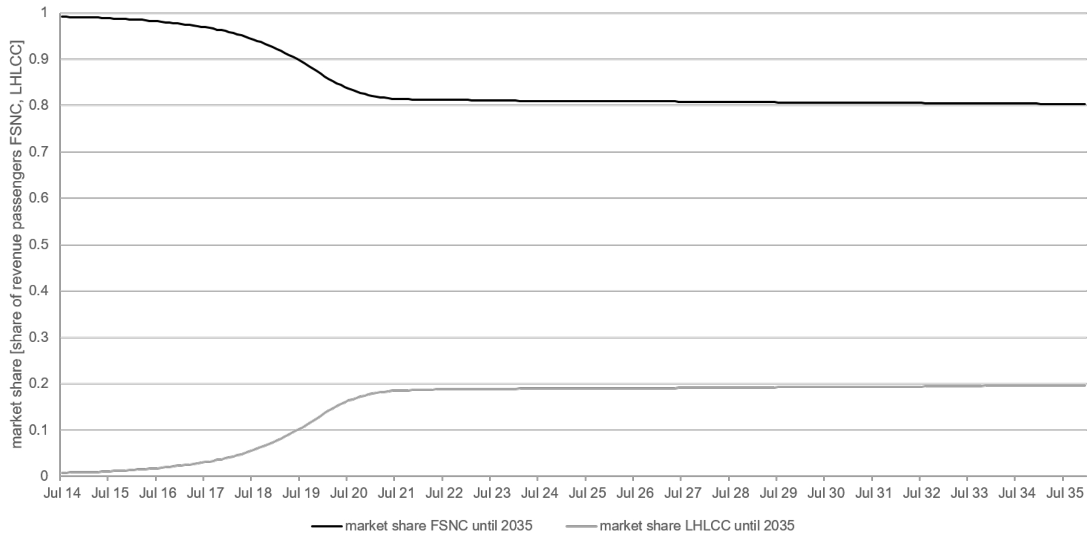

Figure 5.6: *BPAX-03*: "less frequency focus" simulation and its impact on LHLCC market share (own depiction)

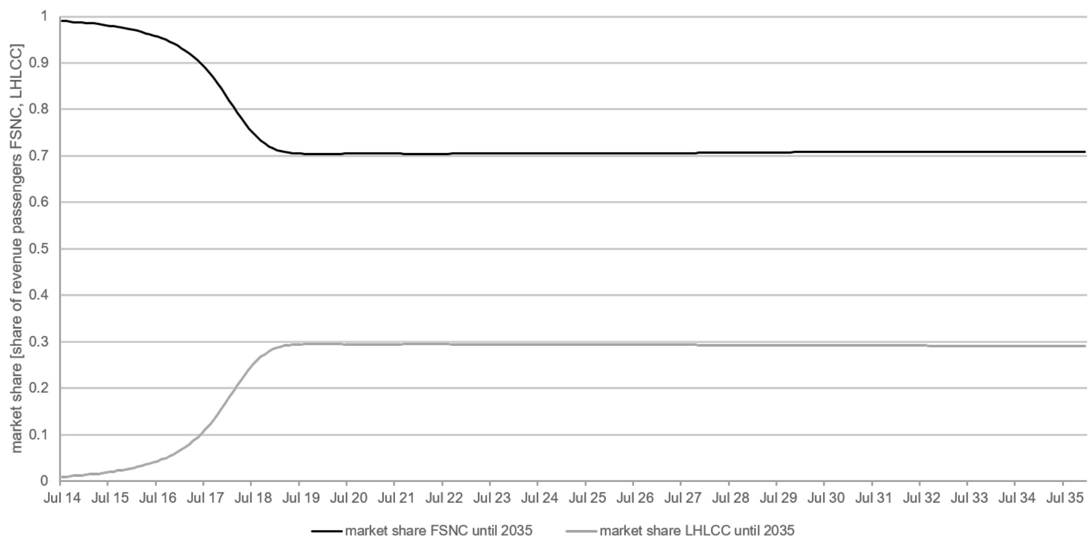

Figure 5.7: *BPAX-04*: "more frequency focus" simulation and its impact on LHLCC market share (own depiction)

In the "more frequency focus" simulation *BPAX-04*, the LHLCC reaches a market share of 29.6 % already in 2019. In contrast to the "more price focus" simulation *BPAX-02*, where the market share overshoots and decreases to a stable market share level of 26 %, the market share ramp-up in simulation *BPAX-04* exhibits a smooth transition from the growth phase between 2014 and 2019 to an equilibrium phase.

To gain a better understanding of the LHLCC market share behaviour within a range of varying passenger preferences, sensitivity studies are performed where the effects of changes in the ticket price and frequency preferences of both passenger groups, leisure as well as business, on the LHLCC market share are investigated. The parameter variation is characterised by a lower boundary value, indicated in blue in the following figures, and an upper boundary value, highlighted in red. Both values are selected iteratively by testing extreme parameter settings in the TATM baseline configuration within a feasible range for the passenger preferences analysed. The x-axis of the following figures is based on the time steps during simulation. One time step is defined as one month. The sensitivity study figures provide an x-axis with the respective time steps between July 2014 (equals time step 0) and December 2035 (equals time step 257).

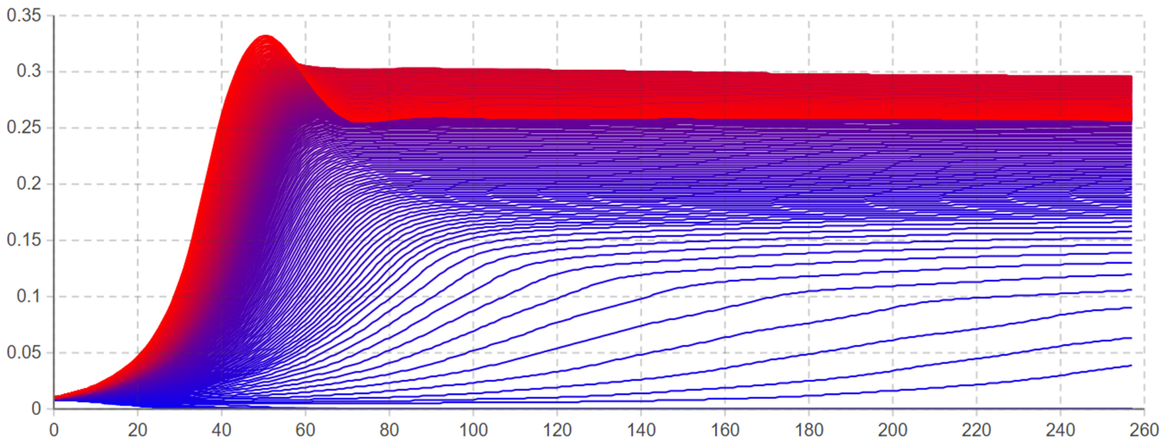

Figure 5.8: Sensitivity analysis: $preferenceTicketPrice_{Leisure}$ (3.0 - 5.0 // step: 0.01) (own depiction)

Figure 5.8 depicts the sensitivity analysis results for the $preferenceTicketPrice_{Leisure}$ parameter variation between 3.0 (initial blue line) and 5.0 (final red line at a LHLCC market share of 26 %) in 0.01 steps. The LHLCC market share potential increases with an increasing ticket price preference of the leisure passenger group since a larger share of potential passengers become more price sensitive and, hence, choose LHLCC services in the transatlantic air transport market.

Figure 5.9 depicts the sensitivity analysis results for the $preferenceFrequency_{Leisure}$ parameter variation between 1.0 (initial blue line) and 4.3 (final red line at a LHLCC market share of 24 %) in 0.01 steps. Both variations in figures 5.8 and 5.9 exhibit a similar maximum market share of 30 % to 32 % for a specific parameter setting. As soon as the varied parameter values increase further, the market share decreases. Hence, a local maximum can be identified for a $preferenceTicketPrice_{Leisure}$ value of 4.65 and a $preferenceFrequency_{Leisure}$ value of 4.12 respectively.

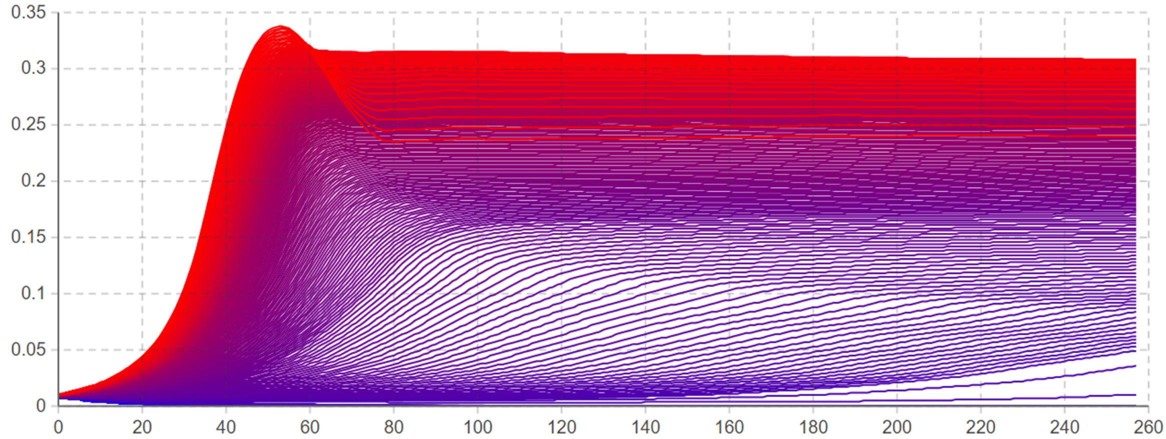

Figure 5.9: Sensitivity analysis: $preferenceFrequency_{Leisure}$ (1.0 - 4.3 // step: 0.01) (own depiction)

Figure 5.10 depicts the sensitivity analysis results for the $preferenceTicketPrice_{Business}$ parameter variation between 1.0 (initial blue line) and 4.0 (final red line) and figure 5.11 provides the sensitivity analysis results for the $preferenceFrequency_{Business}$ parameter variation between 0.0 (initial blue line) and 5.8 (final red line), both simulated with steps of 0.01. The LHLCC market share reacts less sensitive to changes in preferences of the business passenger group. Even at a wider range of a $preferenceTicketPrice_{Business}$ between 1.0 and 4.0 compared to the selected range for the $preferenceTicketPrice_{Leisure}$ between 3.0 and 5.0, the resulting LHLCC market share varies by 8.5 percentage points between a maximum value of around 20.3 % and 28.8 %. In case of frequency preference, the $preferenceFrequency_{Business}$ is varied between 0.0 and 5.8. The resulting LHLCC market share ranges between 17 % and 29 %.

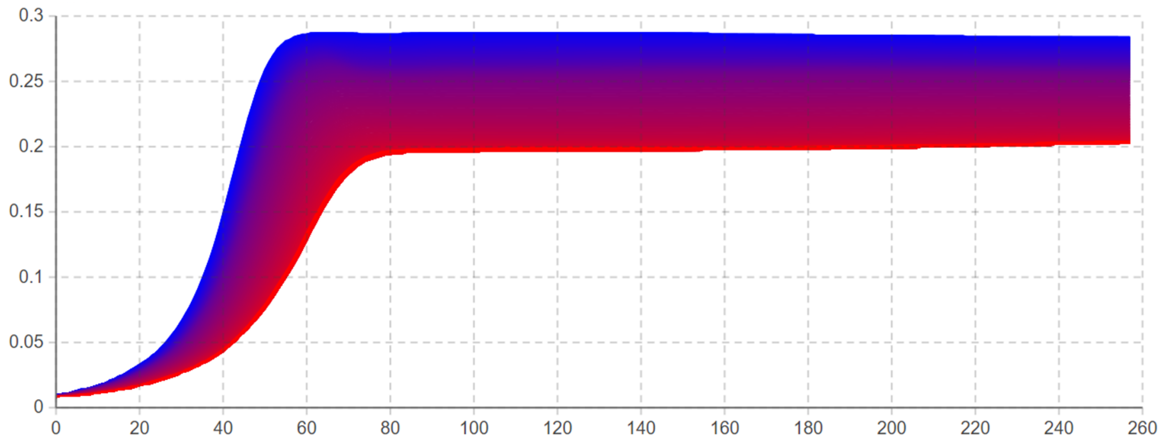

Figure 5.10: Sensitivity analysis: $preferenceTicketPrice_{Business}$ (1.0 - 4.0 // step: 0.01) (own depiction)

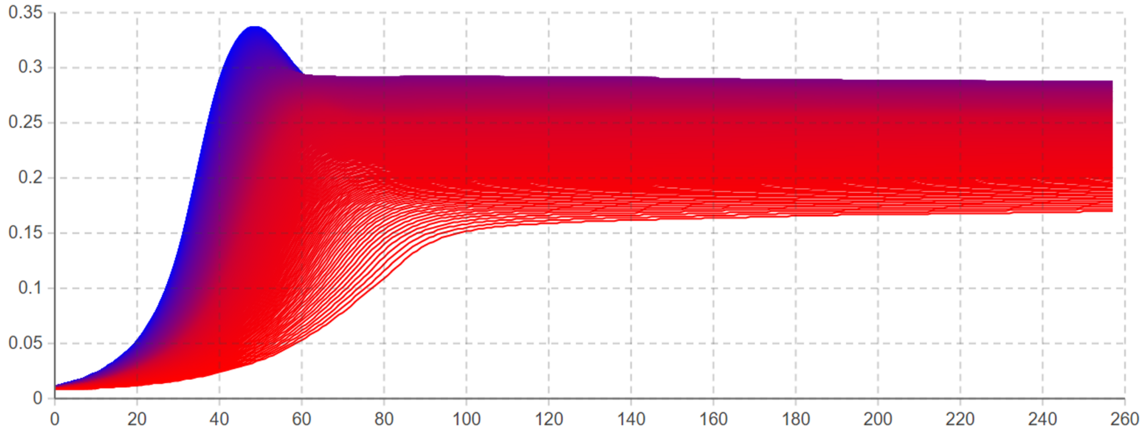

Figure 5.11: Sensitivity analysis: $preferenceFrequency_{Business}$ (0.0 - 5.8 // step: 0.01) (own depiction)

The parameter variation and sensitivity analysis is based on the initial preference parameter setting as applied from [49] as adapted from [130]. To better understand passenger behaviour and preferences in the long-haul market, an updated passenger survey is required. This aspect will be discussed in more detail in the section 6.2 on future work perspectives.

5.2.2 Variations of the long-haul low-cost operating cost advantage

The literature review on the transferability of low-cost services to long-haul air transport markets revealed that LHLCC create a lower average operating cost advantage over their competitors, compared to short-haul markets (see table 2.1) [51]. To investigate the sensitivity of the system to a changing operating cost structure, the $unitTOC_j$ for both airline types is replaced with a fixed parameter in the TATM structure. The unit cost parameters for both airline types are varied between 4.7 % and 30 %. The representative aircraft types, selected for the two different airline types, remain the same in this parameter variation study. The baseline simulation objects a cost advantage of 4.7 %, when the FSNC operate an Airbus A330-300 as reference aircraft and the LHLCC select the Boeing B787-800 as reference aircraft. Table 5.2 summarises the parameter settings for the TOC variation studies.

Table 5.2: Overview of parameter variation: operating cost advantage (own depiction)

Parameter [USD/seat-km]	**Baseline Value (4.7 % LHLCC Cost Advantage)**	**20 % LHLCC Cost Advantage**	**30 % LHLCC Cost Advantage**
Simulation	*B-00*	*BCOST-01*	*BCOST-02*
$unitTOC_{FSNC}$	0.11407	0.11407	0.11407
$unitTOC_{LHLCC}$	0.10872	0.091256	0.079849

Figures 5.12, 5.13 and 5.14 below show the results for the parameter variation of unit cost for both airline types and their impact on the LHLCC market share development.

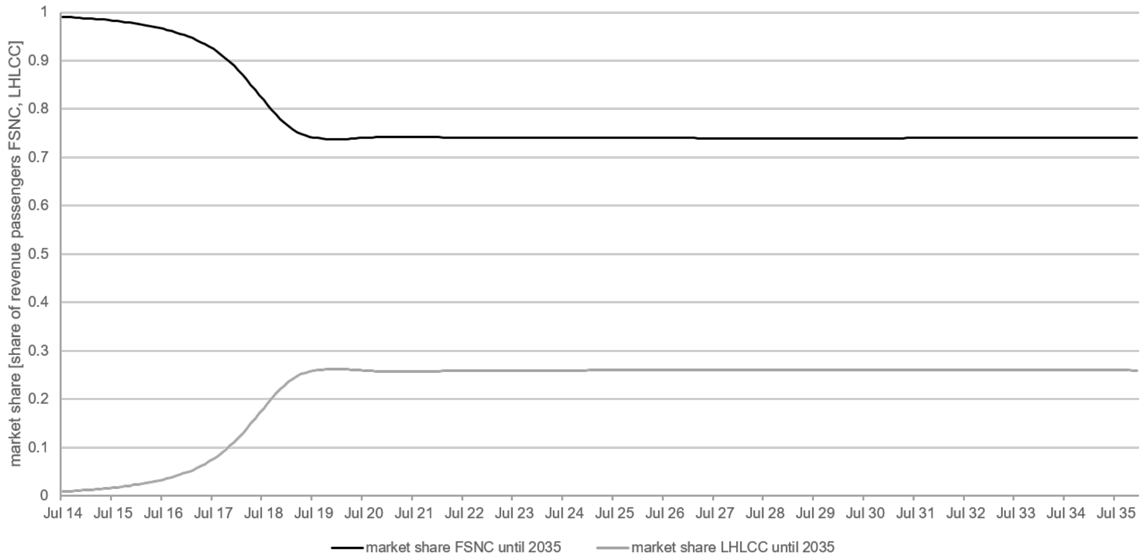

Figure 5.12: *B-00*: baseline simulation until 2035 (own depiction)

The baseline simulation, as already introduced in section 5.1, results in an LHLCC market share potential of 26.1 %. An LHLCC cost advantage of 20 %, as depicted in figure 5.13, results in an increase of 2.3 percentage points to a resulting market share of 28.4 %. An operating cost advantage of 30 % leads to an increase of 3.9 percentage points in market share to a value of 30 % (see figure 5.14).

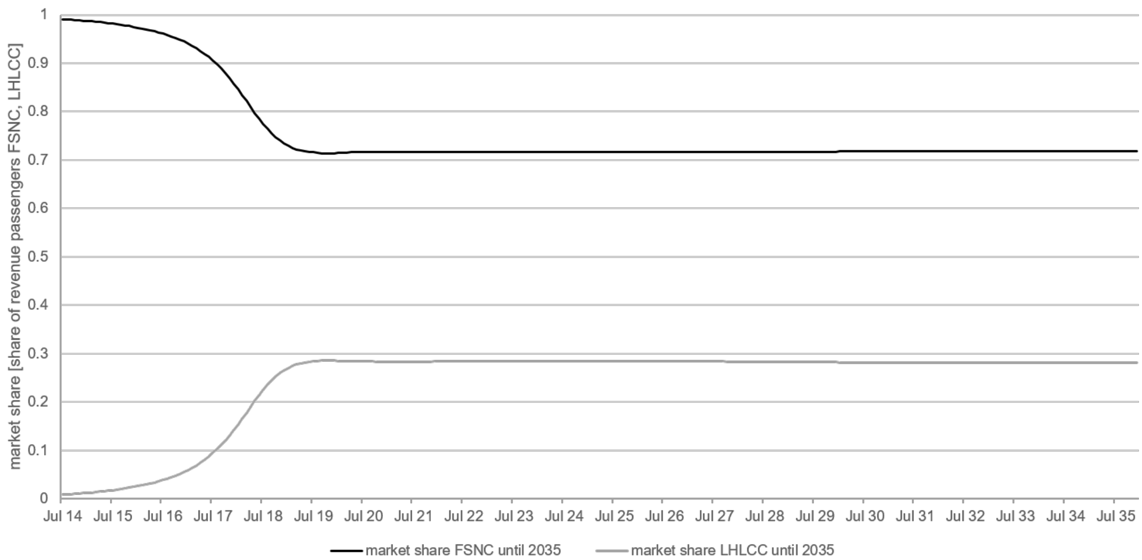

Figure 5.13: *BCOST-01*: 20 % LHLCC cost advantage and its impact on LHLCC market share (own depiction)

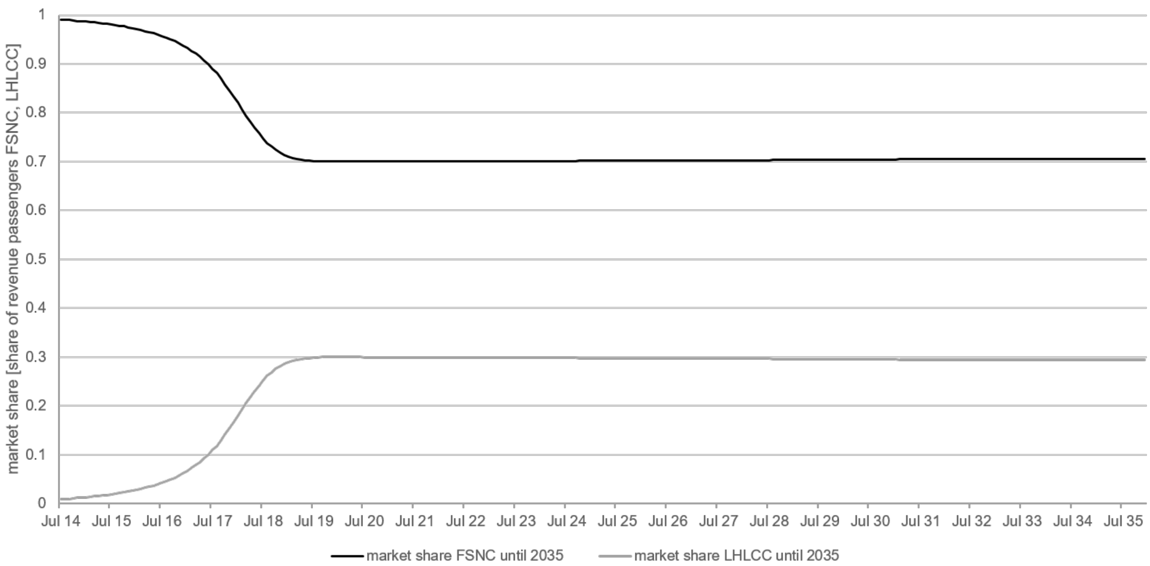

Figure 5.14: *BCOST-02*: 30 % LHLCC cost advantage and its impact on LHLCC market share (own depiction)

The unit cost variations are simulated for the baseline parameter setting of the passenger choice model part with the figures from [130]. The differences in cost advantage that vary in this parameter study between 4.7 % and 30 % span a wide range of potential competitive advantage for the LHLCC. In contrast, the resulting differences in market share differ by only 3.9 percentage points between the baseline simulation in figure 5.12 and the 30 % cost advantage simulation in figure 5.14. Measures applied by LCCs to increase the operating cost advantage were described in detail in chapter 2. It was also highlighted that the transferability of these cost advantages from short-haul to long-haul air transport markets is limited and depends on the market segment that an LHLCC chooses to operate in besides other factors [13, 19, 31, 33, 40]. As indicated in the literature review in section 2.2.3, previous research reveals that the potential cost advantage is lower for the LCC on long-haul routes compared to the short-haul market [13, 18, 78] and that it is linked to specific market conditions [51]. LHLCC operations require dense markets to enter a long-haul market [13, 37, 76]. Hence, a cost advantage for the LHLCC of 20 % to 30 % is an ambitious target and expected only to be achievable on a share of transatlantic routes with a strong OD leisure demand [17].

