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Airport Slot Allocation – From the development of criteria to allocation in  
an airport network

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To my parents, to my two brothers and one sister, and to my grandmother,  
for their love and support.





## Abstract

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This dissertation addresses the concept of airport slot allocation as a major regulatory directive in air transport management. In three sequential parts, today's slot allocation procedure, addressing the assignment of time windows for departure and landing operations at coordinated airports, is being assessed and critically evaluated. The three sections evolve from the evaluation and revision of a suitable criteria set to the development and implementation of a network solution. As a key feature, a carbon emissions price including the air carriers' CO<sub>2</sub> emissions is being provided, serving as the allocation principle. In all three parts, explicit reference to the IATA Worldwide Slot Guidelines, representing today's regulatory framework, is being provided, highlighting explicit deficits and drawbacks of that solution. In the first part, the Analytic Hierarchy Process (AHP), as a concept of decision making based on a comparison of criteria and alternatives, is being applied guiding the allocation decision at a single airport. In this section, a set of multiple criteria is being proposed and weighted according a set of slot coordinators' preferences. As a key feature, the concept of Analytic Hierarchy Process (AHP) is being extended by the conduction of a Pairwise Comparison-based Preference Measurement (PCPM) representing one *stage* of the Analytic Hierarchy Process (AHP). In part two, the perspective of the dissertation changes from a single-point to a multiple-point allocation environment. In this part, a model is being provided that includes the allocation of slots in an airport network. As a key feature, slots are being allocated such that the *two* complementary cost functions are being minimized. On one hand, the developed carbon cost function includes the minimization of the *carbon footprint* per traveling passenger. On the other hand, the developed handling cost function is being minimized incorporating a dedicated airport perspective to the solution. In part three, the proposed model is being further extended by the incorporation of a third directive, the minimization of *connection cost*, related to the application of solution in a hub-and-spoke network. As a result, the study demonstrates how slot allocation can be conducted efficiently in an airport network, and how the consideration of the carbon footprint per traveling passenger serves to calculate the allocation optimum.



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## Acronyms

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ACI	Airports Council International.
AHP	Analytic Hierarchy Process.
BER	Berlin Brandenburg Airport.
CC	Connection Cost.
CI	Consistency Index.
CI	Carbon Intensity per Aircraft Type.
CO <sub>2</sub>	Carbon Dioxide.
CoA	Center of Area.
CR	Consistency Ratio.
ETS	Emissions Trading System.
EUR	Euro.
FCO	Rome Fiumicino Airport.
FRA	Frankfurt Airport.
GHG	Greenhouse Gas Emissions.
IATA	International Air Transport Association.
ICAO	International Civil Aviation Organization.
JFK	New York John F. Kennedy Airport.
LHR	London Heathrow Airport.
LTO	Landing Take-Off Cycle.
OTP	On Time Performance.
PCPM	Pairwise Comparison-based Preference Measurement.
PMAX	Maximum Passenger Load.
PVG	Shanghai Pudong Airport.
RI	Consistency Index of Random-Like Matrix.
RPK	Revenue Passenger Kilometer.
SLF	Seat Load Factor.
STC	Service Type Code.
TALLO	Time of Slot Allocation.
TCOMP	Time of Competition Flight.
TCON	Time of Connection Flight Slot Allocation.
TMAX	Time of Maximum Airport Utilization.
TREQ	Time of Airline Slot Request.
USD	US Dollar.
WL	Wait List.
WSG	Worldwide Slot Guidelines.



## 1 Introduction

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*"The core principles of the slot allocation process have remained largely unchanged for decades, despite the momentous changes that have taken place in the air transport sector worldwide and in Europe during that time."*

— (Odoni, 2021)

### 1.1 RESEARCH MOTIVATION

To begin this dissertation, I would like to explain my personal interest and the related research motivation for conducting this study. My main interest and motivation is seen in the particular relevance of slot allocation for all planning and operations related aspects of the air transport sector. Airport slot allocation, and the corresponding regulatory framework, represent *key enablers* for international air traffic. Particularly at major hubs, defined as slot-coordinated airports, the access to *time windows* for operation, that a *slot* per definition represents, is an essential requirement for market entry and for operation (Kappes and Merkert, 2013). Adding to this, and not less relevant is the fact that slot scheduling as the process of time window allocation at these coordinated airports, is being performed following a process established in year 1974, the year of definition and first issue of the IATA Worldwide Slot Guidelines Odoni (2021) (International Air Transport Association, 2019). Since this period of time, international air transport, especially at large international *hubs*, has increased in a substantial way (International Civil Aviation Organization, 2021). Despite this, the applied procedure on slot scheduling today is following a process designed and implemented in year 1974. This particular relevance of the topic of slot allocation, especially for European airports, is visible in Table 1.1, that provides the amount of passengers and corresponding aircraft movements handled at slot coordinated airports in 2018, compared to the amount of total passengers and aircraft movements handled at all airports for selected, European countries.

	Passenger throughput (million)		Arr. & Dep. movements (thousand)	
	Slot coordinated airports	Total	Slot coordinated airports	Total
2018	1,437 (76.4%)	1,880	10,714 (70.4%)	15,212

Table 1.1: Annual passenger throughput and aircraft movements at slot coordinated airports (Level 3) and in total for selected European countries, 2018 (Odoni, 2021)

Looking at the process of slot coordination in detail, and further referring to the mentioned motivations for conducting this study, we realize that neither the present *passenger demand* between two airports A and B nor the consideration of specific, aircraft-related parameters, such as effecting *carbon dioxide emissions* from a flight play a role in the today's regulatory set-up (Benlic, 2018). As a consequence, the conducted empty flights during the COVID-19 pandemic (Sun et

al., 2021), in accordance with a key component of today's allocation principle, indicate that the process established today is at least partially *de-coupled* from demand (Czerny et al., 2008), and thus from the essential characteristics of a market (NERA Economic Consulting, 2004). This application of a *demand-independent* form of allocation leads to multiple implications regarding operations of the air transport sector (Pellegrini et al., 2017). In this dissertation, a set of five research drivers is developed, serving as the guiding principles for the conduction of work. The main driver for research is hence to be seen in addressing the task of implementing a demand-driven form of allocation. In addition, today's challenge related to the context of industrial *decarbonization* is also addressed in this study, given the explicit consideration of air travelers' carbon emissions (i.e., *carbon footprint* per traveling passenger), serving as the guiding principle for allocation. In chapters four and five, a CO<sub>2</sub> price dependent form of slot allocation is proposed.

	Research Driver	Associated questions for airport slot allocation
A	CO <sub>2</sub> emissions & carbon pricing	Can slot allocation be conducted based on consideration of a CO <sub>2</sub> price? How does the allocation result differ, given a CO <sub>2</sub> price consideration and modification?
B	Efficient utilization of resources, concept of "Grandfathering" & topic of empty flights	Can a modified set-up lead to an improved utilization of flights? How can other assets' utilization rates be incorporated in a satisfactory way?
C	Critical assessment of criteria & development of enhanced criteria set	Can the implementation of a modified criteria set lead to an improved allocation result? How can passenger demand be incorporated in such solution?
D	Establishment of a slot coherent approach in the context of multiple airports	Can a modified set-up be implemented based on a combined optimization pattern for start- and end-points of routes? Does this improve the result in a network environment?
E	Integration & quantification of differing stakeholder interests	Can the implementation of an enhanced mechanism include multiple stakeholder perspectives (e.g., airline, airport, regulator)? How can these be quantified and how does the allocation result differ, given a changed stakeholder focus?

Table 1.2: Principal research drivers for the conduction of this study

Each of the presented research drivers represents one focus point in the slot allocation context, referring to a *deficit* or *drawback* in the currently applied solution (International Air Transport Association, 2019). Driver "A" refers to the point "CO<sub>2</sub> emissions and carbon pricing". It includes the question whether slot allocation applied today can be translated to a carbon emissions-based principle, hence, to a mechanism providing an incentive for establishing an *eco-friendly*, "decarbonized" form of travel (International Council on Clean Transportation, ICCT, 2019). Given this, the associated idea is to develop an approach that allocates slots such that the related carbon emissions per traveling passenger are minimized. Driver "A" finds application in chapters four and five of the dissertation. The second driver, "B", refers to the question of establishing an efficient utilization of resources in the context of slot scheduling, meaning primarily an efficient utilization rate of flights. Here, the evidence of empty flights (Sun et al., 2021) associated to the principle of *Grandfathering* is of particular interest. Grandfathering, as it will be further explained below, refers to the fact of maintaining slots of historic precedence in the allocation status quo, given

the compliance with a defined minimum threshold of operation, currently defined as operation of at least 80% of the respective time that a slot was assigned for (van Houten and Burghouwt, 2022) (Cavusoglu, 2022). This relationship, Grandfathering and associated "80%-rule" represents a key functionality in today's regulatory set-up. As observed during COVID-19, when the global demand for air transport suddenly collapsed (International Civil Aviation Organization, 2021)(Hou et al., 2021), this regulatory principle led to controversial issues and debates (Sun et al., 2022) (European Council, 2020). Thus, the question to be addressed in this context is whether a modified set-up could reduce or even prevent the operation of empty flights, and whether the incorporation of aircraft utilization as an allocation parameter and guiding principle serves to establish a more "carbon-efficient" form of result. Driver "B" is primarily addressed in the chapters four and five. The third driver, "C", is attributed to the assessment of allocation criteria according to the status quo. Here, especially chapter two provides reference, given the application of an Analytic Hierarchy Process (AHP) (Saaty, 1980) in the context of a single-airport optimization. In this chapter, a set of ten allocation criteria is being developed based on a stakeholder interview. The criteria set is in the following being ranked and evaluated according to measured slot coordinators' preferences. For the establishment of an improved solution, the critical assessment of criteria is a necessary task, as multiple studies underline (Madas and Zografos, 2006) (NERA Economic Consulting, 2004). The fourth research driver, "D", is referring to the topic of *slot coherency* (Zografos et al., 2017), meaning to the principle of a combined allocation of slots for a start- and end-point of a route. Notably, and referring to today, this principle does not find application, since a single-point allocation principle per slot-coordinated airport is applied today (Madas and Zografos, 2006). This single-point pattern leads to a effort for coordination (Pellegrini et al., 2017), especially at the establishment of (new) routes, since both points including slots for departure and landing need to be put in a matching order (Czerny et al., 2008). In addition to the inclusion of the principle of slot coherency, chapter five includes additional network constraints in the allocation, extending the scope to a hub-and-spoke network (Adler and Smilowitz, 2007). As a fifth and last research driver, "E", inclusion and quantification of stakeholder interests is an additional area of interest, given today's principle does not include such explicit quantification (International Air Transport Association, 2019). In the developed model in chapter four and five, a concept is proposed that includes a quantification of airline- and airport-related interests. In summary, research drivers "A" to "E" address relevant questions with regard to today's slot allocation status quo, and represent the basis for the conduction of this study.

## 1.2 STRUCTURE OF THIS DISSERTATION

The dissertation is based on three parts. Part one includes a critical assessment of the slot allocation criteria according to the IATA Worldwide Slot Guidelines. Based on this, an enhanced criteria set addressing issues resulting from the research drivers "A" to "E" is provided. The developed criteria set serves as the basis for calculation of a single-point optimization, applied in an Analytic Hierarchy Process (AHP) (Saaty, 1980) (Chang, 1996). In part two, the study extends the single-point allocation question to a multiple-point context. In this approach, the *slot coherency* principle (Zografos et al., 2017), referring to the combined allocation of start- and end-points of a route, finds explicit consideration. As a second feature, the introduction of a carbon price serves to include a carbon emissions focus, measuring and monetizing CO<sub>2</sub> emissions per traveling passenger, resulting from the outcome of an allocation. In the third part, the study further extends by the provision of a perspective on a hub-and-spoke network. Based on this, slots are being allocated based on the applied principle of part two, but extended by the inclusion of multiple network constraints, enabling hub-and-spoke traffic. These constraints include a minimum exchange time for traveling passengers at the hub, and enable the allocation of two flight legs in the airport network in a combined way. The three parts of the dissertation, including main research focus and scope are indicated in Figure 1.1.

	Study 1	Study 2	Study 3
Title:	Airport Slot Allocation: Development of an Analytic Hierarchy Process (AHP) for the allocation of slots	Development of a network allocation approach including the CO <sub>2</sub> price of the European Emissions Trading System (ETS)	Implementation of a carbon price in airport slot allocation: Reduction of CO <sub>2</sub> impact per traveling passenger or no change at all?
Key contribution:	Development & evaluation of modified criteria set	Introduction of a carbon price for allocation (CO <sub>2</sub> emissions)	Introduction of multiple network constraints
Allocation scope:	<b>Single-point allocation</b> (single airport)	<b>Multiple-point allocation</b> (slot coherency of routes)	<b>Network allocation</b> (hub-and-spoke network)
Allocation principle:	Comparison of criteria and alternatives according to AHP	Minimization of objective function including two cost functions	Minimization of objective function including three cost functions

Figure 1.1: Overview of three parts of dissertation



### 1.3 SLOT ALLOCATION STATUS QUO

Airport slot allocation, as a principal regulatory process in air transport management (Czerny et al., 2008), refers to the assignment of time windows for departure and landing operations at coordinated airports (Benlic, 2018). Slots as time windows, allocated to air carriers, include the right to use "the full range of airport infrastructure necessary to operate an air service (...) on a specific date and time" (European Commission, 1993). Given this definition, and given the international relevance and application of this concept, the process of slot allocation implies multiple relevant questions to the context of air transport management. The fact that slots are serving as a direct operations requirement for the conduction of a flight, beginning or ending at a slot-coordinated airport, and the fact of slots serving as market entry barriers to (new) market participants are two of the most relevant issues resulting from the status quo (Kappes and Merkert, 2013). At the assessment of today's solution, it is necessary to distinguish airport slots from other concepts. Given this, a differentiation between the slot at an airport and an airway slot needs to be conducted. Airport slots represent the assignment of time windows for operation at an airport (i.e. utilization of airport infrastructure) and airway slots refer to the utilization of airspace in between two airports (Shone et al., 2021) (Murça, 2018). Both concepts include a strategic and an operational component, and are thus related to each other.

#### 1.3.1 *Process of Strategic Slot Allocation*

The process of strategic slot allocation, applicable at Level 3 airports, is defined by the IATA Worldwide Slot Guidelines [International Air Transport Association, 2019](#). This regulatory framework defines the common principle of allocation, to be carried out by an independent slot coordinator (Lang and Czerny, 2022c). In some regions, and for some countries, additional coordination measures exist, partially or fully integrating the principles defined by the Worldwide Slot Guidelines (Pellegrini et al., 2017). For Level 3 airports in the European Union, the European Commission's Regulation 95/93 on the coordination of community airports represents this legislative framework, integrating features and principles of the IATA Worldwide Slot Guidelines (European Commission, 1993).

Referring to the tasks and responsibilities associated to the allocation process, it is primarily the air carrier's responsibility to request and obtain a slot for a coordinated airport in advance to the operation of a flight (Czerny et al., 2008). It is therefore the airline's intention, to manage open slot requests in advance to the operation of a flight, also given that multiple related planning processes are directly depending on the outcome of that allocation (Pita et al., 2013) (Oliveira and Oliveira, 2022). In this context, the topics of aircraft and crew scheduling are to be mentioned as related activities, but, the assignment of slots can also influence long-term decisions taken by the airline, such as fleet renewal or related form of investments (Forsyth, 2018) (Wang et al., 2017). The airport, as the complementary stakeholder in this set-up, reports a determined capacity

for departure and landing operations in advance of a scheduling period to the coordinator (Jacquillat and Odoni, 2015). Since the capacity of landing or departure operations at Level 3 airports is in general limited, the process of slot allocation can be considered as a process for administration of scarce infrastructure resource (Zografos et al., 2012). The airport, that is providing this scarce infrastructure resource, has only few options to increase (or reduce) the hourly capacity for departure or landing operations (Katsigiannis and Zografos, 2021). First, it can open (or close) an additional runway, which changes the hourly constraint for the operation of flights. Second, and with regard to the definition of a slot, the airport can offer additional slots based on the withdrawal of an air carrier from operations, and lastly the airport can implement operational measures for the increase of hourly capacity, given the existing set of physical infrastructure. Such measures, for example tested and implemented at London Heathrow Airport (LHR) before COVID-19, can include a different scheduling of operations in the stage of departure or arrival, achieving the free up of slots and additional runway capacity (Beasley et al., 2001) (Jacquillat and Odoni, 2018).

To enable the coordination of slots and exchange between airlines, IATA as the international regulatory body, hosts bi-annual slot conferences in advance of a scheduling period. These include the participation of the requesting airlines and representatives of associated airports (Czerny et al., 2008). Such slot conferences, conducted every six months for a summer or winter period, are a *key element* of today's set-up (Pellegrini et al., 2017), given the fact that they enable the management and coordination of an (initial) result including mitigation measures among stakeholders in case of a conflicts (Zografos et al., 2017). The slot conferences are thus being conducted *after* an initial result of allocation has been conducted by the coordinator. The process leading to this establishment of initial allocation result is referred to as slot allocation process (Benlic, 2018), and indicated in Figure 1.2.

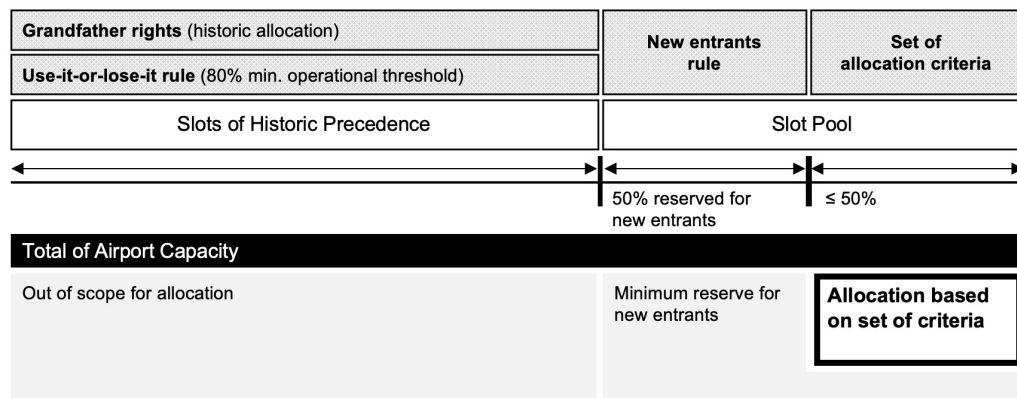


Figure 1.2: Principle of airport slot allocation according to (International Air Transport Association, 2019)

Following the indication of Figure 1.2, the first step of allocation, conducted by the coordinator, includes the consideration of slots of historic precedence, so called *Grandfather rights* (Ribeiro et al., 2019b). These Grandfather rights represent slots assigned to air carriers in a previous period of allocation. They are (re-)allocated to the same air carriers, in case these prove an operational utilization of at least 80% of time, corresponding to the slot time in the previous allocation period (Benlic, 2018). This principle, referred to as Grandfathering, implies that airlines have the right to maintain slots in case of a sufficiently high utilization of the slot, independent from the present (passenger) demand (International Air Transport Association, 2019). This leads to a variety of consequences in light of an effective utilization of assets, as it will be further addressed in this study. After verification of slots of historic precedence, the second step of coordination includes the allocation of slots to a minimum of 50% new entrants, meaning air carriers requesting slots at a respective, coordinated airport for the first time Czerny et al., 2008. This new entrants-rule is the second major directive of IATA's slot allocation mechanism, representing a minimum consideration of new market entries, in case unassigned slots remain available. The third rule to conclude this three-stage approach (Benlic, 2018) is seen in the application of additional criteria for allocation, so called secondary criteria, that guide the coordinator's decision in case of remaining open slots after the rule of Grandfather rights and New entrants-rule have been applied (Pellegrini et al., 2017). The additional criteria set includes principles of allocation and is highlighted in Table 1.3. As being subject to the further course of this study, this criteria set controversial, since none of the provided criteria relates to the fact of (efficient) aircraft utilization (i.e., Seat Load Factor) or to the passenger demand, which is considered to be a key deficit of today's regulatory solution (NERA Economic Consulting, 2004).

No.	Allocation Criterion	Description
1.	Effective Period of Operation	The schedule that will be effective for a longer period of operation in the same season should have priority
2.	Type of Service of Market	The balance of the different types of services (scheduled, charter and cargo) and markets (domestic, regional and long-haul), and the development of the airport route network should be considered
3.	Competition	Coordinators should try to ensure that due account is taken of competitive factors in the allocation of available slots
4.	Curfews	When a curfew at one airport creates a slot problem elsewhere, priority should be given to the airline whose schedule is constrained by the curfew
5.	Requirements of the Traveling Public and Other Users	Coordinators should try to ensure that the needs of the travelling public and shippers are met as far as possible
6.	Frequency of Operation	Higher frequency such as more flights per week should not in itself imply higher priority for slot allocation
7.	Local Guidelines	The coordinator must take local guidelines into account should they exist. Such guidelines should be approved by the Coordination Committee or its equivalent

Table 1.3: Additional allocation criteria according to IATA Worldwide Slot Guidelines (International Air Transport Association, 2019)



## 2 Airport Slot Allocation: Development of an Analytic Hierarchy Process (AHP) for the allocation of slots

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*This chapter refers to the study Weil et al., 2021b<sup>1</sup>.*

### 2.1 INTRODUCTION

The importance of slots as time windows (European Commission, 1993) at coordinated airports was recently highlighted in the bailout of German flag carrier Lufthansa (Financial Times, 2020) as a result of the COVID-19 crisis. The German government offered the airline substantial financial support to help it recover from the collapse in demand associated with the crisis at the beginning of 2020. In return, the airline had to agree to the withdrawal of 24 slots at its two major hubs in Munich and Frankfurt as a condition on competition grounds (Financial Times, 2020). This underlines the relevance of slots to air carriers, yet their definition as true assets is controversial in the international context (Jones et al., 1993). Slots, as a scarce infrastructural resource, represent a right assigned to an air carrier “to use the full range of airport infrastructure necessary to operate an air service [...] on a specific date and time” (European Commission, 1993). In 2018, about 1.5 billion passengers departed from 175 slot-coordinated airports worldwide, representing 43% of annual global passenger traffic (International Air Transport Association, 2018). The importance of slots as time windows at airports has also been revealed in several mergers and acquisitions. In a major example in 2018, Irish low cost carrier Ryanair acquired Austrian carrier Laudamotion resulting in a full transfer of slots from Laudamotion to Ryanair at the airport of Vienna (Financial Times, 2019).

Despite the importance of slots to the worldwide air transport sector, the process of slot allocation is still a manual and time-consuming process. In fact, its principles are based on a framework dating back to 1974 (Czerny et al., 2008). This IATA framework, known as Worldwide Slot Guidelines (WSG) (International Air Transport Association, 2019), determines the allocation process at coordinated airports and specifies important requirements such as segregation of duties. The allocation process is defined as a three-stage hierarchical mechanism (Benlic, 2018). First, the initial allocation is performed by considering historic slots. These are time windows allocated to an air carrier in the previous period (so called "Grandfathering") that it has utilized at least 80% of the time (so called "Use-it-or-lose-it rule"). Second, slots remaining after initial allocation are shifted to a slot pool. At least 50% of slots in the slot pool are reserved for new entrants ("New entrants rule"). Third, the remaining slots are allocated to other participants, taking into consideration a list of secondary allocation criteria (International Air Transport Association, 2019).

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<sup>1</sup> *Airport Slot Allocation: Development of an Analytic Hierarchy Process (AHP) for the allocation of slots, 2021, submission to: EURO Journal on Transportation and Logistics, unpublished working paper; In chapter 2, the term "we" is used to include the authors of Weil et al., 2021b.*

In this study, we develop an AHP model for slot allocation that takes account of an extended set of criteria based on airline-related parameters such as the level of punctuality, CO<sub>2</sub> emissions and the level of location investments. We introduce ten relevant parameters to guide the allocation decision. As a special focus and *in contrast to IATA's existing approach*, we include several relevant externalities in the allocation process. Importantly, we include the applicant's level of CO<sub>2</sub> emissions as a criterion in our model. CO<sub>2</sub> emissions are an important figure to monitor since global aviation accounted for 2.4% of annual emissions in 2018 with an output of about 917 million metric tons (Graver et al., 2019). Remarkably, the level of emissions grew by 32% in just five years between 2013 and 2018. The release of CO<sub>2</sub> is considered to be a major driver of global warming (Dekker et al., 2012). To complete this setup, we consider ten air carriers that compete for the available slot.

The AHP according to Thomas Saaty (1980) is based on the idea of pairwise comparisons of criteria and alternatives. Therefore, in order to derive the allocation result (see Figure 1), we conduct pairwise comparisons of allocation criteria and allocation alternatives (=air carriers). We take a five-level approach (Mu and Pereyra-Rojas, 2017), as illustrated in Figure 1. The first level entails defining the goal, which is the assignment of the slot to the best-fitting slot applicant. In level two we break down the decision into a hierarchy of goals, criteria and alternatives and introduce the set of ten allocation criteria defined for this study. In level three we calculate preference weightings for the criteria. For this - *a special feature of our approach* - we adopt the PCPM (Schlereth et al., 2014) (Scholz et al., 2010) from the AHP. We include this for two reasons. First, PCPM allows us to include several international stakeholders to the process of preference evaluation. Second, we demonstrate that PCPM reduces the number of questions required in the survey from 45 to 20, a reduction of 55%. Level four consists of calculating local results for each criterion, and level five involves deriving overall priorities and answering the allocation question. In this final level, we also conduct a sensitivity analysis of our results.

The contribution of this paper is hence two-fold: First, we extend the established concept of AHP by reducing complexity in the number of pairwise comparisons in the applied industry context. This reduced complexity allows for an easier recruitment of survey participants and a more stable result. Second, by utilizing AHP, we obtain an updated and priority-weighted list of criteria for the specific field of airport slot allocation. Thus, important contemporary challenges such as the eco-efficiency of air travel can be easily incorporated. Both airports and airlines will benefit from greater levels of transparency resulting from the criteria and ensuing ranking of applicants.

In the remainder of our paper, in Section 2 we elaborate on the AHP methodology in the context of slot allocation. We develop the AHP model and introduce the set of allocation criteria. In Section 3 we explain the calculation of results. Section 4 presents analysis of the outputs, paying particular attention to robustness analysis and explicit interpretations of the results. In Section 5 we outline the managerial implications of the results, and in Section 6 we conclude by pointing to future research directions.

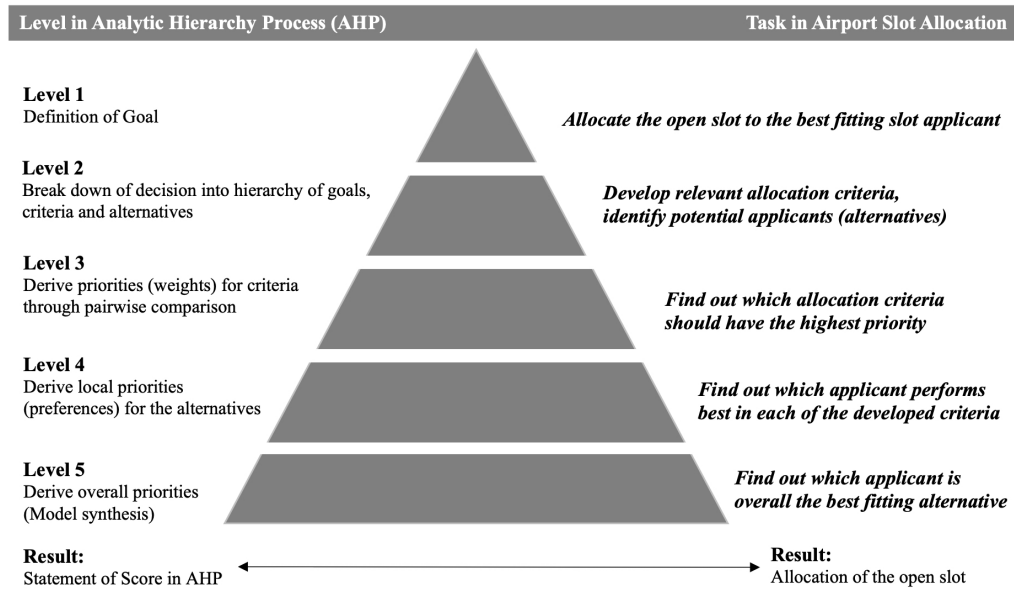


Figure 2.1: Concept of AHP and definition of corresponding tasks in the slot allocation process

## 2.2 MATERIALS AND METHODS

The AHP (Saaty, 1980), as a methodology for multicriteria optimization, has been applied in operational research to various tasks. In the next section we highlight some relevant work and provide furthermore an overview of existing studies in the context of airport slot allocation.

### 2.2.1 Existing studies of the Analytic Hierarchy Process & Airport Slot Allocation

Previous applications of AHP can be found in the study of Vaidya and Kumar (2006) that summarize over 150 application cases in the area of operational research. With a special focus on air transport, Havle and Kilic (2019) develop an application model of the AHP to analyze gross navigation errors during transatlantic flights, structuring the task in sub-categories to reveal major influence factors. Berrittella et al. (2009) investigate relationships between various categories of operating costs and airline business models. In the study of Dozic and Kalic (2014), the AHP is used to analyze the aircraft selection process in the context of airline route management. Strategic slot allocation, as a transport policy phenomenon, has been studied in various works. (Androutopoulos et al., 2020) define the topic as a bi-objective resource constrained project scheduling problem. Verhoef (2010) discusses a potential application of congestion pricing for slot management in combination with sales and a trading system, while Ribeiro et al. (2019b) demonstrate a model with several constraints under real conditions at an airport in Portugal and elaborate a list of improvements to IATA's WSG. Adler et al. (2014) investigate how slot allocation relates to the liberalization of transport systems and public welfare, and Cao and Kanafani (2000) examine slot allocation in terms of the relationship between flight rescheduling and airline profit. Soomer and Franx (2008)



show how the runway arrival problem, as a tactical allocation problem, can be optimized. [Lang and Czerny \(2022c\)](#) question whether the application of Grandfathering can a beneficial solution in comparison to pricing. [Bichler et al. \(2022\)](#) develop a market design in accordance with the IATA Worldwide Slot Guidelines, and [Lang and Czerny \(2022a\)](#) address the topic of slot allocation with regard to the distribution of inbound and outbound passengers. [Cheung et al. \(2021\)](#) analyze the relationship of slot allocation and airline delays on a validated study at Singapore’s Changi Airport, SIN. [Dixit and Jakhar \(2021\)](#) conduct a literature review with the general scope of airport capacity management and solutions, revealing key words and relationships. [Liu et al. \(2022\)](#) provide a network optimization model for slot allocation, including an application at 15 airports in China. [Park and Kim \(2021\)](#) assess the relationship of airlines and airports operating model on the airport efficiency. [Katsigiannis and Zografos \(2021\)](#) develop a solution based on flexibility in flight scheduling, and [Sun et al. \(2022\)](#) investigate on specific outcomes for slots and airport capacity, based on the COVID-19 pandemic. [Cavusoglu and Macário \(2021\)](#) question a potential objective of slot allocation, addressing the question of minimizing delay and maximizing efficiency. [Sun \(2022\)](#) provides a specific review of Korean airports with regard to slots, highlighting the topic of market entries and [Birolini et al. \(2022\)](#) develop an innovative approach, including a customer-centric form of allocation. [Tan et al. \(2021\)](#) refer to the context of slots in an exploratory analysis of flight delays in China. [Presto et al. \(2022\)](#) develop four different measures for flight frequency regulation, focusing on the airways in between two airports. In the study of [Choi \(2021\)](#) specific operational changes in airport operations after the COVID-19 pandemic are analyzed and in [Czerny et al. \(2021\)](#), this topic is also addressed focusing on airports in China. [Shone et al. \(2021\)](#) develop a stochastic solution for the modeling of air traffic management. [Guiomard \(2018\)](#) develops a slot optimization for the specific case of Dublin airport. [Reitzes et al. \(2015\)](#) evaluate the effects of slot exchanges or sales at airports with regard to competition, and [Sheng et al. \(2015\)](#) provide a reference case including slot auctioning. [Zografos and Jiang \(2019\)](#) develop a bi-objective allocation model including fairness.