Figures 5.15 and 5.16 depict sensitivity analysis studies where the unit cost of the LHLCC airline type varies between 0.057035 USD per seat-kilometre (50 % cost advantage) and the baseline unit cost of 0.10872 USD per seat-kilometre (4.7 % cost advantage) respectively 0.11407 USD per seat-kilometre (no cost advantage) when both airline types would have the same operating cost. The results for the sensitivity analysis studies reveal a moderate sensitivity of the LHLCC market share to changes in the operating cost. Even at an operating cost level of -50 %, the LHLCC market share potential is below 33 %.

If we expect lower overall differences between the LHLCC and the FSNC preferences of business and leisure passengers on long-haul routes, the achievable LHLCC market share is

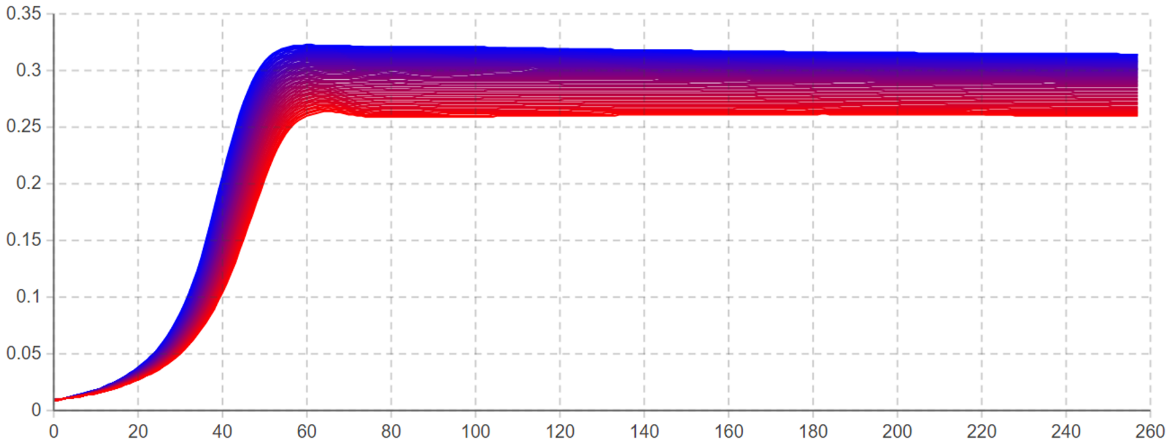

Figure 5.15: Sensitivity analysis: $unitTOC_{LHLCC}$ (0.057 - 0.109 // step: 0.001) (own depiction)

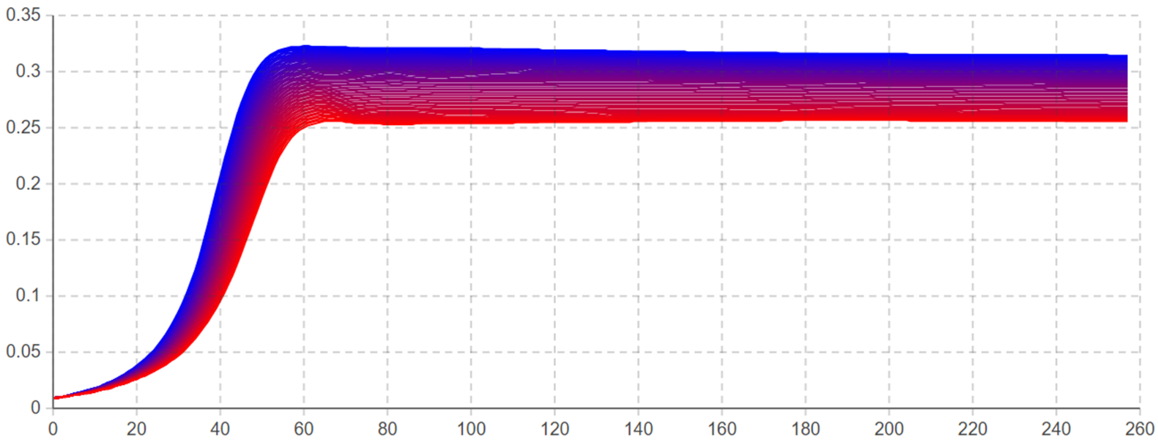

Figure 5.16: Sensitivity analysis: $unitTOC_{LHLCC}$ (0.057 - 0.114 // step: 0.001) (own depiction)

expected to be lower. In general, this can be addressed with a combination of passenger choice parameter values and unit cost advantage of the LHLCC. However, since the passenger preferences are based on short-haul market related data, combined parameter variation studies were not conducted in this thesis.

5.2.3 Variations of the long-haul low-cost cost recovery factor

During the model development, a cost recovery factor is introduced (see section 3.5.3, equations 3.20 and 3.23). This parameter was set to 0.7 for the LHLCC for the model calibration and baseline simulation. The ticket price development over time is based on an initial ticket price from the Sabre database [63]. In turn, the operating cost for the two representative aircraft types, A330-300 for the FSNC and B787-800 for the LHLCC, result from calculations with the smart reference costing model [125]. Hence, the two data sources are combined. Both airline types need to operate economically viable to sustain their position in the market. This is achieved by a minimum break even revenue to cover the operating cost incurred [1, 12]. A reason for adapting the cost recovery factor during the calibration process of the model can be a LHLCC market entrant's strategy to not cover all costs during the ramp-up of services in a new market to aggressively compete with the FSNC market incumbent expecting an increase in revenues over time to cover the initial cost surplus. This is especially the case when a FSNC introduces a low-cost subsidiary to add low-cost services to its existing portfolio to create a hybrid service offer [136] in the respective long-haul market, e. g. Norwegian with Norwegian Air Shuttle or Air Asia with Air Asia X [15]. However, cost coverage needs to be achieved at a certain point in time if the airline objects to attain sustainable market shares. To address this aspect, a parameter variation of the cost recovery factor is conducted to simulate the LHLCC market share behaviour in case of full cost coverage ($costRecoveryFactor_{LHLCC} = 1$). The following figure 5.17 presents the result for this simulation.

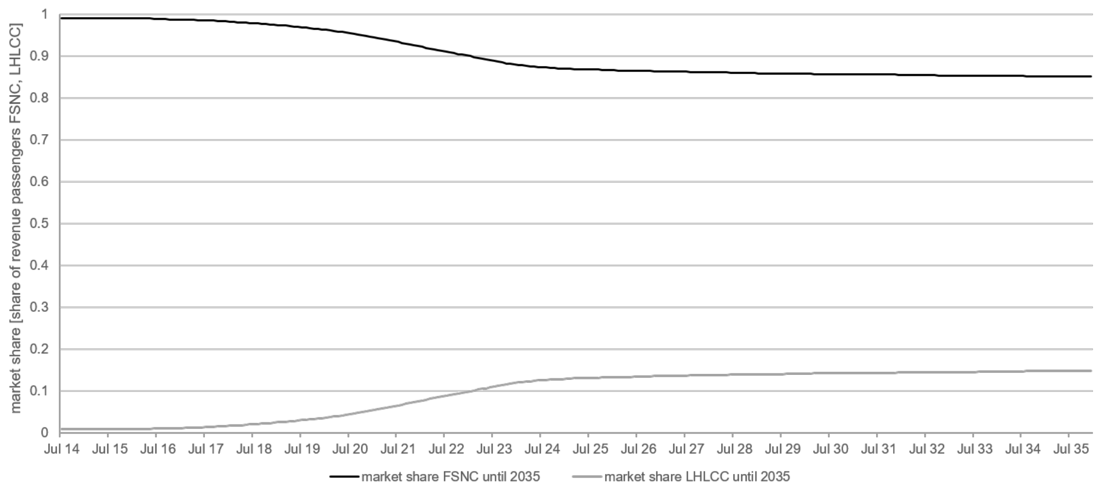

Figure 5.17: *BCOST-03*: LHLCC $costRecoveryFactor_{LHLCC}$ of 1.0 and its impact on LHLCC market share (own depiction)

The simulation result reveals a LHLCC market share potential of 16.6 % in the long term and a longer market share ramp-up duration of over 10 years. The time scope of the historical data available between July 2014 and December 2017 only covers a short period in the growing long-haul low-cost sector. Due to the fact that the Sabre database [63] does not provide the according cost structure to the revenues achieved by the two airline types in this period, the actual cost coverage factor development of the LHLCC airline type over time towards a full cost coverage cannot be investigated in more detail from the data source. The simulation results with full LHLCC cost coverage from entry into the market dampen the market share potential expectations. Since the previous parameter variation on the long-haul low-cost operating cost advantage does not consider full cost recovery, the actual operating cost advantage required for the LHLCC service to achieve market shares beyond 25 % in this parameter variation simulation is comparable to low-cost cost advantages of 50 % or more in short-haul markets [13] which seems unlikely to be achievable in long-haul markets.

5.2.4 Variations of aircraft availability

In this section, variations of the availability of aircraft capacity as a result of varying adjustment times in the production process and their impact on the market share development are investigated. The variation in adjustment times, apart from the baseline parameter setting, is defined to resemble accelerated and decelerated production times and according changes in aircraft capacity availabilities. The following table 5.3 highlights the different parameter settings. The TATM differentiates between purchased and leased aircraft. Since this parameter variation focusses on the aircraft availability from the purchase option, the table only includes the two adjustment time parameters for aircraft purchase. The adjustment times for leased aircraft are kept constant at 12 months for this parameter variation study.

Table 5.3: Overview of parameter variation: aircraft production times (own depiction)

Parameter [months]	**Baseline Production Times**	**Accelerated Production Times**	**Decelerated Production Times**
Simulation	*B-00*	*BAC-01*	*BAC-02*
$aircraftProductionTime_{FSNC,purchase}$	24	12	48
$aircraftProductionTime_{LHLCC,purchase}$	24	12	48

Figure 5.18 provides a fleet development comparison of the baseline *B-00* with the two *BAC-01* and *BAC-02* for both airline types.

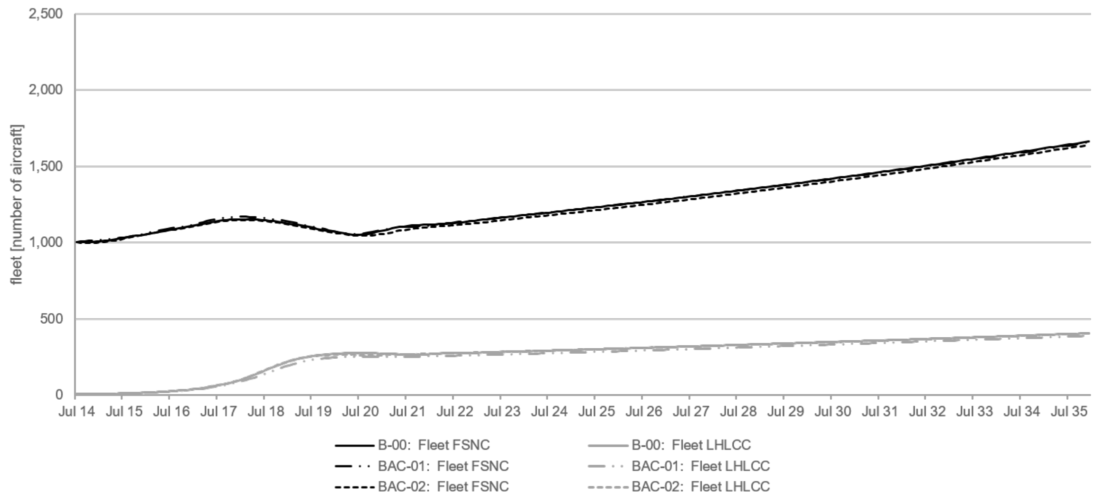

Figure 5.18: *B-00*, *BAC-01*, *BAC-02*: differences in fleet development resulting from aircraft availability sensitivity (own depiction)

Accelerated production times are depicted with a dashed and dotted line and decelerated production times are represented with a dashed line. The $aircraftProductionTime_{j,purchase}$ parameters are varied for both airline types. As a result, not only the LHLCC can profit from accelerated production times in simulation *BAC-01*. As depicted in figure 5.18, the overall effect of varying production times is low on the fleet development of both airline types. The reason for this is, that changes in the aircraft purchase rates can be compensated by changes in the according aircraft leasing rates, especially in the decelerated production times simulation *BAC-02*.

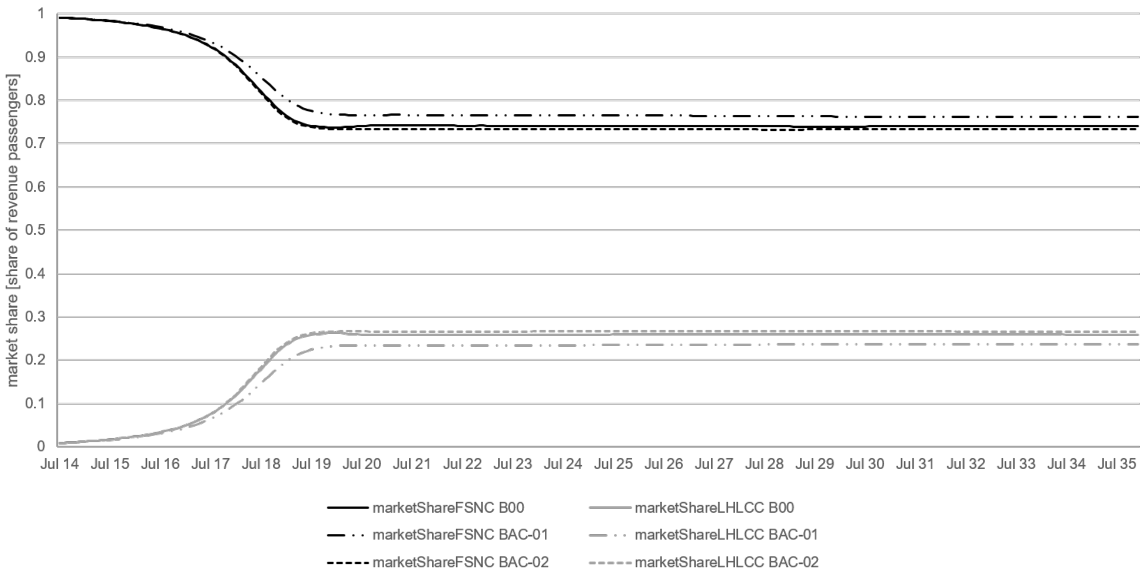

Figure 5.19: *B-00*, *BAC-01*, *BAC-02*: market share comparison (own depiction)

The resulting market shares are represented in figure 5.19. In the accelerated production times simulation *BAC-01*, the overall fleet size of the LHLCC airline type is minimally below the baseline aircraft fleet size. This results in a lower market share of 23.8 % in simulation *BAC-01*. The adjustment times for the desired capacity $adjTimeFleetCapacity_{j,k}$ are not changed in this parameter variation which is why the airline decision on the desired capacity either reacts slower to the accelerated production times in case of simulation *BAC-01* or it reacts faster in case of the decelerated production times in simulation *BAC-02*. Changes in the purchase and lease rates are depicted in the following figures 5.20 for the baseline simulation *B-00*, 5.21 for the accelerating simulation *BAC-01*, and 5.22 for the decelerating simulation *BAC-02*. The $aircraftDeliveryRate_{j,k}$ is represented in the TATM as a flow that decreases the number of aircraft ordered stock and increases the fleet stock (see equation 3.44).

The aircraft purchase rates are depicted with solid lines, black for the FSNC and grey for the LHLCC, and the aircraft lease rates are depicted with dotted lines in the following three figures 5.20, 5.21, and 5.22. In the baseline simulation *B-00*, the lease rates of both the FSNC and the LHLCC airline type are higher during the ramp-up of LHLCC services and the adaptation towards the balanced market share levels until the period between 2019 and 2021. The FSNC delivery rates for purchased aircraft steadily increase from 2024 onwards whereas the according lease delivery rates remain at a constant level of 5.4 aircraft per month. For the LHLCC fleet, the ramp-up of aircraft capacity between 2014 and 2021 is mainly driven

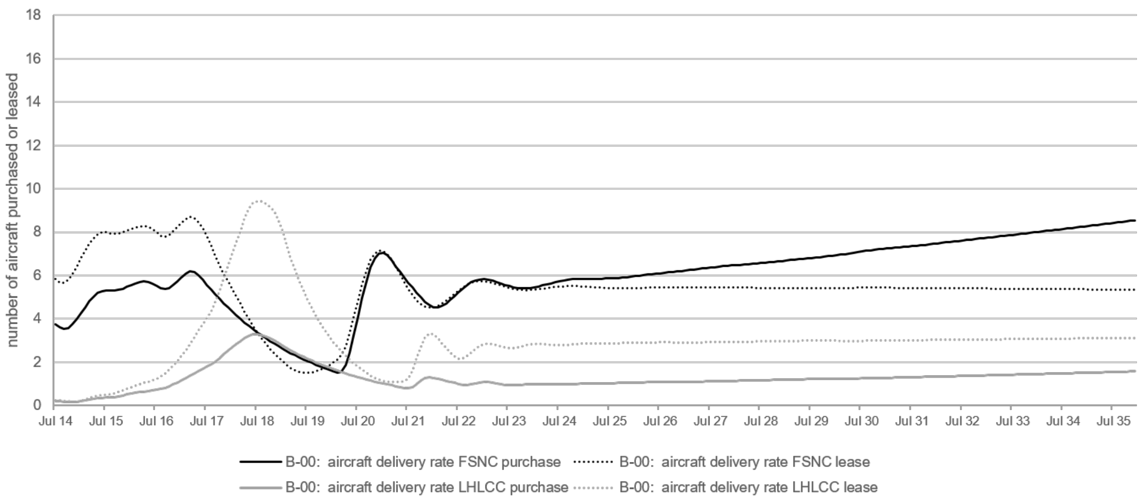

Figure 5.20: *B-00* purchase and lease delivery rates per mont (own depiction)

by the lease option. Monthly lease rates reach its maximum between 2018 and 2019 (9 aircraft per month). After market introduction between 2025 and 2035, the lease delivery rates (3 aircraft per month) are larger compared to the purchase delivery rates (1-1.6 aircraft per month) and remain at this higher level whereas the purchase delivery rates slowly increase until 2035.

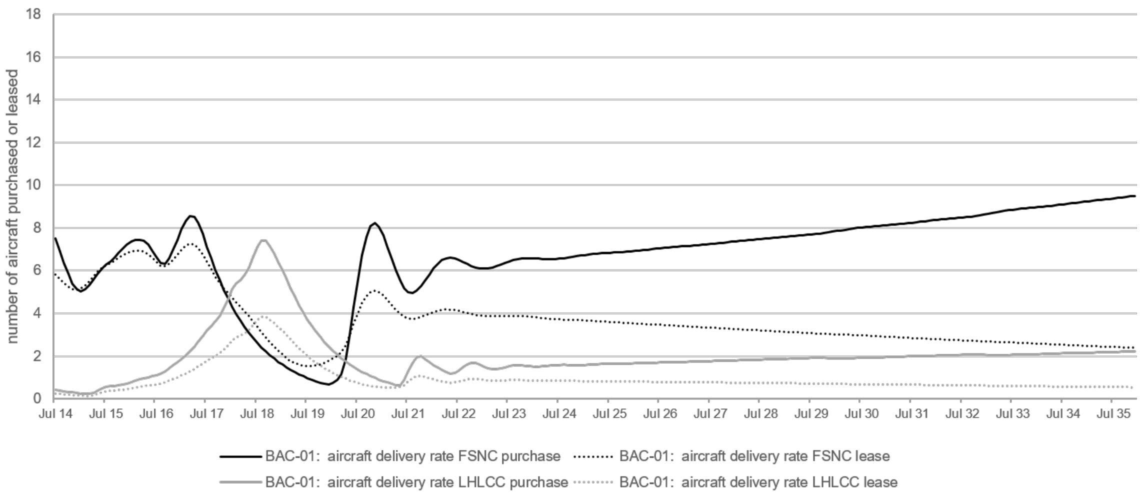

Figure 5.21: *BAC-01* purchase and lease delivery rates per month (own depiction)

In simulation *BAC-01*, the purchase aircraft deliveries increase due to the accelerated production times and become the major driver for the fleet development for both airline types. The purchase delivery rates increase after the ramp-up of the LHLCC services from 2022 onwards whereas the lease delivery rates decrease. In the baseline simulation, the lease delivery rates remain constant. In simulation *BAC-02*, the lease delivery rates strongly increase and are constantly above the according purchase rates due to the increased production times of purchased aircraft. The purchase delivery rate remains on a low level between 4 and 5 aircraft per month for the FSNC and below 1 aircraft per month for the LHLCC airline type after market introduction between 2025 and 2035. The according lease rates, in turn, strongly increase after the LHLCC ramp-up phase from 8 to 13 aircraft for the FSNC airline type and from 5 to almost 7 aircraft per month for the LHLCC airline type by 2035.

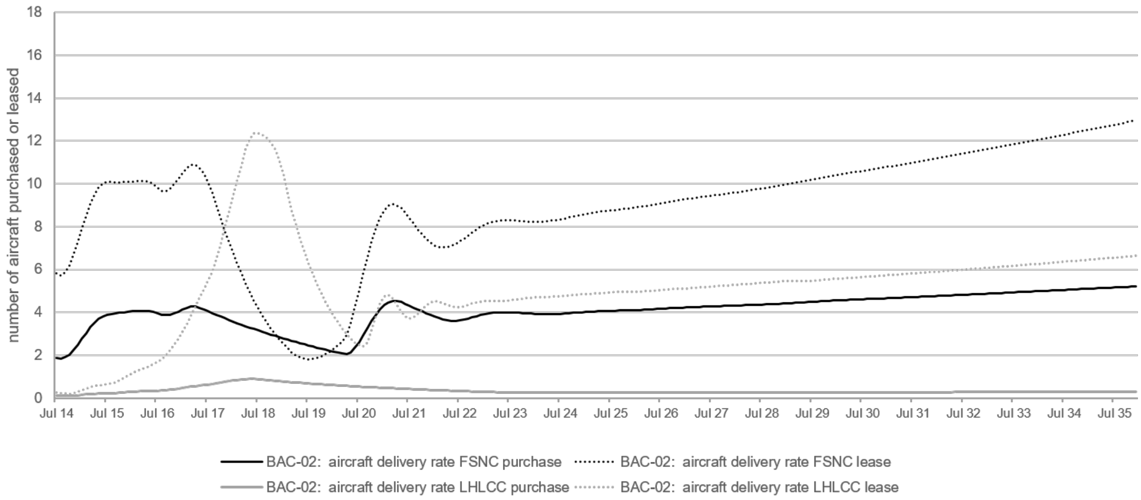

Figure 5.22: *BAC-02*: purchase and lease delivery rates per month (own depiction)

The s-shaped growth of the LHLCC market share is reflected in the exponentially growing LHLCC purchase and lease delivery rates per month between July 2014 and July 2018 in figure 5.20. Subsequently, both rates decrease and adapt to the medium term market equilibrium in the baseline simulation where the LHLCC achieves a market share of 26.1 %. Due to the delay between changes in demand for LHLCC flight services and according supply of available fleet capacity, i. e. $adjTimeFleetCapacity_{j,k}$ required for the purchase or lease decision and $aircraftProductionTime_{j,k}$ representing the duration to process the order, build the aircraft and deliver it to the customer [48], an overshoot occurs, the monthly purchase and lease rates oscillate and adjust to the new demand-supply level. This behaviour can be compared to one of the fundamental modes of SD models, the s-shaped growth with overshoot [86]. The overshoot is more pronounced for the monthly FSNC purchase and lease rates due to the larger number of total aircraft in the fleet. The overshoot and oscillation of the monthly aircraft purchase rates (black solid line) increase with the acceleration of production times of aircraft for purchase in simulation *BAC-01*. This results from the constant $adjTimeFleetCapacity_{j,k}$ in the system. Airline decision on capacity adjustment consequently becomes slower due to the faster availability of aircraft for purchase. This effect reverses when aircraft purchase rates decelerate in simulation *BAC-02*.

Airline fleet planning requires a level of flexibility to adapt to potential changes, most of the time delays, in aircraft deliveries [128]. Hence, the TATM comprises the option to lease aircraft besides purchase during the capacity development process. The initial lease share in the FSNC fleet is set to 40 %, according to typical lease shares of an operating airline [11]. The initial lease share in the LHLCC fleet is set to 43 %, due to the small number of 7 aircraft in the initial LHLCC fleet. The variation of monthly aircraft purchase and lease rates in this section, as depicted in the figures 5.20, 5.21, and 5.22, represent the inflow rates to the respective fleet stock. Hence, they have an impact on the fleet stock composition with purchased and leased aircraft for both airline types. In the baseline simulation *B-00*, the medium term share of purchased aircraft will increase for both airline types due to an increasing monthly aircraft purchase rate (solid lines in figure 5.20) compared to stagnating monthly aircraft lease rates. As the production times for aircraft available for purchase increase in simulation *BAC-01*, the medium term share of purchased aircraft increases even more compared to the baseline simulation *B-00* due to increasing monthly aircraft purchase rates and decreasing aircraft lease rates. In contrast, a slowdown in production times to 48 months, as simulated in *BAC-02*, for aircraft available for purchase causes an increasing rate of leased aircraft per month (see dotted lines in figure 5.22) and therefore, an increasing share of leased aircraft in the respective total fleet of both airline types. The simulation results for the aircraft availability variations underline that the flexibility mechanism of a partly purchased and partly leased aircraft fleet compensates exogenous effects of changes in the manufacturer aircraft production process.

5.3 Scenario simulations

After the parameter variations, the TATM will be applied to scenarios that comprise different exogenous developments which have an impact on the transatlantic air transport market. The exogenous development occurs at a point in time after the ramp-up phase of the LHLCC market shares. Hence, the scenario simulation focusses on the development of these market share after an exogenous impact. Potential impacts include the introduction of environmental cost to compensate for CO_2 emissions generated during flight operations and the occurrence of demand shocks in the transatlantic market. The scenarios can be considered as additional testing of the model robustness for extreme conditions [86]. In scenario 01, the $unitTOC_j$ strongly increase due to additional environmental costs. In scenario 02, the transatlantic market faces a steep drop in demand for air transport services.

Scenario 01 (*B-00-CORSIA, B-00-IPCC*) addresses the internalisation of exogenous effects from air transport on climate change and the attempts of airlines to curb these effects. The International Civil Aviation Organization (ICAO) has designed a global carbon emission scheme for international aviation activities, CORSIA [52, 149]. The carbon prices in the CORSIA scheme are derived from a study of the International Energy Agency (IEA) for the years between 2020 and 2035 [151]. In contrast to this, the Intergovernmental Panel on Climate Change (IPCC) report from 2018 [152] is applied as the basis for deriving necessary carbon prices that reflect the two development pathways towards a 2°C respectively 1.5°C global warming scenario. Scenario 02 (*B-00-COVID*) focusses on the recent demand shock resulting from the COVID-19 pandemic. This unprecedented event has caused massive reduction in air transport, especially on international routes. Airlines that operate on the transatlantic air transport market faced a general ban of flights from Europe to the United States of America in 2020. This resulted in massive capacity reductions on transatlantic routes of more than 90 % [153]. The TATM will be applied to investigate the impact of a demand shock of this magnitude.

5.3.1 Scenario 01: Introduction of CORSIA to international markets

This scenario introduces an obligatory environmental charge for every passenger according to the CORSIA scheme for international air travel [52, 149]. This charge depends on the seat class and the aircraft type of the according flight. The environmental cost per passenger-kilometre will be added for both airline types with a time-dependent path of carbon price increases between 2020 and 2035 as defined by the IEA [151] (see table 5.4).

Table 5.4: Carbon price assumptions: CORSIA framework (adapted from [151])

Carbon Price Assumptions [USD/ton $CO_{2\text{-eq}}$])	**2020**	**2030**	**2035**
IEA high scenario	20	33	40
IEA low scenario	8	15	20

According to IATA [154], the CORSIA scheme accounts for an equivalent of 3.15 kg CO_2 per 1 kg jet fuel. The A330-300 fuel consumption is 0.047 kg per passenger and per nautical miles or 0.0254 kg per passenger-kilometre [155]. With the IEA assumptions of the future carbon price development, the following CORSIA-related environmental costs in USD per passenger-kilometre are listed in table 5.5.

Table 5.5: Environmental Cost for A330-300 Fuel Consumption and CO_2 Generation (own calculation, based on data from [151, 154, 155])

Environmental CORSIA Costs [USD/passenger-km]	**2021-2026**	**2027-2035**	**2035-2050**
IEA high scenario	0.0016	0.0026	0.0032
IEA low scenario	0.0006	0.0012	0.0016

The reference aircraft of the LHLCC, the B787-800 has an average passenger fuel consumption of 0.0239 kg per passenger-kilometre or 0.0443 kg per passenger and per nautical mile [156]. The environmental costs for the operation of the B787-800 resulting from CORSIA are calculated as follows in table 5.6.

Table 5.6: Environmental Cost for B787-800 Fuel Consumption and CO_2 Generation (own calculation, based on data from [151, 154, 156])

Environmental CORSIA costs [USD/passenger-km]	2021-2026	2027-2035	2035-2050
IEA high scenario	0.0015	0.0025	0.003
IEA low scenario	0.0006	0.0011	0.0015

These environmental costs, resulting from the CORSIA scheme, are introduced in addition to the other operating cost for both airline types. The scenario 01 is simulated with the TATM from 2014 until 2035 and, hence, covers the carbon price development period between 2020 and 2035 within the CORSIA time scope. The following figure 5.23 present the results from these simulation runs compared to the baseline simulation.

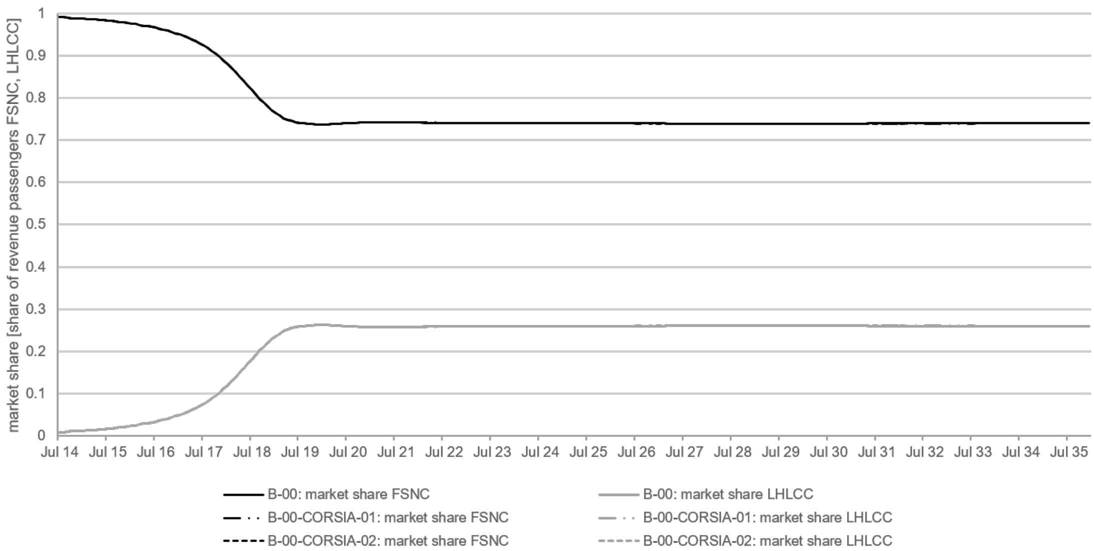

Figure 5.23: Baseline simulation *B-00* compared to CORSIA scenarios *B-00-CORSIA-01* and *B-00-CORSIA-02* until 2035 (own depiction)

The simulation results for the baseline *B-00* scenario as well as for the two scenarios *B-00-CORSIA-01* and *B-00-CORSIA-02* reveal no discernible impact of the CORSIA scheme on the LHLCC market share. All three curves overlap. Against the background that the CORSIA scheme will be applied voluntarily for the pilot phase (2021-2023) as well as for the first phase (2024-2026) [157], a sustainable impact on the environmental footprint of international air transport can be further delayed. With focus on the LHLCC market share, the CORSIA scheme does not provide a significant cost effect on the demand development in the transatlantic air transport market, partly because of the fact that the environmental operational cost are implemented for both airline types. Hence, a cost advantage can only be achieved by the LHLCC if a significant difference in emission performance in terms of fuel burn can be attained by the operation of a novel fuel-efficient aircraft type.

In 2018, the IPCC published a special report on the impacts of global warming of 1.5°C above the pre-industrial levels and related global greenhouse gas emission pathways [152]. Two carbon price development scenarios from chapter 2 in this report were selected for application in the scenario simulation to cover a broader range of potential future carbon price developments. Table 5.7 presents the *higher-2°C pathway* and the more ambitious *below-1.5°C pathway* scenario.

Table 5.7: Carbon price assumptions: IPCC report (own depiction, based on data from [152])

Carbon Price Assumptions [USD_{2010}/ton $CO_{2\text{-eq}}$]	**2030**	**2050**	**2070**	**2100**
higher-2°C pathway range	15-220	45-1,050	120-1,100	175-2,340
below-1.5°C pathway range	135-6,050	245-14,300	420-19,300	690-30,100

The resulting environmental cost are calculated based on the fuel consumption of the two representative aircraft types [154–156]. Tables 5.8 and 5.9 provide the environmental cost in terms of USD per passenger kilometre for the years 2020, 2030 and 2035.

Table 5.8: Environmental Cost for A330-300 Fuel Consumption and CO_2 Generation, resulting from IPCC Mitigation Pathways (own calculation, based on data from [152, 154, 155])

Environmental Costs [USD/passenger-km]	**2020**	**2030**	**2035**
higher-2°C pathway range: lower boundary	0	0.0012	0.0018
higher-2°C pathway range: upper boundary	0	0.0176	0.0342
below-1.5°C pathway range: lower boundary	0	0.0108	0.013
below-1.5°C pathway range: upper boundary	0	0.484	0.6491

Table 5.9: Environmental Cost for B787-800 Fuel Consumption and CO_2 Generation, resulting from IPCC Mitigation Pathways (own calculation, based on data from [152, 154, 156])

Environmental Costs ([USD/passenger-km]	**2020**	**2030**	**2035**
higher-2°C pathway range: lower boundary	0	0.0011	0.0017
higher-2°C pathway range: upper boundary	0	0.0166	0.0322
below-1.5°C pathway range: lower boundary	0	0.0102	0.0122
below-1.5°C pathway range: upper boundary	0	0.4555	0.6107

To provide a continuous increase of the environmental cost as an input for the IPCC scenario simulations, the values in between the environmental cost given in the tables are estimated by interpolation and average cost development pathways are calculated from the lower and the upper boundary. Environmental cost payments for the airlines are defined to start in

2021 in this scenario to reach the levels of environmental costs in 2030 and 2035 accordingly. Appendix E provides an overview of the resulting average environmental cost curves for the two representative aircraft types. The environmental costs for the B787-800 are slightly below the cost for the A330-300 reference aircraft that increases over time. This difference will add up to the initial operational cost advantage of the LHLCC due to lower operating cost resulting from the newer aircraft type operated.

The simulation results for the higher-2°C pathway scenario *B-00-IPCC-2.0* in figure 5.24 depict no notable market share increase resulting from the environmental cost from 2030 onwards. Data on the simulation results reveal a slight LHLCC market share increase of 0.4 percentage points in the *B-00-IPCC-2.0* scenario.

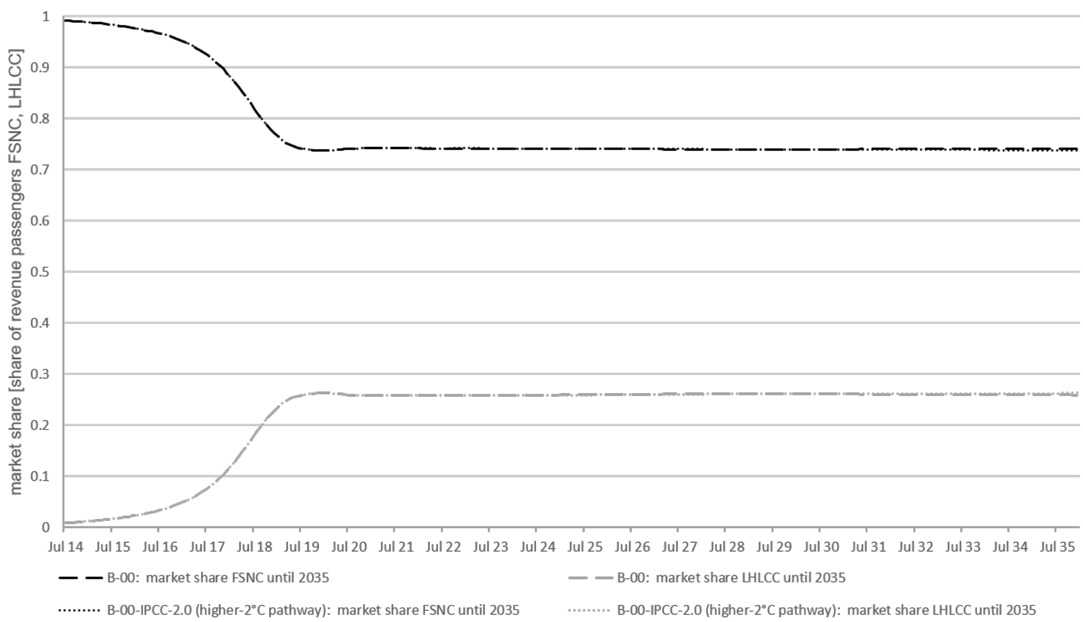

Figure 5.24: Baseline simulation *B-00* compared to IPCC higher-2°C pathway scenario *B-00-IPCC-2.0*: market shares until 2035 (own depiction)

The below-1.5°C pathway scenario *B-00-IPCC-1.5* introduces average environmental cost of factor 26 higher to the according average environmental cost in the higher-2.0°C pathway scenario *B-00-IPCC-2.0* in 2030 and of factor 18 higher in 2035 (see appendix E). Since environmental cost payments are defined to start in 2021, the observed market shares of both airline types react to this payment with a very low decrease of LHLCC market shares followed by a continuous increase to a level of 37.6 % in 2035 in the *B-00-IPCC-1.5* scenario. This market share increase results from an increasing cost advantage from environmental costs due to the more efficient aircraft that the LHLCC operates. This shows that the selection of aircraft in terms of fuel efficiency becomes more important in this scenario.

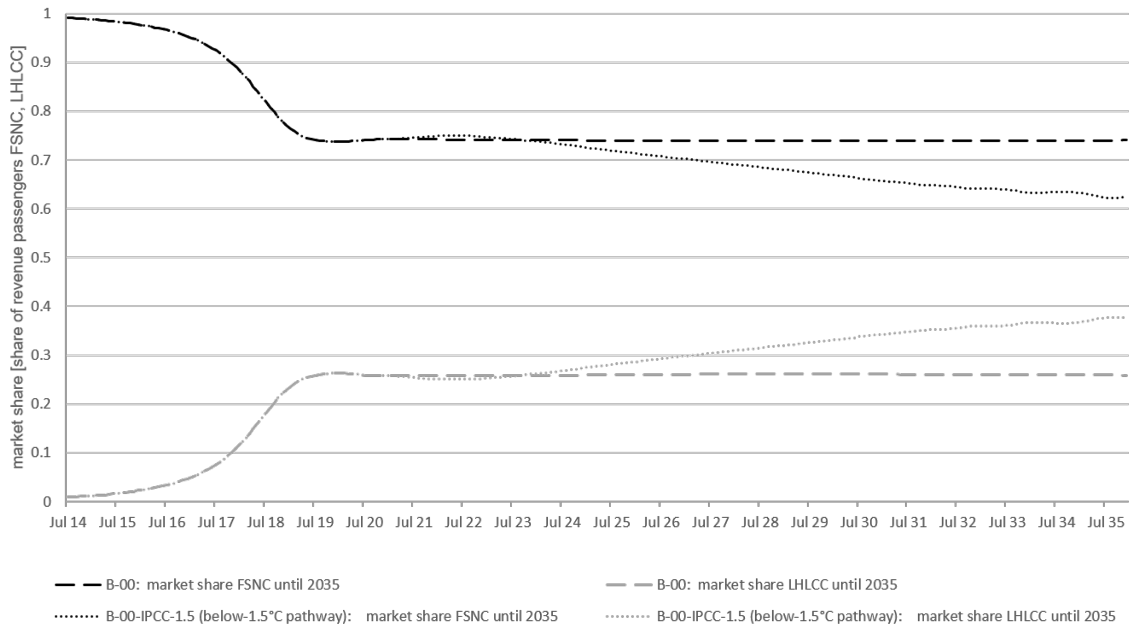

Figure 5.25: Baseline simulation *B-00* compared to IPCC below-1.5°C pathway scenario *B-00-IPCC-1.5*: market shares until 2035 (own depiction)

The resulting environmental cost advantage of the LHLCC for both *B-00-IPCC-2.0* and *B-00-IPCC-1.5* simulations is depicted in figure 5.26.