### 2.2.2 *Definition of multicriteria approach*

Our multicriteria approach consists of ten allocation criteria that guide the allocation decision. Alternatives in our model are represented by air carriers applying for the open slot. Thus, our approach contains two major derivatives of the classic AHP: Priority weightings according to Level 3 (see Figure 1) are derived from a two-cyclic PCPM experiment ([Schlereth et al., 2014](#)) ([Scholz et al., 2010](#)) and the airlines’ performances in Level 4 are calculated through a fuzzification of numbers ([Chang, 1996](#)). The PCPM experiment in Level 3 helps to prioritize the criteria, while also reducing the complexity of our model (see Section 3). The fuzzification of numbers serves to remove uncertainty from the input parameters of the airlines. The applied methodological derivatives and resulting advantages are presented in Table 2.1.



AHP Level	Level 3	Level 4
Applied Model feature	Conduction of a Two-Cyclic PCPM	Fuzzification of Numbers (Fuzzy AHP)
Advantage	Reduction of survey complexity in questionnaire, effort reduction of 55% through reduction of pairwise comparisons from 45 to 20 questions	Consideration of uncertainty in parameters, application of Extent Analysis Method leading to an appropriate model for slot allocation

Table 2.1: Methodological derivatives and resulting advantages for this study

### 2.2.3 Development of allocation criteria

In accordance with the classic AHP, in Level 2 of our approach we break down the criteria. For this purpose, we deconstruct the overall goal of allocating the slot to the best-performing applicant into a variety of (operational) areas. As a starting point, we consider the existing allocation criteria defined in the WSG ([International Air Transport Association, 2019](#)). We then extend IATA’s existing criteria set by including the analysis and recommendations of an experienced slot coordination expert. This expert, an experienced airport manager in charge of determining capacity in the process of slot allocation at a major German airport, was interviewed in parallel with the conduct of this study. He contributed a set of allocation criteria that are (1) relevant to our multicriteria approach, and (2) not considered in IATA’s allocation mechanism as of today.

IATA’s WSG provides common definitions of allocation criteria. The “Key principles of [...] allocation” include statements regarding the segregation of duty (e.g. independence of the coordinator) as well as important timelines in the allocation process. The “Primary slot allocation criteria” define the two highest-priority allocation principles, “Grandfathering” and “New entrants rule” (see Section 1). The “Additional criteria for [...] slot allocation” are employed after applying these two higher-priority rules and guide the slot coordinator in case of remaining open slots. Table 2 presents IATA’s set of (additional) criteria for slot allocation.

For our model, we extract four existing criteria from IATA’s WSG (highlighted in Table 2.2). The first criterion is *Competition*, which relates to the question whether the slot applicant is a new entrant or not. As defined by IATA, competition is an important allocation criterion, and slot coordinators should “try to ensure that due account is taken of competitive factors in the allocation of available slots”. The second criterion is *Time spent on waitlist*, which we define as the effective waiting period in our model. This parameter stipulates that requests “pending on the waitlist should have priority over more recent requests” in the allocation process. The third criterion is *Service type code*, which relates to the airline’s intended type of operations (e.g. charter, passenger, cargo). The fourth is *Route network*, which according to IATA is a sub-function of the *Type of service and market* criterion (see Table 2.2). We split this criterion into two separate entries, given that service type and route network are in principle two different topics. In summary, a total of four allocation criteria were extracted from the WSG on the advice of the interviewed expert. For the remaining six criteria, our model is based on the explicit recommendations of the slot coordination expert, meaning that criteria 5 to 10 were developed specifically for

IATA Criterion	Definition
Effective Period of Operation	The schedule that will be effective for a longer period of operation in the same season should have priority.
Curfews	When a curfew at one airport creates a slot problem elsewhere, priority should be given to the airline whose schedule is constrained by the curfew.
<b>Time Spent on Waitlist</b>	Requests that have been pending on the waitlist should have priority over more recent requests.
<b>Type of Service and Market</b>	The balance of the different types of services (scheduled, charter and cargo) and markets (domestic, regional and long haul), and the development of the airport <b>Route Network</b> should be considered.
<b>Competition</b>	Coordinators should try to ensure that due account is taken of competitive factors in the allocation of available slots.
Requirement of the Traveling Public and Other Users	Coordinators should try to ensure that the needs of the traveling public and shippers are met as far as possible.
Frequency of Operation	Higher frequency such as more flights per week should not in itself imply higher priority for slot allocation.
Local Guidelines	The coordinator must take local guidelines into account should they exist. Such guidelines should be approved by the Coordination Committee or equivalent.

Table 2.2: Allocation criteria according to IATA Worldwide Slot Guidelines ([International Air Transport Association, 2019](#)), Criteria extracted for this study are shown in bold

this study to produce an allocation mechanism that is based on operational parameters.

*Punctuality:* The first advice proposed by the coordination expert is the inclusion of punctuality as an allocation criterion. The level of punctuality is not currently considered in allocation decisions, and hence air carriers have no incentive to operate punctual flights. Indeed, 25% of all flight arrivals in Germany were delayed by more than 15 minutes in 2018, and 45% of these delays were attributable to airline operations ([Deutsche Flugsicherung \(DFS\), 2019](#)).

*CO<sub>2</sub> Emissions:* Greenhouse Gas (GHG) emissions and the related release of carbon dioxide (CO<sub>2</sub>) are an important parameter for the achievement of decarbonization in the aviation sector and more sustainable travel. As mentioned in Section 1, worldwide aviation accounted for 2.4% of annual CO<sub>2</sub> emissions in 2018, with an output of about 917 million metric tonnes ([Graver et al., 2019](#)).

*Passenger satisfaction:* Passengers are a key component of commercial aviation and passenger satisfaction is therefore a crucial parameter for any commercial airline. We include this parameter as the seventh allocation criterion.

*Overbidding rate:* According to our interview partner, and as suggested by ([Czerny et al., 2008](#)), overbidding is a malpractice in the current allocation mechanism. This refers to airlines requesting more slots than they require. One reason may be that airlines attempt to use slots as market entry barriers for competitors, but it may also be due to uncertainty in the business environment. The overbidding rate is included as a criterion in our model, with a defined scale between 1.0 and 2.0.

*Location investments:* Air carriers' location investments are an important parameter for the measurement of long-term interests at a location. One example of location investments is Fraport's A-Plus terminal section in Frankfurt/Main,

with an overall investment of EUR 700 million (Fraport AG, 2012). As a result of establishing a mutual agreement between airport operator and airline, German flag carrier Lufthansa was awarded the exclusive right to operate flights from that new terminal section. This led to the establishment of further infrastructure facilities by the airline, such as business and senator lounges, retail stores and waiting areas (Lufthansa AG, 2020). In fact, location investments can be seen as a measure of airport–airline cooperation.

*Retail business:* Retail business is an important field of activity for any major airport. Of total airport revenues in 2017, 55.8% were declared as aeronautical and 39.9% as non-aeronautical revenues, with 4.3% from other sources. The average cost per passenger for airports over the same period of time was USD 13.69, exceeding global aeronautical revenues per passenger of USD 9.95, making this topic a relevant point to focus on. (International Airport Review, 2019). Table 2.3 summarizes the allocation criteria included in our model:

AHP Criterion	Definition
C1 Competition	Applicant is a new entrant and allocation creates competition
C2 Punctuality	Applicant has a high level of punctuality
C3 Retail Business	Applicant's passengers have a high retail value for the airport
C4 Passenger Satisfaction	Applicant has a high level of passenger satisfaction
C5 Overbidding Rate	Applicant has a low overbidding rate in previous periods
C6 Location Investments	Applicant plans investments at the location
C7 Route Network	Applicant's route network is a network extension for the airport
C8 CO <sub>2</sub> Emissions	Applicant generates low level of CO <sub>2</sub> emissions per aircraft
C9 Effective Waiting Period	Applicant spent a long time on the waitlist
C10 Service Type Code	Applicant's service type code matches best to the open slot

Table 2.3: Allocation criteria and definitions developed for this study

### 2.3 DEVELOPMENT OF THE AHP MODEL

Having defined the criteria, we aimed to derive preference weightings for Level 3 of the AHP for each criterion presented in Table 2.3. One goal was to make the preference weighting process transparent. This was challenging owing to the large number of criteria and the limited availability of slot coordination experts with the knowledge necessary to make rigor judgements in the area of investigation. State-of-the-art preference measurement techniques, such as discrete choice experiments (Schlereth et al., 2018) were not applicable, because they require a large number of respondents (~ 100). Therefore, we decided to apply the recently proposed PCPM approach (Scholz et al., 2010) (Schlereth et al., 2014), which allows the direct measurement of preference weightings with a smaller group of respondents.

To this end, we elicited preference weightings from eight selected industry experts who all had the knowledge required to assess the defined allocation criteria, and several years of professional experience of slot coordination in their respective countries. Two respondents were slot coordination experts from Switzerland, two from Germany, and one each from Austria, UK, USA and

Japan. An example of the experiment conducted, including the pairwise comparison logic of AHP, is provided in the Appendix.

### 2.3.1 Ranking of allocation criteria according to PCPM

To calculate criteria weightings  $w$ , the classic methodology of the AHP requires pairwise comparison of all criteria (e.g. C1 Competition versus C6 Location Investments) in order to determine which criterion should be weighted and by how much. In our case, this would have required our respondents to answer 45 questions. In order to reduce the complexity of preference determination in our survey, and thus also to broaden the set of respondents, we decided to modify the classic AHP to include a PCPM experiment (Schlereth et al., 2014). This enabled us to derive criteria weightings for the AHP and to reduce the pairwise comparison questions from 45 to 20 through a two-cyclic approach (Scholz et al., 2010). This reduction was achieved by calculating the missing preference ratios, as indicated in the Appendix. An application of criteria weightings on the discrete Saaty scale is presented in Table 2.4.

Punctuality					CO <sub>2</sub> Emissions			
Absolutely more important	Strongly more important	Much more important	More important	Equal importance	More important	Much more important	Strongly more important	Absolutely more important
1/9	1/7	1/5	1/3	1	3	5	7	9

Table 2.4: Example of pairwise comparison of criteria and applied discrete Saaty scale

Conducting PCPM with the selected participants resulted in the following ranking of criteria:

Rank	C <sub>k</sub>	Criterion Name	Weightings $w_k$
1	C1	Competition	0.2225
2	C8	CO <sub>2</sub> Emissions	0.1067
3	C3	Retail Business	0.1050
4	C10	Service Type Code	0.0980
5	C2	Punctuality	0.0974
6	C9	Effective Waiting Period	0.0967
7	C7	Route Network	0.0851
8	C6	Location Investments	0.0734
9	C5	Overbidding Rate	0.0699
10	C4	Passenger Satisfaction	0.0454

Table 2.5: Allocation criteria weightings after conducting PCPM with eight slot coordinators

As shown in Table 2.5, participants in the PCPM ranked *Competition*, *CO<sub>2</sub> Emissions* and *Retail Business* as the highest-priority criteria amongst those proposed, while *Passenger satisfaction*, *Overbidding rate* and *Location investments* were regarded as less important.

The above-average result for CO<sub>2</sub> emissions can be interpreted as evidence that the environmental impact of aviation has become a high priority for slot coordination stakeholders. The poor result for passenger satisfaction shows that coordination stakeholders do not value this criterion as important in the allocation process. The same is true of overbidding rate and location investments, both of which are relevant to the long-term planning of airport operations.

With regard to the results shown in Table 2.5, it should be noted that the criteria chosen for our study were based on IATA's existing coordination guidelines and on the expert interview conducted prior to the PCPM. Hence, our criteria are those deemed most relevant by the allocation expert interviewed. The PCPM experiment can therefore be seen as an additional validation of the selected criteria by a further eight international reviewers. The preference weightings  $w_k$  are indicated in the right-hand column of Table 2.5.

### 2.3.2 Verification of Consistency Ratio (CR)

To verify the consistency of the PCPM, we determine the consistency ratio CR of our criteria ranking (Mu and Pereyra-Rojas, 2017). CR is calculated by the division of consistency index CI through the consistency index of a random-like matrix RI (2.1). From Saaty (1980), we know that RI with  $n = 10$  criteria is equal to 1.49 (Saaty, 1980). We calculate CI and CR:

$$CI = \frac{(\lambda_{\max} - n)}{(n - 1)} = \frac{(11.72 - 10)}{(10 - 1)} = 0.19 \quad (2.1)$$

$$\text{With } n = 10 \text{ and } \lambda_{\max} = 11.72$$

$$CR = \frac{CI}{RI} = \frac{0.1911}{1.49} = 0.1283 \quad (2.2)$$

From (2.2) we can state that our result is sufficiently consistent, given Consistency Ratio (CR)  $\sim 0.1$ .

### 2.3.3 Calculation of slot applicants' results

As alternatives, we introduce ten air carriers applying for the open time window in our AHP model. To reflect the allocation process at a large international airport, we consider airlines from different geographic areas, with two each from Europe, North America and Asia and one from Africa, Latin America, Middle East and Oceania. Table 2.6 provides an overview of these air carriers' country of origin and the intended aircraft types. For confidentiality reasons, corporate names are not mentioned.

Table 2.7 indicates how the parameters relating to the developed categories are operationalized. Five are based on empirical sources, one is based on a range decision (between 1.0 and 2.0) and model assumption, and four are based on binary decision variables and model assumptions. Details of the parameter entries considered for each slot applicant are shown in the Appendix.

Europe		North America		Asia		Latin America		Middle East	Africa	Oceania
A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	
Netherlands	Germany	Canada	USA	Singapore	Japan	Brazil	UAE	Ethiopia	Australia	
A319	A320	B757	B767	A380	A350	A340	B777	A330	B787	

Table 2.6: Slot applicants' countries of origin and deployed aircraft type

C <sub>k</sub>	Empirical Based	Source of Data	MIN Value	MAX Value
C2	Punctuality	OTP - On Time Performance 2019	69.9%	100.0%
C3	Retail Business	Average household expenditure per capita per air carrier country of origin 2018	USD 1,043	USD 37,903
C4	Passenger Satisfaction	SKYTRAX World's Top 100 Airlines 2019	Rank 100	Rank 1
C6	Location Investments	Investments per Corporate Financial Data, 2018	1.62	17.99
C8	CO <sub>2</sub> Emissions	CO <sub>2</sub> Emissions during ICAO LTO <sup>1</sup> for deployed aircraft type in kg	13,048 kg	1,000 kg
C <sub>k</sub>	Binary Decision	Model Assumption	MIN Value	MAX Value
C1	Competition	Applicant is a New Entrant	0	1
C7	Route Network	Route is a Network Extension to the Airport	0	1
C9	Effective Waiting Period	Applicant spent a long time on the Waitlist	0	1
C10	Service Type Code	Applicant's Service TC fits to the available slot	0	1
C <sub>k</sub>	Range Decision	Model Assumption	MIN Value	MAX Value
C5	Overbidding Rate	Applied overbidding rate in range of 1.0-2.0	1.0	2.0

<sup>1</sup> ICAO LTO Measurement of CO<sub>2</sub> output per aircraft type in kg during a standardized LTO

Table 2.7: Considered input parameters of slot applicants and defined MIN-/MAX range

### 2.3.3.1 Translation of operational parameters in allocation model

To calculate the results of the allocation, we translate the applicant parameters into the logic of the AHP. For this, we define a MIN and MAX range for each selected parameter entry and translate the values into entries on the discrete Saaty scale (Saaty, 1980). For CO<sub>2</sub> Emissions and Passenger Satisfaction, we apply an inverse logic, since lower values are desirable for these two categories. The minimum and maximum values are based on the best and worst applicant entries in our set, apart from categories C1 Punctuality and C8 CO<sub>2</sub> Emissions, where we manually set the maximum value according to the entry indicated in Table 2.7. Since carrier A7 from Latin America is not represented in the

SKYTRAX Top 100 ranking for passenger satisfaction, we assume the worst possible rank of 100 in this category for this air carrier. The resulting interval borders for each category on the discrete Saaty scale are shown in Table 2.8.

	MIN	1/9	1/7	1/5	1/3	1	3	5	7	9	MAX
C1 Competition	0	0	-	-	-	-	-	-	-	1	1
C2 Punctuality	69.9%	69.9%	73.0%	76.4%	79.9%	83.1%	86.5%	89.9%	93.2%	96.6%	100%
C3 Retail Business	USD 1,043	USD 1,043	USD 5,139	USD 9,235	USD 13,331	USD 17,427	USD 21,523	USD 25,619	USD 29,715	USD 33,811	USD 37,903
C4 Passenger Sat.	100	100	89	78	67	56	44	33	22	11	1
C5 Overb. Rate	2	2	1.88	1.77	1.66	1.55	1.44	1.33	1.22	1.11	1
C6 Location Inv.	1.62	1.6	3.4	5.2	7.1	8.9	10.7	12.5	14.4	16.2	17.99
C7 Route Network	0	0	-	-	-	-	-	-	-	1	1
C8 CO <sub>2</sub> Emissions	13,048kg	13,048kg	11,709kg	10,370kg	9,031kg	7,692kg	6,353kg	5,014kg	3,675kg	2,336kg	1,000kg
C9 Effect. Wait P.	0	0	-	-	-	-	-	-	-	1	1
C10 Service T.C.	0	0	-	-	-	-	-	-	-	1	1

Table 2.8: Definitions of interval borders for applicant parameters on Saaty scale (C1, C7, C9 and C10 have only two possible values given their binary nature)

2.3.3.2 Fuzzification of numbers

At the stage of fuzzification of numbers, we translate the parameters determined on the Saaty scale into a set of fuzzy numbers to produce a characteristic membership function following the extent analysis method (Chang, 1996). We apply this step to remove potential imprecision from the parameter values and to allow for the inclusion of indefinite parameters (Oezdadoglu and Oezdadoglu, 2007). With regard to previous applications of fuzzy AHP in transport research, Kulak and Kahraman (2005) have deployed a multicriteria selection of transportation companies, and (Sheu, 2004) has utilized a fuzzy-based approach for the derivation of logistics strategies. The set of fuzzy numbers obtained for applicant A9 is illustrated in Table 2.9.

2.3.3.3 Calculation of local results through pairwise comparison

Having included the operational parameters, we are able to compute local optima for the allocation task. Our model compares the fuzzy numbers of different applicants within each allocation category. To calculate the result, we receive ten local optima containing pairwise comparison matrices in each category. In order to calculate a local optimum, we first determine the fuzzy geometric mean  $r_i$  of the slot applicant. The fuzzy geometric mean in our example is equal to the multiplication of ten lower values, ten intermediate values and ten upper values of a fuzzy number per applicant row. It is obtained by multiplying all lower values of a row, all medium values of a row and all upper values of a row, and taking the three results to the tenth root.



$C_k$	Applicant A <sub>9</sub>	Entry parameter	D. Saaty scale	Fuzzification
C <sub>1</sub>	Competition	New entrant = 1	9	(9,9,9)
C <sub>2</sub>	Punctuality	69.9%	1/9	(1/9,1/9,1/9)
C <sub>3</sub>	Retail Business	USD 1,043	1/9	(1/9,1/9,1/9)
C <sub>4</sub>	Passenger Satisfaction	Rank 40	3	(2,3,4)
C <sub>5</sub>	Overbidding Rate	1.5	1/3	(1/2,1/3,1/4)
C <sub>6</sub>	Location Investments	4.73	1/7	(1/8,1/7,1/6)
C <sub>7</sub>	Route Network	Netw. extension = 0	1/9	(1/9,1/9,1/9)
C <sub>8</sub>	CO <sub>2</sub> Emissions	6,829 kg	1	(1,1,1)
C <sub>9</sub>	Effective Waiting Period	Long Time on WL = 0	1/9	(1/9,1/9,1/9)
C <sub>10</sub>	Service Type Code	Matching STC = 1	9	(9,9,9)

Table 2.9: Applicant parameters on Saaty scale and set of fuzzy numbers for applicant A<sub>9</sub>

In mathematical terms, we determine  $r_{ik}$  in criterion  $k$  as a geometric mean as indicated in (2.3).

$$r_{ik} = \sqrt[10]{\prod l_{ik}}, \sqrt[10]{\prod m_{ik}}, \sqrt[10]{\prod u_{ik}} \quad (2.3)$$

with  $l_{ik}$  being the lower point,  $m_{ik}$  being the middle point,  $u_{ik}$  being the upper point.

After calculating the fuzzy geometric mean, we continue by determining the fuzzy weight  $v_{ik}$  per slot applicant  $i$ . This is calculated by the multiplication of fuzzy geometric mean of one applicant with the reciprocal of the sum of fuzzy geometric means of all applicants. Hence, according to the following equation:

$$v_{ik} = r_{ik} \times \left( \sum_{i=1}^N r_{ik} \right)^{-1} \quad (2.4)$$

In a last step to derive the local result, we calculate the resulting Center of Area (CoA) from the obtained fuzzy weights. The CoA is the sum of lower, medium and upper fuzzy weight divided by three. This converts the fuzzy numbers into crisp numeric values, using equation (2.5):

$$\text{CoA}_{ik} = \frac{(v_{ik}^l + v_{ik}^m + v_{ik}^u)}{3} \quad (2.5)$$

## 2.4 RESULTS AND SENSITIVITY ANALYSIS

### *Allocation result*

To calculate the global result, we compute all local results using the extent analysis method (Chang, 1996) presented in Section 3. The local results expressed as Center of Area values are then weighted according to the criteria weightings  $w_k$  obtained from PCPM (Table 2.5). In other words, the local performances of air carriers in categories C<sub>1</sub> to C<sub>10</sub> are related to the preference weightings expressed by the slot coordinators. This produces an overall ranking of slot applicants, and answers the question of our study by assigning the slot to the



best-performing applicant. A list of local results for applicants A1 to A10 in each category is shown in the Joint Criteria and Applicants Matrix (Mu and Pereyra-Rojas, 2017) (Saaty, 1980) illustrated in Figure 2.2. This matrix is a useful tool to demonstrate individual applicants' performance, as it reveals the local results for each area. We multiply the joint criteria and applicants matrix by the eigenvector of criteria weightings expressed by the ranking of allocation criteria (Table 2.5) to derive the global AHP result (see Figure 2.3).

Joint Criteria & Alternatives Matrix		Shows the combination of criteria and alternatives									
		1	2	3	4	5	6	7	8	9	10
		Competition	Punctuality	Retail Business	Passenger Satisfaction	Overbidding Rate	Location Investments	Route Network	CO2 Emissions	Effective Waiting Period	Service Type Code
1	A1	0,20%	19,62%	4,31%	12,22%	21,72%	2,66%	19,76%	33,95%	0,20%	19,76%
2	A2	0,20%	2,16%	12,43%	15,84%	16,73%	22,16%	0,24%	26,10%	16,53%	0,24%
3	A3	16,53%	2,16%	12,43%	8,70%	7,08%	1,10%	19,76%	18,56%	0,20%	0,24%
4	A4	16,53%	4,03%	38,82%	1,76%	0,35%	67,86%	19,76%	11,02%	0,20%	19,76%
5	A5	16,53%	19,62%	12,43%	15,84%	0,49%	1,54%	19,76%	0,41%	16,53%	19,76%
6	A6	0,20%	19,62%	4,31%	12,22%	16,73%	0,83%	0,24%	3,77%	16,53%	0,24%
7	A7	16,53%	4,03%	0,87%	0,19%	21,72%	0,83%	0,24%	0,55%	16,53%	0,24%
8	A8	0,20%	6,99%	1,49%	15,84%	0,85%	1,10%	0,24%	1,32%	16,53%	19,76%
9	A9	16,53%	2,16%	0,47%	5,18%	2,41%	1,10%	0,24%	3,77%	0,20%	19,76%
10	A10	16,53%	19,62%	12,43%	12,22%	11,91%	0,83%	19,76%	0,55%	16,53%	0,24%

Figure 2.2: Joint Criteria and Applicants Matrix

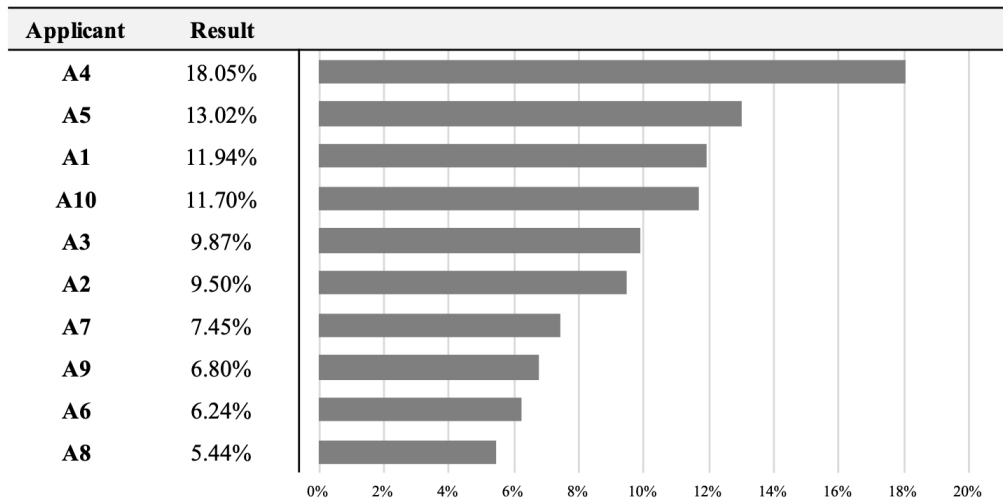


Figure 2.3: AHP Result with ranking of applicants

Figure 3 indicates that the open slot in our model should be awarded to applicant A4, which achieves the highest overall result of 18.05%. The second-best carrier is A5, followed by A1, and the worst is A8 with a score of only 5.44%.

In order to further interpret the results, we perform a sensitivity analysis, the outputs of which are shown in Figure 2.3. This enables us to answer *two important questions about the slot allocation decision*. First, we take the airport manager's perspective and ask what is the maximum admissible change in the weightings of any of the criteria  $w_k$ , such that the overall ranking will remain unchanged? We are able to derive the critical criterion  $c_i$  for each applicant and the minimum modification rate of  $w_k$  at which the applicant changes its ranking position. Second, from an airline's point of view, we ask which category must an applicant improve in order to surpass the next best-positioned competitor? Both questions are highly relevant, as they have important implications for slot coordinators and air carriers when evaluating the results.

#### 2.4.1 Sensitivity analysis of criteria weightings (airport's perspective)

We refer to the methodology proposed by [Triantaphyllou and Sanchez \(1997\)](#), which suggests that AHP robustness can be measured by computing a criticality degree for each criterion,  $\delta_k^*$ . This measures the smallest change in criterion weighting  $w_k$  necessary to effect a rank change in the allocation order (Figure 3).

We compute  $\delta_k^*$  for a list of 45 entries representing all possible combinations of slot applicants. Mathematically, we can determine  $\delta_k^*$  by finding the change in weighting  $\delta_k$  for each criterion  $k$  where the absolute value is lowest. We therefore write for all 45 applicant combinations ( $A_i$  and  $A_j$ ):

$$\delta_{k,i,j}^* = \min\{|\delta_{k=1}|, |\delta_{k=2}|, (\dots), |\delta_{k=10}|\} \quad (2.6)$$

Following [Triantaphyllou and Sanchez \(1997\)](#), we calculate the minimum change in criterion weighting  $w_k$  necessary for two airlines to reverse their positions by dividing the difference in applicants' ranking results, expressed as  $p_i$  and  $p_j$  (see Figure 2.3), by the respective performance of the two in criterion  $k$ , expressed as  $a_{ik}$  and  $a_{jk}$ . The mathematical relationship is described in equations (2.7) and (2.8):

$$\delta_{k,i,j} < \frac{(p_j - p_i)}{(a_{jk} - a_{ik})} \times \frac{100}{w_k} \quad \text{if } (a_{jk} > a_{ik}) \quad (2.7)$$

$$\delta_{k,i,j} > \frac{(p_j - p_i)}{(a_{jk} - a_{ik})} \times \frac{100}{w_k} \quad \text{if } (a_{jk} < a_{ik}) \quad (2.8)$$

Applying these equations reveals that the values of  $\delta$  for  $a_{ik}$  and  $a_{jk}$  sometimes have no feasible result. This is the case if there is no possible factor of change to enable the two applicants to switch positions, which occurs when the value of the ratio:

$$(p_j - p_i) / (a_{jk} - a_{ik}) \quad (2.9)$$

is greater than the original criteria weighting  $w_k$  ([Triantaphyllou and Sanchez, 1997](#)).

#### 2.4.1.1 *Top position change*

The first point arising from the results shown in Figure 2.3 relates to the question of by how much any of the criteria weightings must be changed in order for a different applicant to win the overall ranking result. In order to calculate this, we examine the pair of slot applicants including the first- and second-positioned carrier, which is A4–A5. We observe that the value of  $\delta_{k,i,j}^*$  is 0.308 for C9 Effective Waiting Period. This means that a 0.308 change in absolute terms in the weighting of C9 (such that its new weighting is 0.405), with all other weightings being reduced by the same amount, would result in a change of leading position, with A5 being the new first-positioned air carrier and A4 the second.