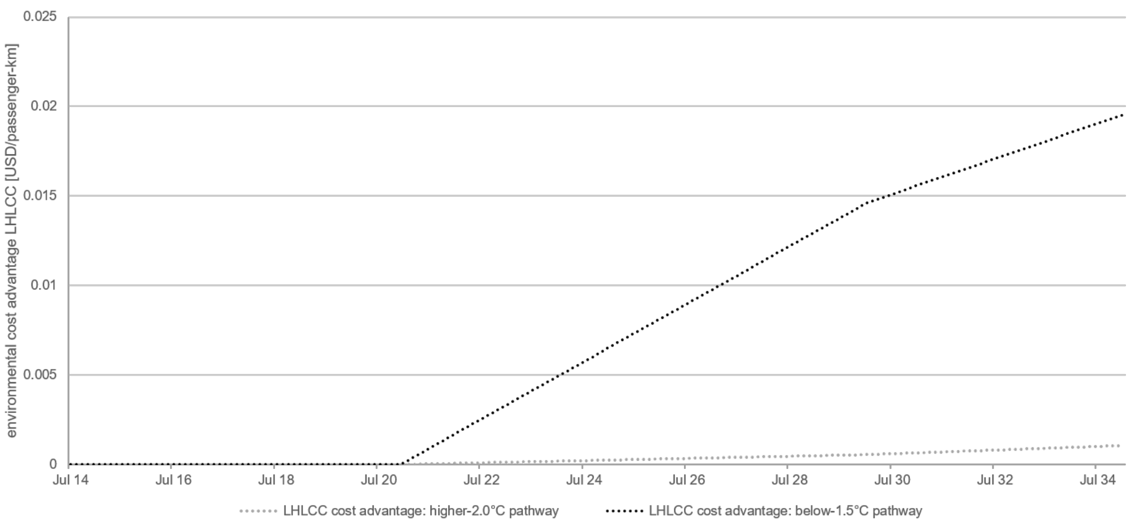

Figure 5.26: IPCC below-1.5°C pathway scenario *B-00-IPCC-1.5*: LHLCC average environmental cost advantage until 2035 (own depiction)

In the *B-00-IPCC-1.5* scenario simulation, the LHLCC achieves an environmental cost advantage of 0.02 USD per passenger-kilometre in addition to the operating cost advantage in the baseline by 2035. The resulting overall LHLCC cost advantage increases from initially

4.7 % to 5.6 %, lower compared to the $unitTOC_j$ variations in the parameter variation studies. However, the effect from this growing cost advantage drives the development of LHLCC attractiveness towards business passengers and reduces the FSNC attractiveness towards leisure passengers. The initial ticket prices are set to 1,285.24 USD for the FSNC service and 910.22 USD for the LHLCC service. These ticket prices increase significantly during the *B-00-IPCC-1.5* scenario simulation due to the sharp rise in overall costs. In 2035, ticket prices reach a level of 4,000 USD (FSNC) and 2,400 USD (LHLCC). This increasing difference in ticket prices affects the attractiveness for LHLCC services. Especially, the share of business passengers who are attracted to LHLCC services increases between 2014 and 2035 whereas FSNC attractiveness for leisure passengers decreases according to the scenario simulation results. As a result, the LHLCC market share increases. In addition, the increasing presence of LHLCCs in the transatlantic market leads to a rise of the passengers' willingness to consider LHLCC services for both passenger groups over time until it reaches full willingness to consider in 2026.

The increase in LHLCC market shares seems unstable since it develops small oscillation between 2033 and 2035. It is expected that the LHLCC will have to increase its ticket prices due to a high cost pressure to a point in time where the minimum ticket price (see equation 3.30) steers the targeted ticket price and a delayed increase in capacity, stronger than the demand increase, leads to a decrease of SLF and at the same time an increase in unit cost. As a consequence, a ticket price increase reinforces demand decrease which leads to even higher ticket prices. The LHLCC will increase its ticket prices prior to its competitor due to a shorter adjustment time as defined for the baseline scenario. This scenario addresses a limitation of the TATM: the lack of feedback from increasing prices to demand, i. e. price elasticity of demand [1]. In general, price elasticities of demand are lower for business passengers than for leisure passengers and higher in short-haul than in long-haul markets [12, 150]. In case of cost and according ticket price increases of high magnitudes during the simulation period, such as in the *B-00-IPCC-1.5* scenario simulation, a feedback from increasing ticket prices to the overall demand is expected to lead to overall demand decreases. This would require a passenger group specific demand generation in the TATM as a feasible model extension.

5.3.2 Scenario 02: Demand shocks

This scenario resembles a demand shock in the transatlantic air transport market. The COVID-19 pandemic and its unprecedented effects on the global airline industry as well as previous demand shocks such as the oil crisis in 1979, the Gulf war, 9/11, SARS, and the global financial crisis in 2008-2009 [1, 2] emphasise the importance of investigating demand shock scenarios. The impact of a demand shock in scenario 02 will vary in time and intensity of a reduction in demand for air transport services. The impact of this demand shock on the transatlantic market shares and especially the LHLCC capabilities to remain in the market will be investigated. Figure 5.27 introduces the demand shock resulting from the COVID-19 pandemic in early 2020.

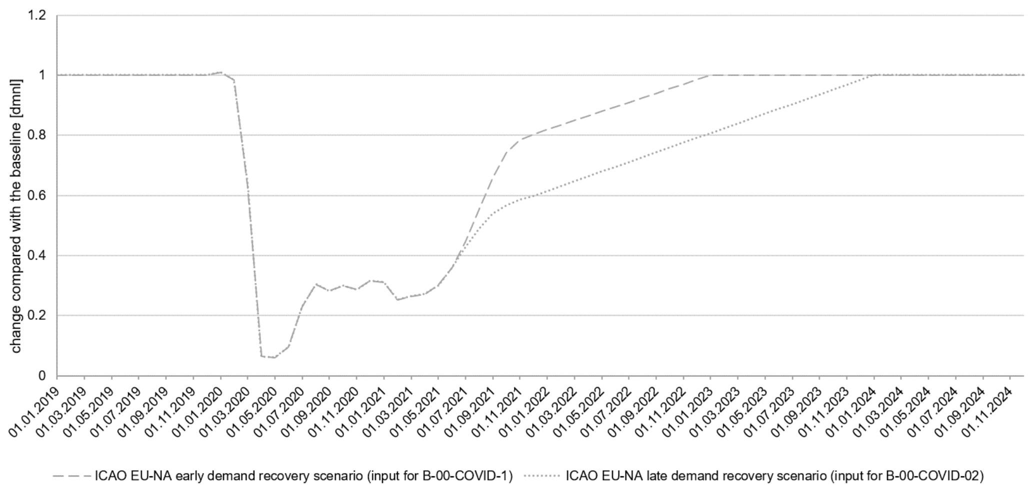

Figure 5.27: Seat capacity development 2020 COVID-19 (own depiction, calculated with data from [153])

The ICAO analysis focusses on the demand shock resulting from the COVID-19 pandemic based on historical data between January 2020 and June 2021, a development forecast from July 2021 until December 2021, and a linear recovery until December 2022 (input for early recovery scenario *B-00-COVID-01*) respectively December 2023 (input for late recovery scenario *B-00-COVID-02*) [153]. The data is derived as an average of two datasets on changes in the seat capacity on international flights from Europe and from North America [153]. The percentage share of capacity change compared to a baseline is used as a proxy for the reduction of potential passengers resulting from the COVID-19 pandemic since the available data results from scheduled passenger traffic. It is expected that the number of scheduled passengers resembles the demand shock quite directly without a significant time delay since airlines must respond directly to minimise the resulting losses. Figure 5.28 depicts the comparison of the baseline simulation *B-00* and the two COVID-19 demand shock scenarios *B-00-COVID-01* and *B-00-COVID-02*. The demand drop in the transatlantic market starts in January 2020 and reaches a minimum of below 10 % potential passengers between April and June 2020 compared to 2019 levels according to the ICAO data [153].

The scenario simulation results in the TATM reacting to the demand shock with the collapse in May 2020 and the simulation is cancelled by the program because the TATM does not include measures to cope with an unprecedented event such as the demand shock that was triggered by the COVID-19 pandemic. At this time step, the LHLCC market share already decreases from 26.1 % to 21 % due to a decline in revenues compared to the constant operating costs and according profit losses. The FSNC compensates the drop from positive profits whereas the LHLCC has to increase its ticket prices due to a lack of reserves from positive profits since it operates at a zero profit level during the market entry, not considering the LHLCC cost recovery factor of already only 0.7. Many airlines entered bankruptcy, ceased operations or have been subsidised by governments [158]. Hence, the TATM simulation results feasibly describe the development in the transatlantic air transport market in the course of the COVID-19 pandemic.

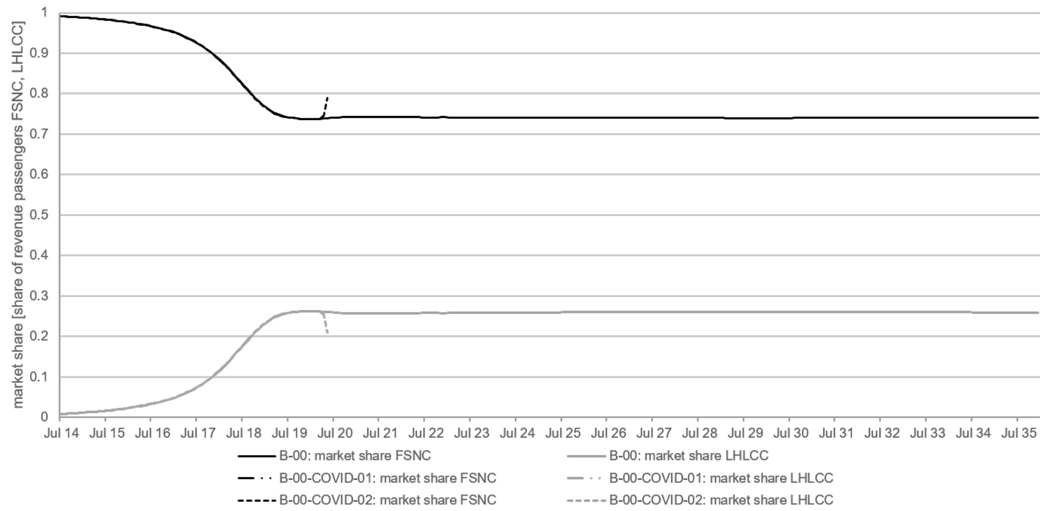

Figure 5.28: Comparison baseline simulation *B-00* with *B-00-COVID-01* and *B-00-COVID-02* scenarios until 2035 (own depiction)

To gain a better understanding of the TATM boundary in terms of demand drop, a parameter to represent the reduction of demand is introduced and multiplied with the potential transatlantic passengers *potPAXTA*. This parameter is used in a step function applying the demand shock in June 2020. The demand shock variation is further investigated in a sensitivity analysis of the baseline simulation with a range between 0 % and -7 % demand drop in June 2020. The results of this sensitivity analysis are depicted in the following figure 5.29 in scenario *B-00-DS-VAR*. The x-axis represents the respective time steps between July 2014 (equals time step 0) and December 2035 (equals time step 257). A drop in demand between -7 % and -6.3 % leads to a market exit of the LHLCC between July 2024 and July 2026. In contrast, LHLCCs can recover from demand reductions in June 2020 between -6.2 % and 0 % and achieve market shares between 13 % and 26 % by 2035.

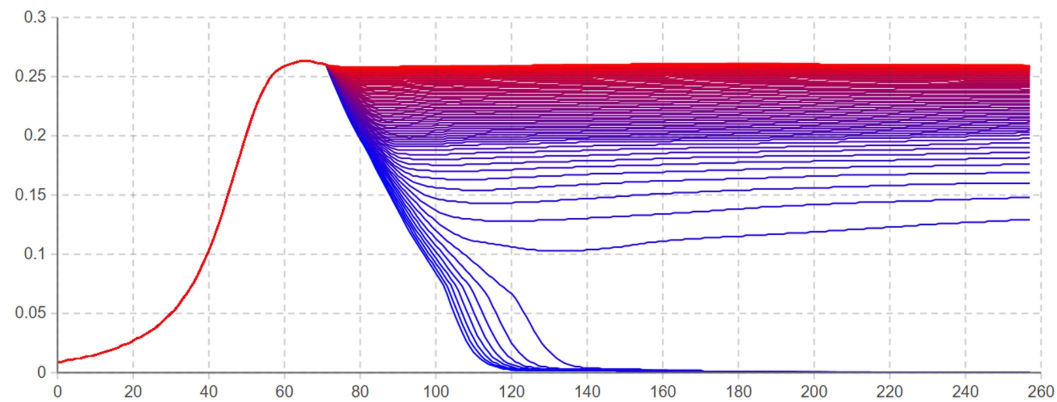

Figure 5.29: Sensitivity analysis: demand shock variation -7 % - 0 % // 0.1 % until 2035 (own depiction)

The scenario simulation result reveals that the TATM is capable of simulating demand shocks without any measures such as governmental subsidies [158] up to moderate levels where the LHLCC exits the market. The introduction of these measures to the TATM opens up possibilities for the further development of the TATM that go beyond the research question posed in this thesis. However, looking into potential strategies to overcome unexpected changes in demand can increase the resilience and robustness of an airline business model, especially in long-haul markets, in future research attempts.

5.4 Discussion of results

The utilisation of the TATM to analyse market shares in the transatlantic air transport market and to derive implications on low-cost airline operations from long-haul future airline market dynamics was twofold. The first part of chapter 5 introduced baseline simulation results up to 2035 based on the parameter setting from the model calibration. The baseline simulation reveals a market potential for low-cost long-haul air services in the transatlantic market of 26.1 %. In addition, this first part comprised parameter variations of the operational cost, the passenger choice parameters, and the availability of aircraft capacities in terms of production and delivery times. The second part of chapter 5 presented scenario simulations. These included the impact of CORSIA as well as the impact of demand shocks resulting from unprecedented events, i. e. as the COVID-19 pandemic. The parameter variation studies complemented the calibration activities from chapter 4 in terms of analysing the model behaviour. This included the variation of exogenous parameters and the consequential impact on the LHLCC market share. The simulation of the two scenarios served as model robustness tests for extreme values [86].

Figure 5.30 summarises the results of market share development from the variation of passenger preferences, unit cost, the cost recovery factor, and the availability of aircraft for the capacity development process. It comprises the resulting LHLCC market shares (depicted in grey lines of different shapes) and FSNC market shares (depicted in black lines of different shapes). The thick solid lines represent the baseline simulation *B-00* where the LHLCC achieves a market share of 26.1 %. A combination of parameter variations is not included in this summary figure.

The LHLCC market potential ranges between 10 % and 30 % depending on the parameter setting. This matches results from Gross and Schroeder [33] that expect LHLCC market shares below the according levels in continental markets. The intra-European LCC market share reached a level of 41 % in 2016 (see figure 3.4 [51], based on data from [5–9]). Market shares at the upper boundary of this range can be achieved if a shift in leisure passenger preferences towards a stronger focus on flight frequencies occurs (simulation *BPAX-04*) or by actively generating an operating unit cost advantage of 30 % (simulation *BCOST-02*). However, passenger preferences cannot be actively steered by an airline and an operating unit cost advantage of 30 % is unlikely to be achieved [13, 18, 19, 32, 35, 37].

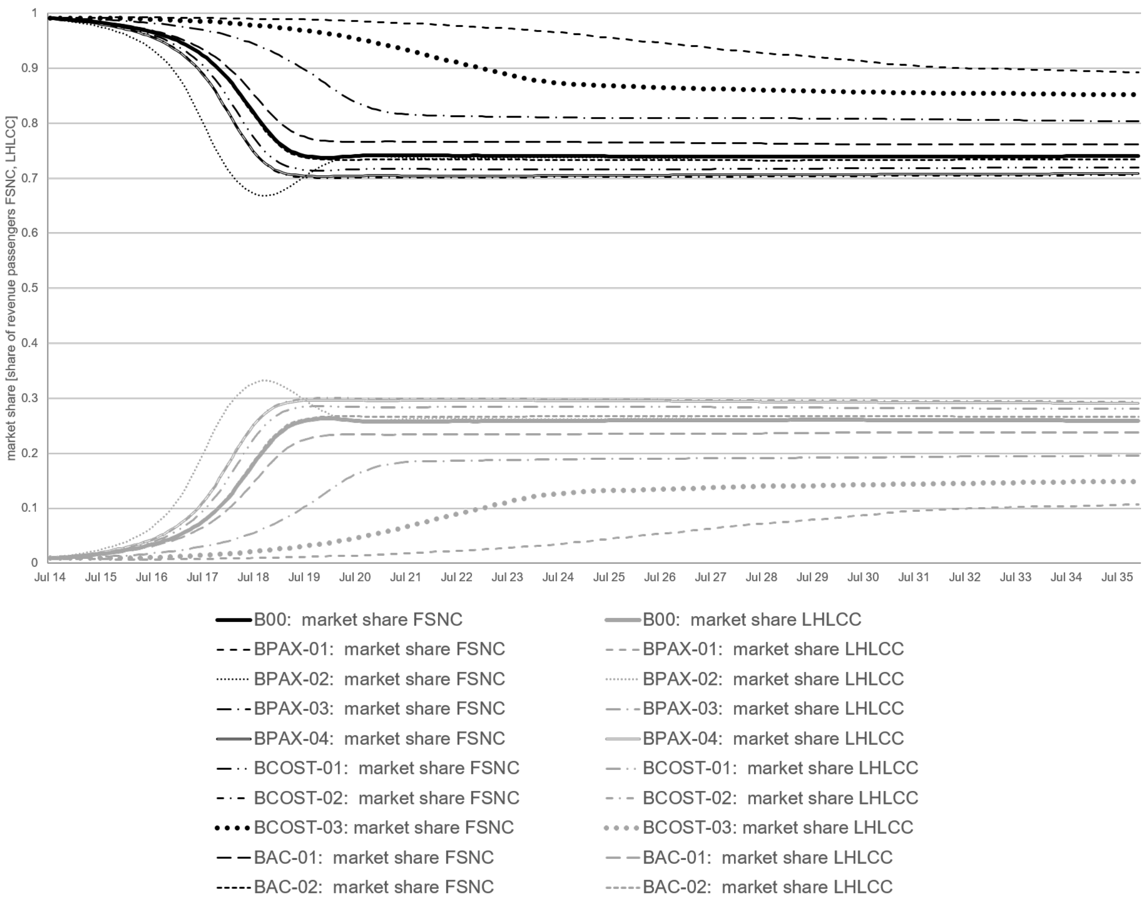

Figure 5.30: Summary of parameter variation simulation results until 2035 (own depiction)

The input for the passenger choice setting in the TATM is adopted from a survey [130] that was applied in an SD research model by Kleer et al. [49]. Due to a lack of specific long-haul passenger choice data, it was compromised to apply general short-haul market data and sustained by varying the selected parameters to cover also expected passenger choice on long-haul markets. That is a decrease of passenger ticket price preferences with increasing flight distances as other factors such as in-flight services and other comfort aspects become more important [11]. Long-haul or even transatlantic specific data on passenger preferences would be beneficial to investigate the shift in preferences on long-haul routes and the according impacts on the LHLCC market share development. A unit cost advantage of 30 %, as provided in simulation *BCOST-02*, is a very ambitious target for the LHLCC airline type. Previous research suggests that LCC airlines can achieve lower operating cost advantages on long-haul routes compared to short-haul equivalents [13, 18, 78]. The variation of the cost coverage factor which leads to a resulting market share of 16.6% at full LHLCC cost coverage, confirms this assumption. Expected figures for the LHLCC cost advantage in long-haul markets range between 10 % and much lower than 50 % to 60 % [13, 18, 19, 32, 35, 37]. The potential cost advantage strongly depends on market requirements [13, 17, 19, 20, 31–34, 36–40] as well as cost-cutting measures [72] (see table 2.1 in section 2.2.3). The baseline setting defines a LHLCC cost coverage factor of 0.7, which leads to an overall unit cost advantage in the parameter variation studies of between 34.7% and 60% which seems very unlikely compared with the figures from the literature. Therefore, a parameter variation simulation with full LHLCC operating cost coverage was conducted. Results reveal a LHLCC market share potential of 16.6 % in the long term with a longer duration of market share ramp-up of over 10 years. These findings reduce the overall market share expectations for long-haul low-cost services in the transatlantic market. Most promising potential markets require price sensitive OD demand from passengers who strongly focus their air travel activities on VFR [13, 19, 31, 33, 40]. Cost-cutting measures comprise a high aircraft utilisation [54] and the reduction of indirect operating cost such as ground handling, labour, maintenance, and overhead costs [2]. Even though it is more challenging on long-haul routes to achieve significant cost advantages as an LHLCC airline type compared to short-haul markets [2], flight operations on routes with the market requirements described above enable a sustainable cost-saving potential of 24 % according to Soyk et al. [37].

Scenario 01 investigates the impact of environmental cost on the LHLCC market share development. The application case is the introduction of the CORSIA scheme, a market-based measure to internalise the environmental impacts from international air transport [52, 149]. The scenario simulation results for *B-00-CORSIA-01* and *B-00-CORSIA-02* reveal no significant impact of the additional environmental cost. The environmental cost are derived from carbon price development as defined by the IEA [151] for both reference aircraft types. They are applied to both competitors in the transatlantic market. Thus, the only effect on the LHLCC market share relates to differences in the fuel burn and according carbon emissions from the two reference aircraft types. The LHLCC operates the B787-800, a more fuel efficient aircraft compared to the A330-300 FSNC reference aircraft type. However, the market shares are not affected when considering environmental cost as additional cost resulting from the CORSIA scheme. One of the main criticisms of CORSIA relates to expected low- to mid-term environmental effectiveness due to low carbon prices as well as the voluntary participation in the initial implementation phases [52]. To address this, two additional scenarios based on carbon prices estimated in the IPCC report on global warming of 1.5°C [152] were applied to the TATM. The scenario *B-00-IPCC-2.0* targets a maximum global warming of 2°C whereas scenario *B-00-IPCC-1.5* considers an even more ambitious target of a maximum global warming of 1.5°C. Both scenarios are defined with an average pathway of the environmental cost development, derived from a lower and an upper boundary for expected carbon prices. The LHLCC market share provides no changes in the scenario *B-00-IPCC-2.0* simulation. In scenario simulation *B-00-IPCC-1.5*, the LHLCC market share increases to a level of 37.6 % in 2035 as a cause of an increasing cost advantage of the LHLCC and an overall increasing difference between the absolute ticket prices during the simulation period. This leads to a shift in passenger choice because attractiveness for LHLCC services rises for both passenger groups due to overall lower ticket prices compared to the competitor. However, the LHLCC market share seems unsustainable and a market exit of the LHLCC is expected due to an increasing cost pressure at a point where the minimum ticket price steers the targeted ticket price, as described in section 5.3.1. The impact of the CORSIA scheme depends on the level of the underlying carbon prices. In the ambitious IPCC scenario to reduce greenhouse gas emissions to below 1.5 % below pre-industrial levels [152], it becomes clear that the internalisation of exogenous environmental costs will strongly affect ticket prices. It remains unanswered, how passengers on the demand side will react to ticket prices in 2035 of up to 4,000 USD in the lower price segment. Since the TATM does not include a feedback loop of the effects of increasing costs on the overall demand, it cannot be investigated to which extent the introduction of carbon prices leads to a reduction in environmental impacts from decreasing demand in international air transport markets. This feedback loop would be a feasible extension of the current version of the TATM.

Scenario 02 focusses on the impact of exogenous demand shocks. The COVID-19 pandemic was selected for the application case. Simulation results of the two scenarios *B-00-COVID-01* and *B-00-COVID-02* depict a collapse of the transatlantic air transport markets for both seat capacity development pathways. The demand shock resulting from the COVID-19 pandemic led to a reduction in transatlantic demand of more than 90 %. Many airlines either ceased operations, went bankrupt or received subsidies by the respective governments [158]. The TATM does not include specific measures to overcome an unprecedented demand shock. The model simulation collapses because both airline types cannot cover the operating cost, especially the indirect operating cost, when demand fails to materialise. As a consequence, the airline decisions on capacity development implemented in the model lead to a rapid reduction of aircraft in the airline fleet. This capacity reduction is delayed which is why operating costs cannot be reduced fast enough to manage the cost coverage. After the simulation of the two COVID-19 scenarios, a sensitivity study was performed to investigate the model demand to demand shocks. The simulation results reveal that the LHLCC airline type can cope with a demand shock up to a reduction of 7 %. When demand drops between -7 % and -6.3 %, the LHLCC exits the market. In case of demand shocks below -6.3 %, the LHLCC can recover and achieve market shares between 13 % and 26 % by 2035. The TATM reaches a limit in the COVID-19 scenario simulations. Feasible model extensions are required to investigate the COVID-19 pandemic in more detail with regard to airline mechanisms in case of LHLCC operations as an affiliation of an established FSNC [2] or the availability to receive subsidies from governmental institutions as could be observed in many countries during the pandemic in 2020 [159].

In summary, it can be stated that the TATM provides insights to the market potential in terms of market share, defined in this research as the share of revenue passengers, and to the future development of an LCC that wants to establish long-haul flight services in the transatlantic air transport market. The simulation results in the baseline simulation reveal that the LHLCC operates with a cost recovery factor of 70 % as derived during the calibration process. This aspect raises the question whether an LHLCC airline type can operate profitably in the transatlantic air transport market in the medium- to long-term. The pressure of cost is an important aspect for an airline when operating low-cost services in the this market. However, several LHLCC services are provided by an affiliated partner of an established FSNC [2]. The question remains how long and to which extent this FSNC is willing to and able to subsidise low-cost services in a complementary long-haul market to cover a wider range of market segments with an extended portfolio. The example of Norwegian Air Shuttle shows that as soon as financial pressure such as from the unprecedented COVID-19 pandemic in the global air transport market, airlines have an even stronger focus on profitability and rigorously cut unprofitable services [160, 161]. The cost recovery factor variation of 1.0 with a resulting LHLCC market share of 16.6 % further dampens the expectations for a general LHLCC market share potential above 20 % in the transatlantic market.

Chapter 6

Conclusion and outlook

The introduction of low-cost services has significantly shaped the landscape of air transport markets [1]. This thesis investigates the transferability of low-cost services to the transatlantic long-haul market and the LHLCC market potential in terms of revenue passenger share. For this, systems thinking and SD modelling was introduced and applied to the transatlantic air transport market. An SD model, the TATM, was developed to analyse the dynamics within the transatlantic air transport market after the introduction of low-cost services and to evaluate the market potential in terms of share of revenue passengers for the LHLCC airline type. The TATM comprises a demand module, a passenger choice module including passenger awareness of services and passenger choice, and an airline market module. The following research questions were addressed in this thesis:

- **How did airline market structures evolve in the past and which key drivers influence their future development?**
- **Which methodological approach is feasible to investigate the introduction and operation of long-haul low-cost services?**
- **How can interrelations between airlines and other stakeholders in the air transport system be modelled?**
- **Which implications on low-cost airline operations can be derived from long-haul future airline market dynamics?**

The thesis commenced with an introduction stating the motivation for this research, a definition of the problem to be investigated, and the scope and expected results of this research (see chapter 1). Chapter 2 provided a review of airline strategies within air transport markets, including an overview of the historical development of the air transport market, specific characteristics of the transatlantic market, and an introduction to airline market strategies and business models and a detailed literature review of long-haul low-cost characteristics. After this, the methodological approach to model the air transport system was selected and the major steps of the SD methodology were introduced and conducted for the development of the TATM (see chapter 3). These included a problem articulation with the introduction of a reference mode, a dynamic hypothesis of the expected model behaviour, the actual model formulation, model testing including calibration and validation, and the formulation and evaluation of policies applied to the model developed. The TATM comprises three major aspects of the transatlantic air transport system: the passenger demand generation, the passenger choice, and the airline market. The TATM development was followed by calibration based on historical data and validation of the model structure as well as the model behaviour (see chapter 4). Besides, reference and input data were introduced for application in the TATM. The actual analysis of the transatlantic air transport market and the LHLCC market potential was conducted in chapter 5 with the simulation of parameter variation and scenario studies. These included parameter variations of passenger preferences, operating cost, the cost recovery factor, and the aircraft availability based on aircraft production times as well as the introduction of the CORSIA scheme to international markets (scenario 01) and the occurrence of demand shocks (scenario 02). The thesis concluded with a critical discussion of the TATM and its simulation results, the discussion of model boundaries, and concluding remarks on perspectives for future work.

The baseline simulation up to 2035 reveals an LHLCC market potential of 26.1 %. Parameter variation studies exhibit a range of potential LHLCC market shares between 10 % and 30 % in the transatlantic air transport market (see figure 5.30). The variation of the LHLCC cost coverage factor with a resulting 16.6 % market share for a cost coverage factor of 1.0 dampens the expectations. The internalisation pricing of exogenous environmental effects, as analysed in scenario 01, has an impact on the LHLCC market share development as soon as according environmental costs reach levels of 0.23 USD per passenger kilometre in 2030 to 0.31 USD per passenger kilometre in 2035 (see figure 5.25). Demand shocks above -6.2 % reduction in passenger demand, as investigated in scenario 02, lead to market exit of the LHLCC (see figure 5.29). The demand shock from the COVID-19 pandemic leads to a collapse of the simulation due to a lack of coping measures implemented in the TATM. The following sections highlight model boundaries and other limits of the approach and methodology applied to investigate the transferability of low-cost services to long-haul markets as well as perspectives for future research.

6.1 Critical discussion of the Transatlantic Air Transport Model limitations

SD models are developed with the objective to provide insights to a specific research question [86]. Hence, an SD model cannot cover all aspects of the transatlantic air transport market and rather simplifies this system to a feasible level to investigate the research question [85, 86]. This leads to limitations of the TATM which will be discussed in the following.

Several challenges are addressed during the development process of the TATM in this thesis. These include the availability of required data, the calibration time period, and the involvement of experts via group modelling sessions during the model development process. The major source for the model structure development is scientific literature on the implementation of low-cost services in long-haul markets as well as on general economic basics of air transport markets such as an airline's cost structure or fleet development and pricing strategies. To complement this source of information, the different development stages of the model were presented to aviation economists and SD modelling experts at several occasions, i. e. conferences and workshops. The objective was to share and discuss the model structure and its basic functionalities and to iteratively improve it with the feedback from the experts. However, group building workshops with representatives of all stakeholders included in the model would have usefully complemented this. As a lesson learned, it is recommended for future research to implement the tool of group model building if possible and to contact all stakeholders required in the model development process at an early stage. This can be beneficial for developing the model structure as well as estimating and discussing parameters and other model input with experts.

The availability of historical data on the transatlantic air transport activities is another crucial aspect in the development of the TATM. The two major sources were applied for historical data besides others, the Sabre database [63] and the OAG database [9, 123, 124]. Since the major parameter of investigation, the LHLCC market share, is calculated from the share of transatlantic revenue passengers, the time period for which revenue data is covered in the Sabre database predefines the time scope for the calibration between 2014 and 2017. One time step in the TATM simulation equals one month. The calibration period comprises 42 months or 42 time steps. It would be beneficial to increase this calibration period and to check additional available sources for monthly data, especially with focus on the short-term effects in the FSNC ticket price development (see section 4.2.3). Additionally, cost in relation to revenue data from one source would be beneficial to investigate the cost coverage potential of the airline types, especially during the market introduction phase.

Airlines are represented as two generic business model types which is why the transatlantic air transport market is represented from a macroscopic perspective without including single airlines. Thus, the overall demand from business and leisure passengers is operated by the summarised capacity of one airline type, i. e. the sub-fleet of each FSNC or LHLCC is aggregated into one aircraft fleet that represents the sum of these sub-fleets. This resulting fleet per airline type does not distinguish between different aircraft types operated in the market. It is rather derived from the capacity required initially in 2014 and a representative aircraft type that is most frequently operated in the market. However, different reference aircraft types are selected for each airline type. The representative aircraft type of the FSNC is the A330-300. The LHLCC aircraft fleet is represented by the B787-800 aircraft type. These two aircraft types were selected as representative since they are most frequently operated per respective airline type on distances above 4,000 kilometres between Europe and North America, based on OAG Data from 2014, 2016, and 2018 [9, 123, 124]. The aircraft type selection has an influence on the resulting total operating unit cost $unitTOC_j$. LHLCCs that operate an aircraft type with overall lower unit cost, gain an operating cost advantage. The number of available seats is another lever: the more available seats the aircraft type has, the higher the number of potential passengers among which the operational costs can be distributed. If the two representative aircraft types are switched, the FSNC operates the

B787-800 and the LHLCC the A330-300, a slightly lower LHLCC market share potential of 25.1 % results from the baseline simulation (see appendix F) due to higher LHLCC operating unit cost that can only be compensated partially with the higher seat density in the LHLCC reference aircraft. If both airline types operate the same aircraft type, the operating cost advantage potential for the LHLCC only results from a higher seat density in the aircraft type operated. The resulting LHLCC market share potential lies between 25.5 % and 25.7 %.

A cost recovery factor of 0.7 is introduced for the LHLCC airline type during the model calibration process. This parameter was required to align the average ticket price resulting from the Sabre database [63] for each airline type with the average operating cost for the two representative aircraft types that result from the smart reference costing model [125] due to a lack of data on corresponding operating cost in the Sabre database. As a result, the average ticket prices of the LHLCC airline type only cover 70 % of the operating cost resulting from the smart reference costing model. This aspect was addressed during the parameter variation studies with a simulation of the baseline with full LHLCC cost recovery that resulted in a LHLCC market share potential of 16.6 %. This fact lowers the LHLCC market share expectations. Insights into actual long-haul operating costs for the representative aircraft types would be beneficial. In addition, the airline cost structure is static and does not consider changes over time, e. g. in the jet fuel market price or reductions in cost per passenger kilometre due to efficiency gains in maintenance processes or labour required for the flight operations. A dynamic representation of the operating cost development is valuable especially for longer simulation periods.

The limitations outlined above open up a multitude of starting points for future research. Additional data sources strongly depend on availability and potential costs for this data. Other aspects such as changes or additions to the model structure and further model development should be considered in close alignment with the underlying research question that the model is intended to answer. The following and final section 6.2 provides an overview of future research perspectives.

6.2 Perspectives for future research

Several limitations of the TATM leave room for further development and future research for the investigation of low-cost services in the transatlantic as well as other long-haul markets. These include the extension of available data sources as well as further development of the model structure to introduce additional aspects that exogenously affect the transatlantic air transport market over time.

According to the available data sources, it would be beneficial to extend the revenue data from the Sabre database [63] with a time extension of the calibration period and to complement the existing data with e. g. monthly historical data of the average ticket price development for the two representative airline types. This would allow a more precise examination of the observed short-term effects of the FSNC ticket price that lead to an increase in an immediate response to the LHLCC market entrance before reducing the ticket price as expected (see section 4.2.3). An increase of the calibration time period furthermore enables more robust statistical results of the model behaviour.

One major addition to the TATM presented in this thesis is the introduction of a feedback loop that resembles the impact of changes in the ticket price on the overall transatlantic demand, expressed in potential transatlantic air passengers. Such an extension would allow for analysis of future demand development pathways facing the increasing challenge of aviation to reduce its environmental footprint. As depicted in scenario 01 (see section 5.3.1), measures to curb the environmental impact of aviation is closely linked to the internalisation of exogenous effects, for example through the introduction of environmental costs. An increase in overall costs and according average ticket prices does not have a uniform effect on the overall demand for air transport services. Especially, the demand for low-cost services of price sensitive passengers decreases and consequently the market potential for low-cost services is reduced. Besides, ancillary revenues can be introduced to the model structure by distinct feedback loops that describe the generation of this revenue type and the underlying strategies to optimise this revenue stream. Ancillary revenues have recently become crucial as different airline types gravitate towards each other [26, 65] and competing airlines adopt business model aspects of their respective competitor.

The introduction of a feedback loop of price effects on aggregate demand should be accompanied by a sound analysis of the behaviour of the passenger groups under consideration. Passenger choice in the TATM comprises two aspects: the consideration of flight services offered and the actual assessment and choice of these services based on service characteristics, i. e. ticket price, flight frequency, and the availability of a FFP [51]. Business and leisure passenger utilities implemented in the TATM result from a survey on passenger preferences for FSNC and LCC airline types in the in short-haul markets, [130] as applied in [49]. These utilities are adapted to long-haul market conditions and further analysed during the parameter variation studies. Since this thesis investigates the market potential of low-cost services to the transatlantic air transport long-haul market, it would be beneficial to replace the choice set and utilities implemented in the TATM by updated survey results with focus on long-haul markets in general or the transatlantic market specifically. An updated survey on long-haul passenger preferences could be complemented with additional aspects such as airline reputation, measured in e. g. safety reputation or airline branding, or service features during a flight, e. g. the seat pitch offered, in-flight services offered, and available internet connection during a flight [2]. Especially, airline reputation should be considered for future research since global passenger surveys rank airline reputation as the third most important decision factor when selecting an airline besides ticket price and flight schedule [2]. Passenger consideration of service is characterised by the overall number of seats offered by the two airline types as well as by the two exogenous parameters on the marketing and the word-of-mouth effect. These two exogenous parameters could be internalised in the TATM structure, e. g. with a link to market shares or other drivers for an increase of marketing efforts and according costs for advertising activities. In addition, passenger decision could be introduced with an agent-based modelling approach and integrated as an extension of the TATM. Different passenger characteristics as well as service features can be taken into account with such an extended model. A combination of SD models with agent-based modelling approaches is already applied to the automotive industry in analysing the impact of introducing new power train technologies [87].

In the light of COVID-19 and its unprecedented impact on global aviation, the scope of this thesis seems to loose its radiance. Border closures led to the sudden cancellation of a large proportion of international air flight services [158]. The airline industry coped with high losses on the revenue side combined with a significant amount of fixed costs and several airlines disappeared from the markets [158, 162]. Many former flag carriers were supported by financial aid from their state to sustain airline operations at least on a minimum level [162]. IATA expects a recovery in the industry back to passenger volumes of 2019 between 2023 and 2024, depending on the market and associated with a high degree of uncertainty [162]. Airlines that operate on international long-haul air transport routes need to focus on their survival in the market rather than competing with long-haul low-cost market entrants. Those LHLCCs who entered the transatlantic market within the last decade will withdraw, as the framework conditions for a feasible competition with sufficient demand for long-haul flights, especially from price-sensitive customers, are not expected before the global air transport system recovers. In market theory, less airlines in the market combined with state subsidies would lead to less competition and higher ticket prices [12]. In the current situation, airlines cope with the challenge to operate profitably at average SLFs of 65 % in 2020 and expected 67 % in 2021 [162]. Potential passengers hesitate to book flights which is why the re-start amid the different ongoing global travel restrictions develops much more cautious than initially expected. Potential future research should focus on the air transport market conditions in general as well as the transatlantic and other long-haul markets in particular and investigate the resilience of different strategic airline approaches to enter and operate in these markets.

References

[1] R. Conrady, F. Fichert, and R. Sterzenbach. *Luftverkehr: Betriebswirtschaftliches Lehr- und Handbuch*. De Gruyter Oldenbourg, Berlin, Boston, 6th edition, 2019. ISBN 978-3-11-056329-0.

[2] R. S. Doganis. *Flying Off Course: Airline Economics and Marketing*. Routledge, Taylor & Francis Group, London, 5th edition, 2019. ISBN 978-1-138-22424-7.

[3] B. Vasigh, K. Fleming, and T. Tacker. *Introduction to Air Transport Economics: From Theory to Applications*. Ashgate Publishing Limited, Aldershot, 2008. ISBN 978-0-7546-7081-0.

[4] A. Wittmer and T. Bieger. Fundamentals and Structure of Aviation Systems. In T. Bieger A. Wittmer and R. Müller, editors, *Aviation Systems: Management of the Integrated Aviation Value Chain*, pages 5–38. Springer Berlin Heidelberg, Berlin, Heidelberg, 2011. ISBN 978-3-642-20079-3.

[5] Official Airline Guide (OAG). Scheduled Flight Database, 2000.

[6] Official Airline Guide (OAG). Scheduled Flight Database, 2004.

[7] Official Airline Guide (OAG). Scheduled Flight Database, 2008.

[8] Official Airline Guide (OAG). Scheduled Flight Database, 2012.

[9] Official Airline Guide (OAG). Scheduled Flight Database, 2016.

[10] M. E. Porter. *Competitive Advantage: Creating and Sustaining Superior Performance*. The Free Press, New York, 1985. ISBN 978-0-02-925090-7.

[11] G. N. Cook and B. G. Billig. *Airline Operations and Management: A Management Textbook*. Routledge, Taylor & Francis Group, London, New York, 1st edition, 2017. ISBN 978-1-138-23752-0.

[12] S. Holloway. *Straight and Level: Practical Airline Economics*. Ashgate Publishing Limited, Aldershot, Burlington, 3rd edition, 2008. ISBN 978-0-7546-7258-6.

[13] G. Francis, N. Dennis, S. Ison, and I. Humphreys. The transferability of the low-cost model to long-haul airline operations. *Tourism Management*, 28(2):391–398, 2007. doi:10.1016/j.tourman.2006.04.014.

[14] Airbus. Global Market Forecast 2018-2037: Global Networks, Global Citizens. Technical report, 2018. URL `https://www.airbus.com/content/dam/corporate-topics/publications/media-day/GMF-2018-2037.pdf`. Accessed: 24.10.2019.

[15] S. V. Gudmundsson. Limits to the low-cost niche? Finding sustainable strategies for low-cost long-haul a1irlines. *Discussion Paper Paris Air Forum*, June 12, 2015. doi:10.2139/ssrn.2621767.