#### 2.4.1.2 *Any change*

The second question resulting from Figure 2.3 relates to the minimum change required in any parameter to effect a different overall ranking result. This can be determined by examining the smallest change required in  $w_k$ , expressed as a value of  $\delta_{k,i,j}^*$ , which in this case is for criterion C8 CO<sub>2</sub> Emissions for the pair of applicants A1 and A10. The respective value of  $\delta_{8,1,10}^*$  is 0.007, indicating that by modifying the criterion weighting  $w_8$  by 0.007 in absolute terms, candidates A1 and A10 will reverse their positions. This is the smallest change required in any criteria weightings to effect a different ranking result.

#### 2.4.1.3 *Most changes*

The most common criterion to effect any rank changes in our model is criterion C10 Service Type Code. This criterion is able to effect a maximum of eleven reverses in the applicants' rankings (visible and non-visible dependencies). Modifying the criteria weighting  $w_{10}$  to the highest value of  $\delta_{10,i,j}^*$  results in eleven pairs of applicants being reversed. To effect all eleven changes,  $w_{10}$  must be modified by 0.321, such that the new weighting is 0.419.

#### 2.4.1.4 *Specific change*

The next analysis resulting from Figure 2.3 relates to which criterion must be changed and by how much in  $w$  such that a specific pair of applicants will be reversed. For this we examine the relevant pair of applicants in the ranking order. Hence, we combine each applicant with its better positioned competitor (e.g. A4 – A5 for the first and second positions). We then analyze the values obtained for  $\delta_{k,i,j}^*$ . The results of this analysis are given in Table 2.10.

Notably, for four applicants, C8 CO<sub>2</sub> Emissions is the specific change criterion. This is because all carriers differ in this regard since our model considers different aircraft types in each case, and because C8 is positioned second in the criteria ranking, and therefore has a relatively high criterion weighting  $w_k$ .

Rank	Ap- pli- cant	Sp. Change	Interpretation of Result
1	A4	-	Since A4 is in the leading position, there is no criterion of specific change for the carrier to improve its position.
2	A5	C9	As indicated in Top Position Change, the criterion of specific change for A5 to surpass A4 is C9. If the importance of C9 changes by 0.308, A5 and A4 will reverse positions.
3	A1	C8	A1's criterion of specific change is C8 CO <sub>2</sub> Emissions. Since its largest difference to A5 is located here, increase of criteria weighting of 0.032 in C8 would result in A1 surpassing A5.
4	A10	C8	A10 and A1 can reverse positions by a change of 0.007 in weighting of criterion C8 CO <sub>2</sub> Emissions. This specific change is also the criterion for "Any Change" in our model.
5	A3	C8	The criterion of specific change for A3 is C8 Level of CO <sub>2</sub> Emissions. A change of 0.102 in that criterion weighting will effect that A3 and competitor A10 will change their positions.
6	A2	C6	For A2 to surpass A3, the smallest criterion change is required in C6 Location Investments. A change of 0.017 would result in A2 surpassing competitor A3.
7	A7	C8	A7 and A2 will reverse positions in our model when changing parameter C8 CO <sub>2</sub> Emissions by 0.08. This is the criterion of specific change for applicant A7.
8	A9	C10	For a reverse of positions among A9 and A7, C10 needs to be modified in weighting by 0.033. This is the criterion of specific change for applicant A9.
9	A6	C10	For applicant A6, the criterion of specific change is C10 Service Type Code. Through a modification of 0.029, A6 and A9 will reverse rank positions.
10	A8	C10	For A8 the criterion of specific change is C10 Service Type Code. In order to effect a reverse of positions, weighting of C10 needs to be changed by 0.041 such that A8 and A6 change ranks.

Table 2.10: Analysis of specific changes required to improve applicants' positions

#### 2.4.2 Sensitivity analysis of applicant performances (applicant's perspective)

Using the sensitivity analysis of criterion weightings, we analyze slot applicants' performance, enabling us to answer the question of how much improvement is required in which criterion to surpass another competitor. For this, we leave the criterion weighting parameter  $w_k$  unchanged. In order to perform this analysis, we must determine for each applicant the required improvement in a specific criterion to achieve an allocation result at least equal to the better-positioned competitor. We refer to this criterion as the focus criterion.

##### 2.4.2.1 Focus criterion

To calculate the criterion on which each applicant should focus in order to improve by one position, the required improvement for each applicant is determined according to the following logic. For each pair of applicants (e.g. A1 – A2, A1 – A3), we determine the difference in current performance on criterion  $C_k$ . This value,  $\gamma_{i,k}$ , is calculated by equation (2.10):

$$\gamma_{i,k} = \frac{|a_{jk} - a_{ik}|}{a_{jk}} \times 100 \quad (2.10)$$

Derived from the logic of an improvement, we calculate  $\gamma$  only for those cases where:

$$a_{jk} < a_{ik} \quad (2.10a)$$

Condition (2.11) implies that for some comparisons, the required improvement does not have a feasible result. These cases are those where applicant  $A_j$  is already performing better than competitor  $A_i$ ; hence, condition (2.11) is not satisfied.

In a final step, we identify the focus criterion with the required improvement factor for each slot applicant. The required improvement in the focus criterion,  $\gamma^*$ , is calculated by applying equation (2.10) to the criterion with the largest weighting  $w_k$ :

$$\gamma_{i,k_w(\max)}^* = \frac{|a_{jk} - a_{ik}|}{a_{jk}} \times 100 \quad (2.11)$$

This improvement  $\gamma^*$  of applicant  $a_i$  will cause  $a_i$  to surpass competitor  $a_j$  in the ranking order. To calculate  $\gamma^*$ , we discard the binary decision variables because these four categories are assumption parameters that can no longer be influenced by applicants once the slot request has been made. For example, C1 Competition determines whether or not the applicant is a new entrant in our model. When raising the slot request, the air carrier cannot influence or improve this parameter. Hence, we focus our analysis on the remaining six criteria, the results for which are presented in Table 2.11. The required improvement in percentage terms represents the value of  $\gamma^*$ .

Rank	Ap- pli- cant	Rele- vant Pair	Deter- mining criterion	Req- im- prov. $\gamma^*$	Interpretation of Result
1	A4	-	-	-	-
2	A5	A4 – A5	C8	58%	Applicant A5 should fully focus on CO2 Emissions. An improvement of at least 58% is necessary to surpass A4.
3	A1	A5 – A1	C3	19%	Applicant A1 should fully focus on Retail Business. An improvement of at least 19% is necessary to surpass A5.
4	A10	A1 – A10	C8	80%	Applicant A10 should fully focus on CO2 Emissions. An improvement of at least 80% is necessary to surpass A 1.
5	A3	A10 – A3	C2	17%	Applicant A3 should fully focus on Punctuality. An improvement of at least 17% is necessary to surpass A10.
6	A2	A3 – A2	C3	5%	Applicant A2 should fully focus on Retail Business. An improvement of at least 5% is necessary to surpass A3.
7	A7	A2 – A7	C8	76%	Applicant A7 should fully focus on CO2 Emissions. An improvement of at least 76% is necessary to surpass A2.
8	A9	A7 – A9	C3	81%	Applicant A9 should fully focus on Retail Business. An improvement of at least 81% is necessary to surpass A7.
9	A6	A9 – A6	C6	76%	Applicant A6 should fully focus on Location Invest-ments. An improvement of at least 76% is necessary to surpass A9.
10	A8	A6 – A8	C8	21%	Applicant A8 should fully focus on CO2 Emissions. An improvement of at least 21% is necessary to surpass A6.

Table 2.11: Results for focus criterion per slot applicant and required improvement in %

Table 2.11 demonstrates that different carriers must focus on different categories in order to improve. This is partly because their initial performance differs, but also relates to the weightings of the allocation criteria in our model. For example, it is very relevant for applicant A5 to focus on its level of CO<sub>2</sub> Emissions. An improvement of 58% is necessary to at least equal competitor A4’s result, so in order to surpass A4 in our model, A5 must improve its CO<sub>2</sub> Emissions by more than 58%.

## 2.5 MANAGERIAL IMPLICATIONS

In this section, we discuss the implications of the proposed allocation model for stakeholders in the industry. We focus on four stakeholders involved in the allocation process: airports, air carriers, passengers, and IATA as the framework-providing organization.

For airports, the application of proposed allocation model will be beneficial. The extension of allocation criteria through the conduction of an expert interview and validation of results with eight other slot coordination experts produces a criteria set that is particularly relevant to airports. Applying our model will allow to include relevant parameters in the slot allocation processes based on local and individual requirements. In our case, the inclusion of CO<sub>2</sub> emissions as a criterion shows how externalities caused by air carriers can be included in the decision process, and how a feasible incentivization approach can be taken to environmentally-friendly air travel. This can be seen from criterion C8, which prioritizes flights with lower CO<sub>2</sub> emissions per standard LTO over flights with higher emissions. Our approach therefore depends on the type of aircraft used by each air carrier and the corresponding level of CO<sub>2</sub> emissions (see Section 2).

For air carriers, implementing the proposed approach will have several consequences. First, introducing the extended criteria set results in additional operational parameters that air carriers are able to influence. Air carriers must perform well on these criteria in order to be competitive and obtain the open slot. Consequently, different factors become relevant to them that play no role in current allocation patterns (see Section 4.3.1). Air carriers should therefore analyze their individual performance against these criteria. Another consequence is that the importance of grandfathering rights (see Section 1) will decrease or even become obsolete. The introduction of a competition-based approach with a defined set of criteria does not take account of slots historically reserved for specific carriers. In summary, on the one hand, air carriers will be challenged by the extension of influenceable criteria and the establishment of a competition-based mechanism, while on the other hand, they will be likely to benefit from increased transparency in the proposed solution and a clear framework of allocation principles.

For passengers, implementing the proposed model will also be beneficial, owing to increased transparency on the one hand, and the increase in market-based components of the mechanism on the other. In fact, the abolition of grandfathering rights proposed in the model will lead to the eradication of current market entry barriers at major hubs with regard to slot allocation. It will free up time windows operated by dominant carriers and enable their potential reallocation based on the developed criteria set. The implementation also entails more passenger-oriented allocations, expressed in passenger-oriented performance indicators, such as passenger satisfaction. In summary, passengers will benefit from increased competition and an increase in passenger-related parameters that are not considered in the current mechanism.

For IATA, as the fourth industry stakeholder, the implications of implementing the model are very clear. Based on our stakeholder interview and subsequent development of criteria, it is crucial to rethink two main aspects of the

common allocation procedure. First, the principle of "Grandfathering" may be considered to be questionable, given its implications for market mechanisms and the related loss of competition. Second, allocating slots according to the given IATA framework has several drawbacks with regard to the criteria applied. In fact, the current framework omits several important aspects of air transportation: CO<sub>2</sub> emissions, punctuality and non-aviation-related revenues, expressed in sales from retail business in our model, are not considered, despite their relevance to the sector today. Furthermore, the existing framework fails to exhibit clearly-defined weighting criteria, which in our approach are obtained from the PCPM experiment. From the PCPM results, we observe that Competition is the most important aspect, given its criterion weighting of 22.25%. In light of this finding, IATA's current rule of reserving at least 50% of available slots for new entrants (see Section 2) seems to be high. In summary, our stakeholder interview and PCPM experiment reveal that IATA needs to revise its slot allocation procedure to incorporate additional criteria, particularly in relation to environmentally-friendly air transportation, given the prospect of global warming. One approach to including externalities is presented in this study, as criterion C8 asks about the CO<sub>2</sub> emissions of each aircraft type and thus provides an incentive for lower emissions.

## 2.6 CONCLUSION

In this study, we present a multicriteria approach for the allocation of airport slots. We introduce the AHP as a concept based on criteria and alternatives, with the overall target of allocating the slot to the best-performing applicant. We demonstrate that the novel application of AHP together with PCPM is a relevant tool to obtain a market-driven set of allocation criteria. Our study shows how the current slot allocation process can be modified, especially by considering the additional operational criteria developed in our stakeholder interview. PCPM is shown to be key in enabling the incorporation of expertise from eight additional slot allocation experts, which would probably be infeasible through a traditional data-gathering approach.

Future research should focus on critically assessing and revising IATA's current allocation mechanism. The concept of "Grandfathering" is especially questionable from a market perspective since it prevents a competition-based mechanism and is a market-entry barrier to new carriers. Nevertheless, grandfathering rights provide operational stability to enable air carriers' long-term planning. This dichotomy is yet to be resolved, as are the tasks of taking sufficient consideration of externalities in the slot allocation process (e.g. CO<sub>2</sub> emissions) and developing appropriate incentives, as proposed in this study.



### 3 Airport Slot Allocation: Development of a Network Allocation Approach Including the CO<sub>2</sub> Price of the European Emissions Trading System (ETS)

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*This chapter refers to the study Weil et al., 2021a<sup>1</sup>.*

#### 3.1 INTRODUCTION

Recent increases in passenger demand and airline operations after the COVID-19 crisis (Airports Council International, 2021) underline that strategic slot allocation is back on the international agenda (Oliveira, 2021). Moreover, trends indicate that the air transport sector is at a turning point towards climate-neutral and decarbonized form of transportation (Graver et al., 2020) (International Council on Clean Transportation, ICCT, 2019). Both of these areas, slot management and decarbonization, are addressed in this paper given the development of an allocation approach based on a carbon cost function of the applying air carriers. We demonstrate, how slot allocation can be managed in a network of airports and how the level of carbon emissions can play a role for the allocation decision.

To further emphasize on the importance of CO<sub>2</sub> emissions for today's industrial world, recent developments such as the court decision of Den Haag, Netherlands, against multinational oil giant Shell to reduce its carbon footprint and the footprint of its sold products by 45% until year 2030 (Joselow, 2021), indicate we have entered the pivotal decade for achievement of industrial decarbonization. This is further stressed by the European Commission's Green Deal "Fit for 55" that includes various measures to address and incentivize industrial decarbonization. Among others, this program includes the full incorporation of aviation into the Emissions Trading System (ETS) and build up of an emissions trading platform for road transport and heating (European Parliament, 2021). Based on this, we observe that the trend of decarbonization will certainly not exclude commercial aviation from achieving its global transformation target especially due to the fact aviation is an important sector for application and combustion of fossil fuels (Dekker et al., 2012). To be precise on the share of global emissions, aviation accounted for 2.4% of CO<sub>2</sub> emissions in 2018 including all passenger and cargo operations. Notably, and further emphasizing on the relevance of this fact, this figure increased about 30% only in the years 2013-2019 (Graver et al., 2019).

Looking at the mentioned court decision in detail, we can state that enterprises are not only responsible for an upright conduction of their own business, but also for contributing fair shares towards achieving a global state of economy that does not include unfair balances or harming points towards future generations with regard to implications from the utilization of resources

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<sup>1</sup> *Airport Slot Allocation: Development of a network allocation approach including the CO<sub>2</sub> price of the European Emissions Trading System (ETS), 2021, submission to: Transportation Research Part A, unpublished working paper; In chapter 3, the term "we" is used to include the authors of Weil et al. (2021a).*

(Joselow, 2021). The European Union, as a major regulative power, has set its target to achieve this state of "net zero", meaning achievement of neutrality in terms of emitted CO<sub>2</sub>, to the year 2045 (Belardo, 2021). It will be interesting to observe, how aviation as a major emitting instance will play its fair role in this process, given that direct electrification and complete avoidance of fossil fuels is not a feasible option to be realized within the next couple of years (International Council on Clean Transportation, ICCT, 2019). This underlines that other options need to be considered when discussing potentials for decarbonization of the aviation sector. These include the assessment and critical discussion of future energy carriers such as hydrogen or synthetic fuels and the assessment of options for reform of the existing operational processes. In this study, we contribute to this assessment by focusing on the slot allocation process as a major coordinative process based on the WSG, issued by the IATA (International Air Transport Association, 2019).

The process of slot allocation represents the allocation of time windows at coordinated airports (Czerny et al., 2008) that represent the right to use "the full range of airport infrastructure necessary to operate a flight on a specific date and time" (European Commission, 1993). The Worldwide Slot Guidelines, as the major ruling framework, define how this process is carried out by an independent coordinator. The mechanism applied today is a three-stage hierarchical process (Benlic, 2018). The first step consists of the consideration of slots of historic precedence, so called Grandfather rights, meaning slots assigned to carriers in the previous allocation period. These slots, operated by incumbent carriers, are (re-)allocated to these, in case they prove an operational utilization of at least 80% of time in mentioned previous period. This implies airlines are endowed with the right to maintain slots in case of enough operational utilization, independently from the actual booking situation or utilization of seats on the routes. The second step of allocation is dedicated to the allocation of remaining slots to a minimum of 50% new entrants, meaning air carriers requesting slots at the respective airport for the first time. This New entrants-rule is the second major directive of IATA's allocation mechanism resulting in a minimum chance for new market entries, if unassigned slots are available. The third rule to conclude this three-stage approach is effected by application of additional criteria, so called secondary allocation criteria, that guide the allocation decision in case of remaining open slots after Grandfather rights and New entrants-rule have been applied. Notably, none of the existing allocation parameters are related to the question of aircraft type utilization, number of carried passengers in previous periods or the level of associated CO<sub>2</sub> emissions (International Air Transport Association, 2019). When requesting a departure or landing slot, there is no difference for carriers to have the intention of operation of a fully-booked leisure flight or an empty cargo flight. In fact, this evidence was observed during COVID-19 crisis, when multiple European airlines operated empty flights to maintain their right of operation after the global demand for passenger air transportation had collapsed (European Parliament, 2020).

By conduction of this study, we address two relevant improvement areas of the current slot allocation mechanism: First, we include an aircraft type- and passenger-related carbon emissions function to guide the allocation decision, and second, we develop a network optimization approach referring to the con-

cept of slot coherence (Zografos et al., 2017) that enables joint allocation of start- and end-slot of a route in one operation. Both features are not present in today’s slot allocation mechanism and represent contributions to an improvement of the status quo. Figure 3.1 indicates how the allocation in our study is fulfilled.

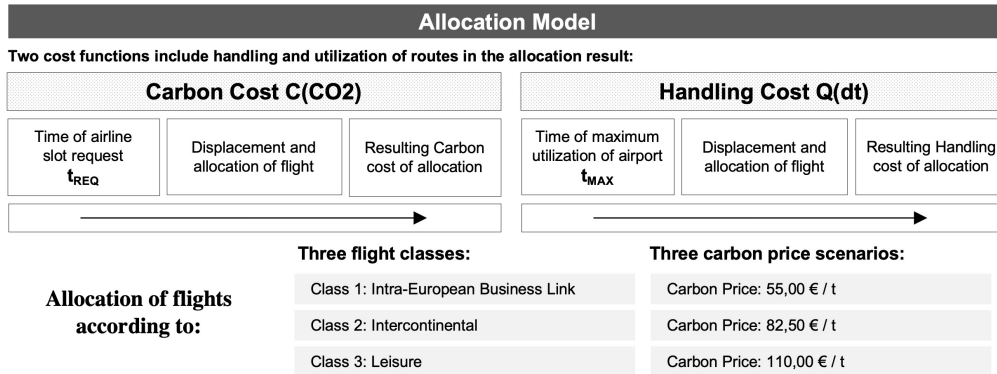


Figure 3.1: Overview of allocation model and major components

The remainder of this paper is structured as follows. In section two, we elaborate further on the concept of strategic slot allocation at airports explaining relevant existing literature & methods. We provide a view on drawbacks & optimization potentials. In section three, we demonstrate the allocation model of this study and in section four, we highlight our results. Section five includes the discussion about managerial implications for the involved stakeholders and section six concludes with final comments & outlook.

### 3.2 LITERATURE REVIEW

Existing literature in the field of airport slot allocation can mainly be classified in three areas: Studies dedicated to improvement potentials mainly maintain the current allocation process and set targets to improve the allocation mechanism. The second area of studies is related to the concept of auctioning mechanisms. The third area of studies is related to market options, referring to the approach of transferring slot allocation to a market of (free) trading. All options have their pros and cons and are based on the fact that the applied mechanism of today has drawbacks and shows potential for optimization. To provide a first view, we will demonstrate a list of most commonly discussed drawbacks and functionalities of the IATA slot allocation system below.

#### 3.2.1 Drawbacks & disputable functionalities of IATA slot allocation status quo

To understand today’s slot allocation mechanism and related critical points, Czerny et al. (2008) provide a thorough analysis on major options for reform. Further, the studies of NERA Economic Consulting (2004), Pellegrini et al.

(2017), Zografos et al. (2017) and Benlic (2018) serve to understand the important points of discussion that we summarize in Table 3.1:

No.	Topic	Description	Authors
1.	Market entry barriers	Slots (incl. Grandfather rights) are typical market entry barriers. They (partially) prevent competition and market access to new entrants.	Kappes and Merkert (2013), NERA Economic Consulting (2004)
2.	Disregard of demand	Slots do not refer to a route's passenger (or cargo) demand. They imply a certain <i>de-coupling</i> from mechanisms of a market, expressed in the interaction of supply and demand.	Sun et al. (2022) European Parliament (2020)
3.	Missing network perspective (i.e., no link between start- & end-point of route)	Slots are allocate based on a single-point optimization. Hence, they do not imply a slot coherent optimization.	Zografos et al. (2017) Pellegrini et al. (2017)
4.	Criteria set in need of reform	The applied criteria set in IATA WSG does not consider important functionalities such as the aircraft type in operation or the level of (CO <sub>2</sub> ) emissions.	Odoni (2021), Benlic (2018)
5.	Inconsistent financial accounting	Slots' monetary value and accounting is controversial among countries. Generally, no capitalization as assets in the EU, capitalization as assets in USA/UK.	Jones et al. (1993) Czerny et al. (2008)
6.	Missing link to daily operations	Certain amount of flights operated off slot times at major hubs implies requirement of scheduling improvement.	Benlic (2018), Zografos et al. (2017)
7.	Overbidding of carriers	Air carriers tend to overbid for slots in current mechanism, current mechanism does not address such behavior with penalty.	Czerny et al. (2008) van Houten and Burghouwt (2022)
8.	Unaccommodated requests	Current mechanism unable to cover total number of requests at major hubs. Requirement for continuous improvement and assessment of efficiency improvement in allocation.	Zografos et al. (2012) Benlic (2018)

Table 3.1: Identified drawbacks and deficits of the IATA WSG according to literature

As observed during the COVID-19 crisis, the existence of Grandfather rights and the related disregard of competitive factors can be seen as the most commonly discussed area in literature. Airlines were forced to operate flights without passengers during this time, given the slot allocation mechanism of today. To address this problem of empty flights, the concept of Grandfathering was partially put out of operation within the European Union through the establishment of a decreased threshold of minimum operations from 80 to 60% (European Council, 2020).

### 3.2.2 Existing studies on airport slot allocation

Concepts on slot allocation have been widely discussed and assessed in literature. With regard to the establishment of an optimization approach that consists of the slot coherency principle, meaning consideration of departure and arrival point of a route, the study *SOSTA* of Pellegrini et al. (2017) serves as major reference point. In fact, *SOSTA* establishes an allocation pattern for the alloca-

tion of slots on a European level and includes both sides of routes for allocated flights. The study minimizes the cost of displacement time from allocation at the considered locations. Given *SOSTA*, this study takes the approach of Pellegrini et al. (2017) and further enhances the allocation on a network level by the inclusion of a carbon cost function as we further demonstrate.

The study of Madas and Zografos (2006) provides a list of relevant strategies to enhance the slot allocation status quo. These include concepts of auctioning, congestion pricing and secondary trading. Ball et al. (2018) and Li et al. (2013) discuss approaches for modification of the status quo based on auctioning. Slot trading approaches are discussed in Pellegrini et al. (2012). The studies of Basso and Zhang (2010) and Czerny (2010) relate to the concept of congestion pricing. Adler et al. (2014) discuss implications of slot allocation on economic welfare and the regulative context. Gillen et al. (2016) develop a framework that combines interdependencies of managerial and economic aspects at the management of airport capacity. Zografos et al. (2018) investigate on relationships between schedule results and utility for involved airlines. Detailed allocation approaches are provided by Jacquillat and Odoni (2015), that develop a model for joint optimization of flight scheduling and airport capacity. Jorge et al. (2021) develop a single point allocation approach based on a decision support tool for the airport Guarulhos (Brazil). Hou et al. (2021) propose an approach for slot allocation focusing on air traffic recovery after COVID-19 in the Chinese market. The study of Fukui (2012) examines whether carriers tend to abuse the slot allocation system to inhibit airport capacity usage in the North American market. Corolli et al. (2014) elaborate on the concept of simultaneous network scheduling by development of a two-stage framework. This study enhances the existing approach of Zografos et al. (2012) that addresses the same matter. The study of Castelli et al. (2010) develops an optimization approach on a network level that is similar to the one provided by *SOSTA*. Nevertheless, this study does not consider some of the features, for example the consideration of return flights. Ribeiro et al. (2018) develop a model that optimizes slot allocation based on multiple objectives: The number of rejected requests, maximum schedule displacement, total schedule displacement and the number of displaced requests. Jiang and Zografos (2021) develop a decision making framework for the incorporation of fairness in the allocation of slots. Fairbrother and Zografos (2021) develop an optimal scheduling of slots with season segmentation. Ribeiro et al. (2019a) apply a large-scale neighborhood search to airport slot allocation. (Ribeiro et al., 2019b) apply a modified allocation approach for a small set of airports, highlighting explicit options for reform. Avenali et al. (2015) develop a pricing mechanism for slots including incentives and Baek and Balakrishnan (2020) develop a slot (re-)allocation mechanism based on a game theoretic method. Aravena et al. (2019) address slot scheduling with regard to asymmetric information availability and Androutopoulos and Madas (2019) propose an allocation approach including fairness. Grunewald et al. (2017) assesses priority rules for the utilization of airport capacity and de Arruda et al. (2015) develop a decision making algorithm based on deferred acceptance in a two-sided market. Liang et al. (2018) propose a column generation-based heuristic for aircraft recovery including airport capacity constraints. Pyrgiotis and Odoni (2015) propose a solution based on a case study at Newark Liberty

Airport, EWR. In the study of Wang et al. (2017), specific reference is made to the operational model of Low Cost Carriers, LCC, and slots as entry patterns at Hong Kong International Airport, HKG. Katsigiannis and Zografos (2019) incorporate a value for slots in an airport's allocation context.

### 3.3 DEVELOPMENT OF ALLOCATION MODEL

In this section, we lay out and explain our allocation model. The model consists of six airport locations and air traffic in both directions between these six airport locations. The airports are: New York (JFK), London-Heathrow (LHR), Berlin-Brandenburg Airport (BER), Shanghai Pudong (PVG), Rome Fiumicino (FCO) and Frankfurt Airport (FRA). All airports are operational between 05:00 AM (earliest slot) and 23:55 PM (latest slot). To carry out the allocation, we consider a set of assumptions that we introduce in section 3.2. Slot requests can be executed by air carriers in advance to the allocation period. This means that expressed information about start-/ end-point of requested routes and aircraft type are unchangeable parameters once a request has been received. Slots in our model are allocated based on a start- and end-point of with the target to minimize the objective function. The objective function consists of two essential components that guide the allocation decision. The allocation decision is based on the emissions-based carbon cost of allocation on one hand side (first part of the objective function), and handling cost of allocation at both airports of route on the other hand side (second part of the objective function). These two serve to enable a core principle of the developed model, the consideration of airline and airport utilization. These are expressed in the minimization of carbon function for the airline side (airline wants to operate flights at the requested time and hence achieve a high Seat Load Factor, SLF) and in the minimization of the (two) handling costs for the departure and arrival operations at airports (airports want to smoothen operations throughout the day and avoid operational bottlenecks and congestion). The two sides are therefore included in the objective function together with a weighting factor that enables a scenario-based evaluation, as we demonstrate in Section 4. Hence, the two cost functions in our model are  $C(\text{CO}_2)$  for the airline-related carbon cost function, and  $Q(\text{dt})$  for the airport-related handling cost function.

#### 3.3.1 *Motivation for allocation model development*

To elaborate on our guiding principles and to explain our motivation, we refer to the observed industry trends pointed out in Section 1. The challenge of transformation towards carbon-neutral, decarbonized way of transportation requires - next to the question about a carbon-neutral energy carriers - the assessment of processes and structures in terms of their efficiency. The assessment of processes will play a crucial role for the airline sector since regulative norms (e.g. EU "Fit for 55") will oblige the air transport sector to realize decarbonization in all regards. In our previous study, we address the question of improvement areas at allocation criteria to a set of international slot coordinators. The result was that slot coordinators answered that  $\text{CO}_2$  emissions may serve as potential



criterion to guide the question of slot allocation (Weil et al., 2021b). The task at model development was hence clear: We develop an allocation model based on the coordinator’s perspective, that includes the CO<sub>2</sub> footprint of passengers ("Carbon cost of allocation") to the allocation decision and we address the question of slot allocation for a route on both points simultaneously, applying the slot coherency principle (Zografos et al., 2017). Table 3.2 demonstrates guiding principles at development of this study. Figure 3.2 demonstrates the selected network of airports in our study.

Carbon Cost (CO <sub>2</sub> )	Handling Cost (Q)	Airline & Airport View	Slot Coherency Concept
Inclusion of the CO <sub>2</sub> price according to ETS as major driver of allocation decision. Development of a cost function based on emissions per passenger.	Inclusion of a passenger-based handling cost factor that is dependent on the airport utilization. Development of a cost function based on handling cost per passenger.	Inclusion of airline and airport interests in allocation decision. Development of two cost functions to incorporate airlines’ and airports’ points of view.	Consideration of both ends of a route at allocation decision, addressing the question how to allocate slots simultaneously (e.g. network flight from A to B).
<b>Ref. to IATA WSG:</b>			
Criteria Set in need of reform	Criteria Set in need of reform	Criteria Set in need of reform	Missing integration of multiple locations

Table 3.2: Four guiding principles at allocation model development

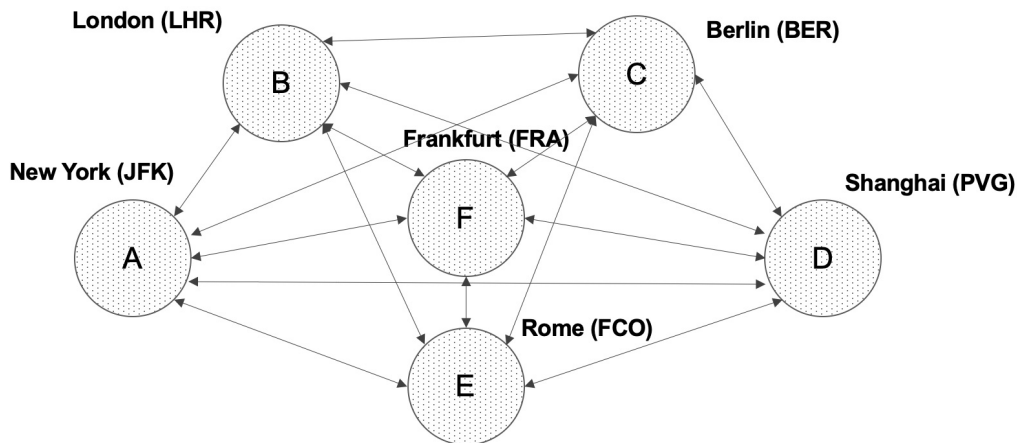


Figure 3.2: Considered airports in allocation model

3.3.1.1 Validation of model approach by conducted flight data analysis at Frankfurt Airport (FRA)

To validate the chosen approach based on airline and airport utilization, we have conducted a flight data analysis at one of the most frequented airports in Europe, Frankfurt, to assess detailed flight movements and slot requests during one calendar week (30th May - 06th June 2021). During this time, we have assessed arrival and departure movements at the airport taking notes about flight origins & destinations, deployed aircraft types and respective flight classes. The

information about flight classes serves to specify the purpose of operations of each airline and consists in this model of: Intra-European Business Links (Class 1), Intercontinental flights (Class 2) and Leisure flights (Class 3). We have assigned departure and arrival movements at Frankfurt Airport (FRA) to these classes, see Table 3.3. By this, we were able to understand the conducted operations at the observed airport and could derive implications on the handling cost function for our model. The result of the flight data validation is indicated in the Table below:

<b>Class 1: Intra-Eur. Business Link</b>	<b>Class 2: Intercontinental</b>	<b>Class 3: Leisure</b>
1. London Heathrow (LHR)	1. New York (JFK)	1. Palma de Mallorca (PMI)
2. Vienna (VIE)	2. Chicago O'Hare (ORD)	2. Ibiza (IBZ)
3. Madrid-Barajas(MAD)	3. Washington Dulles (IAD)	3. Gran Canaria (LPA)
4. Lisbon (LIS)	4. Toronto (YYZ)	4. Tenerife South (TFS)
5. Istanbul (IST)	5. Denver (DEN)	5. Heraklion (HER)
6. Paris Ch. de Gaulle (CDG)	6. Dallas-Fort Worth (DFW)	6. Rhodes (RHO)
7. Milan Linate (LIN)	7. Los Angeles (LAX)	7. Malta (MLA)
8. Rome Fiumicino (FCO)	8. San Francisco (SFO)	8. Nice Cote d'Azur (NCE)
9. Budapest (BUD)	9. Delhi (DEH)	9. Malaga (AGP)
10. Oslo (OSL)	10. Mumbai (BOM)	10. Naples (NAP)
11. Stockholm Arlanda (ARN)	11. Shanghai (PVG)	11. Palermo (PMO)
12. Athens (ATH)	12. Singapore (SIN)	12. Antalya (AYT)
13. Barcelona (BCN)	13. Dubai (DXB)	13. Faro (FAO)
14. Amsterdam (AMS)	14. Hong Kong (HKG)	
15. Zürich (ZRH)	15. Beijing (PEK)	
16. Copenhagen (CPH)	16. Abu Dhabi (AUH)	
17. Manchester (MAN)	17. Johannesburg (JNB)	
18. Warsaw (WAW)	18. Lagos (LOS)	
	19. Sao Paulo (GRU)	
	20. Buenos Aires (EZE)	

Table 3.3: Origin/destination airports for assessment of flight movements and slot requests at Frankfurt Airport (FRA)



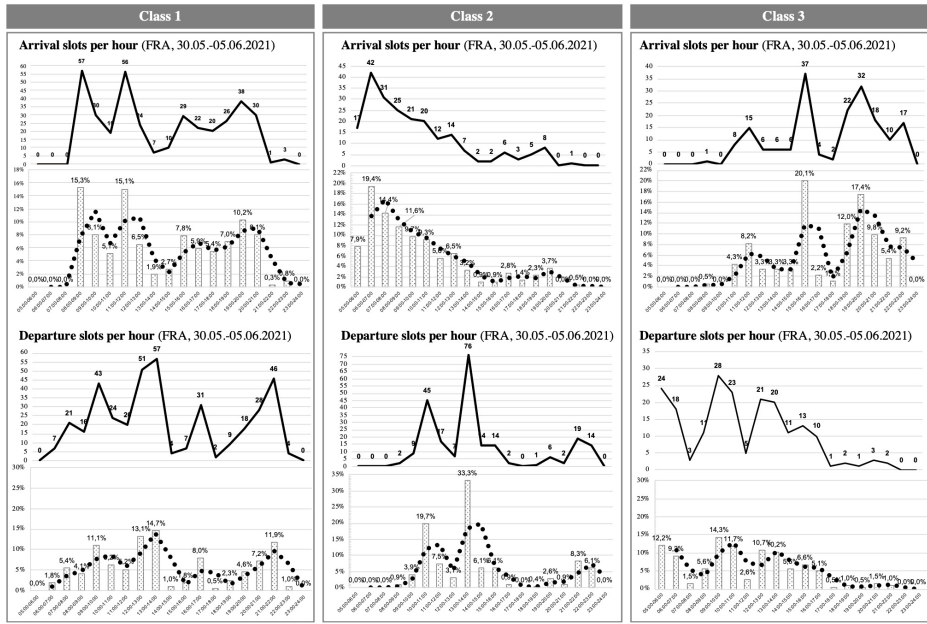


Figure 3.3: Distribution of arrival & departure slots at Frankfurt Airport, FRA (May 30th - June 6th, 2021)

From Figure 3.3 we observe that different flight classes have different departure/arrival patterns at the airport in Frankfurt. Class 1 flights have two peaks in arrival movements between 08:00 - 09:00 AM and between 11:00 AM - 12:00 PM. For departures, this peak is reached between 13:00 and 14:00 PM. To incorporate this, we translate the hour of peak arrivals and departures into the hour of maximum utilization of assets,  $t_{MAX}$ , of the airport. This incorporates the airport utilization in the allocation model, expressed by the handling cost function  $Q(dt)$ , see Figure 3.1. The values  $t_{MAX}$  obtained from the flight data analysis for the three flight classes are indicated in Table 3.4:

	Class 1	Class 2	Class 3
<b>Arrivals</b>			
Number of observations	372	216	184
$t_{MAX}$	08:55 AM	06:10 AM	15:30 AM
<b>Departures</b>			
Number of observations	388	228	196
$t_{MAX}$	12:45 PM	13:30 PM	09:30 AM

Table 3.4: Results of flight data analysis at Frankfurt Airport (FRA) and resulting hours of maximum utilization  $t_{MAX}$  for allocation model according to flight classes 1,2 & 3

### 3.3.2 Development of cost functions $C(\text{CO}_2)$ and $Q(dt)$ to derive objective function

The objective function in our model is composed of two separate functions,  $C(\text{CO}_2)$  and  $Q(dt)$ . Minimization of the objective function leads for each requested flight to a cost-minimizing point of allocation. This point is called  $T_{\text{ALLO}}$  for each flight. The first part of the objective function,  $C(\text{CO}_2)$ , includes an aircraft type and passenger related carbon cost for each route that is determined by the utilization of seats and emissions per aircraft type and route. The second part,  $Q(dt)$ , is composed of the airport-related part that includes handling costs for the allocated flight on both ends of the route that are determined by the values  $T_{\text{MAX}}$  at each location. This two-part lay out accounts for the below demonstrated points of view that airlines and airports bring into the slot allocation process and that are considered in our model:

Stakeholder	Airlines	Airports
Strategic intention:	Intention to operate flights closest to the point of slot request, $T_{\text{REQ}}$ . Operation as rational agent and intention to carry out flights maximizing corresponding revenue and profit. Assumption: At point $T_{\text{REQ}}$ , the achievable Seat Load Factor (SLF) from sales of tickets for the airline is highest.	Confronted with diverging demand patterns for terminal & runway infrastructure throughout the day. Conducted flight analysis shows clear distributions based on type of operations. Assumption: Intention to smoothing operations throughout the day avoiding bottlenecks & congestion, allocating physical resources effectively.
Cost function:	<b>Carbon Cost</b> $C(\text{CO}_2)$	<b>Handling Cost</b> $Q(dt)$
Relationship:	$t_{\text{REQ}} - t_{\text{ALLO}}$	$t_{\text{MAX}} - t_{\text{ALLO}}$

Table 3.5: Two-part objective function and corresponding airline and airport point of view in allocation model

The resulting objective function of our model looks as follows:

$$Z_{t_{\text{ALLO}}} = \lambda_{\text{AIR}} \times C(\text{CO}_2) + (1 - \lambda_{\text{AIR}}) \times Q(dt) \quad (3.1)$$

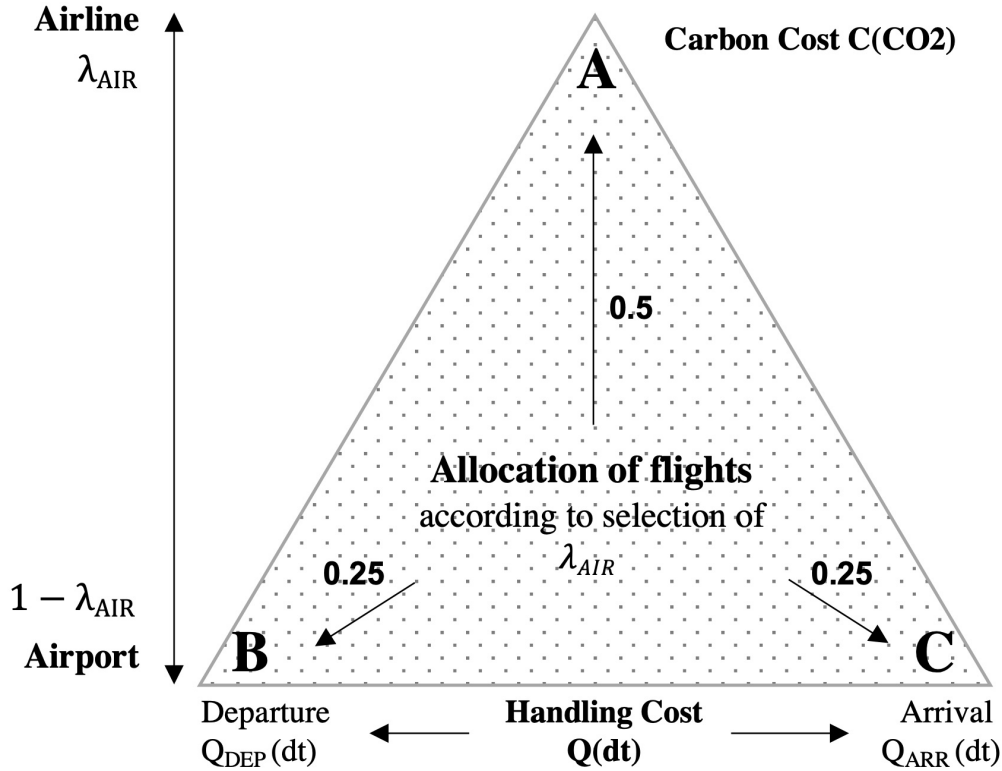


Figure 3.4: Relationship of two cost functions  $C(\text{CO}_2)$  and  $Q(dt)$  and associated role of airport and airline expressed by selection of weighting factor  $\lambda_{AIR}$

The factor  $\lambda_{AIR}$  expresses the weighting of airline view in the allocation approach. Hence, the value  $1 - \lambda_{AIR}$  equals the airport weighting, given that carbon costs and handling costs are two opponent cost factors determining the objective. In a first state, we weight airline and airport views by the same quantity,  $\lambda_{AIR}$  is therefore set to 0.5.

### 3.3.2.1 Carbon cost of allocation $C(\text{CO}_2)$

To incorporate the cost of carbon emissions of a route, we refer to the relationship of yield management of airlines, passenger demand and achievable Revenue Passenger Kilometer (RPK) per flight based on the point of time. The carbon cost of allocation is therefore incorporated in our model by the expression *carbon intensity* per flight measuring the amount of carbon emissions per Revenue Passenger Kilometer (RPK) (Graver et al., 2019). This definition serves to incorporate a passenger-related emissions factor to the model and to guide the allocation decision. The allocation decision is derived from the consideration of time differences between time of allocation,  $t_{ALLO}$ , per flight and requested time of the air carrier,  $t_{REQ}$ , that in our model implies the point with the highest achievable Seat Load Factor (SLF) for the route. The assessed values of carbon intensity per flight imply a decreasing relationship between the parameter and the length of a flight, as the study of Graver et al. (2019) finds. While the measurement of total emissions per flight would lead to a higher

value of emitted CO<sub>2</sub> for long distance flights, the carbon intensity of a flight considers the relationship demonstrated in Figure 3.5. Short distance flights result in a much higher amount of carbon emissions per passenger compared to long haul flights. This important relationship is incorporated through the parameter carbon intensity when answering the allocation question. The considered aircraft types and related values for carbon intensity in our model are demonstrated in Table 3.6.

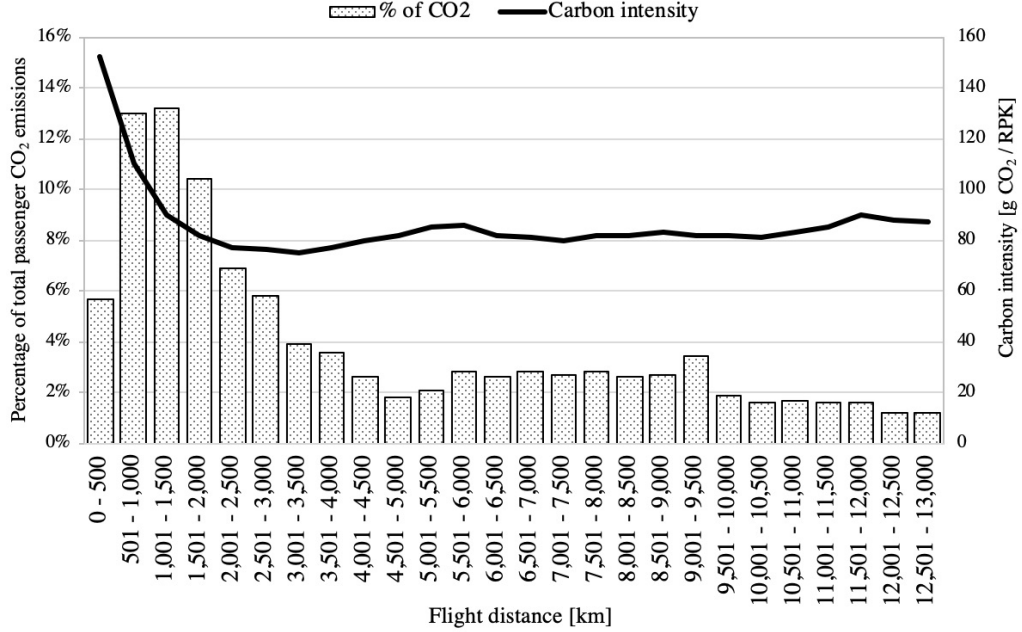


Figure 3.5: Decreasing carbon intensity with length of flight according to (Graver et al., 2019)

Table 3.6 indicates the values of carbon intensity for selected aircraft types in our model and corresponding maximum passenger loads,  $P_{MAX}$ . These parameters will determine the carbon cost of allocation according to the following steps. The carbon cost function looks as follows:

$$C_{AB}(\text{CO}_2) = E_{AB} \times p_{\text{CO}_2} \times \frac{1}{\text{SLF}^2} \quad (3.2)$$

Term  $E$  equals the amount of emitted CO<sub>2</sub> on a route between two points  $A$  and  $B$  that is multiplied by the price per emitted ton of CO<sub>2</sub> according to the ETS,  $p_{\text{CO}_2}$  (3.2). The correction factor  $1/\text{SLF}^2$  serves to incorporate the utilization of aircraft in terms of utilized seats as we will demonstrate in Table 3.8. The emissions per kilometer  $e_{AB}$  are calculated by multiplication of carbon intensity of aircraft type,  $CI$ , maximum passenger load of aircraft type,  $P_{MAX}$ , and achieved Seat Load Factor of the route,  $\text{SLF}_{AB}$  (3.4). The multiplication of emissions per km  $e_{AB}$  and distance of route  $d_{AB}$  leads to the amount of emissions of route  $E_{AB}$ .

$$E_{AB} = e_{\text{km}} \times d_{AB} \quad (3.3)$$

Aircraft type	Maximum passenger load [P <sub>MAX</sub> ]	Carbon intensity [g CO <sub>2</sub> /RPK]
CRJ-900	90	155*
A319	138	104
A320	180	85
A321	210	77
A330-300	255	87
A340-300	279	96*
B737-800	189	82
B747-400	364	108
B777-300	313	90
B787-9	286	76

Table 3.6: Considered carbon intensities per revenue passenger kilometer [RPK] and maximum passenger loads per aircraft type according to representative study (Graver et al., 2019); \*Note: For aircraft types "CRJ-900" and "A340-300", approximation values were considered in calculation of CI

$$e_{AB} = CI_{RPK} \times (P_{MAX} \times SLF_{AB}) \quad (3.4)$$

The Seat Load Factor  $SLF_{AB}$  is defined by (5):

$$SLF = \frac{\text{Number of carried passengers} \times \text{Distance [km]}}{\text{Number of carried seats} \times \text{Distance [km]}} \times 100\% \quad (3.5)$$

The inclusion of correction factor  $1/\text{SLF}^2$  to equation (3.2) serves to incorporate the aircraft utilization in our model: The underlying hypothesis is related to the following relationship. The more passengers that are on a flight, the higher the take off weight and resulting emissions of  $\text{CO}_2$ , but, on the other hand the lower the amount of carbon footprint per passenger, given that the carbon intensity of a flight decreases by definition with more passengers being on the plane. The resulting consequence of this is accounted for by inclusion of the correction factor  $1/\text{SLF}^2$ . Through multiplication of  $C_{AB}$  with  $1/\text{SLF}^2$  we set an incentive to allocate flights such that the achievable Seat Load Factor (SLF) is highest, incorporating the intention of the requesting airline, operation of the flight close to the point  $t_{\text{REQ}}$ . To provide an example, we demonstrate Table 3.7 indicating values for  $E_{AB}$  and  $C_{AB}$  resulting from three Seat Load Factors of an exemplary flight:

$\text{SLF}_{AB}$	$\text{PAX}_{AB}$	$E_{AB(\text{CO}_2)}$	C actual	$1/\text{SLF}^2$	$C(\text{CO}_2)$
$\text{SLF}_{\text{MAX}}$	209	218 t	11,990 €	1.78	21,342 €
$\text{SLF}_{70\%}$	146	152 t	8,360 €	3.65	30,514 €
$\text{SLF}_{50\%}$	105	109 t	5,995 €	7.06	42,325 €

Table 3.7: Relationship of cost function parameters, number of passengers and emitted tons of  $\text{CO}_2$ , here: Example of a A-340 flight between LHR and PVG, application of market price 55,00 €, per ton  $\text{CO}_2$ , resulting model costs

In Table 3.8 we demonstrate the effect of flight allocation to the carbon cost function  $C(\text{CO}_2)$ . The flight that is requested for allocation at 08:30 AM results in the highest achievable Seat Load Factor SLF for the respective airline. For any hour the flight is allocated before or after  $t_{\text{REQ}}$ , the value of  $\delta_{\text{SLF}}$ , indicating the change in achievable Seat Load Factor, changes as indicated. The more the flight is shifted away from its originally requested slot, the fewer the achievable SLF for the airline and the higher the carbon cost per passenger, since we consider aircraft types to be not changeable and the scheduled flight to be operated with a fewer amount of passengers. The same pattern occurs at allocation of a competition flight in our model, indicated as  $t_{\text{COMP}}$ , within the time horizon of two hours before or after allocation of a flight, that results in a reduction of achievable SLF according to the indicated values of  $\delta_{\text{SLF}}$ .

$\delta_{SLF}$	03:30	04:30	05:30	06:30	07:30	08:30	09:30	10:30	11:30	12:30	13:30
1.0						$t_{REQ}$					
0.9					-1h		+1h				
0.8				-1h				+1h			
0.7			-1h						+1h		
0.6		-1h								+1h	
0.5	-1h										+1h

$\delta_{SLF}$	$t_{COMP}$	$t_{COMP}$	$t_{COMP}$	$t_{COMP}$	$t_{COMP}$
0.75				$t_{REQ}$	
0.75			-1h		+1h
0.75		-1h			+1h

Table 3.8: Effects of change in  $t_{ALLO}$  on objective func. based on requested time  $t_{REQ}$  & hour of comp. flight  $t_{COMP}$

3.3.2.2 Handling cost of allocation  $Q(dt)$

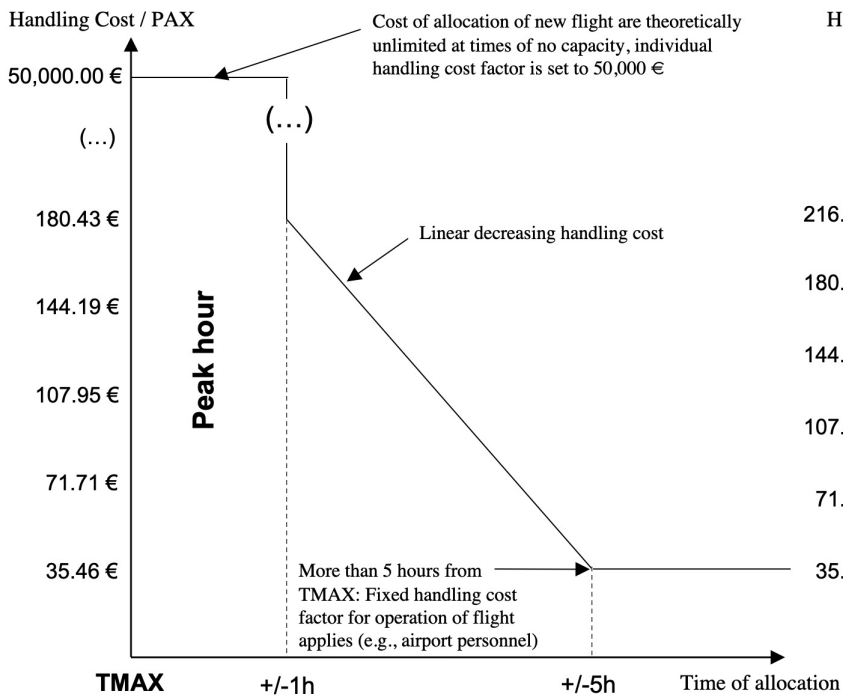
To incorporate the airport side of allocation, we introduce the second cost variable,  $Q(dt)$ , to our model, which represents the applicable handling cost factor per passenger on both points of a route based on the allocated point of time  $t_{ALLO}$ . This handling cost factor,  $q(dt)$ , is determined by the relationship of time of allocation of a flight,  $t_{ALLO}$ , and hour of maximum utilization of assets at the two airports in question,  $t_{MAX}$ , assessed in the flight analysis (see above). To facilitate this special question, and to account for the different passenger capacities on aircrafts, we split the handling cost function in two separate functions for *widebody* and *narrowbody* aircrafts. Narrowbody aircrafts have smaller passenger capacities and are therefore considered as additional bottlenecks during peak hours in our model. Hence, the two handling cost functions are designed to avoid any narrowbody operation during peak hours at an airport in the model, as Figure 3.6 demonstrates. The associated handling cost per passenger is therefore set to the value of 50,000€ during these hours for narrowbody traffic. The time difference of  $t_{ALLO}$  and  $t_{MAX}$  hence answers the allocation question from the airport point of view, as we have demonstrated in Table 3.5. The two handling cost functions and applicable handling cost factors  $q$  per hour of allocation are demonstrated in Figure 3.6:

The applicable equation for handling costs  $Q(dt)$  looks as follows:

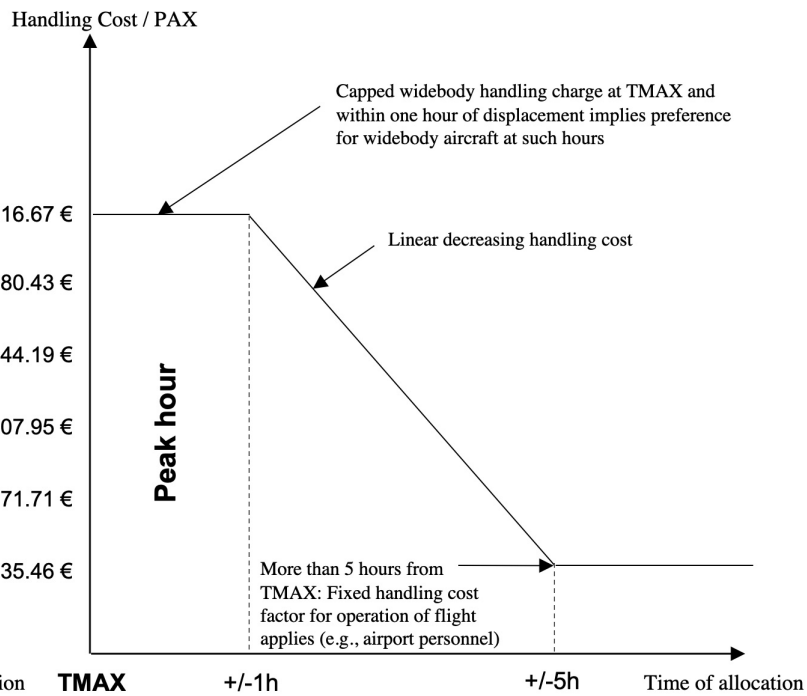
$$Q_{AB}(dt) = dt_{AB} \times q(dt) \tag{3.6}$$

Figure 3.6: Two considered handling cost functions for narrowbody and widebody aircraft operations

**Narrowbody:** (A319, A320, A321, B737, CRJ-900)



**Widebody:** (A330, A340, B747, B777, B787)





### 3.3.2.3 Model constraints & functional prerequisites

As indicated, our model operates based on a set of functional requirements that are translated to constraints. To provide details about these constraints, we provide Table 3.9 including descriptions:

Requirement/Constraint	Description
Six airports in network	We operate the model based on six locations. Flights are operated between locations in two directions.
Flight services	Flights are served in two directions between all locations. There are no constraints regarding network connections (only Point-to-point traffic).
Routes	Requested routes between two points A and B are of known duration and distances. Flights between the same two points always have the same duration and distance. Arrivals are determined by requested departures.
Three classes of flight operations	Flights are operated according to three classes, they are: Intra-European Business Link, Intercontinental, Leisure. Only one class per flight, furthermore no cargo flights and no general aviation flights considered.
Aircraft types	Deployed aircraft types for service are fix in model. No ad hoc changes in aircraft, we assume decision taken prior to requesting slot.
Operational hours	All network locations operate between 05:00 AM and 24:00 PM. The first slot can be requested at 05:00 AM. The last slot to be allocated is 23:55 PM.
Slots	Slots are time windows of five minutes. In each time window one flight movement (landing or departure) is allowed. Requested times between two five minute border intervals are associated to a five minute interval.
Seat Load Factor SLF	The achievable Seat Load Factor at $t_{REQ}$ at its highest value. In case of deviation from requested time, the achievable SLF decreases by the indicated values $\delta_{SLF}$ . The demand pattern is assumed to be the same for the three flight classes.
Competition flights	Competition flights are flights between the same two points (e.g. A and B) and of the same flight class (e.g. Leisure). They reduce the achievable SLF by the indicated value $\delta_{SLF}$ (see above).
CO <sub>2</sub> emissions / RPK	To include carbon costs, we calculate with the carbon emissions per revenue passenger kilometer (see Section 3). This factor is dependent on the deployed aircraft.
Carbon Price (ETS)	The carbon price is linked to the ETS. We assume three different price levels for the allocation in our model.
Handling Cost $Q(dt)$	To incorporate handling, we charge a fix handling fee $q$ per passenger that is dependent on the hour of allocation.
Displacement Time $(dt)$	Displacement time $(dt)$ in our model is calculated as the time difference between $t_{ALLO}$ and $t_{MAX}$ and effects the handling charge $q(dt)$ .
Correction factor $1/SLF^2$	To incorporate incentivization for full aircraft utilization, we include the indicated correction factor to the cost function $C$ .
Airline & Airport interests	Airports and Airlines interests are incorporated with the same weighting factor $\lambda = 0,5$ in the beginning. We run two more versions with a change in $\lambda$ to 0,3 and 0,7 respectively.

Table 3.9: Functional requirements of allocation and translation to model constraints

## 3.4 RESULTS

In this section, we demonstrate the achieved results of our allocation model. As indicated in the introduction part, we ran the model in three different configuration settings that are demonstrated in detail in Table 3.11. All model operations were conducted with the same amount of flights, 50, and corresponding flight data. The first configuration of the model consisted of an equal consideration of airline and airport in allocation, resulting in values of  $\lambda$  equal to 0,5 for both sides. In the second scenario, we changed the weighting to a more airport-related view, introducing a value  $\lambda$  of 0,7 for the airport and 0,3 for the airline side. The third scenario was conducted vice versa, assigning  $\lambda$  of 0.7 to airlines and 0.3 to airports. To provide a sensitivity assessment of the carbon price, we ran the model in three different price categories per ton of carbon emissions, beginning with the price  $p_{CO_2} = 55.00\text{€}$  then increasing to 82.50 € per ton of emissions and in the third configuration 110.00 € per ton of emitted  $CO_2$ . The results of the model are indicated in Tables 3.10 and 3.11:

Allocation Scenario	A	B	C
Configuration:	Hybrid/Network	Airport	Airline
Number of considered flights:	50	50	50
$1 - \lambda_{AIR}$ & $\lambda_{AIR}$	50%/50%	70%/30%	30%/70%
<b>Results:</b>			
Result 1 [Carb. price = 55,00 €/t]	417,148 €	334,630 €	469,012 €
Result 2 [Carb. price = 82,50 €/t]	557,123 €	445,184 €	666,412 €
Result 3 [Carb. price = 110,00 €/t]	688,306 €	530,370 €	845,925 €
Marginal increase [per 1€ $p_{CO_2}$ ]:	0.83	0.79	0.90
Avg. Carbon Cost / PAX [€]:	84.00 €	110.13 €	66.32 €
Avg. Handling Cost / PAX [€]:	81.07 €	73.82 €	95.57 €
Avg. Displacement / Flight [min.]:	278.6	344.4	237.7
Max. Displacement time / Flight:	785	915	860
Total Displacement time [minutes]:	13,930	17,220	11,885
Avg. SLF / Flight:	45.0 %	40.3 %	52.1 %
Flights operated at $T_{REQ}$ :	1	0	6
Flights operated at $T_{MAX}$ :	0	0	0
No. of slots utilized:	40	41	40
Double utilization:	10	9	10
Class 1: Mean departure time:	810	790	840
Class 2: Mean departure time:	470	490	450
Class 3: Mean departure time:	810	890	560
Class 1: Mean arrival time:	925	900	950
Class 2: Mean arrival time:	680	645	655
Class 3: Mean arrival time:	580	550	560

Table 3.10: Three configurations of the allocation model and obtained results

Table 3.11 indicates results of flight allocation including the allocated departure slots for each flight. The table also includes information on entry data for the allocated flights. In Figures 3.7, 3.8 and 3.9 we provide a visualization of results including demonstration of flight allocation and displacement time analysis per flight class. Figures 3.10, 3.11 and 3.12 provide further visualization of data based on the obtained allocation. We explain these graphs in Section 4.1.