[16] J. G. Wensveen. *Air Transportation: A Management Perspective*. Ashgate Publishing Limited, Aldershot, 6th edition, 2007. ISBN 978-0-7546-7171-8.

[17] M. de Poret, J. F. O'Connell, and D. Warnock-Smith. The economic viability of long-haul low cost operations: Evidence from the transatlantic market. *Journal of Air Transport Management*, 42:272–281, 2015. doi:10.1016/j.jairtraman.2014.11.007.

[18] J. van der Bruggen. *Low-cost aiming for long-haul - New low-cost business model: the feasibility of long-haul low-cost*. Master Thesis, University of Amsterdam, 2008.

[19] M. E. Moreira, J. F. O'Connell, and G. Williams. The Viability of Long-Haul, Low Cost Business Models. *Journal of Air Transport Studies*, 2(1):69–91, 2011. doi:10.38008/jats.v2i1.106.

[20] J. Daft and S. Albers. A profitability analysis of low-cost long-haul flight operations. *Journal of Air Transport Management*, 19:49–54, 2012. doi:10.1016/j.jairtraman.2012.01.010.

[21] K. Button. The impact of US–EU "Open Skies" agreement on airline market structures and airline networks. *Journal of Air Transport Management*, 15(2):59–71, 2009. doi:10.1016/j.jairtraman.2008.09.010.

[22] Eurocontrol. Glossary for Flight Statistics & Forecasts. Technical report, 2005.

[23] K. Button, R. Neiva, and J. Yuan. Economic development and the impact of the EU–US Transatlantic Open Skies Air Transport Agreement. *Applied Economics Letters*, 21 (11):767–770, 2014. doi:10.1080/13504851.2014.889794.

[24] International Air Transport Association (IATA). Vision 2050, 2011. URL `https://www.iata.org/contentassets/bccae1c5a24e43759607a5fd8f44770b/vision-2050.pdf`. Accessed: 09.05.2020.

[25] N. K. Taneja. *21st Century Airlines: Connecting the Dots*. Routledge, Taylor & Francis Group, London, New York, 1st edition, 2017. ISBN 978-1-138-09313-3.

[26] J. Daft and S. Albers. An empirical analysis of airline business model convergence. *Journal of Air Transport Management*, 46:3–11, 2015. doi:10.1016/j.jairtraman.2015.03.008.

[27] Air Transport Action Group (ATAG). Aviation Benefits Beyond Borders: Powering global economic growth, employment, trade links, tourism and support for sustainable development through air transport, despite global crisis, Report, 2020. URL https://aviationbenefits.org/downloads/aviation-benefits-beyond-borders-2020/. Accessed: 31.01.2021.

[28] Air Transport Action Group (ATAG). Fact Sheet #3 / February 2021 - Tracking Aviation Efficiency: How is the aviation sector performing in its drive to improve fuel efficiency, in line with its short-term goal?, 2021. URL https://aviationbenefits.org/downloads/fact-sheet-3-tracking-aviation-efficiency/. Accessed: 28.04.2021.

[29] Air Transport Action Group (ATAG). Beginner's Guide to Aviation Efficiency, Report, 2010. URL http://large.stanford.edu/courses/2017/ph240/chhoa1/docs/atag-nov10.pdf. Accessed: 28.10.2020.

[30] European Commission, Directorate-General for Mobility and Transport, Directorate-General for Research and Innovation. Flightpath 2050: Europe's vision for aviation: maintaining global leadership and serving society's needs, Publications Office of the European Union, Luxembourg. 2011. doi:10.2777/50266.

[31] E. Pels. Airline network competition: Full-service airlines, low-cost airlines and long-haul markets. *Research in Transportation Economics*, 24(1):68–74, 2008. doi:10.1016/j.retrec.2009.01.009.

[32] P. Morrell. Can long-haul low-cost airlines be successful? *Research in Transportation Economics*, 24(1):61–67, 2008. doi:10.1016/j.retrec.2009.01.003.

[33] S. Gross and A. Schroeder. Low cost business model on long-haul routes - a promising market segment? In *Proceedings of the 12th Air Transport Research Society World Conference*, Athens, Greece, 2008. URL https://www.atrsworld.org/s/2008_Program.pdf.

[34] J. G. Wensveen and R. Leick. The long-haul low-cost carrier: A unique business model. *Journal of Air Transport Management*, 15(3):127–133, 2009. doi:10.1016/j.jairtraman.2008.11.012.

[35] R. Whyte and G. Lohmann. Low-cost long-haul carriers: A hypothetical analysis of a 'Kangaroo route'. *Case Studies on Transport Policy*, 3(2):159–165, 2015. doi:10.1016/j.cstp.2015.01.003.

[36] D. Wilken, P. Berster, and M. C. Gelhausen. Analysis of demand structures on intercontinental routes to and from Europe with a view to identifying potential for new low-cost services. *Journal of Air Transport Management*, 56(B):79–90, 2016. doi:10.1016/j.jairtraman.2016.04.018.

[37] C. Soyk, J. Ringbeck, and S. Spinler. Long-haul low cost airlines: Characteristics of the business model and sustainability of its cost advantages. *Transportation Research Part A: Policy and Practice*, 106:215–234, 2017. doi:10.1016/j.tra.2017.09.023.

[38] C. Soyk, J. Ringbeck, and S. Spinler. Revenue characteristics of long-haul low cost carriers (LCCs) and differences to full-service network carriers (FSNCs). *Transportation Research Part E: Logistics and Transportation Review*, 112:47–65, 2018. doi:10.1016/j.tre.2018.02.002.

[39] A. Gualini, M. Valli, G. Martini, and M. Dresner. Airline Competition in the North Atlantic Market. In *Proceedings of the 23th Air Transport Research Society World Conference*, Amsterdam, Netherlands, 2019. URL `https://www.atrsworld.org/s/2019_Program.pdf`.

[40] J. Hunt and D. Truong. Low-fare flights across the Atlantic: Impact of low-cost, long-haul trans-Atlantic flights on passenger choice of Carrier. *Journal of Air Transport Management*, 75:170–184, 2019. doi:10.1016/j.jairtraman.2018.12.005.

[41] M. Liehr, A. Größler, M. Klein, and P. M. Milling. Cycles in the sky: understanding and managing business cycles in the airline market. *System Dynamics Review*, 17(4): 311–332, 2001. doi:10.1002/sdr.226.

[42] S. P. Sgouridis. *Symbiotic strategies in enterprise ecology: modeling commercial aviation as an Enterprise of Enterprises*. PhD Thesis, Massachusetts Institute of Technology, 2007. URL `https://dspace.mit.edu/handle/1721.1/43859`.

[43] F. Behrens, E.-M. Cronrath, and A. Zock. How to Approach New Industries and Gain Insights Into Their Development Dynamics - Examples of the German Aviation Industry. In *Proceedings of the 26th International Conference of the System Dynamics Society*, Athens, Greece, 2008. URL `https://proceedings.systemdynamics.org/2008/proceed/papers/BEHRE313.pdf`.

[44] K. Pierson. *Profit Cycle Dynamics*. PhD Thesis, Massachusetts Institute of Technology, 2011. URL `https://dspace.mit.edu/handle/1721.1/68865`.

[45] K. Pierson and J. D. Sterman. Cyclical dynamics of airline industry earnings. *System Dynamics Review*, 29(3):129–156, 2013. doi:10.1002/sdr.1501.

[46] P. von Beuningen. Application of System Dynamics to assess competitive rivalry in the airline industry - A Case Study. In *Proceedings of the 32nd International Conference of the System Dynamics Society*, Delft, Netherlands, 2014. URL `https://proceedings.systemdynamics.org/2014/proceed/papers/P1339.pdf`.

[47] S. P. Shepherd and A. Orta. Modelling open skies agreements and air passenger competition. In *Proceedings of the 35th International Conference of the System Dynamics Society*, Cambridge, Massachusetts, USA, 2017. URL `https://proceedings.systemdynamics.org/2017/proceed/papers/P1350.pdf`.

[48] E.-M. Cronrath. *The Airline Profit Cycle: A System Dynamics Analysis of Airline Industry Dynamics*. Routledge studies in transport analysis. Routledge, Taylor & Francis Group, London, New York, 2018. ISBN 978-1-138-73196-7.

[49] B. Kleer, E.-M. Cronrath, and A. Zock. Market development of airline companies: A system dynamics view on strategic movements. In *Proceedings of the 26th International Conference of the System Dynamics Society*, Athens, Greece, 2008. URL `https://proceedings.systemdynamics.org/2008/proceed/papers/KLEER484.pdf`.

[50] J. G. Kuljanin. *A Model for Air Transport Market Competition Assessment: Airline and Alliance Perspective*. PhD Thesis, University of Belgrade, 2019. URL `https://uvidok.rcub.bg.ac.rs/bitstream/handle/123456789/3257/Doktorat.pdf`.

[51] M. Urban and M. Hornung. Mapping causalities of airline dynamics in long-haul air transport markets. *Journal of Air Transport Management*, 91:101973, 2021. doi:10.1016/j.jairtraman.2020.101973.

[52] S. Maertens, J. Scheelhaase, W. Grimme, and M. Jung. Klimaschutz im Luftverkehr: vom EU-Emissionshandel zu CORSIA. *Wirtschaftsdienst*, 97(8):588–595, 2017. doi:10.1007/s10273-017-2181-7.

[53] M. W. Tretheway and K. Markhvida. The aviation value chain: Economic returns and policy issues. *Journal of Air Transport Management*, 41:3–16, 2014. doi:10.1016/j.jairtraman.2014.06.011.

[54] L. Budd and S. Ison. *Air Transport Management: An International Perspective*. Routledge, Taylor & Francis Group, London, New York, 2016. ISBN 978-1-4724-5106-4.

[55] W. Pompl. *Luftverkehr: Eine ökonomische und politische Einführung*. Springerlink Bücher. Springer Berlin Heidelberg, Berlin, Heidelberg, 5th edition, 2007. ISBN 978-3-540-32752-3.

[56] P. Belobaba. The Airline Planning Process. In P. Belobaba, A. Odoni, and C. Barnhart, editors, *The Global Airline Industry*, pages 153–181. John Wiley & Sons, Ltd., Chichester, 1st edition, 2009. ISBN 978-0-470-74077-4.

[57] A. Odoni. The International Institutional and Regulatory Environment. In P. Belobaba, A. Odoni, and C. Barnhart, editors, *The Global Airline Industry*, pages 19–46. John Wiley & Sons Ltd., Chichester, 1st edition, 2009. ISBN 978-0-470-74077-4.

[58] K. Mayor and R. S. J. Tol. Aviation and the environment in the context of the EU–US Open Skies agreement. *Journal of Air Transport Management*, 15(2):90–95, 2009. doi:10.1016/j.jairtraman.2008.09.018.

[59] Y.-C. Chang, G. Williams, and C.-J. Hsu. An Ongoing Process - A Review of the Open Skies Agreements between the European Union and the United States. *Transport Reviews*, 29(1):115–127, 2009. doi:10.1080/01441640802196293.

[60] European Commission (EC). Communication from the Commission: Developing a Community civil aviation policy towards Canada. *Official Journal of the European Commission*, COM/2006/0871 final, 2007. URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52006DC0871.

[61] International Civil Aviation Organisation (ICAO). Convention on International Civil Aviation: Chicago Convention (Original version. Signed at Chicago on 7 December 1944), 1944. URL https://www.icao.int/publications/pages/doc7300.aspx.

[62] European Commission (EC). Agreement on Air Transport between Canada and The European Community and its Member States, *Official Journal of the European Union*, L207, 06/08/2010 p. 32-59, 2009. URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A22010A0806%2801%29&qid=1648212864314.

[63] Sabre Data & Analytics Market Intelligence 5.15 (Proprietary Data Access): data selected for the years between 2010 and 2017.

[64] R. Casadesus-Masanell and J. E. Ricart. From Strategy to Business Models and onto Tactics. *Long Range Planning*, 43(2-3):195–215, 2010. doi:10.1016/j.lrp.2010.01.004.

[65] J. Daft and S. Albers. A conceptual framework for measuring airline business model convergence. *Journal of Air Transport Management*, 28:47–54, 2013. doi:10.1016/j.jairtraman.2012.12.010.

[66] C. Zott, R. Amit, and L. Massa. The Business Model: Recent Developments and Future Research. *Journal of Management*, 37(4):1019–1042, 2011. doi:10.1177/0149206311406265.

[67] A. Osterwalder and Y. Pigneur. *Business Model Generation: Ein Handbuch für Visionäre, Spielveränderer und Herausforderer*. Campus Verlag, Frankfurt am Main, 1st edition, 2011. ISBN 978-3-593-41908-4.

[68] T. Bieger and A. Wittmer. Airline Strategy: From Network Management to Business Models. In A. Wittmer, T. Bieger, and R. Müller, editors, *Aviation Systems: Management of the Integrated Aviation Value Chain*, pages 77–102. Springer Berlin Heidelberg, Berlin, Heidelberg, 2011. ISBN 978-3-642-20079-3.

[69] P. Belobaba. Airline Operating Costs and Measures of Productivity. In P. Belobaba, A. Odoni, and C. Barnhart, editors, *The Global Airline Industry*, pages 113–151. John Wiley & Sons, Ltd., Chichester, 1st edition, 2009. ISBN 978-0-470-74077-4.

[70] P. Hanlon. *Global Airlines: Competition in a Transnational Industry*. Butterworth-Heinemann Elsevier imprint, Oxford, Burlington, 3rd edition, 2007. ISBN 978-0-7506-6439-4.

[71] Mott MacDonald. Annual Analyses of the EU Air Transport Market 2016: Final Report for the European Commission, 2017. URL https://ec.europa.eu/transport/sites/transport/files/2016_eu_air_transport_industry_analyses_report.pdf. Accessed: 04.10.2020.

[72] L. Budd and S. Ison, editor. *Low Cost Carriers: Emergence, Expansion and Evolution*. Routledge, Taylor & Francis Group, London, New York, 2014. ISBN 978-1-4094-6903-2.

[73] T. Bieger and S. Agosti. Business Models in the Airline Sector - Evolution and Perspectives. In W. Delfmann, H. Baum, S. Auerbach, and S. Albers, editors, *Strategic Management in the Aviation Industry*, pages 41–64. Ashgate Publishing Limited, Aldershot, 1st edition, 2005. ISBN 978-0-7546-4567-2.

[74] M. Urban, M. Klemm, K. O. Plötner, and M. Hornung. Airline categorisation by applying the business model canvas and clustering algorithms. *Journal of Air Transport Management*, 71(3):175–192, 2018. doi:10.1016/j.jairtraman.2018.04.005.

[75] P. Chiambaretto. Air passengers' willingness to pay for ancillary services on long-haul flights. *Transportation Research Part E: Logistics and Transportation Review*, 147: 102234, 2021. doi:10.1016/j.tre.2021.102234.

[76] J. Kuljanin, M. Kalić, B. Begović, N. Mijović, and M. Renold. The effect of LCC market entry on dominant FSC's price into long haul sector: A case of Norwegian competition on British Airways' prices on selected transatlantic routes. *Journal of Air Transport Management*, 91:102016, 2021. doi:10.1016/j.jairtraman.2020.102016.

[77] Scimago Lab. Scimago journal & country rank: Journal rankings for "transportation" in "2018". URL `https://www.scimagojr.com/journalrank.php?category=3313&year=2018`. Accessed: 13.01.2020.

[78] R. S. Doganis. *The Airline Business*. Routledge, Taylor & Francis Group, London, New York, 2nd edition, 2006. ISBN 0-203-59680-3.

[79] CAPA - Centre for Aviation. Longhaul low cost airlines: World Airways to be US' first, 2018. URL `https://centreforaviation.com/analysis/reports/longhaul-low-cost-airlines-world-airways-to-be-us-first-405559`. Accessed: 17.05.2019.

[80] P. Morrell and W. Swan. Airline Jet Fuel Hedging: Theory and Practice. *Transport Reviews*, 26(6):713–730, 2006. doi:10.1080/01441640600679524.

[81] J. G. de Wit and J. Zuidberg. The growth limits of the low cost carrier model. *Journal of Air Transport Management*, 21:17–23, 2012. doi:10.1016/j.jairtraman.2011.12.013.

[82] X. Fageda, P. Suau-Sanchez, and K. J. Mason. The evolving low-cost business model: Network implications of fare bundling and connecting flights in Europe. *Journal of Air Transport Management*, 42:289–296, 2015. doi:10.1016/j.jairtraman.2014.12.002.

[83] C. Soyk, J. Ringbeck, and S. Spinler. Effect of long-haul low-cost carriers on North Atlantic air fares. *Transportation Research Part E: Logistics and Transportation Review*, 152:102415, 2021. doi:10.1016/j.tre.2021.102415.

[84] W. Domschke, A. Drexl, R. Klein, and A. Scholl. *Einführung in Operations Research*. Springer Berlin Heidelberg, Berlin, Heidelberg, 9th edition, 2015. ISBN 978-3-662-48215-5.

[85] H. Bossel. *Systeme Dynamik Simulation: Modellbildung, Analyse und Simulation komplexer Systeme*. Books on Demand, Norderstedt, 2004. ISBN 3-8334-0984-3.

[86] J. D. Sterman. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Irwin/McGraw-Hill Higher Education Ltd, Boston, 2000. ISBN 0-07-231135-5.

[87] K. Kieckhäfer. *Marktsimulation zur strategischen Planung von Produktportfolios: Dargestellt am Beispiel innovativer Antriebe in der Automobilindustrie*. Springer eBook Collection. Springer Fachmedien Wiesbaden, Wiesbaden, 2013. ISBN 978-3-658-02470-3. doi:10.1007/978-3-658-02471-0.

[88] H. Bossel. *Modellbildung und Simulation: Konzepte, Verfahren und Modelle zum Verhalten Dynamischer Systeme*. Vieweg, Braunschweig, 2nd edition, 1994. ISBN 978-3-322-90519-2.

[89] F. Klügl. *Multiagentensimulation: Konzepte, Werkzeuge, Anwendungen*. Addison-Wesley, München, 2001. ISBN 978-3827317902.

[90] A. M. Law. *Simulation Modeling and Analysis*. McGraw-Hill Higher Education, New York, 5th edition, 2014. ISBN 978-0-07-340132-4.

[91] F. Liebl. *Simulation: Problemorientierte Einführung*. Oldenbourg Verlag, München, 2nd edition, 1995. ISBN 978-3-486-23373-5.

[92] Michael Pidd. *Computer Simulation in Management Science*. John Wiley & Sons Ltd., Chichester, 4th edition, 1998. ISBN 978-0471979319.

[93] L. Suhl and T. Mellouli. *Optimierungssysteme: Modelle, Verfahren, Software, Anwendungen*. Springer-Lehrbuch. Springer Berlin Heidelberg, Berlin, Heidelberg, 3rd edition, 2013. ISBN 978-3-642-38936-8.

[94] S. Robinson. Discrete-Event Simulation: A Primer. In S. Brailsford, L. Churilov, and B. T. Dangerfield, editor, *Discrete-Event Simulation and System Dynamics for Management Decision Making*. John Wiley & Sons Ltd., Chichester, 2014. ISBN 978-1-118-34902-1.

[95] J. W. Forrester. Industrial Dynamics. A major breakthrough for decision makers. *Harvard Business Review*, 36(4):37–66, 1958.

[96] S. P. Shepherd. A review of system dynamics models applied in transportation. *Transportmetrica B: Transport Dynamics*, 2(2):83–105, 2014. doi:10.1080/21680566.2014.916236.

[97] J. W. Forrester and P. M. Senge. Tests for building confidence in system dynamics models. *TIMS Studies in the Management Sciences*, 14:209–228, 1980.

[98] Y. Barlas. Formal aspects of model validity and validation in system dynamics. *System Dynamics Review*, 12(3):183–210, 1996. doi:10.1002/(SICI)1099-1727(199623)12:3<183::AID-SDR103>3.0.CO;2-4.

[99] J. B. Homer. Partial-model testing as a validation tool for system dynamics (1983). *System Dynamics Review*, 28(3):281–294, 2012. doi:10.1002/sdr.1478.

[100] K. A. Abbas and M. G. H. Bell. System dynamics applicability to transportation modeling. *Transportation Research Part A: Practice and Policy*, 28(5):373–390, 1994. doi:10.1016/0965-8564(94)90022-1.

[101] J. M. Lyneis. System dynamics for market forecasting and structural analysis. *System Dynamics Review*, 16(1):3–25, 2000. doi:10.1002/(SICI)1099-1727(200021)16:1<3::AID-SDR183>3.0.CO;2-5.

[102] B. Miller and J. P. Clarke. Investments under uncertainty in Aair transportation: A real options perspective. *Journal of the Transportation Research Forum*, 44(1):61–47, 2005.

[103] B. Miller and J. P. Clarke. The hidden value of air transportation infrastructure. *Technological Forecasting & Societal Change*, 74(1):18–35, 2007. doi:10.1016/j.techfore.2004.03.011.

[104] E. Suryani, S.-Y. Chou, and C.-H. Chen. Air passenger demand forecasting and passenger terminal capacity expansion: A system dynamics framework. *Expert Systems with Applications*, 37(3):2324–2339, 2010. doi:10.1016/j.eswa.2009.07.041.

[105] E. Suryani, S.-Y. Chou, and C.-H. Chen. Dynamic simulation model of air cargo demand forecast and terminal capacity planning. *Simulation Modelling Practice and Theory*, 28:27–41, 2012. doi:10.1016/j.simpat.2012.05.012.