Allocation:							A	B	C
No.	Flight No.	AC Type	F. Class	Start	End	t <sub>REQ</sub>	t <sub>ALLO</sub>	t <sub>ALLO</sub>	t <sub>ALLO</sub>
1	LH701	A340	2	FRA	PVG	510	335	210	455
2	BA992	B777	2	PVG	LHR	240	195	85	170
3	AZ520	B787	2	PVG	FCO	240	225	115	240
4	CA440	A340	2	PVG	LHR	300	335	240	300
5	LH2240	A321	1	LHR	FRA	540	760	820	995
6	LH2860	CRJ900	1	BER	FRA	960	885	900	845
7	XS849	A330	3	FCO	LHR	885	1045	1080	915
8	DE125	A320	3	FRA	FCO	20	805	855	0
9	AZ420	A319	1	FCO	LHR	540	775	850	735
10	AZ400	A340	2	FCO	JFK	690	895	915	810
11	EW220	A330	2	JFK	BER	730	950	1010	870
12	LH7450	A340	2	JFK	FRA	195	175	160	195
13	LH647	A321	1	LHR	BER	725	935	895	910
14	LH221	A320	1	FRA	BER	275	835	815	925
15	DE234	A330	3	FCO	BER	275	785	915	1135
16	DE235	B737	3	LHR	FRA	300	870	855	0
17	DL256	B787	3	FCO	JFK	445	565	655	555
18	DL447	B747	2	FRA	JFK	80	125	120	80
19	DL446	B747	2	JFK	LHR	35	95	110	35
20	EW240	CRJ-900	3	FCO	LHR	20	775	935	0
21	LH4700	A319	1	LHR	BER	420	785	800	775
22	CA340	A340	2	BER	PVG	780	945	900	945
23	DE250	A321	3	LHR	BER	570	1055	1075	805
24	CA300	B777	2	FRA	PVG	570	800	870	730
25	CA220	B777	2	JFK	PVG	405	225	225	225
26	LH999	A320	1	FRA	LHR	420	775	755	750
27	LH406	A330	1	FRA	BER	400	830	860	785
28	AZ499	A320	1	FRA	FCO	375	895	895	770
29	CA100	B787	2	FCO	PVG	485	290	165	370
30	BA100	CRJ-900	1	FCO	LHR	840	890	825	865
31	AZ999	A321	1	FCO	FRA	960	785	740	795
32	BA72	A320	1	LHR	FRA	840	765	765	850
33	AA120	B777	2	LHR	JFK	820	1045	1045	940
34	BA76	B747	2	LHR	PVG	80	80	105	80
35	EW8000	A319	1	BER	LHR	255	810	855	750
36	EW8220	A319	1	BER	FCO	250	765	775	870
37	EW8400	A319	1	BER	LHR	245	755	905	910
38	AZ125	CRJ-900	1	FCO	LHR	445	915	940	560
39	DE440	A320	3	FRA	LHR	385	850	935	1055
40	XS9940	B747	3	FRA	PVG	275	490	570	375
41	BA234	B787	2	PVG	LHR	310	205	225	295
42	LH489	A321	1	FRA	LHR	180	795	815	990
43	LH490	A319	1	FRA	FCO	185	740	780	1000
44	LH491	A321	1	FRA	LHR	190	745	745	870
45	AA85	B747	2	LHR	JFK	505	280	130	335
46	AA86	A340	2	JFK	PVG	690	720	790	730
47	XS9900	A330	3	LHR	FCO	600	840	1040	765
48	BA28	B747	2	LHR	PVG	520	350	840	410
49	CA89	A340	2	BER	PVG	690	805	1135	810
50	CA90	A340	2	BER	PVG	695	815	855	665

Table 3.11: Result of slot allocation and considered entry data, here: carbon price  $p_{CO_2} = 55.00 \text{ €/t}$ .

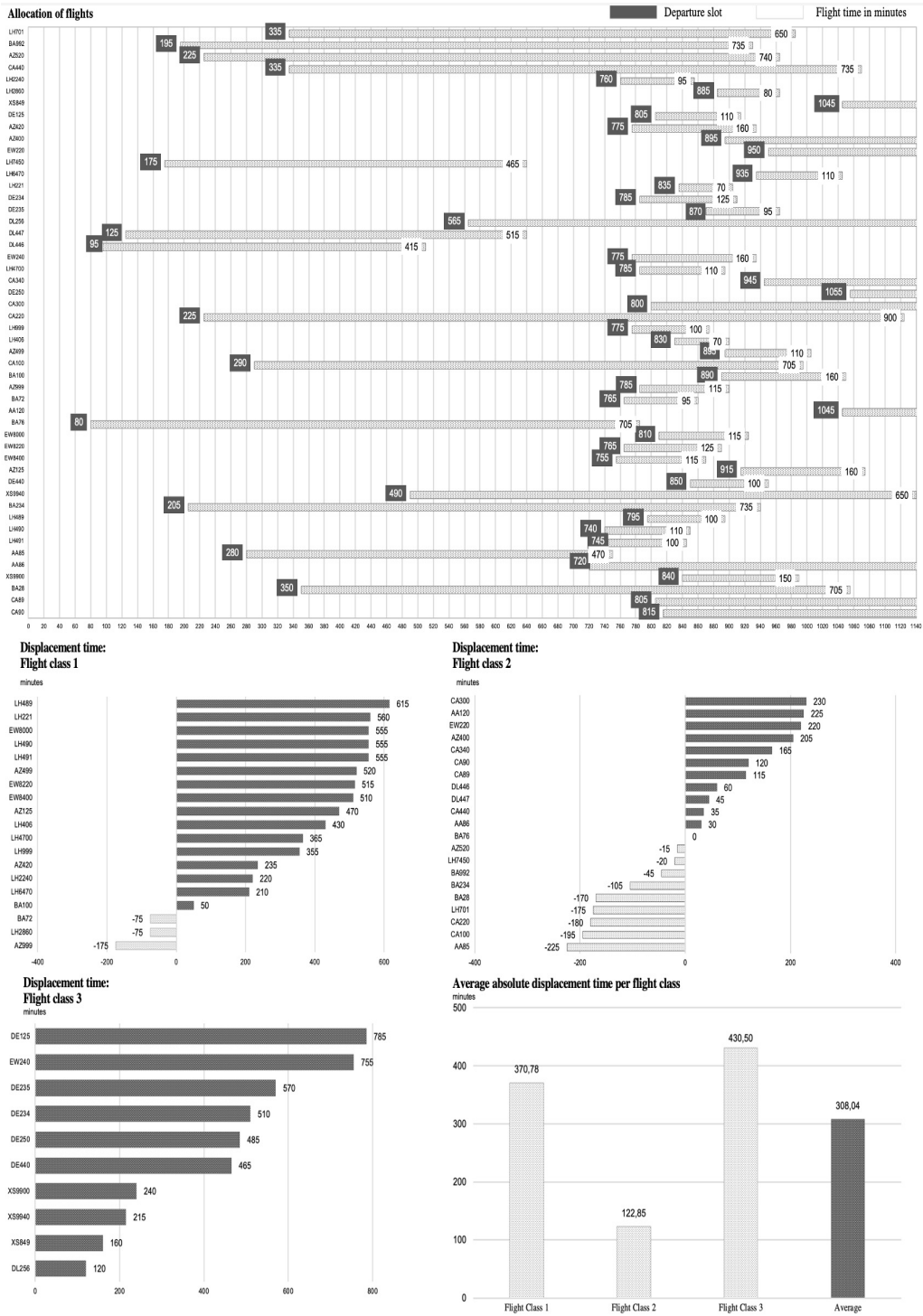


Figure 3.7: Result of flight allocation in network, allo. scenario "A", price per ton CO<sub>2</sub> 55.00 €/t

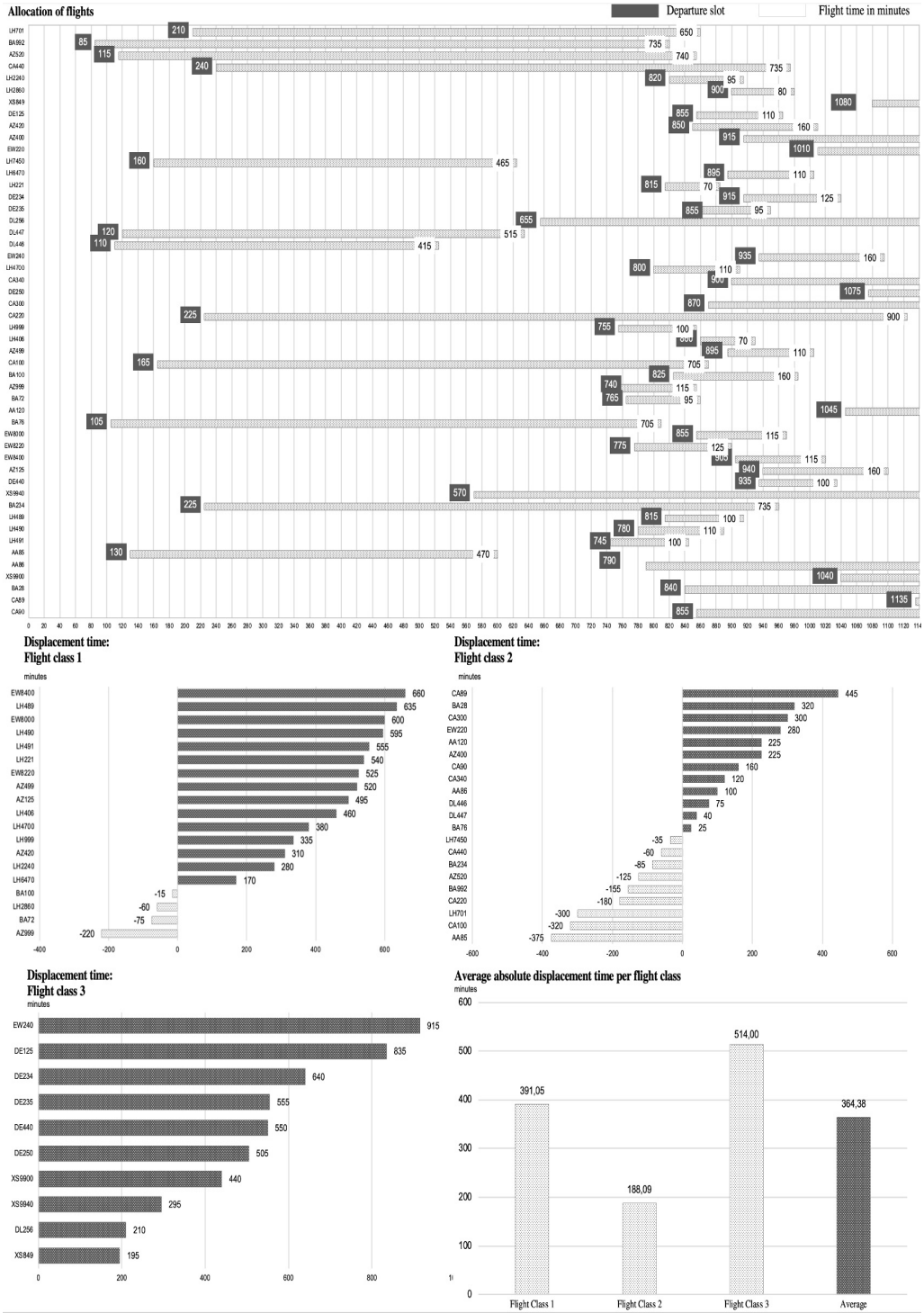


Figure 3.8: Result of flight allocation in network, allo. scenario "B", price per ton CO<sub>2</sub> 55.00 €/t

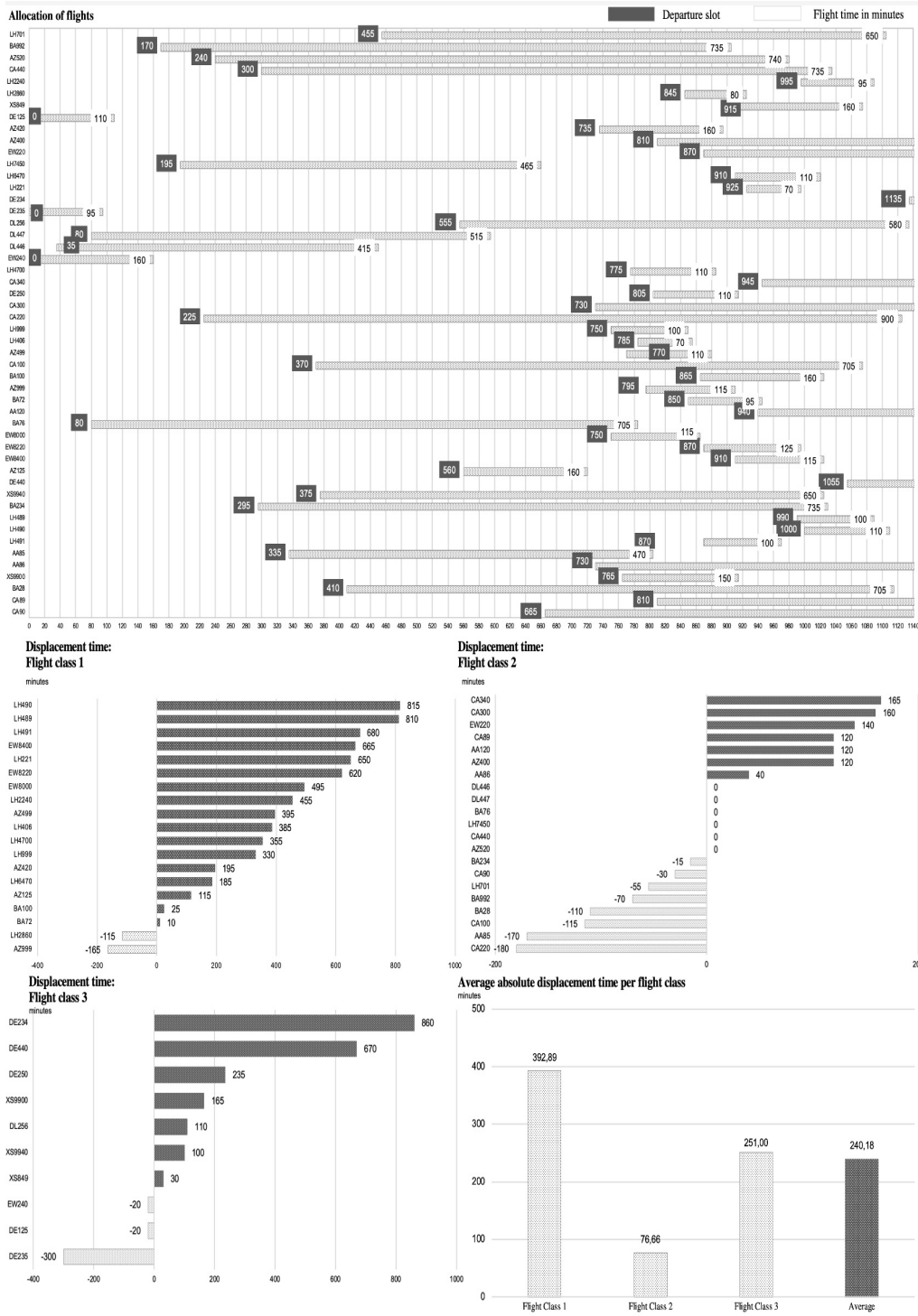


Figure 3.9: Result of flight allocation in network, allo. scenario "C", price per ton CO<sub>2</sub> 55.00 €/t

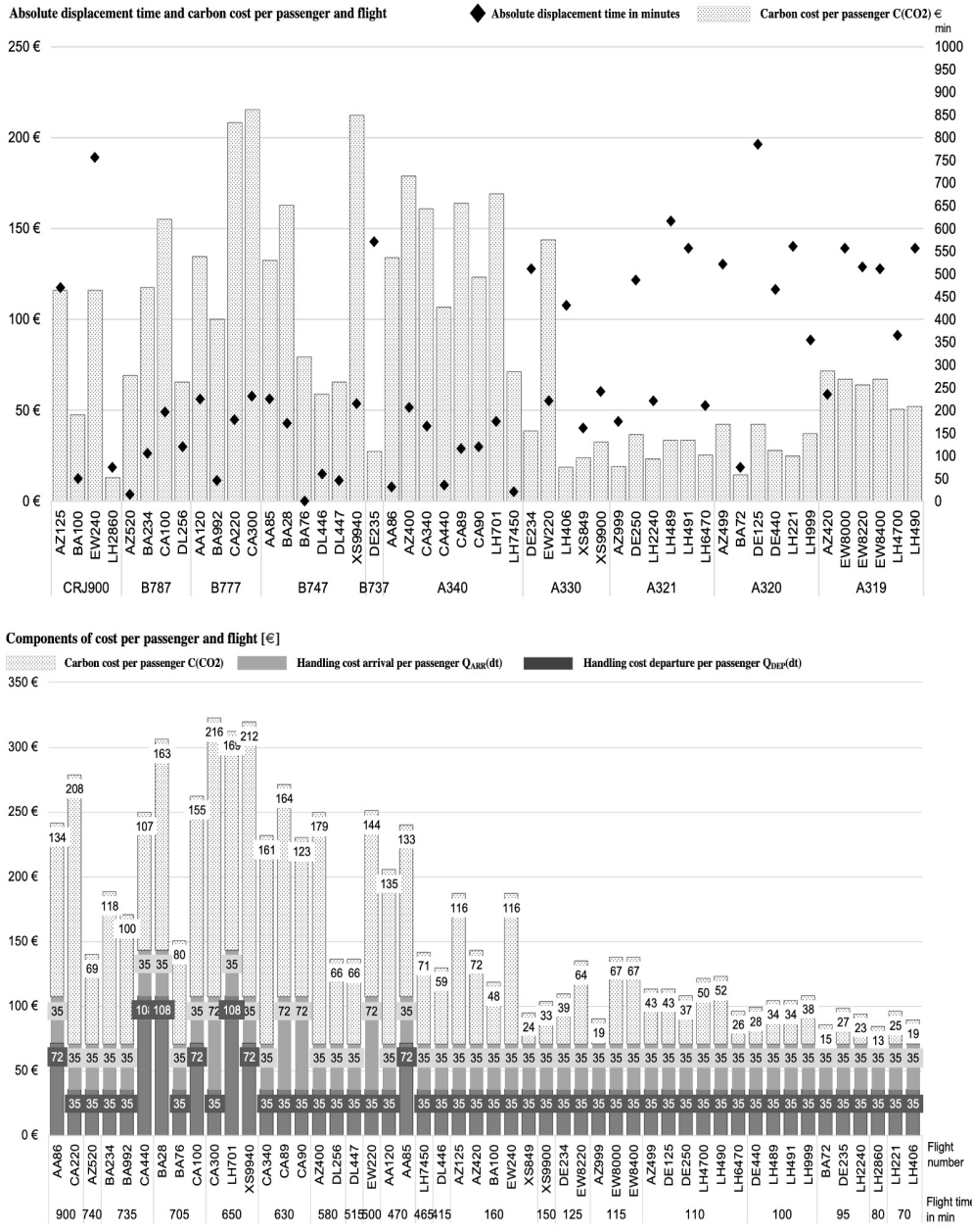


Figure 3.10: Relationship of displacement time and carbon cost per passenger and flight (top), Components of cost function per passenger and flight (bottom)



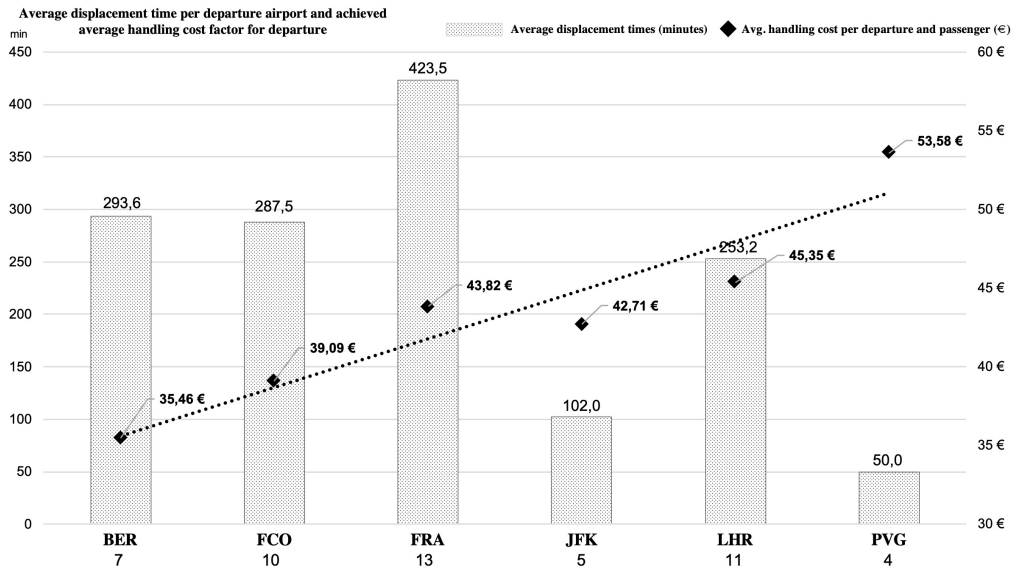


Figure 3.11: Relationship of average displacement times in minutes and achieved average handling cost factor in € per passenger at departure airports

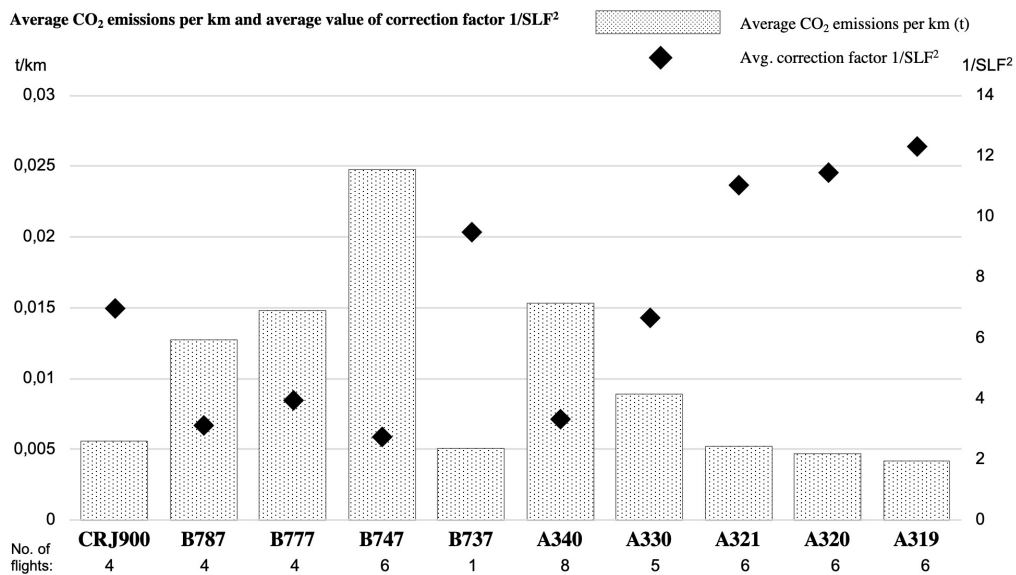


Figure 3.12: Relationship of average CO<sub>2</sub> emissions per km and considered correction factor 1/SLF<sup>2</sup> per aircraft type

### 3.4.1 Assessment & interpretation of results

In Table 3.11 we see the allocation of flights based on the respective scenarios. Indicated on the left side are the flights with aircraft type and flight class as well as departure and landing airport. The value  $t_{REQ}$  indicates the received slot request of the airline and the values  $t_{ALLO}$  per scenario indicated the assigned departure slot per flight.

We observe that only one flight operates at the originally requested time slot  $t_{REQ}$  in allocation scenario "A" and six in allocation scenario "C". In scenario "B", none of the flights operates at  $t_{REQ}$ . Further, we observe that the number of displacements is higher at the airport-related scenario "B", since the achievement of lower handling costs that is required in this scenario implies more displacements of slots. In addition to this, we observe, that the average displacement time is highest for flight class 3, leisure, and lowest for flight class 2, intercontinental flights in scenarios "A" and "B". In scenario "C" the highest average displacement time is in class 3. The lowest average displacement per flight class 2 in all scenarios is related to the fact that intercontinental flights predominantly consist of longer routes. Longer routes require a higher utilization of seats, *Seat Load Factor*, in our model, to fly economically and environmentally-friendly (see also Figures 3.10 & 3.12). The obtained displacements result in movements in two directions for all classes, evidentially about two third of flights are shifted to a later slot (positive displacement), one third shifted to an earlier slot (negative displacement). This can relate to the entry data of the model with a relatively large number of requested morning and mid-day flights and has no further relevance. The highest displacement time of a flight is obtained in scenario "B", with leisure flight "EW 240". That flight requested a slot for the route Rome to London at minute "20", meaning the hour 05:20 AM since operations start at 05:00 AM. In scenario "B", this flight is transferred to the start slot "935", meaning the time 20:35 PM.

With regard to carbon costs and handling costs per passenger, we can state that average carbon costs per passenger  $c$  are lowest in scenario "C". The highest value is obtained in the airport-related scenario "B", where additional displacements to avoid congestion on ground are taken into consideration for the achievement of lower Seat Load Factors. The lowest handling costs are achieved in scenario "B" that represents the airport-focussed allocation. In this allocation, operational congestions are avoided at any price, therefore, handling factors in the model decrease. The highest handling costs occur in scenario "C". The marginal increase of model costs based on a 1% increase in carbon costs per ton  $CO_2$  are related to a similar relationship. Given that the weighting factor  $\lambda_{AIR}$  determines the importance of carbon costs in the objective function, the scenario "C" counts with the highest sensitivity in terms of the carbon price, a one per cent increase in carbon price  $p_{CO_2}$  results in a 0.9 per cent increase in model costs. At scenario "B", this value is lowest, with a 0.79 per cent increase resulting from a one per cent increase in the price of  $CO_2$ . The obtained Seat Load Factors SLF are highest at allocation scenario "C", since the focus point is here on the airline side. The respective value of average SLF is 52.1 %. At the airport related scenario "B", this value is lowest, with an average SLF of 40.3 %.

From Figure 3.10 we observe that carbon costs per passenger and flight  $c$  are dependent on the aircraft type and hence also on the length of flight. Given that the carbon intensities (see Section 3) are lower for the aircraft types A320, A321 and given that these operate usually on shorter flights, these flights account for a lower amount of carbon emissions per passenger meanwhile the larger aircrafts (e.g. B747-400) account for a larger amount in our model. The relationship between displacement times and carbon costs per passenger implies that the model is able to balance this fact given that flights with a larger aircraft and hence also a longer flight distance count with fewer displacement times and therefore higher value of SLF. In contrast, the mentioned short haul flights are allowed a larger displacement time and hence fewer passengers, resulting in a larger amount of carbon emissions per passenger that is still lower than the one from a long haul flight.

In Figure 3.10 (bottom) we see that the relationship of cost function components also depends on the length of a flight. While the shorter flights on the right side of the graph count with an equal share of carbon costs, handling costs departure and handling costs landing per passenger, the longer flights on the left side count with a relatively larger amount of carbon costs in this mix of cost factors. Hence, we observe that the amount of carbon costs per passenger is dependent on the flight distance in our model. This results from the fact that longer the flight, the more tons of emissions occur (see Section 3). Further, we see that the model (in configuration "A") is able to achieve at almost all locations the lowest possible handling factor 35,00 € per passenger. Only at some locations, this is not feasible and the respective value increases.

In Figure 3.11 we see the relationship of average displacement times per departure airport and achieved handling cost factor for departure. The average displacement time per flight is highest at the airport FRA and lowest at the airport PVG. In addition to this, the applicable handling cost factor at each location tends to be around 40 € , coming again to the related point in the previous paragraph that the model achieves lowest applicable handling costs in almost all cases. Notably, to achieve this, at FRA the highest number of displacements are required, at PVG the fewest.

Lastly, in Figure 3.12 we see the relationship of average CO<sub>2</sub> emissions per passenger and applicable correction factor  $1/\text{SLF}^2$  in the model. We see that the highest carbon emissions per passenger occur at the B747-400 aircraft and the lowest at the A319. Further we see that for the cases of high carbon emissions per aircraft type, the respective correction factor is lower and the value SLF by this higher. Vice versa at the low-emitting aircraft types (e.g. A319), the correction factor is higher and the resulting Seat Load Factor SLF is lower. This means that the model considers the relationship of passengers on the flight and effect on carbon footprint. High-emitting aircraft require a high Seat Load Factor SLF, low emitting aircraft are allowed to operated with a lower value of SLF.

## 3.5 MANAGERIAL IMPLICATIONS

The conducted study implies a number of implications for the context of airport slot allocation. In the following, we describe these in a brief discussion, focusing our view on the three involved parties, airports, airlines and IATA as the regulative body.

We can state that the conduction of a flight allocation based on a two cost function set up leads to a feasible solution in the given context and that all flights have been allocated to a slot. Further, we state that the two cost function set up leads to an allocation result considering airline and airport interests based on the selected value of weighting parameter  $\lambda_{AIR}$ . The inclusion of a carbon cost function is hence a feasible option for the task of slot allocation and the inclusion of consideration of both points of a route, departure slot and landing slot, can be realized, too. As the main contribution of this study, we can state that two of the analyzed drawbacks of the slot allocation mechanism of today (see Section 2) can be addressed by application of our model.

For IATA, as the regulative party in this context, the results of our study show several implications. First, we point out that our model can be interpreted as an extension to the existing IATA status quo, meaning that none of the deployed functionalities contradict any of the existing principles (e.g. concept of Grandfather rights). In contrary, the deployment of a carbon-emissions based allocation can be seen as a further enhancement of the existing allocation criteria set provided by IATA, given that we refer in this context only to the secondary criteria. With regard to the continuation of the principle of Grandfather rights, we point out that the implications of this are not assessed in this study. It remains therefore to be seen whether a carbon cost based allocation can lead to a solution without consideration of Grandfather rights. The concept of Grandfather rights is disputable not just since the appearance of COVID-19 and the resulting operations of empty flights. In fact, this concept leads to the existence of market entry barriers and harmed or prevented form of competition. In terms of an efficient allocation of resources and referring again to the industry task of decarbonization, this concept needs to be critically assessed given that for the achievement of a "net-zero" state, empty flights in contrast to actual passenger demand cannot be a solution. Hence, we emphasize that onward research is relevant on this regard. In our view, slot allocation should be more competition-based and the existence of market entry barriers should be reduced. We derive from our model that the inclusion of a carbon emissions function in the allocation mechanism is a relevant point to focus on, especially at addressing given challenges of "net zero" and decarbonization. For IATA, it will therefore be important to establish an appropriate mechanism that considers likely increases in passenger demand and a rather fix set of physical infrastructure in the next years (e.g. terminals and runway infrastructure) and that copes with the implications of decarbonization set out by the regulative bodies, e.g. "Fit-for-55".

For airlines, the implications of our study relate to the same point of reduction of carbon emissions. The focus on carbon emissions per passenger, *carbon footprint*, becomes an important point to take into consideration, also in the context of flight planning and requesting of slots. The implications of recent

legislative changes and related measures (e.g. incorporation of aviation into the ETS) will incentivize incumbent carriers to further decrease their emissions and to modernize existing fleets. To achieve a decarbonized way of transportation, the second point of focus next to deployed aircraft is therefore the parameter Seat Load Factor SLF. Since the carbon footprint per passenger decreases by the operation of a full aircraft, the second strategic task for airlines will remain the conduction of an efficient yield management that considers nonetheless the implications on the carbon footprint.

For airports, the handling cost factor, calculated as fix amount per passenger, serves to incorporate the related tasks of flight operation. It remains important to strengthen operational efficiency at ground services in order to allocate resources effectively. Based on our flight data assessment (see Section 3), this effective allocation of resources is not yet achieved given that many flights arrive or depart at the same point of time. Further, the extension of existing infrastructure for many airports is very limited in the next upcoming years. The efficient allocation of flights on existing infrastructure remains therefore the most important task.

### 3.6 CONCLUSION

To finalize this study, we provide a brief conclusion regarding the current slot allocation mechanism, results of our model and potentials for onward research.

#### *"Slot allocation of the future"*

As pointed out in the Introduction section, today's allocation mechanism for slots implies a number of drawbacks and disputable areas. Given the concept of Grandfathering, perfect market entry barriers are in place that prevent the application of competitive factors. Further, the integration of airports on a global scale lacks of coordinative efficiency and technical realization.

The *slot allocation of the future*, as a task to deliver for the regulative bodies, should therefore include a threefold functionality: First, with view on the topic of decarbonization, the regulator should ask: How to facilitate decarbonization of industry in the best possible way? E.g. through an increased operational efficiency, reduction of administrative burdens, inclusion of the CO<sub>2</sub> output as an allocation criterion. Second, the regulator should focus on the integration of slot allocation at multiple locations when addressing the slot allocation of a route (see: Principle of slot coherency). This can significantly reduce coordinative efforts for the involved stakeholders and improve the number of allocations. It can further set the path towards an integrated and automated coordination of slots on a global scale, with the relevant point in the focus of observation: The demand-driven coordination of routes. Lastly, and with regard to the applied market functionalities, slot coordination should follow a more competition-based form of allocation in our point of view. Competition and the existence of markets proof to be the best manner for the efficient allocation of resources, not only in the context of air transportation. An increased application of market mechanisms will therefore prevent functional misuse of assets (e.g.

operation of empty flights) and lead to a transparent, demand-driven view for all involved parties. In our point of view, operations of empty flights by incumbent carriers for maintaining rights of operation, is an example that indicates that the current allocation mechanism requires some reform and modification. In this way, air carriers should not be encouraged to perform flights just to not lose their right of operation. Instead, the performance of flights and herewith the coordination of slots should follow strict implications set out by the passenger demand. Air carriers, in this way, should serve the market as agents for the operation of these flights. The inclusion of market mechanisms may therefore prevent the air carriers from operating flights against this logic.

## 4 Implementation of a carbon price in airport slot allocation: Reduction of CO<sub>2</sub> footprint per traveling passenger or no change at all?

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This chapter refers to the study [Weil et al., 2022](#)<sup>1</sup>.

### 4.1 INTRODUCTION

In the midst of recovery of international air traffic after the COVID-19 pandemic, the launch of multiple decarbonization initiatives, such as *Fit-for-55*, issued by the European Union, underline the importance of decarbonization for today's industrial world including the air transport sector. In this special context, we develop this study focusing on the task of airport slot allocation at coordinated airports. The process of airport slot allocation represents a major regulatory process in air transport management [Czerny et al., 2008](#) and includes multiple relevant aspects to address, especially in light of a changing regulatory environment connected to the task of decarbonization. In the developed model, we transfer the single point allocation question, defined by the IATA Worldwide Slot Guidelines [International Air Transport Association, 2019](#) to a network solution. We establish a fix relationship between start- and end-points of routes and the allocation of corresponding slots, referring to the principle of *slot coherency* [Zografos et al., 2017](#). The approach thus contributes three innovations to the slot allocation context: First, the development of a network approach in a hub-and-spoke environment results in multiple constraints for the developed solution. In contrast to today's regulatory setting, the developed model enables a multiple-point coordination in a hub-and-spoke network considering constraints such as a minimum exchange time for passengers at the hub. We conduct the task of slot allocation in a network of six airports, "A" to "F". All flight connections operated in the model consist of two flight legs and a connected stop over at the hub "F". As a second contribution, we demonstrate how the parameter CO<sub>2</sub> emissions per traveling passenger, i.e., *carbon footprint* per passenger, can serve to calculate an allocation optimum. Incorporating this, we refer to the mentioned decarbonization initiatives applied by policymakers around the globe today, focusing on the question whether slot coordination as major regulatory process can contribute an incentive to achieve decarbonization in the air transport sector. As a third contribution, we provide a stakeholder-based approach enabling the inclusion and quantification of specific interests, such as the airline or airport point of view to the task of slot coordination. As a key feature, the developed carbon cost function in our approach includes the airlines' interest in maximizing Seat Load Factors (SLF), by requesting a slot at the point of time with the highest expected passenger demand. The airport instead is represented by an opponent cost function, the handling cost func-

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<sup>1</sup> *Implementation of a carbon price in airport slot allocation: Reduction of CO<sub>2</sub> footprint per traveling passenger or no change at all?* submission to: *Int. Journal of Sustainable Transportation*, 2022, unpublished working paper; In chapter 4, the term "we" is used to include the authors of [Weil et al., 2022](#).

tion. By the inclusion of this demand-driven approach, we explicitly refer to the existing drawbacks of today's regulatory solution and the implied consequences, such as the conduction of empty flights [European Parliament, 2020](#) in accordance with the principle of Grandfathering [Pellegrini et al., 2017](#).

In summary, the proposed model includes the minimization of three objectives that are considered to calculate the allocation result: The minimization of the *carbon footprint* per traveling passenger is represented in the carbon cost function. The establishment of sufficient network connectivity at hub airport "F" is included by the connection cost function, and the minimization of individual handling cost per passenger is represented in a handling cost function, applicable at each airport facilitating a departure or landing operation. In the model, we optimize the allocation of 50 inbound flights, representing inbound traffic from the airports New York (JFK), London-Heathrow (LHR), Berlin-Brandenburg (BER), Shanghai-Pudong (PVG) and Rome-Fiumicino (FCO) to the hub, which is represented by Frankfurt Airport (FRA). The resulting outbound traffic includes flights to the same destinations, starting at hub FRA. The introduction of weighting factors for the three mentioned cost functions serves to develop explicit allocation scenarios, focusing on stakeholder interests. In the given set-up, we calculate results based on a set of six different carbon price levels,  $p(\text{CO}_2)$ , referring to the price for one ton of  $\text{CO}_2$  emissions. The functioning of the developed approach is briefly explained in Figure 4.1.

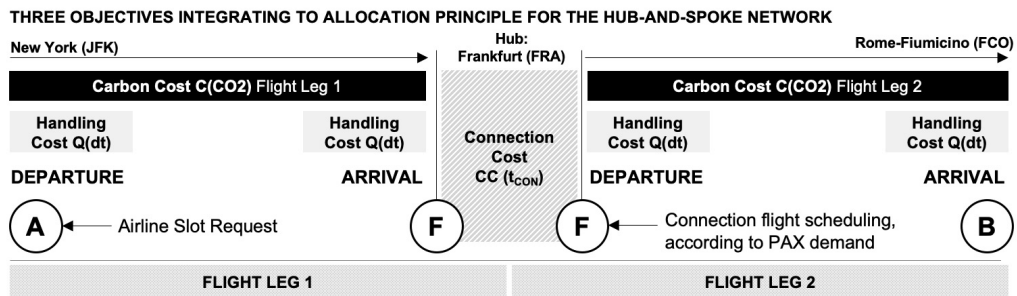


Figure 4.1: Overview of allocation model for the hub-and-spoke context including three defined allocation objectives: Carbon cost, connection cost, handling cost per traveling passenger

The remainder of this paper is structured as follows. In Section 2, we provide a literature review including relevant work on airport slot allocation and network optimizations. We focus on explicit drawbacks and areas for improvement regarding today's allocation approach. In Section 3, we introduce the proposed model in detail. Section 4 includes the observation and assessment of results. In Section 5, we derive managerial implications based on the model outcomes and we conduct an assessment and comparison of carbon emissions based on the results. In Section 6, we conclude our study providing implications and outlook for further research.



## 4.2 LITERATURE REVIEW

The literature review is based on two parts. In the first part, we review definitions and functionalities of the slot allocation status quo, according to the IATA Worldwide Slot Guidelines. This results in a set of drawbacks and improvement potentials that we identify based on the current set up and that we highlight in Table 4.1. In the second part, we refer to relevant work on slot coordination, applied in previous studies, focusing on slot auctioning, secondary trading and improvement of the status quo.

### 4.2.1 *Slot allocation of today and implications for the operation of hub-and-spoke networks*

The process of slot allocation represents the allocation of time windows at coordinated airports [Czerny et al., 2008](#). These include the right to use "the full range of airport infrastructure necessary to operate a flight on a specific date and time" [European Commission, 1993](#). The Worldwide Slot Guidelines, as major ruling framework for the allocation process of today, define how this process is conducted by an independent coordinator. The applied mechanism is a three-stage hierarchical process [Benlic, 2018](#) containing a single-point allocation logic, meaning allocation of time windows at a single airport [Zografos et al., 2017](#). The first step consists of the consideration of slots of historic precedence, so called Grandfather rights, representing slots that have been assigned to air carriers in a previous allocation period. These time windows are (re-)allocated to carriers in case these prove an operational utilization of at least 80% of time of these slots in the previous allocation period. This implies air carriers are endowed with the right to maintain their right of operation in case of a sufficient operational utilization, independent from the utilization of seats on the offered routes. The second step consists of the allocation of remaining slots to a minimum of 50% of new entrants. This New entrants-rule is the second directive in IATA's allocation mechanism resulting in a minimum chance for new market entries in case unassigned slots are available [Zografos et al., 2012](#). The third rule is the rule of application of additional allocation criteria, so called secondary criteria. These guide the allocation decision in case of remaining slots after previous two rules of higher priority have been applied. Notably, none of these criteria include the parameter aircraft type, seat utilization or number of carried passengers [International Air Transport Association, 2019](#). Further, the level of CO<sub>2</sub> emissions is also not included. In addition, the consideration of network traffic such as of a at operation of hub-and-spoke network is not included in today's context, given that only a single point is considered in the allocation process [Pellegrini et al., 2017](#). To underline the importance of a hub-and-spoke coordination, many of the coordinated airports today serve as Hub for major international airlines implying a direct relationship between the task of network planning and airport slot coordination. The observed procedure of today implies multiple functional deficits, that we indicate in Table 3.1 (see Chapter 3).

#### 4.2.2 Existing studies on airport slot allocation

Existing studies in the field of slot allocation can be classified according to three areas: First, the area of studies focusing on improvement of the status quo mainly maintain the approach provided by the IATA Worldwide Slot Guidelines and develop potentials for improvement. Here, two studies conducted by consulting agencies [NERA Economic Consulting \(2004\)](#) and [Steer Davies Gleave \(2011\)](#) are to be mentioned in a first place, analyzing drawbacks and potentials in of the solution. The work of [Czerny et al. \(2008\)](#) provides a good classification and overview of slot allocation potentials and deficits. The second area of research is related to auctioning mechanisms. Here, the studies of [Ball et al. \(2018\)](#) and [Li et al. \(2013\)](#) are to be mentioned. Both investigate the implementation of auctioning mechanisms for slots. Thirdly, the area of market-based approaches includes studies opting for a procedure based on competitive measures, such as free trading or trading on a secondary market ([Bichler et al., 2021](#)). Slot trading approaches are discussed in [Verhoef \(2010\)](#), [Pellegrini et al. \(2012\)](#) and [Lang and Czerny \(2022b\)](#). Among the studies including network approaches, the study *SOSTA* by [Pellegrini et al. \(2017\)](#) is to be mentioned in a primary place. The study allocated slots on a European scale including the slot coherency principle, meaning slots being allocated considering start-and end-points of a route. The study of [Madas and Zografos \(2013\)](#) provides a list of relevant adaptations and measures for slot allocation, including concepts of auctioning, congestion pricing and secondary trading. The studies of [Basso and Zhang \(2010\)](#) and [Czerny \(2010\)](#) relate to the concept of congestion pricing. [Adler et al. \(2014\)](#) discuss implications of slot allocation on economic welfare and the regulative context. [Gillen et al. \(2016\)](#) develop a framework that combines interdependencies of managerial and economic aspects at the management of airport capacity. [Adler and Yazhemsy \(2018\)](#) investigate on marginal values of slots and associated capacities and [Zografos et al. \(2018\)](#) investigate on relationships between schedule results and utility for involved airlines. Detailed allocation approaches are provided by [Jacquillat and Odoni \(2015\)](#), that develop a model for joint optimization of flight scheduling and airport capacity. [Bolic et al. \(2017\)](#) demonstrate an integer programming model for a network-based flight scheduling problem. [Ivanov et al. \(2017\)](#) develop a two-level mixed integer model to simultaneously reduce delay and allocation displacements. The study of [Corolli et al. \(2014\)](#) deals with the concept of simultaneous network scheduling by development of a two-stage framework. This study enhances the existing approach deployed in [Zografos et al. \(2012\)](#) that addresses the same matter. The study of [Castelli et al. \(2010\)](#) develops an optimization approach on a network level that is similar to the one provided by *SOSTA*. Lastly, [Ribeiro et al. \(2018\)](#) develop a model that optimizes slot allocation based on multiple objectives: The number of rejected requests, maximum schedule displacement, total schedule displacement and the number of displaced requests. [Gillen and Tudor \(2008\)](#) elaborate on a potential market value of slots, referring to stock market prices, and [Valdes and Gillen \(2018\)](#) develop a field study for slot allocation at the airport of Mexico City, MEX. [Gillen and Starkie \(2016\)](#) refer to explicit questions of slot allocation at European airports, and [Grunewald \(2016\)](#) develops an incentive-based alloca-

tion mechanism. [Dziedzic and Warnock-Smith \(2016\)](#) evaluate implications of airport coordination for the specific business model of low cost carriers and [Forsyth \(2018\)](#) investigate the relationship of financing of airport investments and the topic of market access and slots. [Murça \(2018\)](#) include a more air traffic related approach, including the assessment of airline influences on routes. The study of [Fu et al. \(2015\)](#) provides an assessment of air carriers' operations in the context of market liberalization.

#### 4.3 ALLOCATION MODEL

The developed model consists of five network airports and one hub. We allocate slots for two flight legs per connection between two network locations "A" and "B", such that the objective function is minimized. For a connection between "A" to "B", a total of four slots is allocated in the model: Two departure slots for leg 1 and leg 2 and two landing slots for leg 1 and leg 2. To transfer our approach to a real application, we chose Frankfurt Airport (FRA) to be the hub in our model, and London-Heathrow (LHR), New York John F. Kennedy (JFK), Berlin-Brandenburg (BER), Shanghai-Pudong (PVG), Rome-Fiumicino (FCO) serving as the inbound and outbound network locations. Frankfurt airport serves as a good representation for a hub in the context, since a large share of network traffic is handled via this airport. Observed flights further contain a significant share of intercontinental flights. The network airports in our solution are connected to the hub by direct flights. Traffic can be operated in both directions. Given the known distances between a network location and the hub, and the expected travel time in minutes, the allocation of the two landing slots is determined by allocation of the corresponding departure slot. In Figure 4.2, we demonstrate the set up our model including six locations. We refer to our previous study, containing the same set of airports, but an operation of point-to-point traffic [Weil et al., 2021](#).

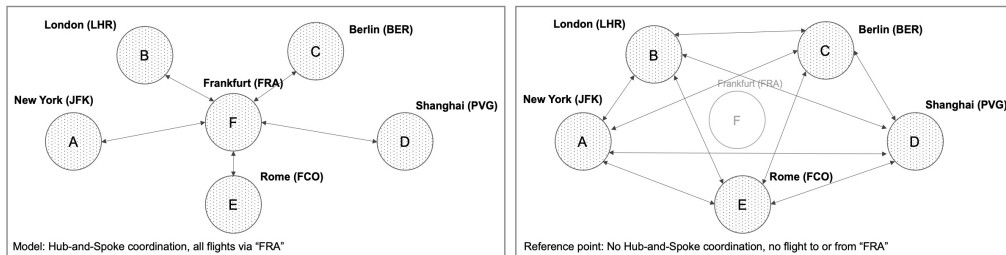


Figure 4.2: Overview of network airports including hub-and-spoke coordination and deployed approach in previous study ("reference point") [Weil et al. \(2021a\)](#)

To conduct the allocation of slots for leg 1 and leg 2 flights, our model is based on three objectives. These represent three parts of the objective function, including different stages of the allocation process. The carbon cost of allocation, indicated as  $C(\text{CO}_2)$ , defines the cost of allocation resulting from the carbon footprint per individual passenger. Based on the allocation of a leg 1 or leg 2 flight, the *Seat Load Factor (SLF)* increases or decreases, leading to an effect on this cost function. Second, we consider different aircraft types in the solution, also contributing to this context based on the considered calculation method for

CO<sub>2</sub> emissions. To calculate CO<sub>2</sub> emissions, we refer to the concept of *Carbon intensity* per aircraft and flight, developed in the study of Graver et al. (2019). The handling cost,  $Q(dt)$ , as second, and opponent cost function, represents a charge per passenger applying for handling operations at the airport. This type of cost includes the airport perspective in the given context, applying in our solution, per network connection four times. As an assumption, we determine that the handling cost charge varies throughout a day, depending on the rate of utilization of the respective airport. During the peak hour, the individual handling cost charge per passenger reaches its highest value, and during off-peak times, lower individual handling costs apply. The third cost contributor completing our three-part principle is represented by the connection cost of allocation, indicated as CC. This function represents a cost per passenger based on the achieved connectivity at the hub FRA. The objective here is to minimize connection costs by assigning slots for connecting flights during times of high demand for a connecting flight. Hence, the lowest connection cost per passenger applies in hours containing most passengers awaiting a connection flight to a respective network destination. In contrast, the largest connection cost factor per passenger applies during hours containing fewest onward traveling passengers to a network destination. To establish this representation of outbound traffic, our approach develops *outbound groups* per destination airport served from the hub. In section 3.1, we provide a detailed definition of the considered three cost functions.

To further understand the applied principle of allocation, we introduce four points of time that are relevant to determine the result of each of the three cost functions. Based on these and based on the respective airline slot request, the corresponding value for carbon cost, handling cost and connection cost changes. These four points of time determining the allocation result are  $t_{REQ}$  representing the time of slot request expressed by the airline,  $t_{MAX}$  representing the hour of maximum airport utilization (i.e., peak hour),  $t_{CON}$  representing the optimum departure time for a connection flight (based on the number of waiting, onward traveling passengers) and  $t_{ALLO}$  that represents the allocated slot for a flight after minimization of the objective function. To calculate the result, we introduce a set of model constraints ensuring a minimum exchange time at the hub (i.e., exchange time constraint). In addition, we define that the number of inbound passengers at hub FRA must be equal to the number of outbound passengers (i.e., inbound/outbound constraint). Third, we ensure that all passengers arriving at hub FRA must be transferred to one out of nine outbound groups per network destination, including a departure slot for leg 2, named  $t_{CON}$  (i.e., outbound group constraint). The four points of time establishing the allocation result and the eight primary hub-and-spoke allocation constraints are indicated in Table 4.2.

Nr.	Component	Description
1.	$t_{REQ}$	Time of airline slot request for departure of the first leg, contributes optimum departure time for the first leg. Achievable SLF is at highest value.
2.	$t_{MAX}$	Time of maximum utilization of airport, contributes time of highest handling cost for conduction of flight. Handling fee is at its highest value.
3.	$t_{CON}$	Optimum departure time for connection flight, contributes earliest feasible departure time for connecting passenger at hub considering constraints.
4.	$t_{ALLO}$	Time of slot allocation, per first and second leg flight after minimization of objective function. The minimized, weighted system cost apply.

Nr.	Constraint	Description
1.	Inbound- /Outbound constraint	Ensures that the amount of inbound passengers at hub is equal to the amount of outbound passengers. Every passenger entering the system, leaves the system at the point of destination.
2.	Exchange time con- straint	Ensures that a minimum of 60 minutes is maintained as connecting time per arriving passenger at the hub. Earliest feasible departure slot for a leg 2 flight is the arrival time of latest inbound passenger plus 60 minutes.
3.	Outbound group con- straint	Ensures that all arriving inbound passengers at the hub are being transferred to one out of nine potential outbound groups. Outbound group $T_{CON1}$ contains most passengers waiting for a connection flight. Group $T_{CON10}$ includes passengers that cannot be transferred to any outbound flight, here: highest individual connection costs apply, 10,000.00 €/PAX.
4.	Distance Contribu- tion/PAX	Ensures that the distance contribution per passenger on leg 1 does not differ more than 30% from the distance contribution per passenger on leg 2.
5.	Cost Contri- bution/PAX	Ensures that the cost contribution per passenger on leg 1 does not differ more than 30% from the cost contribution per passenger on leg 2.
6.	Carbon Cost/km	Ensures that the applicable carbon cost per kilometer does not differ on average more than 40% between flights on leg 1 and leg 2.
7.	Group size constraint	Ensures that the amount of passengers in outbound group $T_{CON1}$ does not extend to more than five times the amount of passengers included in the smallest outbound group $T_{CON9}$ .
8.	Flights per time win- dow con- straint	Ensures that each five minute time interval includes a maximum of two operated flights (leg 1 only)

Table 4.1: Points of time determining slot allocation result and eight hub-and-spoke allocation constraints

The functioning of our model including the defined set of constraints and three cost functions is demonstrated in Figure 4.3. Here, we indicate how a passenger arriving from JFK and onward traveling to LHR is being "charged" by the system, given the individual arrival and departure time at the hub. The airline, as the slot requesting entity, requests a slot for operation of the leg 1 flight. This point,  $t_{REQ}$ , defines the optimum departure point, leading to the highest achievable SLF. Given the operational constraints, and interaction with the two other cost functions, flight 1 is allocated minimizing the defined objective. The resulting flight of the passenger begins at point  $t_{ALLO}$ .  $t_{ALLO}$  plus the flight time in minutes determines the arrival slot at hub FRA, which is again being evaluated and charged by a per passenger handling cost function. The traveling passenger arrives at the hub FRA and determines by the time of his arrival the earliest feasible connection flight, leading him to his point of destination, LHR. This earliest feasible departure slot for a connection flight is being determined for each arriving inbound passenger. Given that in total there are five inbound connections contributing flights to hub airport FRA, the arriving passenger from JFK is now "mixed" with other arriving passengers from other originating locations. Given this, each passenger "reports" his earliest feasible departure time for an onward connection. The set up of the connection cost function, minimizing cost per passenger, leads to a cumulation of passengers into groups. Given our explanation of the connection cost principle, the group containing the largest amount of (mixed) inbound passengers, leads to the smallest charge per person. By this, the smallest applicable cost charge is equal to €5.00, and the highest cost charge equal to €10,000. After cumulation of passengers, the respective outbound departure slot is being determined. At this step, and given our idea of a passenger cumulation, we indicate a slot as a time window of one hour requiring the conduction of a flight. By this, we open the possibility of multiple flights to be conducted, serving more than 364 passengers per individual group (364 represents the largest seat capacity of aircrafts in our model, representing a Boeing 747-800). The summary of objectives and minimization of the objective function leads to the optimum result of allocation for flights on leg 1 and leg 2.

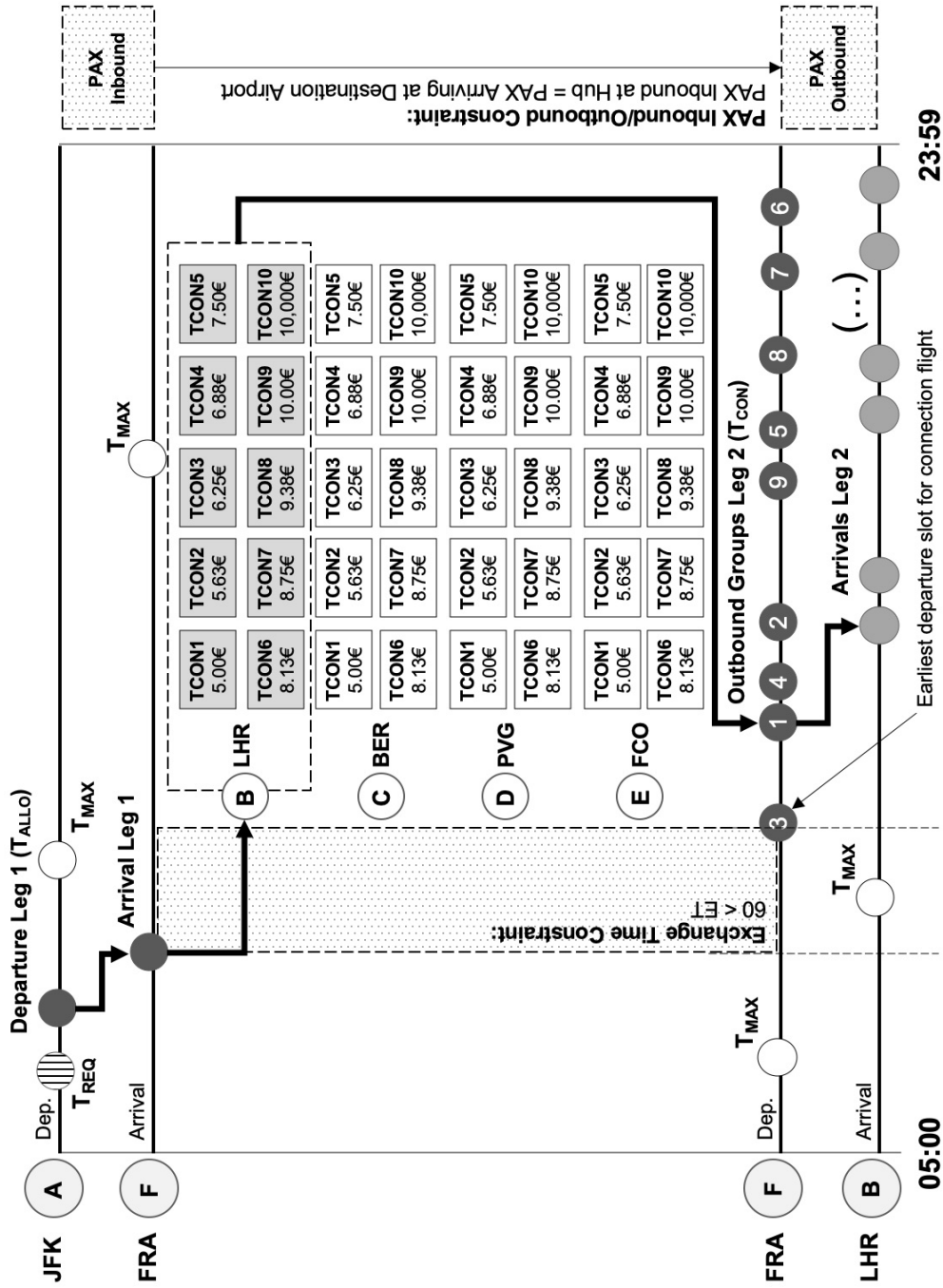


Figure 4.3: Functioning of hub-and-spoke allocation model, here: allocation of a flight on leg 1 and leg 2 enabling the connection "New York (JFK)" to "London (LHR)" for the traveling passenger; minimum and maximum connection cost charge per passenger and outbound group indicated in the center

## 4.3.1 Three cost functions integrating to the objective function

In the following, we provide a detailed definition of the developed three cost functions, to further explain the functioning of the model, including the three primary, weighted objectives of the objective function.

*Carbon cost of allocation C(CO<sub>2</sub>)*

The carbon cost function per leg 1 and leg 2 flight incorporates the achieved *Seat Load Factor (SLF)* and corresponding *carbon footprint* per individual, traveling passenger. The individual carbon footprint is calculated by the amount of carbon emissions per deployed aircraft type, route distance and the amount of passengers per flight. Since we consider that the achievable SLF at point  $t_{REQ}$  reaches the highest amount, this point is also the most favorable in terms of an achievable carbon footprint per passenger. The airline, as the slot requesting entity, brings in the intention to operate a flight at the time  $t_{REQ}$ . By this, she also defines the lowest achievable carbon emissions per passenger for that flight, given that the other two input variables, aircraft type and route distance are assumed unchangeable, once a slot request has been issued. In Table 4.3, we demonstrate how a displacement of a departure slot leads to a reduction in SLF, expressed by the value  $\delta_{SLF}$ . With each hour of displacement, the "addressable" SLF in the model is reduced by 10.0%. After reaching a total of 5 hours of displacement, the resulting SLF equals 50% of the originally addressable passengers. This value remains for further displacements (>5.0h).