[106] I. E. Manataki and K. G. Zografos. A generic system dynamics based tool for airport terminal performance analysis. *Transportation Research Part C: Emerging Technologies*, 17(4):428–443, 2009. doi:10.1016/j.trc.2009.02.001.

[107] I. E. Manataki and K. G. Zografos. Assessing airport terminal performance using a system dynamics model. *Journal of Air Transport Management*, 16(2):86–93, 2010. doi:10.1016/j.jairtraman.2009.10.007.

[108] J. H. Pfaender. *Competitive Assessment of Aerospace Systems using System Dynamics*. PhD Thesis, Georgia Institute of Technology, 2006. URL `https://smartech.gatech.edu/bitstream/handle/1853/14014/pfaender_j_holger_200612_phd.pdf`.

[109] D. Csala and S. Sgouridis. Modeling Dynamic Transitions in the Global Air Transport System: A System Dynamics Tool for Competitive Industry Assessment. In *Proceedings of the 31th International Conference of the System Dynamics Society*, Cambridge, Massachusetts, USA, 2013. URL `https://proceedings.systemdynamics.org/2013/proceed/papers/P1127.pdf`.

[110] P. Bießlich, M. Schröder, V. Gollnick, and K. Lüdjens. A System Dynamics Approach to Airport Modeling. In *Proceedings of the 14th AIAA Aviation Technology, Integration, and Operations Conference*, Altanta, Georgia, USA, 2014. URL `https://arc.aiaa.org/doi/10.2514/6.2014-2159`.

[111] J. Qin. *System Dynamics Based Simulation Modelling for Airport Revenue Analysis*. PhD Thesis, The University of Western Australia, 2016. URL `https://research-repository.uwa.edu.au/files/11789819/THESIS_DOCTOR_OF_PHILOSOPHY_QIN_Jing_2016.pdf`.

[112] M. Urban, U. Kluge, K. O. Plötner, G. Barbeito, S. Pickl, and M. Hornung. Modelling the European Air Transport System: A System Dynamics Approach. In *Proceedings of the 66th Deutscher Luft- und Raumfahrtkongress 2017*, Garching, Germany, 2017. URL `https://publikationen.dglr.de/?tx_dglrpublications_pi1[document_id]=450125`.

[113] A. Mayrhofer. *Modelling of Airport Dynamics and the Interaction between Airports and Airlines*. Master Thesis, Technische Universität München, 2019.

[114] F. M. Bass. A New Product Growth for Model Consumer Durables. *Management Science*, 15(5):215–227, 1969. URL `https://www.jstor.org/stable/2628128`.

[115] J. D. W. Morecroft. *Strategic Modelling and Business Dynamics: A Feedback Systems Approach*. John Wiley & Sons Ltd., Chichester, 2nd edition, 2015. ISBN 978-1-118-99481-8.

[116] J. Struben and J. D. Sterman. Transition Challenges for Alternative Fuel Vehicle and Transportation Systems. *Environment and Planning B: Urban Analytics and City Science*, 35(6):1070–1098, 2008. doi:10.1068/b33022t.

[117] C. Thies, K. Kieckhäfer, and T. S. Spengler. Market introduction strategies for alternative powertrains in long-range passenger cars under competition. *Transportation Research Part D: Transport and Environment*, 45:4–27, 2016. doi:10.1016/j.trd.2015.05.002.

[118] D. R. Keith, J.R. Struben, and S. Naumov. The Diffusion of Alternative Fuel Vehicles: A Generalised Model and Future Research Agenda. *Journal of Simulation*, 14(4):260–277, 2020. doi:10.1080/17477778.2019.1708219.

[119] G. Walther, J. Wansart, K. Kieckhäfer, E. Schnieder, and T. S. Spengler. Impact assessment in the automotive industry: mandatory market introduction of alternative powertrain technologies. *System Dynamics Review*, 26(3):239–261, 2010. doi:10.1002/sdr.453.

[120] F. Dobruszkes, M. Givoni, and T. Vowles. Hello major airports, goodbye regional airports? Recent changes in European and US low-cost airline airport choice. *Journal of Air Transport Management*, 59:50–62, 2017. doi:10.1016/j.jairtraman.2016.11.005.

[121] Airbus. Global Market Forecast 2019-2038: Cities, Airports & Aircraft. Technical report, 2019.

[122] D. M. McEvoy. *A Guide to Business Statistics*. John Wiley & Sons Ltd., Hoboken, 2018. ISBN 978-1-119-13835-8.

[123] Official Airline Guide (OAG). Scheduled Flight Database, 2014.

[124] Official Airline Guide (OAG). Scheduled Flight Database, 2018.

[125] M. Schmidt and K. O. Plötner. IB 2013/13003 SMART Reference Costing Model: Internal Report, Bauhaus Luftfahrt e. V., 2013.

[126] Boeing. Current Market Outlook 2017-2036. Technical report, 2017. URL `www.boeing.com/resources/boeingdotcom/commercial/market/current-market-outlook-2017/assets/downloads/2017-cmo-6-19.pdf`. Accessed: 24.10.2019.

[127] M. Ben-Akiva and S. R. Lerman. *Discrete Choice Analysis: Theory and Application to Travel Demand*. MIT Press series in transportation studies. MIT Press, Cambridge, Massachusetts, 1985. ISBN 978-0-262-02217-0.

[128] P. Clark. *Buying the Big Jets: Fleet Planning for Airlines*. Routledge, Taylor & Francis Group, New York, 3rd edition, 2017. ISBN 978-1-138-74982-5.

[129] The AnyLogic Company. Anylogic, Simulation Modelling Software. University Edition, Version 8.5.1.

[130] P. L. Ostrowski and T. V. O'Brian. Predicting customer loyalty for airline passengers. In *Tourism: building credibility for a credible industry – Proceedings of the Travel and Tourism Research Association twenty-second annual conference*, Long Beach, California, USA, 1991.

[131] M. Fishbein. An Investigation of the Relationships between Beliefs about an Object and the Attitude toward that Object. *Human Relations*, 16(3):233–239, 1963. doi:10.1177/001872676301600302.

[132] H. Meffert, C. Burmann, M. Kirchgeorg, and M. Eisenbeiß. *Marketing: Grundlagen marktorientierter Unternehmensführung: Konzepte - Instrumente - Praxisbeispiele*. Springer Gabler, Wiesbaden, Heidelberg, 13th edition, 2019. ISBN 978-3-658-21195-0. doi:10.1007/978-3-658-21196-7.

[133] G. Pasaoglu, G. Harrison, L. Jones, A. Hill, A. Beaudet, and C. Thiel. A system dynamics based market agent model simulating future powertrain technology transition: Scenarios in the EU light duty vehicle road transport sector. *Technological Forecasting and Social Change*, 104:133–146, 2016. doi:10.1016/j.techfore.2015.11.028.

[134] P. Pfaffenbichler, G. Emberger, and S. Shepherd. A system dynamics approach to land use transport interaction modelling: the strategic model MARS and its application. *System Dynamics Review*, 26(3):262–282, 2010. doi:10.1002/sdr.451.

[135] U.S. Energy Information Administration. U.S. Gulf Coast Kerosene-Type Jet Fuel Spot Price FOB (Dollars per Gallon). URL `https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EER_EPJK_PF4_RGC_DPG&f=M`. Accessed: 24.10.2020.

[136] C. M. Christensen, R. McDonald, E. J. Altman, and J. E. Palmer. Disruptive Innovation: An Intellectual History and Directions for Future Research. *Journal of Management Studies*, 55(7):1043–1078, 2018. doi:10.1111/joms.12349.

[137] P. Belobaba. Overview of Airline Economics, Markets and Demand. In P. Belobaba, A. Odoni, and C. Barnhart, editors, *The Global Airline Industry*, pages 47–72. John Wiley & Sons, Ltd., Chichester, 1st edition, 2009. ISBN 978-0-470-74077-4.

[138] P. Belobaba. Fundamentals of Pricing and Revenue Management. In P. Belobaba, A. Odoni, and C. Barnhart, editors, *The Global Airline Industry*, pages 73–111. John Wiley & Sons, Ltd., Chichester, 1st edition, 2009. ISBN 978-0-470-74077-4.

[139] International Civil Aviation Organisation (ICAO). ICAO Carbon Emissions Calculator Methodology: Version 10, June 2017, 2017. URL `https://www.icao.int/environmental-protection/CarbonOffset/Documents/Methodology%20ICAO%20Carbon%20Calculator_v10-2017.pdf`. Accessed: 21.07.2020.

[140] International Civil Aviation Organisation (ICAO). List of Low-Cost-Carriers (LCCs), 2017. URL `https://www.icao.int/sustainability/Documents/LCC-list.pdf`. Accessed: 11.02.2018.

[141] Boeing. Current Market Outlook 2019-2038: Regional Passenger Traffic Growth -Data for Forecasted RPK Growth 2018-2038 [billions] (EUR-NAM). Technical report, 2019. URL `https://public.tableau.com/app/profile/theboeingcompany/viz/2019CommercialMarketOutlook-TEST/COMMERCIALMARKETOUTLOOK`. Accessed: 30.03.2020.

[142] P. L. Ostrowski, T. V. O'Brien, and G. L. Gordon. Service quality and customer loyalty in the commercial airline industry. *Journal of Travel Research*, 32(2):16–24, 1993. doi:10.1177/004728759303200203.

[143] S. Steinke. Dauerläufer Airbus A330, 2021. URL `https://www.flugrevue.de/zivil/widebody-bestseller-dauerlaeufer-airbus-a330/`. Accessed: 02.02.2022.

[144] Boeing. Current Market Outlook 2015-2034. Technical report, 2015. URL `https://aidat.in/wp-content/uploads/2016/09/Boeing-Current-Market-Outlook-2015.pdf`. Accessed: 21.10.2016.

[145] Flightradar24. data query on transatlantic flight frequencies per month in 2018. URL `www.flightradar24.com`. Accessed: 27.11.2019.

[146] M. Heinemann. *Messung und Darstellung von Ungleichheit*. Working Paper Series in Economics No. 108, Leuphana Universität Lüneburg, Institut für Volkswirtschaftslehre, Lüneburg, 2008. URL `http://hdl.handle.net/10419/28226`.

[147] Eurocontrol. Base of aircraft data (BADA), 2015. URL `https://www.eurocontrol.int/services/bada`. Accessed: 13.07.2016.

[148] N. P. Randt. *Aircraft Technology Assessment Using Fleet-Level Metrics*. PhD Thesis, Technische Universität München, 2016. URL https://mediatum.ub.tum.de/603786?query=randt&show_id=1277838&srcnodeid=603786.

[149] Bundesverband der Deutschen Luftverkehrswirtschaft (BDL). CORSIA: Globales marktbasiertes Klimaschutzinstrument für den internationalen Luftverkehr: Positionspapier, 2017. URL https://www.bdl.aero/wp-content/uploads/2018/08/BDL-Positionspapier-zum-ICAO-Klimaschutzinstrument-CORSIA-Juni-2017.pdf. Accessed: 10.07.2021.

[150] D. W. Gillen, W. G. Morrison, and C. Stewart. Air travel demand elasticities: Concepts, issues and measurement: Final Report, Department of Transport, Ottawa. Technical report, Government of Canada, Ottawa, 2002.

[151] International Civil Aviation Organisation (ICAO). Frequently Asked Questions (FAQs) related to Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA): 3. What would be the impact of joining CORSIA?, 2017. URL https://www.icao.int/environmental-protection/Documents/A39_CORSIA_FAQs.pdf. Accessed: 07.06.2021.

[152] Intergovernmental Panel on Climate Change (IPCC). Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above the pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the thread of climate change, sustainable development, and efforts to eradicate poverty, 2018. URL https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf. Accessed: 14.07.2021.

[153] International Civil Aviation Organisation (ICAO). Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis, 2021. URL https://www.icao.int/sustainability/Documents/COVID-19/ICAO%20COVID%202021%2007%2006%20Economic%20Impact%20TH%20Toru.pdf. Accessed: 24.10.2021.

[154] International Air Transport Association (IATA). Aviation Carbon Offset Programme: Frequently Asked Questions, Version 10.1, 2020. URL https://www.iata.org/contentassets/922ebc4cbcd24c4d9fd55933e7070947/icop_faq_general-for-airline-participants.pdf. Accessed: 09.05.2020.

[155] L. Jenkinson, P. Simpkin, and D. Rhodes. Civil Jet Aircraft Design: Aircraft Data File for Airbus Aircraft - A330-300, 1999. URL https://booksite.elsevier.com/9780340741528/appendices/data-a/default.htm. Accessed: 14.07.2021.

[156] V. Grewe, L. Bock, U. Burkhardt, K. Dahlmann, K. Gierens, L. Hüttenhofer, S. Unterstrasser, A. G. Rao, A. Bhat, F. Yin, T. G. Reichel, O. Paschereit, and Y. Levy. Assessing the climate impact of the AHEAD multi-fuel blended wing body. *Meteorologische Zeitschrift*, 26(6):711–725, 2017. doi:10.1127/metz/2016/0758.

[157] International Civil Aviation Organisation (ICAO). Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA): Frequently Asked Questions, 2020. URL `https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_FAQs_December%202020_final.pdf`. Accessed: 24.03.2021.

[158] L. Budd, S. Ison, and N. Adrienne. European airline response to the COVID-19 pandemic – Contraction, consolidation and future considerations for airline business and management. *Research in Transportation Business & Management*, 37:100578, 2020. doi:10.1016/j.rtbm.2020.100578.

[159] Organisation for Economic Co-operation and Development (OECD). State Support to the Air Transport Sector: Monitoring developments related to the Covid-19 crisis, 2021. URL `https://www.oecd.org/corporate/State-Support-to-the-Air-Transport-Sector-Monitoring-Developments-Related-to-the-COVID-19-Crisis.pdf`. Accessed: 18.08.2021.

[160] D. Renehan and M. Efthymiou. Transatlantic Market Competition Between Hybrid Carrier and Long-Haul Low-Cost Carrier Business Models. *Journal of Aerospace Technology and Management*, (12):e1820, 2020. doi:10.5028/jatm.v12.1110.

[161] L. Kökény, Z. Kenesei, and G. Neszveda. Impact of COVID-19 on different business models of European airlines. *Current Issues in Tourism*, 25(3):458–474, 2021. doi:10.1080/13683500.2021.1960284.

[162] International Air Transport Association (IATA). Outlook for the global airline industry - April 2021 update: Airline Industry Financial Forecast, 2021. URL `https://www.iata.org/en/iata-repository/publications/economic-reports/airline-industry-economic-performance---april-2021---report/`. Accessed: 10.06.2021.

Appendix A

Link to the transatlantic air transport model documentation

A documentation of the basic TATM as implemented in Anylogic can be accessed using this link: `https://drive.google.com/file/d/1TB1xONBZmTOtYjRsy2ng-9hqgSNKrmjt/view?usp=sharing`.

Appendix B

Airline list from the Sabre database by airline type: FSNC, LHLCC

Table B.1: List of airlines with flight operations above 4,000 km by airline type: FSNC, LHLCC (own depiction, based on data from [63, 79])

IATA airline Code	**Airline name**	**Airline business model**
77	PrivatAir	FSNC
5O	ASL Airlines	FSNC
5W	ASTRAEUS LTD.	FSNC
6G	Go2Sky spol s r.o	FSNC
6O	Orbest S.A.	FSNC
9W	Jet Airways (India) Limited	FSNC
AA	American Airlines	FSNC
AB	Air Berlin GmbH Co. Luftverkehrs KG	FSNC
AC	Air Canada	FSNC
AF	Air France	FSNC
AI	Air India Limited	FSNC
AM	Aeromexico Aerovias de Mexico S.A. de C.V.	FSNC
AY	Finnair Oyj	FSNC
AZ	Alitalia - Societa Aerea Italiana S.p.A	FSNC
B0	DreamJet SAS t/a La Compagnie	FSNC
BA	British Airways p.l.c.	FSNC
BG	Biman Bangladesh Airlines Limited	FSNC
CL	Lufthansa CityLine Gmbh	FSNC
CO	Cobaltair Ltd	FSNC
CU	Cubana de Aviacion S.A.	FSNC
DL	Delta Air Lines, Inc.	FSNC
DU	HEMUS AIR	FSNC
E9	Evelop Airlines S.L.	FSNC
EB	Wamos Air S.A.	FSNC
EC	Openskies	FSNC
EG	Ernest S.p.A dba Ernest Airlines	FSNC

Table A.2.1 continued: List of airlines by airline type: FSNC, LHLCC (own depiction, based on data from [63, 79])

IATA airline Code	Airline name	Airline business model
EI	Aer Lingus Limited	FSNC
EK	Emirates	FSNC
ET	Ethiopian Airlines Enterprise	FSNC
FI	Icelandair	FSNC
GW	Go Fly, LLC.	FSNC
HT	HELLENIC IMPERIAL AIRWAYS	FSNC
HY	Uzbekistan Airways	FSNC
I9	Air Italy S.p.A.	FSNC
IB	Iberia Lineas Aereas de Espana Sociedad Anonima Operadora	FSNC
IP	IBERWORLD AIRLINES S.A. DBA ORBEST	FSNC
J2	Azerbaijan Hava Yollary	FSNC
JU	JSC for Air Traffic-Air SERBIA Belgrade t/a Air Serbia a.d. Beograd	FSNC
KL	KLM Royal Dutch Airlines	FSNC
KU	Kuwait Airways	FSNC
LH	Deutsche Lufthansa AG	FSNC
LM	Loganair Limited	FSNC
LO	LOT - Polish Airlines	FSNC
LT	LongJiang Airlines Co., Ltd.	FSNC
LX	SWISS International Air Lines Ltd. dba Swiss	FSNC
LZ	Swiss Global Air Lines AG	FSNC
MP	Martinair Holland N.V.	FSNC
MT	THOMAS COOK AIRLINES LIMITED	FSNC
MX	COMPANIA MEXICANA DE AVIACION	FSNC
NA	Nesma Airlines Company Ltd.	FSNC
NO	Neos	FSNC
NW	NORTHWEST AIRLINES INC.	FSNC
NZ	Air New Zealand Limited	FSNC
OR	TUI Airlines Nederland B.V.	FSNC
OS	Austrian Airlines AG dba Austrian	FSNC
OY	Andes Lineas Aereas S.A.	FSNC
P6	Privilege Style S.A.	FSNC
PK	Pakistan International Airlines	FSNC

Table A.2.1 continued: List of airlines by airline type: FSNC, LHLCC (own depiction, based on data from [63, 79])

IATA airline Code	**Airline name**	**Airline business model**
PS	Private Stock Company Ukraine International Airlines	FSNC
PU	Plus Ultra Lineas Aereas, S. A.	FSNC
S4	SATA Internacional - Azores Airlines, S.A.	FSNC
SE	XL Airways France	FSNC
SK	Scandinavian Airlines System	FSNC
SN	Brussels Airlines N.V.	FSNC
SQ	Singapore Airlines Limited	FSNC
SS	Corsair t/a Corsair International	FSNC
SU	PJSC Aeroflot	FSNC
TN	Air Tahiti Nui	FSNC
TP	TAP Portugal	FSNC
TS	Air Transat	FSNC
UA	United Airlines, Inc.	FSNC
UN	TRANSAERO AIRLINES	FSNC
US	US AIRWAYS INC.	FSNC
UX	Air Europa Lineas Aereas, S.A.	FSNC
VN	Vietnam Airlines JSC	FSNC
VO	VLM Airlines D.D.	FSNC
VS	Virgin Atlantic Airways Limited	FSNC
VV	Viva Airlines Peru S.A.C.	FSNC
W2	FlexFlight ApS	FSNC
WK	Edelweiss Air AG	FSNC
YU	EUROATLANTIC Airways Transportes Aereos, S.A.	FSNC
ZT	TITAN AIRWAYS LIMITED	FSNC
D8	NORWEGIAN AIR INTERNATIONAL	LHLCC
DY	NORWEGIAN AIR SHUTTLE A.S.	LHLCC
RV	Canada Rouge	LHLCC
WS	WestJet	LHLCC
WW	WOW Air	LHLCC

Appendix C

Overview of additional model input data for calibration

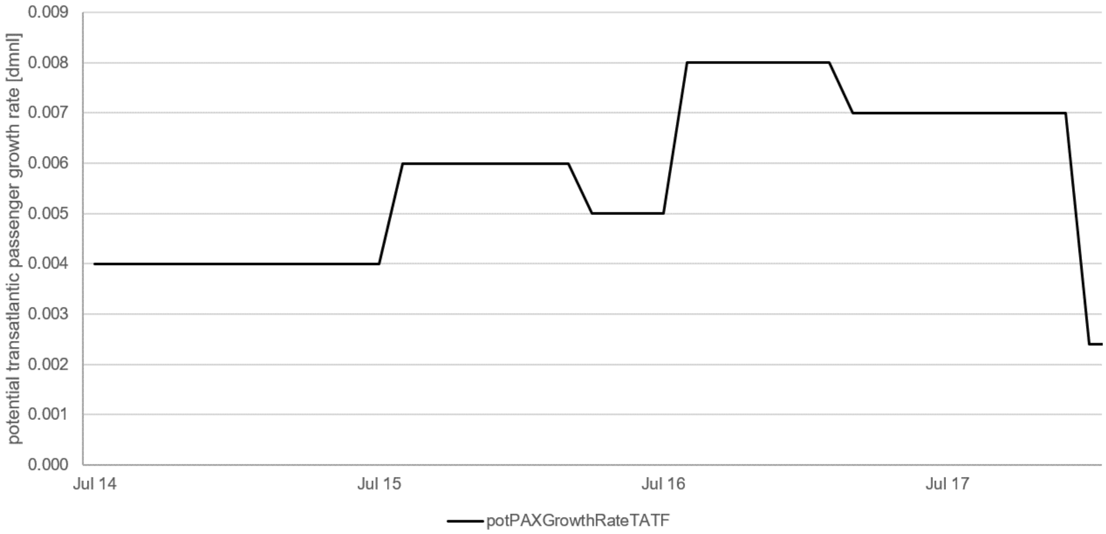

Figure C.1: TATM input data: monthly *potPAXGrowthRateTATF* (own calculation, based on data from [63, 141])