$\delta_{SLF}$	03:30	04:30	05:30	06:30	07:30	08:30	09:30	10:30	11:30	12:30	13:30
1.0						$t_{REQ}$					
0.9					-1h		+1h				
0.8				-1h				+1h			
0.7			-1h						+1h		
0.6		-1h								+1h	
0.5	-1h										+1h

Table 4.2: Considered variation of Seat Load Factor (SLF) based on displacement time of departure slot for leg 1 flight

The resulting carbon cost function for a flight from JFK to FRA is defined as follows:

$$C_{AF}(CO_2) = E_{AF} \times p_{CO_2} \times \frac{1}{SLF^2} \quad (4.1)$$

In (4.1), the term  $e_{AF}$  represents the amount of emitted CO<sub>2</sub> on a route between two network point "A" and "F", representing the locations JFK and FRA.



This amount is multiplied by the price per ton of CO<sub>2</sub> emissions according to the applicable market price  $p_{CO_2}$ . The correction factor  $1/SLF^2$  serves to incorporate the utilization rate of a flight: The inverse logic implies, that the higher the utilization rate of a flight, the lower the applicable carbon cost. The emissions per kilometer,  $e_{AF}$ , are calculated by multiplication of *Carbon intensity* per aircraft type, CI, and number of passengers on a route [Graver et al., 2019](#). To translate this method of calculation to a fix, passenger-independent approach, we multiply the value of CI, representing the carbon efficiency of the deployed aircraft, always with the same amount of passengers, represented by  $P_{FIX}$  (4.3). By this, we exclude a variation in passenger load from consideration, including an inverse logic for SLF and multiplication with the applicable carbon cost (4.1). The multiplication of emissions per km  $e_{AF}$  and distance of a route  $d_{AF}$  leads to the amount of CO<sub>2</sub> emissions of route  $e_{AF}$  (4.2):

$$E_{AF} = e_{km} \times d_{AF} \quad (4.2)$$

$$e_{AF} = CI_{RPK} \times (P_{FIX}) \quad (4.3)$$

For the calculation of Seat Load Factor  $SLF_{AF}$  for a flight from "A" to "F", we refer to:

$$\text{Seat Load Factor (SLF)} = \frac{\text{Number of carried passengers} \times \text{Distance [km]}}{\text{Number of carried seats} \times \text{Distance [km]}} \times 100\% \quad (4.4)$$

For the determination of carbon intensity (CI) per aircraft type, we refer to the definition of CO<sub>2</sub> emissions per Revenue Passenger Kilometer (RPK), developed in the study of [Graver et al. \(2020\)](#). As indicated, we utilize this definition in combination with a fix amount of passengers applicable on all flights ( $P_{FIX}$ ), to detach the amount of CO<sub>2</sub> emissions from the passenger load.

#### *Handling cost of allocation Q(dt)*

The second integrating function to the allocation objective is the handling cost function, defined as  $Q(dt)$ . The handling costs per passenger and flight are defined by the relationship of points  $T_{MAX}$  and  $t_{ALL0}$  in the solution:  $T_{MAX}$  indicates the hour of maximum utilization of airport infrastructure for the given flight class and type of operation (i.e., landing or departure).  $t_{ALL0}$  includes the time of allocation of that flight. As an assumption, we consider that the closer we allocate a flight to point  $T_{MAX}$ , the higher the applicable handling cost per passenger will be. By this, we refer to the developed handling cost principle and integration of the airport interest in coordination. During  $T_{MAX}$ , the largest amount of departure or arrival operations occurs, meaning that the utilization of physical infrastructure is at its highest point. As a further distinction, we separate handling costs for *Widebody* and *Narrowbody* aircrafts in this context, given that the contribution to operational congestion of an airport partially depends on the size of an aircraft: It is more convenient to operate

large aircrafts during the time  $T_{MAX}$ , given that more passengers are transported in a single operation. To exclude narrowbody operations from the hour of maximum utilization  $T_{MAX}$ , we set the applicable handling cost charge per passenger for this type of aircraft to 50,000.00 € during the mentioned hour  $T_{MAX}$ . The associated handling cost function for widebody and narrowbody operations are indicated in Figure 4.4.

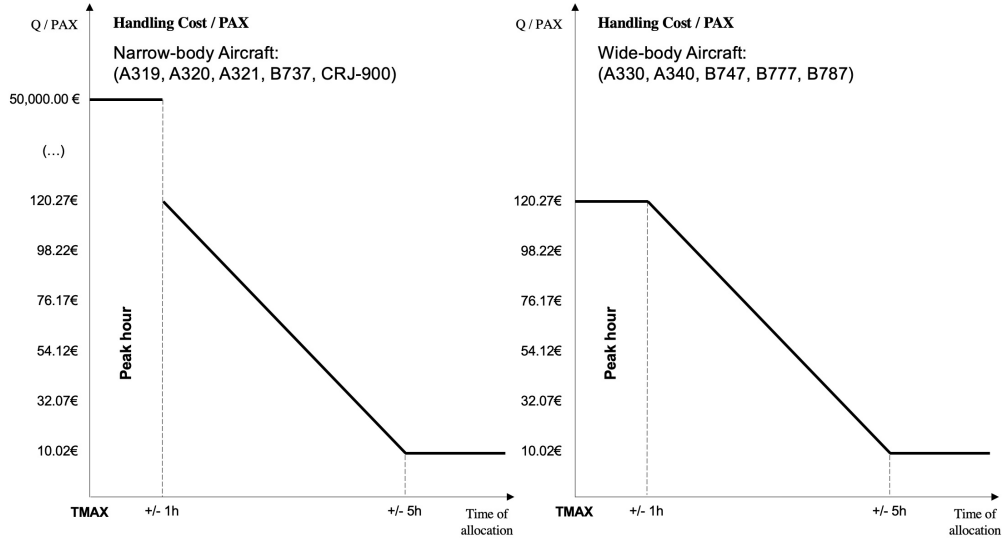


Figure 4.4: Two considered handling cost functions for narrowbody and widebody operations, note: distinction of handling cost functions not utilized in current model setup

The resulting handling cost function for a flight from JFK to FRA is defined by the applicable handling cost charge per passenger  $q_{dt}$ , defined as per displacement time  $dt$  (i.e., difference of points  $T_{MAX}$  and  $t_{REQ}$ ), multiplied with the applicable number of passengers on the respective flight:

$$Q_{AF}(dt) = q(dt) \times PAX_{AF} \quad (4.5)$$

4.3.1.1 Connection cost of allocation CC ( $T_{CON}$ )

As the third and last contributor to the objective, we introduce the connection cost function. It represents a charge per passenger based on the achieved outbound group,  $T_{CON1}$  to  $T_{CON10}$ , that an individual traveling passenger is associated to. The amount of connection cost thus depends on the allocation of inbound flights (leg 1) and outbound flights (leg 2) at hub FRA. The allocated slot per outbound group  $T_{CON}$  represents the departure slot for an outbound operation in leg 2, including the earliest feasible departure time for the conduction of such flight, based on the individual arrival time of the represented passengers in that group. Per definition, group  $T_{CON1}$  contains the largest amount of onward traveling passengers to a destination, and group  $T_{CON9}$  the least amount of onward traveling passengers to that location. The "worst" group,  $T_{CON10}$ , contains all onward traveling passengers that cannot be allocated to a cumulated group of passengers. Given this, we set the applicable connection cost factor in that group to 10,000.00 €, establishing on this way the outbound group constraint, defined in Table 4.2. To provide an incentive for a smooth distribution of aircrafts among the composed groups, we further define that for outbound groups requiring operation of more than two flights (i.e., number of aircrafts > 2.0), ten times the original connection cost factor per individual passenger applies. As a result, the connection cost function fulfills two objectives: First, it cumulates passengers based on their airports of destination in a way that most passengers are assigned to the group with least applicable individual cost. Second, it ensures a smooth distribution of flights among these composed groups, given the fact of an increased cost charge for groups including more than two flights. The applicable connection cost function per passenger and outbound group is indicated in Figure 4.5. On the right side, we demonstrate the applicable cost charge per passenger for outbound groups including more and less than two flights. The outbound groups  $T_{CON}$  are defined as a time interval of one hour.

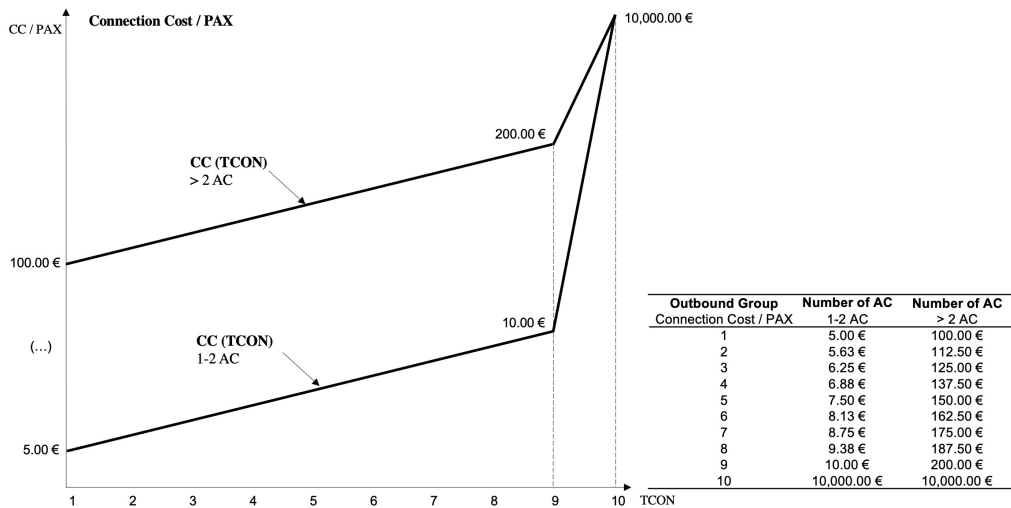


Figure 4.5: Connection cost function and applicable cost charge per passenger based on outbound group and required flights

The connection cost function for a leg 2 flight from FRA to LHR is defined as:

$$CC_{FB}(T_{CON}) = cc(T_{CON}) \times PAX_{FB} \quad (4.6)$$

The summary of the three developed objectives results in the objective function  $Z$  of our model, including a weighting factor  $\lambda$  per individual cost contribution, developed to integrate and prioritize an individual stakeholder interest, as we demonstrate in the upcoming part. The objective function of the model is indicated in (4.7):

$$Z(C, Q, CC) = \lambda_c \times C(CO_2) + \lambda_q \times Q(dt) + \lambda_{cc} \times CC(T_{CON}) \quad (4.7)$$

#### 4.3.2 Development of allocation scenarios including multiple carbon price levels

For the evaluation of results, we develop six scenarios including different parameter settings. Given the proposed model set up, these scenarios can include a different applied weighting factor  $\lambda$  per individual cost contributor, or a different carbon price level  $p(CO_2)$ , leading to a different weighting of solutions within the carbon cost function. Given the principal orientation of our study, evaluating the allocation results based on a carbon price variation, we calculate different allocation solutions including a different carbon price  $p(CO_2)$ . The applied weighting factor  $\lambda$  remains unchanged in these solutions. To incorporate a carbon cost related focus, we set the weighting parameter  $\lambda_c$  for carbon costs to 5.0 in all solutions, increasing the relative importance of that contributor by the factor five. The two other weighting factors  $\lambda_q$  and  $\lambda_{cc}$  remain unchanged in all scenarios, at the value 1.0. The six different scenarios, including a carbon price variation, are indicated in Table 4.4. We calculate the result based on a  $CO_2$  price between €50.00/t and €250.00/t. We also calculate a scenario without application of the carbon cost function, including a carbon cost of €0.00/t, indicated as *Scenario 0*.

Scenario	Applied carbon price and weighting
Scenario 1 (Reference sc.)	$p(\text{CO}_2) = 50.00 \text{ €/t}$ , Weighting: $\lambda_c = 5.0$ , $\lambda_q = 1.0$ , $\lambda_{cc} = 1.0$
Scenario 2	$p(\text{CO}_2) = 100.00 \text{ €/t}$ , Weighting: $\lambda_c = 5.0$ , $\lambda_q = 1.0$ , $\lambda_{cc} = 1.0$
Scenario 3	$p(\text{CO}_2) = 150.00 \text{ €/t}$ , Weighting: $\lambda_c = 5.0$ , $\lambda_q = 1.0$ , $\lambda_{cc} = 1.0$
Scenario 4	$p(\text{CO}_2) = 200.00 \text{ €/t}$ , Weighting: $\lambda_c = 5.0$ , $\lambda_q = 1.0$ , $\lambda_{cc} = 1.0$
Scenario 5	$p(\text{CO}_2) = 250.00 \text{ €/t}$ , Weighting: $\lambda_c = 5.0$ , $\lambda_q = 1.0$ , $\lambda_{cc} = 1.0$
Scenario 0	$p(\text{CO}_2) = 0.00 \text{ €/t}$ , Weighting: $\lambda_c = 5.0$ , $\lambda_q = 1.0$ , $\lambda_{cc} = 1.0$

Table 4.3: Six developed scenarios including applied carbon price and weightings

#### 4.3.3 Prerequisites of the hub-and-spoke model approach and considered constraints

To calculate the result of the proposed solution, we define a set of constraints. In Table 4.2, we already pointed out a set of eight constraints with specific regard to the enablement of slot allocation in a hub-and-spoke network. In Table 4.7, we extend this set by provision of additional constraints defining relevant terms of the solution, such as the considered time interval of a slot.

Requirement/Constraint	Description
Airports in network	Flights are operated between five network airports "A"- "E" and hub "F"
Hub-and-spoke traffic	Only hub-and-spoke traffic, all network flights begin or end at hub "F". Flights operated in two directions between network locations and hub "F".
Inb./Outb. traffic	All connections to be established consist of a leg 1 and leg 2 flight, number of inbound PAX at the hub must be equal to number of outbound PAX
Routes	Requested flights between two points "A" and "B" are of known duration and distances. Arrival slots are therefore determined by the requested departure slots.
Three classes of flight operations	Flights are operated according to three classes, they are: Intra-European Business Link, Intercontinental and Leisure. No cargo flights and no general aviation is operated. Leg 2: Only two flight classes are applicable, Intra-European Business Link and Intercontinental.
Aircraft types	There are nine different aircraft types available in the model. These are fix for each flight. Leg 2: Six aircraft types are available, three short-haul aircraft types and three long-haul aircraft types.
Demand of connecting passengers	For all network flights, the ratio of connecting passengers is known between two destinations (e.g., 45% of PAX from "A" continue to "C").
Operational hours	All network airports operate between 05:00 AM and 24:00 PM. The first slot can be allocated at 05:00 AM, the last slot at 23:55 PM.
Slot	A slot is a time windows of five minutes. Requested departure times that are in between two five minute intervals are associated to one respective five minute interval.
Seat Load Factor SLF	The achievable SLF for an airline is at its highest point at $t_{REQ}$ . In case of a displacement from this time, SLF decreases by the values $\delta_{SLF}$ .
CO <sub>2</sub> emissions / RPK	Carbon emissions are calculated per Carbon intensity and Revenue Passenger Kilometer, see Section 3.
Carbon price (ETS)	The applied carbon price refers to the concept of an Emissions Trading System (ETS). We assume six different price levels for CO <sub>2</sub> .
Displacement time (dt)	Displacement time (dt) in our model is calculated as the time difference between $t_{ALL0}$ and $T_{MAX}$ and effects the handling charge $q(dt)$ .

Table 4.4: Set of considered model constraints, extension of constraint set of reference study [Weil et al., 2021](#)

#### 4.4 RESULTS

To evaluate the obtained model output, and to answer the defined research questions in the beginning of this study, we split our results assessment into two parts: First, we demonstrate the cost minimizing allocation of flights, corresponding to the six carbon price levels for leg 1 and leg 2 flight operations. In the second part, we compare these allocations of flights with regard to defined key parameters including the corresponding CO<sub>2</sub> performance. We address the question, which allocation result leads to the overall most beneficial result for the traveling public, and what the consequences of a CO<sub>2</sub> price implementation to airlines, airports and the regulator will be.

##### 4.4.1 Cost minimizing allocation of flights

We indicate the cost minimizing allocation of flights for flight leg 1 in Figures 4.6 and 4.7. The minimization of the objective function leads to the respective allocation, given an applied carbon price level of €50.00/t, €100.00/t and €150.00/t. These price levels are indicated in Figure 4.6. In Figure 4.7, we indicate the price levels €150/t, €200.00/t and €0.00/t CO<sub>2</sub>. On the left of the figure, the 50 inbound flights are indicated including the aircraft type, flight class and airport of origin. These inbound flights, including a dedicated airline slot request are *fix* in the model and remain as unchanged input variables in all six scenarios. The set of aircraft types includes nine potential aircrafts, each contributing a respective value CI per RPK, determining the individual CO<sub>2</sub> output. The indicated flight class is relevant for the determination of handling cost charges per passenger, according to the relationship of value  $T_{MAX}$  and  $t_{ALL0}$ . The value  $T_{MAX}$  per airport is also a fix input variable, defined per individual flight class and including a peak hour at a certain point of the day. The value  $t_{REQ}$  in Figures 4.6 and 4.7 indicates the corresponding requested time slot of the operated flight. Hence, the value "1010" for flight number 1, refers to the time "21:50 PM", translating the five minute interval to a corresponding departure time. The set of time intervals for slot requests includes values between minute "0", corresponding to 05:00 AM, and "1135", corresponding to 23:55 PM which is representing the last feasible departure slot in our solution. Next to  $t_{REQ}$  in Figure 6 and 7, there is the value  $T_{MAX}$  per inbound flight. This value includes the corresponding time of maximum airport utilization (i.e., peak hour) per corresponding flight. Next to this, indicated in yellow, there is the value  $t_{ALL0}$ , indicating the allocated time slot for the corresponding flight after minimization of the objective function. The slot time in yellow includes the allocation solution for each of the 50 inbound flights. Next to it, there is the verification of time window constraint, indicated as *ZW*, representing a verification whether each slot of five minutes is only being utilized at maximum two times, meaning that per each five minute slot, a maximum of two (inbound) flights can be conducted. The red field *ABS Delta* includes the measurement of displacement time. It calculates the absolute value of difference between allocated slot  $t_{ALL0}$  and original slot request  $t_{REQ}$ . Below, the value *MAX* indicates the maximum value of slot displacements in minutes.

The values  $P_{t_{REQ}}$  and  $P_{t_{ALLO}}$  indicate the respective amount of passengers, at the point of slot request ( $P_{t_{REQ}} = P_{MAX}$ ) and time of slot allocation. We assume full utilization of flights in point  $t_{REQ}$ . The corresponding value of correction factor  $1/SLF^2$  and the obtained SLF is indicated next to it.



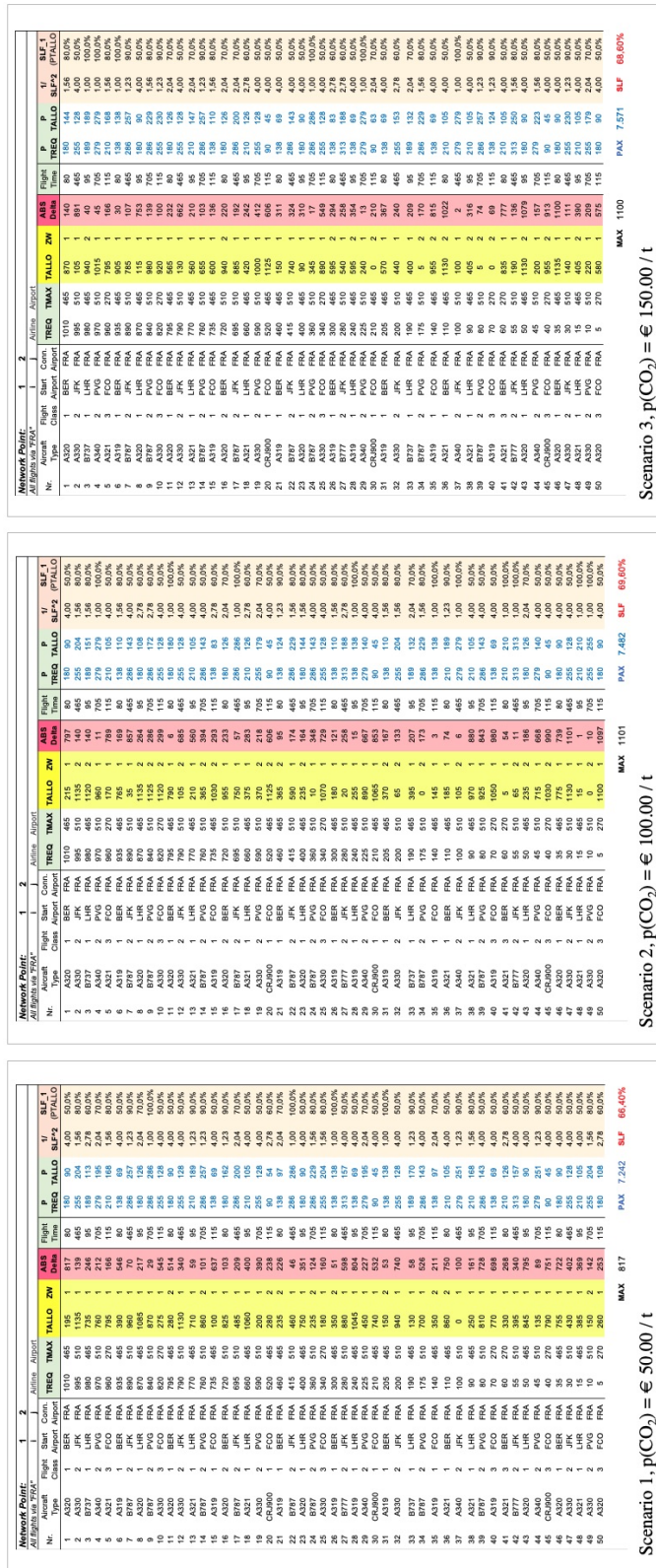


Figure 4.6: Cost minimizing allocation of flights, flight leg 1, scenarios: 1-3 (CO<sub>2</sub> price according to scenario)

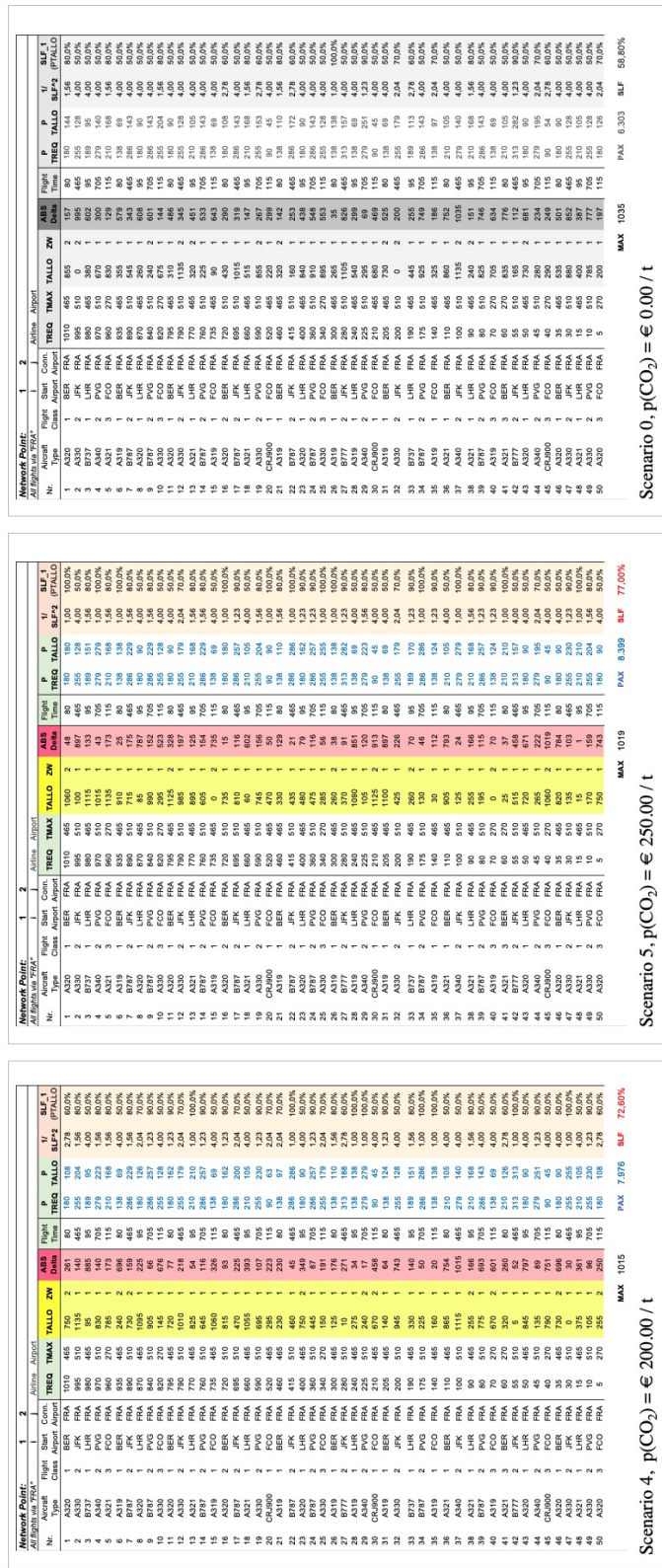


Figure 4.7: Cost minimizing allocation of flights, flight leg 1, scenarios: 4-5 & 0 (CO<sub>2</sub> price according to scenario)

Based on the obtained solutions for flight leg 1, we observe that a different carbon price leads to different results. While in the reference scenario,  $p(\text{CO}_2) = \text{€}50.00$ , flight 1 including an A-320 service between BER and FRA is allocated to time 195, the same flight is allocated to slot 215 in Scenario 2, and to 870 in Scenario 3. In the first case, the respective displacement time, representing the time between  $t_{\text{REQ}}$  and  $t_{\text{ALLO}}$ , is equal to 817 minutes, while in the second scenario this amount is reduced to 797 minutes. In the third solution, the amount of displacement time is corresponding to only 140 minutes, representing the lowest value of these three. The result is that in Scenario 3, the largest amount of passengers are being transported by this flight, leading to an SLF of 80.0%. In Scenario 2, including a larger time of displacement, the achievable SLF is - corresponding to the carbon cost function - lower, at value 50.0%. In the reference scenario 1, this value is also equal to 50.0%. As a consequence, the corresponding correction factor  $1/\text{SLF}^2$  for the scheduled flight 1 is *lowest* in Scenario 3, equaling 1.56, and *highest* in Scenarios 1 and 2, given the value 4.0. We observe, that the number of passengers corresponds to the SLF, given the values 90 PAX in scenarios 1 and 2, and 144 in Scenario 3. The highest amount of passengers on the respective flight is reached in Scenario 5, including a carbon price of  $\text{€}250.00/\text{t}$ , leading to a full utilization of that flight and a corresponding amount of 180 passengers (SLF = 100.0%). Thus, we observe that the relationship between *displacements*, *passengers* and  $1/\text{SLF}$  depends on the considered carbon price: The higher the carbon price in the model, the fewer the scheduled displacements, and the higher the transported passengers per flight. Based on this relationship, resulting from the increased weighting of the carbon cost function, we see a similar relationship for the remaining inbound flights. Notably, the amount of total passengers increases with each carbon price increase, and the same applies for the achievable SLF. Despite this, the number of maximum displacements does not decrease, as the values below the figure indicates. To summarize the relationship of displacements, passengers and the carbon price, there is one additional component to be considered: The aircraft size. Based on the results, we observe that an increase of the carbon price can lead to an increase in total passengers, *despite* the fact of no reduction in total displacement time in minutes. This means that at a higher carbon price, the system optimizes larger aircrafts in a first priority, increasing the amount of passengers in the system. This can be seen at flight 4, including an A-340 operation, with a capacity of 279 passengers. In scenario 1, a total of 195 passengers is being transported, resulting from a rather high amount of displacement of 212 minutes. In the Scenario 5, this displacement of the A-340 flight reduces to only 43 minutes, which leads to a passenger increase to 279 passengers (SLF = 100.0%). Here we see, that the relative displacement time based on a total of 1,135 minutes is reduced by 14.82%, but the amount of additional passengers included in that flight is increased by 43.1%, given the variation from Scenario 1 to Scenario 5. Scenario 0, including a "no-application" of carbon cost ( $p(\text{CO}_2) = \text{€}0.00/\text{t}$ ) is indicated in grey. The resulting number of passengers and SLF is the lowest among the calculated solutions.

For flights on leg 2, representing the outbound side at hub FRA, the resulting cost minimizing allocations of flights are indicated in Figures 4.8 and 4.9. Here, the compound outbound groups,  $T_{CON}$ , per destination airport can be found on the left side, including the corresponding time of allocation. As a difference to leg 1, the allocation of slots for outbound groups  $T_{CON}$  includes time intervals of one hour. This means, that at allocation of the interval "13:00-14:00" in the first example for flights to JFK, the indicated number of flights (see "Required AC") is required to onward transport the indicated number of passengers (see "PAX") to their point of destination. In Scenario 1, this defined group  $T_{CON1}$  for destination airport JFK requires 1 flight to be operated between the time "13:00-14:00", enabling the network connection for 238 passengers. In this example, 18.0% of onward traveling passengers are allocated to this first group, representing the largest amount of such passengers. The resulting SLF, depending on the selected aircraft type of operation, equals 63.9%. The second largest group to JFK includes 232 onward traveling passengers, leading to one flight between "21:00-22:00", including an SLF of 63.3%. As observed in Figures 8 and 9, the largest amount of passengers is always represented in  $T_{CON10}$ , given that the lowest connection cost factor per individual passenger applies here. The lowest number of PAX is in  $T_{CON9}$ . Here, the highest individual connection cost factor applies. The two values indicated in blue, corresponding to  $T_{CON10}$  and "Const1" refer to the two applicable network constraints at this point (see Table 2).  $T_{CON10}$  includes passengers that cannot reach any connecting flight. They are per definition excluded from being a feasible solution. For this reason, the corresponding value of PAX reaches the amount "0". The second constraint refers to the "PAX In PAX Out" constraint of the model, meaning the verification that arriving (inbound) passengers at the hub need to arrive at their point of destination and no single passenger can remain at the airport FRA. For this reason, this value is also (close to) zero, even though we observe, some decimal points leading to a minimum remaining PAX, representing a certain degree of "slack" in the solution. The corresponding values for SLF, and number of passengers and flights are indicated below each distribution of outbound groups. The right side includes the amount of connection costs in total, and per passenger (indicated in red).