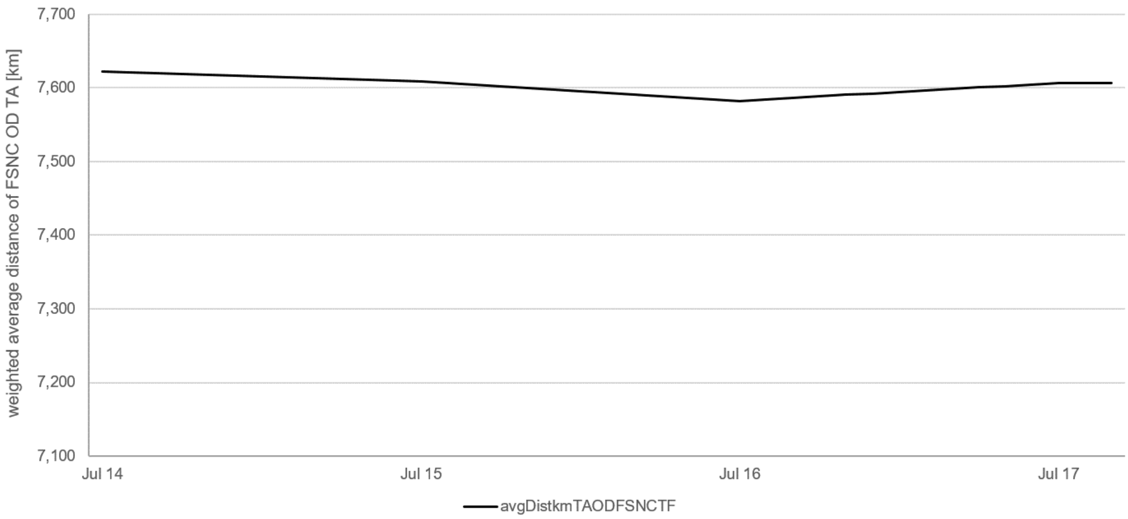

Figure C.2: TATM input data: *avgDistkmTAODFSNCTF* (own calculation, based on data from [63])

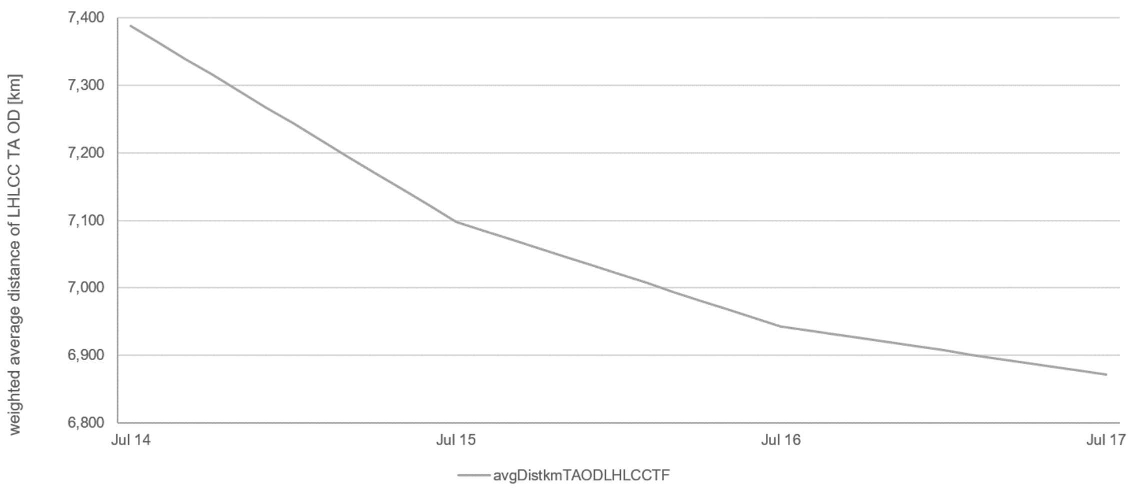

Figure C.3: TATM input data: *avgDistkmTAODLHLCCTF* (own calculation, based on data from [63])

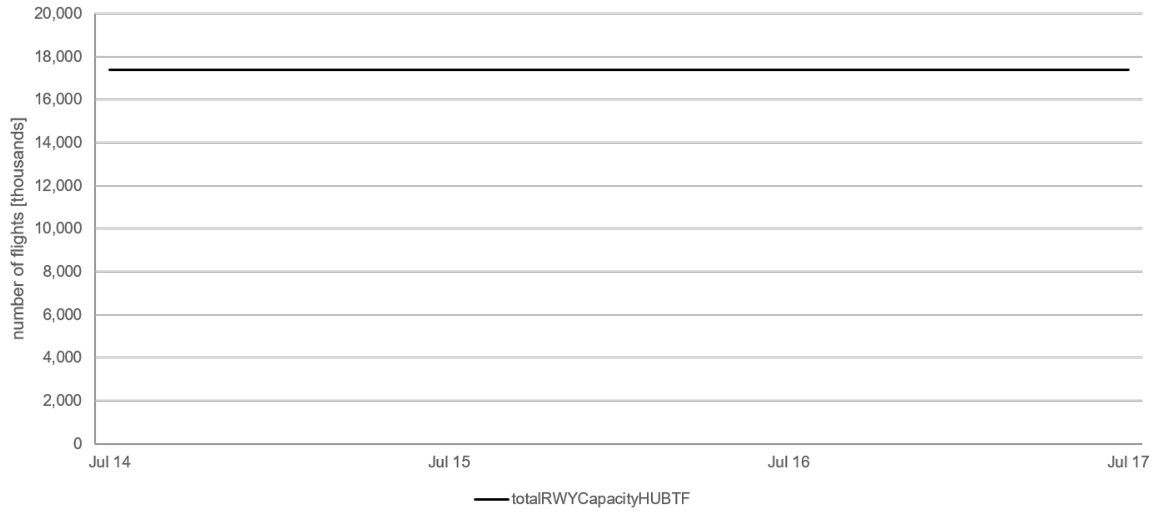

Figure C.4: TATM input data: *totalRWYCapacityHUBTF* (own depiction, based on data from OAG database [7–9, 123, 124] and [113])

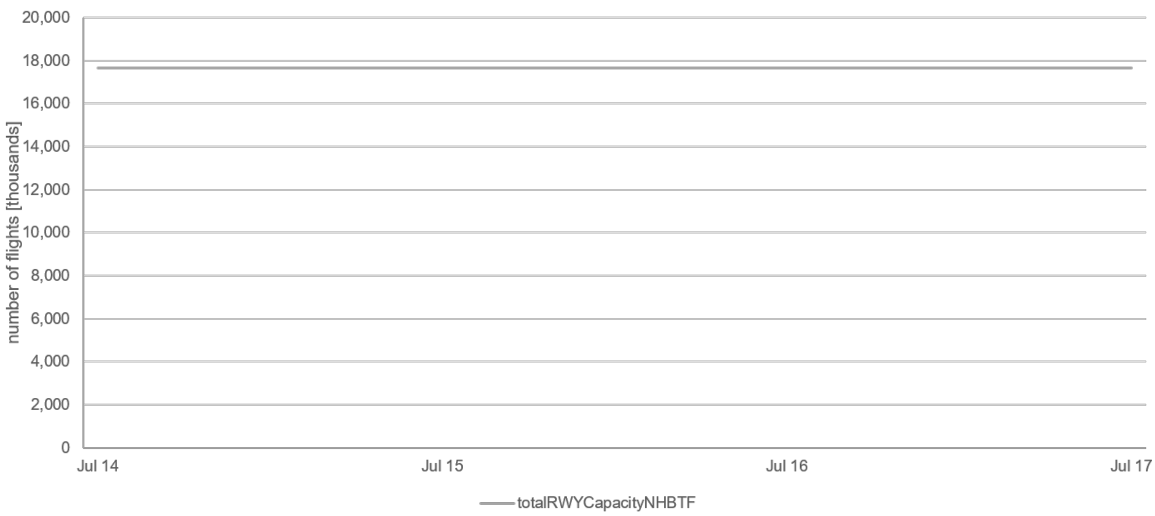

Figure C.5: TATM input data: *totalRWYCapacityNHBTF* (own depiction, based on data from OAG database [7–9, 123, 124] and [113])

Appendix D

List of countries considered in Europe and North America

Table D.1: List of countries considered in Europe and North America (own definition, based on matching country data from [9, 123, 124] with [63])

Countries in Europe		Countries in North America
Albania	Lithuania	Canada
Armenia	Luxembourg	United States of America
Austria	Macedonia	
Azerbaijan	Malta	
Belarus	Republic of Moldova	
Belgium	Monaco	
Bosnia and Herzegovina	Montenegro	
Bulgaria	Netherlands	
Croatia	Norway	
Cyprus	Poland	
Czech Republic	Portugal	
Denmark	Romania	
Estonia	Russian Federation	
Faroe Islands	Serbia	
Finland	Slovakia	
France	Slovenia	
Georgia	Spain	
Germany	Sweden	
Gibraltar	Switzerland	
Greece	Ukraine	
Hungary	United Kingdom	
Iceland		
Ireland		
Italy		
Latvia		

Appendix E

Environmental cost input for Scenario 01

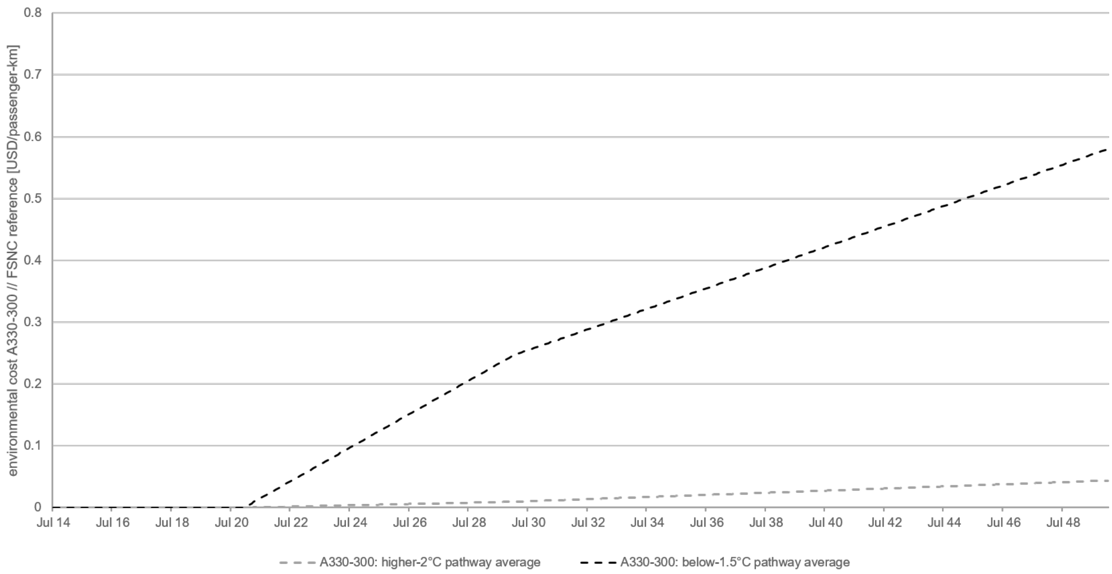

Figure E.1: Average environmental cost development for the FSNC representative aircraft type A330-300 (own depiction, based on data from [151, 152, 155])

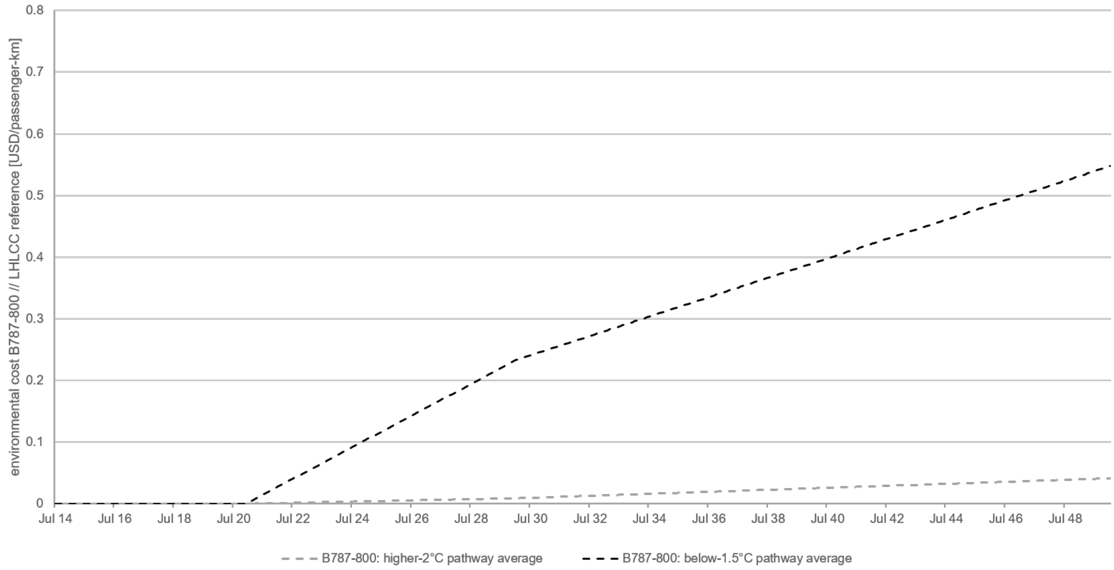

Figure E.2: Average environmental cost development for the LHLCC representative aircraft type B787-800 (own depiction, based on data from [151, 152, 156])

Appendix F

Baseline simulation with reference aircraft type switch

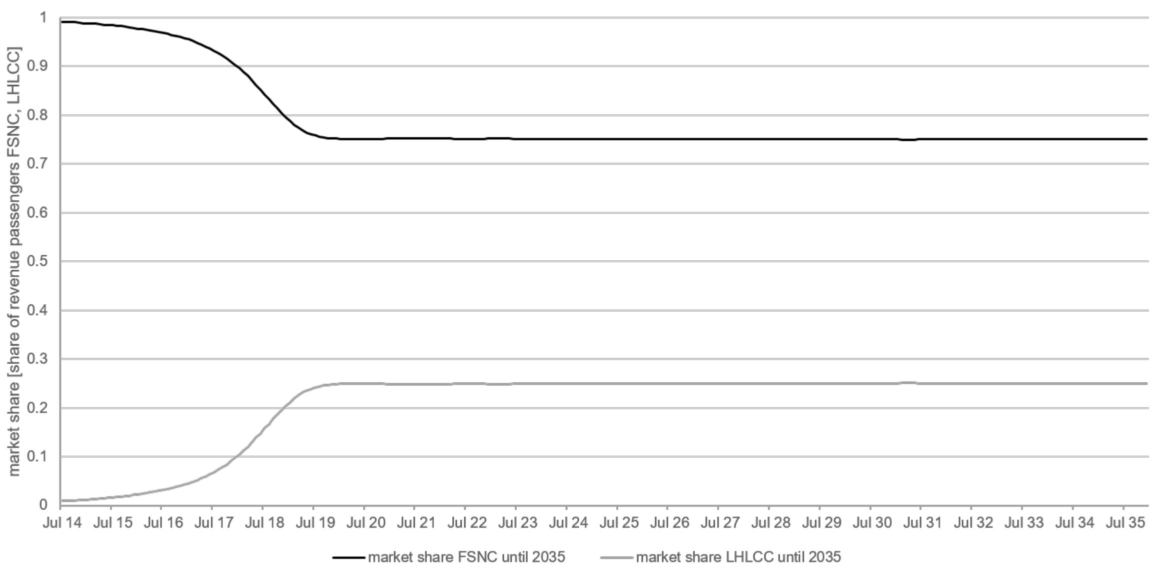

Figure F.1: *B-00*: FSNC operating B787-800 and LHLCC operating A330-300 aircraft type (own depiction)

The resulting LHLCC market share potential for an aircraft type switch is 25.1 %.

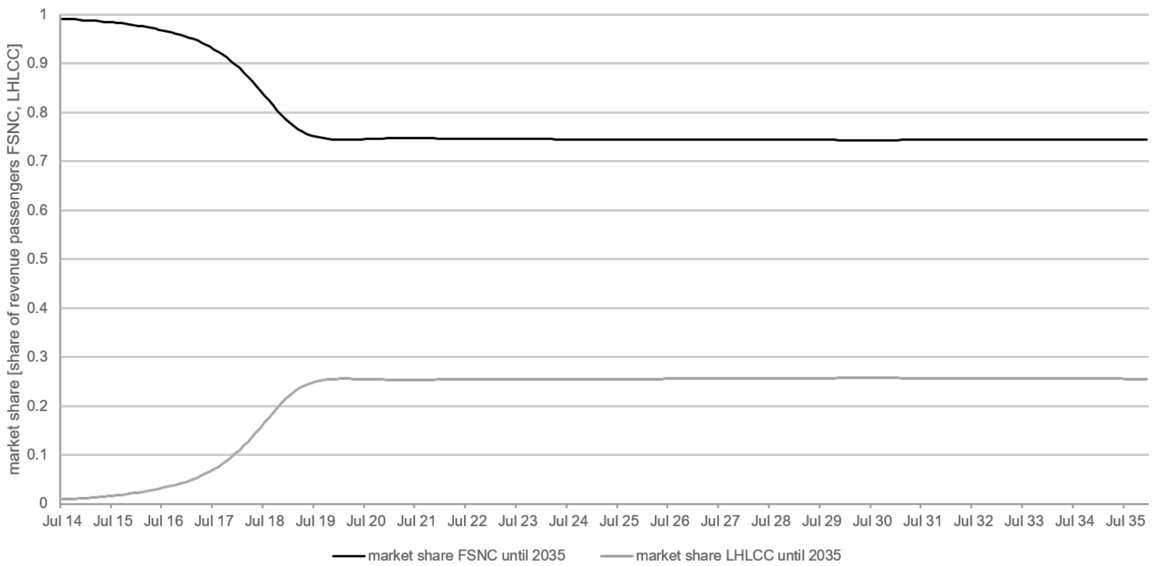

Figure F.2: *B-00*: FSNC and LHLCC operating A330-300 aircraft type (own depiction)

The resulting LHLCC market share potential for an aircraft type switch is 25.7 %.

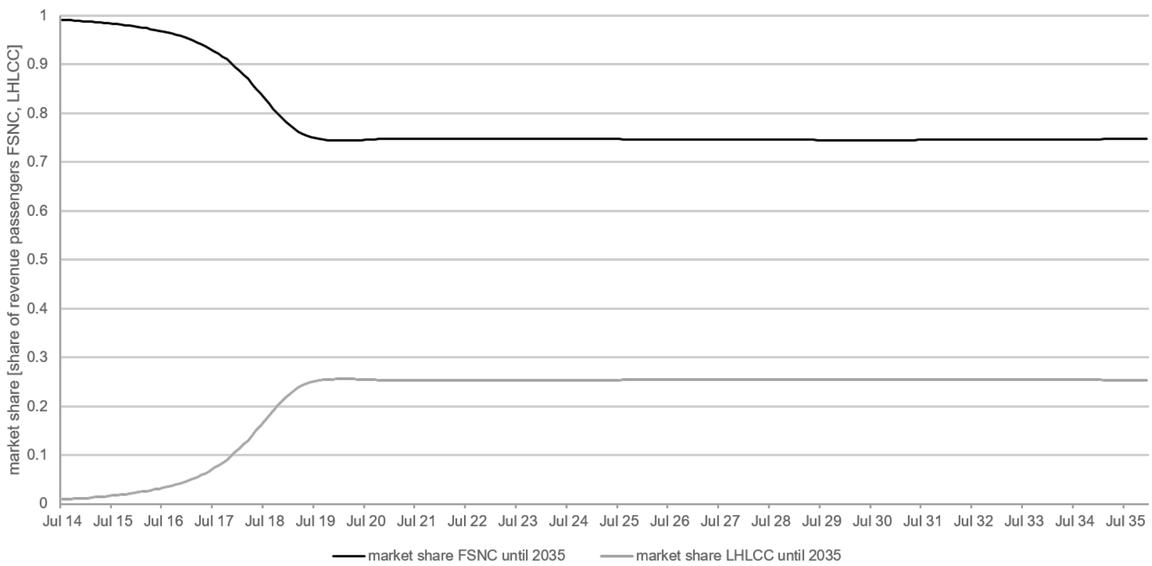

Figure F.3: *B-00*: FSNC and LHLCC operating B787-800 aircraft type (own depiction)

The resulting LHLCC market share potential for an aircraft type switch is 25.5 %.