We observe that in all scenarios, the distribution of passengers is conducted according to nine outbound groups, except for the case of LHR,  $p(\text{CO}_2) = \text{€}150.00/\text{t}$ , where only eight compound groups find an application. This is at least partially attributable to the set "group size constraint" (see Table 4.2), that we define to "cap" the maximum number of transported passengers in a group as being five times the amount of passengers of the smallest outbound group to the same destination. By this, we establish a flexible cap on passenger numbers per group, and also guarantee, that the smallest groups are supplied with passengers always in a sufficient manner. This effect is observable, looking at the achieved SLF. In all groups, including flights between  $T_{CON1}$  and  $T_{CON9}$ , the average SLF varies between 31.5% in the worst and 100.0% in the best case. This shows, that the establishment of the group size constraint in combination with the definition of the connection cost function excludes any low-utilized flight, below a value of 31.5% for SLF. Referring to our initial set of research questions, this can be seen as a valuable insight, since we do not allow the operation of

poorly utilized, or even empty flights. Most of the scheduled connections reach an SLF in the range between 70.0% and 95.0%, indicating a good utilization rate for connecting flights. The fact of an increased individual connection cost factor per passenger in groups including the requirement of operation of more than two aircrafts, leads further to the effect of only few groups containing more than two outbound flights.





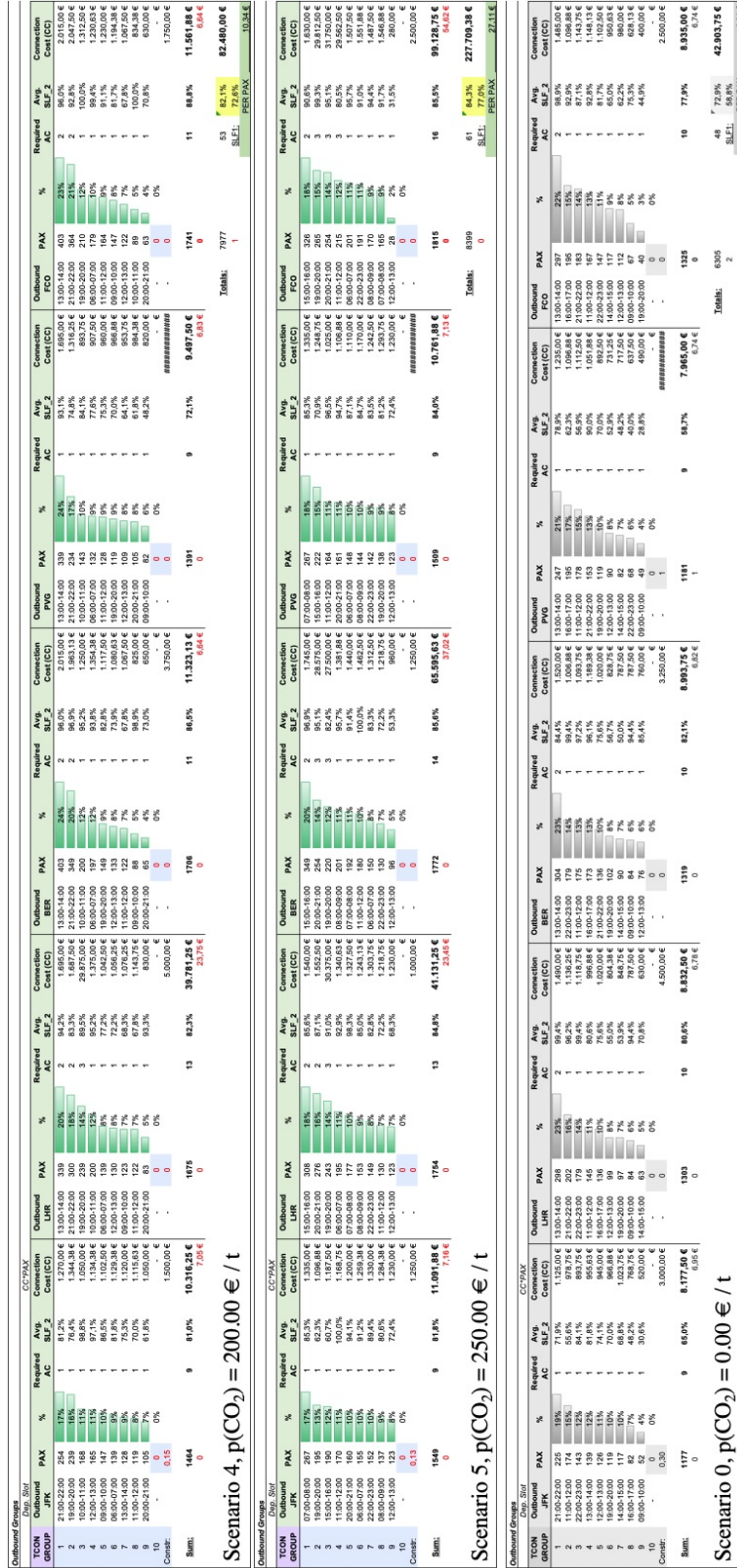


Figure 4.9: Leg 2: Cost minimizing allocation of flights, scenarios: 4-5 & 0, (CO<sub>2</sub> price according to scenario)

#### 4.4.2 *Comparison of scenarios and effect of a carbon price increase*

To conclude the assessment of results, we introduce a set of key parameters to assess the effect of a carbon price increase on the conducted allocations. This set of parameters includes the number of passengers transported in the system, achieved SLF on both legs and in total, and the number of (required) flights. Further, it contains the amount of CO<sub>2</sub> emissions, according to the definition provided in section 3, and the corresponding value of CO<sub>2</sub> per passenger. We conclude the assessment providing the amount of accrued kilometers based on the result and amount of displacement times in minutes. The set of evaluation parameters is indicated in Figure 4.10 for each of the developed scenarios.



PAX			FLIGHT UTILIZATION (%)				FLIGHTS			CO2 PERFORMANCE					KM CONTRIBUTION			DISPLACEMENT	
Scenario	PAX	Var. %	SLF1	SLF2	SLF	Var. %	L1	L2	Total	CO2 Leg 1	CO2 Leg 2	CO2 Total	CO2/ PAX	Var. %	KM Leg 1	KM Leg 2	KM Total	Slot Displ. Total	Slot Displ./ Flight
Carbon Price 50.00€ / t (Reference Scenario)																			
<b>Scenario 1</b>	<b>7,242</b>	<b>-</b>	66.4%	75.5%	<b>71,0%</b>	<b>-</b>	50	51	<b>101</b>	2,459.8 t	2,392.8 t	4,852.6 t	<b>670.1 kg</b>	<b>-</b>	169,760 km	156,828 km	<b>326,588 km</b>	17,253 min	<b>345.1 min</b>
Carbon Price 100.00€ / t																			
<b>Scenario 2</b>	<b>7,482</b>	<b>+3.3%</b>	69.6%	75.6%	<b>72,7%</b>	<b>+1.7%</b>	50	52	<b>102</b>	2,459.8 t	2,409.3 t	4,869.1 t	<b>650.8 kg</b>	<b>-2.9%</b>	169,760 km	157,578 km	<b>327,338 km</b>	18,837 min	<b>376.7 min</b>
Carbon Price 150.00€ / t																			
<b>Scenario 3</b>	<b>7,571</b>	<b>+4.5%</b>	68.6%	80.8%	<b>74,8%</b>	<b>+3.8%</b>	50	51	<b>101</b>	2,459.8 t	2,389.0 t	4,848.8 t	<b>640.4 kg</b>	<b>-4.4%</b>	169,760 km	156,615 km	<b>326,375 km</b>	16,797 min	<b>335.9 min</b>
Carbon Price 200.00€ / t																			
<b>Scenario 4</b>	<b>7,976</b>	<b>+10.1%</b>	72.6%	82.1%	<b>77,5%</b>	<b>+6.5%</b>	50	53	<b>103</b>	2,459.8 t	2,415.3 t	4,875.1 t	<b>611.2 kg</b>	<b>-8.8%</b>	169,760 km	158,100 km	<b>327,860 km</b>	14,739 min	<b>294.8 min</b>
Carbon Price 250.00€ / t																			
<b>Scenario 5</b>	<b>8,399</b>	<b>+16.0%</b>	77.0%	84.3%	<b>81,0%</b>	<b>+10.0%</b>	50	61	<b>111</b>	2,459.8 t	2,539.0 t	4,998.8 t	<b>595.2 kg</b>	<b>-11.2%</b>	169,760 km	164,184 km	<b>333,944 km</b>	14,561 min	<b>291.2 min</b>
<b>WITHOUT APPLICATION OF CARBON COST FUNCTION:</b>																			
Carbon Price 0.00€ / t																			
<b>Scenario 0</b>	<b>6,305</b>	<b>-12.9%</b>	58.8%	72.9%	<b>65,7%</b>	<b>-5.3%</b>	50	48	<b>98</b>	2,459.8 t	2,353.8 t	4,813.6 t	<b>763.5 kg</b>	<b>+13.9%</b>	169,760 km	154,806 km	<b>324,566 km</b>	21,869 min	<b>437.4 min</b>
<b>Scenario 0-1</b>	<b>7,054</b>	<b>-2.6%</b>	65.8%	75.0%	<b>70,3%</b>	<b>-0.7%</b>	50	48	<b>98</b>	2,459.8 t	2,353.8 t	4,813.6 t	<b>682.4 kg</b>	<b>+1.8%</b>	169,760 km	154,806 km	<b>324,566 km</b>	16,744 min	<b>334.9 min</b>

Figure 4.10: Result of six allocation scenarios, overview of key parameters

Based on the obtained results for a cost-minimizing allocation of flights in leg 1 and 2 and the indicated set of key metrics, we observe that the applica-

tion of a different carbon price  $p(\text{CO}_2)$  leads to different results. In the initial set up, including a carbon price of €50.00/t, a total of 7,242 passengers can be transported through the system, given the conducted allocation of corresponding inbound and outbound flights. For this operation, a total of 101 flights is necessary, of which 50 are operated as leg 1 flights and 51 as leg 2 flights. Given an increase of carbon price to the next level,  $p(\text{CO}_2) = 100.00/\text{t}$ , the number of passengers in the system increases by 3.3%, to the amount of 7,482, while the number of corresponding flights (only slightly) increases to the value 102. Of these 102 flights, 50 flights are operated in leg 1 and 52 flights in leg 2. Comparably, given a further increase of the  $\text{CO}_2$  price to €150.00/t, the amount of passengers further increases to 7,571 and the amount of required flights reduces again to 101. We thus observe that a carbon price increase, in the chosen set up of a carbon cost focus ( $\lambda_c = 5.0$ ), leads to an increase in passenger numbers, while the amount of operated flights remains rather unchanged, among all observed allocations. As a consequence, the rate of utilization per flight, SLF, also increases, given a  $\text{CO}_2$  price increase. In the reference set up, the average SLF on leg 1 equals 66.4% and on leg 2 75.5%. The resulting weighted average for all flights operated in the model equals 71.0%. Given an increase of the carbon price from €50.00 to €100.00 and to €150.00, the utilization rate per aircraft increases to the values 72.7% and 74.8%, respectively. The same trend continues with a further increase of the carbon price. The highest amount of passengers and aircraft utilization is reached in the scenario including the highest carbon price, Scenario 6. Here, the amount of passengers reaches 8,399 in total, and the average utilization rate per flight is equal to 84.3%. We thus state that the set up of the model including a carbon cost function leads to an improvement of utilization of flights, given a carbon price increase. With regard to  $\text{CO}_2$  emissions, this relationship has the following consequences: In Scenario 1, including a  $\text{CO}_2$  price of €50.00/t, the total emissions of the allocation system reaches the amount of 4,852.6t  $\text{CO}_2$ . Of this amount, 2,459.8t are attributable to operations of flights in leg 1, and 2,392.8t to flights in leg 2. Dividing the amount of total  $\text{CO}_2$  by the number of transported passengers, we obtain the value 670.1kg  $\text{CO}_2$  per passenger. Increasing the carbon price in this context, we observe that a similar relationship as in the field of passengers and flights occurs. An increase in the carbon price leads to an improved utilization of flights and thus to a reduced carbon impact per individual passenger. As a consequence, the total amount of emissions per passenger (i.e., carbon footprint) decreases, despite the total amount of resulting emissions remains rather constant among all allocations. In Scenario 1, including the carbon price of €50.00/t, the carbon impact per PAX equals 670.1 kg, while the total output (resulting from 101 flights) equals 4,852.6t. In Scenario 6, including the  $\text{CO}_2$  price of €250.00/t, a total of 4,998.8t  $\text{CO}_2$  is reached, even *above* the calculated emissions of the original set up, but the individual contribution per passenger is reduced to 595.2kg  $\text{CO}_2$ . The application of a higher carbon price therefore increases the utilization of (infrastructure) resource in the given context, answering the main research question at development of our study. The development of slot displacements, including the time difference between allocated slot and original slot request, varies between 16,744 min in the worst and 14,561 min in the most convenient scenario. The average amount per flight varies between 376.1 min and 291.2

min displacements. Also in this context, the best result is reached in Scenario 6 including the highest carbon price. Despite this fact, the trend is not as clear as in the case of passengers numbers, SLF and carbon footprint per passenger. The answer to this, meaning an increasing passenger number despite the fact of a (slightly) increasing amount of displacements is seen in the varying aircraft sizes and corresponding seat capacities in the model: Given the range of  $P_{MAX}$  being in between of 90 and 364 passengers, corresponding to the smallest and largest aircraft type in operation, the impact of this factor is quite significant: In case of an increasing passenger number and an increasing amount of displacements, larger aircraft types are better utilized, while smaller aircraft types count with fewer utilization, resulting from more individual times of displacement. Given this, the amount of passengers can increase in the system, even though the number of displacements increases, too.

To conclude the evaluation of scenarios, we again refer to the application of the scenario including a carbon price of €0.00/t. In this special set up, all effects of the carbon cost function to the result of the objective function are lapsed, given a multiplication of carbon emissions and correction factor  $1/SLF^2$  with the carbon price "0". What are the implications of this to the obtained model results? The amount of transported passengers is lowest, compared to all other solutions and also the amount of individual  $CO_2$  contribution per passenger reaches the worst (=highest) amount. We observe that the total effect of the carbon cost function, namely "pushing" passengers into the system (by application of the inverse of the SLF and the fact of being a "per passenger"-calculation) does completely not apply. In the proposed solution, the carbon cost function is the only function including a significant "pushing effect" with regard to passenger numbers, given the application of mentioned multiplication factor  $1/SLF^2$ . Hence, given a carbon price equal to "€0", the remaining two cost functions need to contribute their part, minimizing handling and connection costs per passenger. The fact, that also these two functions are calculated as per passenger, effect that also here, a certain amount of passengers is being "pushed" into the system, given a minimization of the objective function. Based on the minimization of the allocation objective, passenger numbers need to increase and the applicable costs (per passenger) need to decrease to calculate an optimum solution. To explain this effect of a "per passenger" optimization a little further, we calculate *Scenario 0* also in the setting of a *total cost* minimization. In this case, we do not minimize the applicable cost per passenger, but the total cost of allocation. As a consequence, the term PAX disappears from the divisor part of the equation and remains as a multiplier for handling and connection cost of operations. As a consequence to this, the amount of PAX further decreases, reaching the amount of 6,303 passengers in Scenario 0, representing this calculation. The utilization rate per flight is results also on a low level, equaling the value 65.7%. To summarize, the exclusion of a per passenger-optimization decreases the utilization of assets in the developed solution: The same amount of flights is being operated (98), but with a lower corresponding rate of utilization and number of passengers. The carbon impact per individual passenger is therefore also higher.

We conclude, that the consideration of the carbon cost function in our model fulfills the necessary step of integrating passengers into the model. Leaving

out this integral part, the amount of passengers decreases and the utilization rate of assets reduces. We also conclude that an increase of the carbon price is beneficial in the given model context, given an improved result for passengers, SLF and carbon impact per passenger.

#### 4.5 MANAGERIAL IMPLICATIONS

The conduction of this study and calculation of the different carbon price scenarios lead to multiple implications: First, we demonstrate how the integration of a CO<sub>2</sub> price can be fulfilled in the context of slot allocation. We show that the integration of a carbon price, as an integral part of the objective function serves to "incentivize" passenger numbers, SLF and resulting carbon impact of the conducted flights - expressed by the value CO<sub>2</sub> emissions per passenger. The integration of the carbon price in the carbon cost function also addresses the idea of establishing a demand-driven form of allocation: Given a decreasing passenger demand, expressed in the value  $\delta_{SLF}$ , based on a slot displacement, the corresponding carbon cost *increases* in the model, representing an inverse relationship between number of passengers and the resulting carbon cost function. This is seen as the major driver for the *positive* relationship between passenger numbers and the CO<sub>2</sub> price in the proposed solution.

In addition to the integration of a carbon price, we demonstrate how different stakeholder interests in the process (e.g., airlines, airports, coordinator) can be incorporated and quantified through the set-up of the three developed cost functions. Based on this setup, an increased weighting of carbon costs is possible (conducted in this study), representing an increase of the airline intentions in the allocation. At the same time, an increase of handling cost weighting is possible, increasing the airport intentions in the process. As pointed out, airlines and airports pursue different objectives in the slot coordination context. While airlines intend to request and operate flights, such that the SLF (and addressable revenue) is highest, the airport intends to schedule flights such that no operational congestion is to be expected, hence avoiding the hour of maximum utilization  $T_{MAX}$ . This play of two opponent influences is completed by the connection cost function, bringing in the intention of "connectivity" of traveling passengers to the model. In the light of stakeholders of the process, connection cost can therefore represent the role of the passengers, given that a passenger in a hub-and-spoke model, has the intention to reach a connection flight, based on a certain arrival time of the previously conducted inbound operation.

For the regulator, our model also indicates that the establishment of a multiple-point allocation is possible, referring to the principle of slot coherency (Zografos et al., 2017). The allocation principle applied today, which is based on a single-point optimization including the conduction of bi-annual slot conferences is indeed not very efficient. Our proposed approach shows, that such inefficiency can be overcome by application of a combined solution. In the context of our model, this multiple-point set up is even extended by the integration of a network constraint, leading to a four-point allocation of connections.

## 4.6 CONCLUSION

To conclude this study, we again refer to the different interest groups, mentioned in the beginning of our work. Among these, there is the traveling passenger having the intention to travel from point A to B in the developed model setup. The airport, as "facilitator" for flight operations and as the provider of the infrastructure resource, adds to this list as well as the airline, serving as "agent" in this context. In the proposed solution, we demonstrate how all three parties can be integrated into one common approach for slot allocation, each being represented by the integration of a (weighted) cost function. We point out, that it will remain the slot coordinator's task, to balance among these differing interests according to the applicable legislative framework (Hou et al., 2022). In this context, it is necessary to question the objective of slot allocation in general and the intentions expressed by the regulator, representing the interest of the traveling public. Today's mechanism, defined by the IATA Worldwide Slot Guidelines, includes multiple criteria for the allocation of slots. These apply after consideration of Grandfathering principle (primary objective) and New entrants-rule (secondary objective). The set of defined criteria includes a set of seven entries. Notably, and in contrast to our proposed solution, none of the criteria includes a precise weighting of priority or interest with regard to a potential slot allocation objective. The IATA Worldwide Slot Guidelines therefore remain rather imprecise in this context. By the provision of this study, we demonstrate how multiple criteria can be included in an objective function, and how these can be weighted to incorporate specific stakeholder interest.

The slot coordinator is hence being provided with a tool, that manages the allocation of flights in the context of a hub-and-spoke network. The inclusion of a carbon price shows, how slot scheduling can serve as an incentive to facilitate *decarbonization* in the air transport sector, focusing on an improvement of utilization of the conducted flights. We highlight that, despite an overall unchanged amount of total CO<sub>2</sub> emissions, the individual contribution per passenger decreases at the increase of a carbon price. In the light of decarbonization, it will remain relevant to improve the utilization of existing assets in the air transport sector, especially also considering an effective allocation of slots. In fact, the air transport sector of today is confronted with the fact that a decarbonization can only be achieved by the implementation of alternative combustion and propulsion systems (e.g., establishment of Sustainable Aviation Fuel SAF) or a reduction in overall transport numbers, both leading to an improvement in CO<sub>2</sub> emissions. The remaining third option in this context is an improvement of utilization of the *status quo*, meaning an operation of the same amount of flights leading to the same amount of emissions, but with an increased - where ever possible full - utilization of flights. This third option at addressing eco-friendly forms of travel will be the most feasible option in a short-term, given that the introduction of alternative combustion forms will still require some time. Our approach thus provides a valuable tool to stimulate such improvement of utilization of flights, focusing on the regulatory process of airport slot allocation.

The fact that the best performing scenario in terms of carbon impact per passenger represents an improvement over the worst scenario of about 11.2%,

underlines that an effective utilization of flights can improve the carbon impact per passenger. In summary, the integration and increase of the carbon price leads to multiple beneficial results for the regulator and for the traveling public: First, the number of passengers and connectivity in the model is improved. Second, the utilization rate of aircrafts increases, and thirdly, most important with regard to the defined research question, the individual carbon impact per passenger is being reduced.

Declarations of interest: None.

## 5 Summary and Outlook

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To summarize this dissertation, we<sup>1</sup> provide a set of six contributions based on the conducted work, defined as *insights*. The set of insights refers to the provided work in the three papers and includes answers to the defined research drivers explained in the introductory part of the dissertation. In a second part of the summary, we provide a concluding view on limitations of the provided work and an outline on implications for further research.

### 5.1 CONCLUSION

In the following, a set of six *insights* is provided, including key contributions with regard to the developed three papers.

*Insight I: A demand-driven criteria set can be implemented in the slot allocation procedure*

Referring to the deficits and drawbacks of today's slot allocation solution, we observe that the applied criteria set does not sufficiently consider passenger demand. The fact of conducted empty flights during the COVID-19 pandemic in accordance with the rule of Grandfather rights implies a substantial dis-balance between passenger demand and the behavior of air carriers with regard to slots (Sun et al., 2021). Based on the developed model in chapters three and four, we demonstrate how the *passenger demand per route can be incorporated* in an allocation solution, given the developed *carbon cost* function. Our study demonstrates how the increase in seat utilization (i.e., SLF) can be utilized as a guiding principle to calculate an efficient allocation of slots. The related consequence is an improved allocation with regard to the **utilization of flights** and to resulting CO<sub>2</sub> emissions per traveling passenger, as our two studies indicate. The conducted evaluation of stakeholder preferences, ranking CO<sub>2</sub> emissions on the second place further underlines the idea of a utilization-based allocation encounters positive feedback from this involved party.

*Insight II: The carbon impact per traveling passenger can be a relevant criterion for allocation and can be useful for the achievement of an eco-friendly form of travel*

Given the results of the AHP in chapter two, we observe the criterion carbon emissions ranks second among the evaluated set of criteria, after evaluation of considered stakeholders' preferences. Given this, and given the implications related to the task of *decarbonization* that the air transport sector is confronted with, we conclude that CO<sub>2</sub> emissions per traveling passenger can be a relevant criterion to incorporate in the slot scheduling process. Further, the two applied carbon cost functions in chapters three and four demonstrate, how such inclu-

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<sup>1</sup>In chapter 5, the term "we" is used for consistency and refers to the author of this dissertation.

**sion of a CO<sub>2</sub> price** can be fulfilled, considering particularly the emissions per passenger. For a future form of allocation, we emphasize the consideration of a potential incentive effect that a carbon price could have in the context of slot allocation. In light of the recently issued policy measures, i.e., EU Fit-for-55, the application of a carbon price in airport slot allocation could be a supplementary measure. The evidence of low-utilized or empty flights could be avoided and the carbon impact per traveling passenger be reduced.

*Insight III: Multiple stakeholder perspectives can be incorporated and quantified in a common slot scheduling approach*

Based on today's mechanism, including tasks and responsibilities for airlines, airports and the coordinator we observe that the principal responsibility for slot allocation is given to the airlines. These are confronted with the task to request and obtain slots in advance to a scheduling period, as a prerequisite for the operation of a flight. Given this, the airport, as the *complementary stakeholder* in this process, remains with little to no influence on the outcomes of slot allocation result: While the air carrier pro-actively decides, when a slot request (and operation of flight) is a suitable option, the airport only declares the state of capacity, meaning capacity for operation of a flight being available or not. In the developed solutions of chapters three and four, a detailed approach is being provided for the **inclusion and quantification of stakeholder interests**. Given this, the airport is being provided the right to express a timely preference in the same way as the airline, given by the application of the handling cost function. For a future slot allocation approach, it will be relevant to consider both sides of the process, airlines and airports, to achieve the best utilization of resources.

*Insight IV: Slot coherency among a network of airports can be established and the application of that principle is a useful characteristic in light of allocation results*

Section 1 points out that IATA's procedure includes a single-point allocation principle. This implies that all criteria and relationships are defined referring to the question of optimization of a single-point, meaning a single airport. This concept is critical since resulting air traffic including routes, and resulting flight networks is dependent on the assignment of complementary slots at minimum at two points. As a consequence, bi-annual slot conferences are hosted to mitigate the consequences of this form of optimization. In the conducted slot conferences, the results of slot allocation are discussed among air carriers and airports. In case of a mismatch between departing and landing side of a route, bilateral agreements serve to exchange slots between airlines, such that a route can be established - *or not*. In the presented approach of chapters three and four, we demonstrate how **the integration of slot coherency** can be conducted, by simple means of flight time consideration in the allocation process. Based on this, the model optimizes flight allocations at two points, including the characteristic play of objectives, expressed in the carbon and handling cost function. In a modernized world, the concept of single-point allocation is to be considered outdated and should be replaced by a slot-coherent, multiple-point approach.



*Insight V: In a hub-and-spoke network, flight connections can be established including network requirements such as the exchange times of traveling passengers*

Referring to chapter four in particular, we demonstrate how the presented slot coherent approach of chapter three is **translated to a hub-and-spoke context**. Based on this, we demonstrate how the developed solution is extended by a set of constraints, particularly focusing on the operation of a hub-and-spoke network. The inter-dependencies of flights, especially given in the operation of an airline network are considered are functionally underrepresented in today's applied solution. For an improved form of allocation, the consideration of a demand-driven criteria set including network constraints in case of a hub-and-spoke network can be a beneficial solution, as our study finds.

*Insight VI: The implementation of different optimization objectives (e.g., carbon costs, handling costs, connectivity) leads to different results*

As a last contribution, we refer to the developed three cost functions in our approach. These include the two primary stakeholders of the allocation process, the airline and the airport. In addition, they prove that slot allocation can be conducted based on **different allocation objectives** and that each focus on an objective leads to a specific result. In the carbon cost function, we demonstrate how the implementation of a CO<sub>2</sub> price can guide the slot allocation decision in light of achievement of a high utilization of flights. The implementation of handling and connection costs instead includes the airport side of the process, focusing on the utilization rates at network airports and the hub. For a future airport slot allocation, it is necessary to define explicit principles for allocation, including a consideration of all involved stakeholders. Our solution demonstrates how such differentiation in objectives can be established in an airport network.

## 5.2 LIMITATIONS OF THE DEVELOPED THREE STUDIES

Closing the chapter of summary and outlook, we provide a brief summary of limitations of the developed work, addressing particular model assumptions and requirements. In chapter two, a single airport is being considered for optimization, and in chapters two and three this optimization is conducted in a network of airports. Thus, the developed model considers airlines' and airports' intentions by the inclusion of carbon and handling cost functions and further extends this perspective in chapter four by the inclusion of a network constraint. The fundamental assumption behind the approach of the *carbon* and *handling* cost function is, that the two opponent participants in this play of influence act as rationale agents, meaning that each of them is optimizing their individual utility. In addition, and especially addressing the considered carbon cost function, the model assumes that the air carrier requests slots at the point of time where the highest expected passenger demand takes place. Thus, the model considers at this point the amount of passengers per flight to be equal to the maximum capacity of passengers for that type of aircraft. In addition, the model also assumes that with each hour of displacement "away" from the originally requested slot, the passenger demand *decreases* by the value 10%. This assumption should be subject to further validation in case of adapting the developed model in a real context. In this context, it can be possible, that the point of slot request not always includes the point of highest amount of passengers, given the operation of network flights (requirements of a hub-and-spoke network). The proposed approach hence remains to be further developed and translated to a larger scale. The same applies for the handling cost function that includes the idea of *smoothing* operations at the airport throughout the day. In the given context, it can be relevant to change this procedure, given also here the existence of network inter-dependencies. Further, we point out, that capacities and peak hours at airports differ according to different asset types (e.g., runway, terminal) and that not only the runway operation should be considered for such determination of an operational peak hour.

## 5.3 OUTLOOK ON FURTHER RESEARCH

To finalize this dissertation, a brief outlook on further research will be provided. As outlined, the implementation of a *carbon pricing* can be a beneficial tool for the enhancement of the slot allocation status quo. Given today's requirements of industrial transformation, including a decarbonization of the transport sector, the inclusion of a price mechanism for CO<sub>2</sub> emissions is a relevant measure, not only with regard to slots. The implementation of an Emissions Trading System (ETS) for aviation, as it is foreseen in the EU *Fit-for-55* package, will be a relevant step to address an *eco-friendly* form of travel. For a continuous research, we emphasize the analysis of additional carbon pricing methods and a potential adaptation to the slot allocation context. In the proposed model, we demonstrate how a small-scale implementation leads to a beneficial result for the traveling public. In a real application, it will be required to apply the same optimization in a larger context, including additional flights, and an improved

consideration of passenger demand. We underline, that looking at today's allocation procedure ([International Air Transport Association, 2019](#)), multiple drawbacks exist that are to be addressed and further evaluated by air transport research. To provide an overview of additional research topics, we refer to the list of drawbacks and deficits, provided in chapter three and four. Among these, the concept of *Grandfathering* including a lack of passenger demand orientation is one of the most relevant points to focus on. Despite a recent study, indicating that a majority of airport operators is still in favor of maintaining the Grandfather rights ([Airports Council International \(ACI\), 2022](#)), this rule is controversial given the disregard of demand and related market entry barriers, that at least partially, prevent competition ([Kappes and Merkert, 2013](#)). A further area to focus on, resulting from the outcomes of this work, is the question about slot coherency application and the resulting question about the conduction of IATA bi-annual slot conferences. We emphasize, that in a "modernized world", slots should be allocated such that start- and end-points of routes can be considered. Especially relating to this context, conducted studies, such as the study of ([Pellegrini et al., 2017](#)) underline how slot coherency can be established in a network of airports and how the result of allocation can be improved. Further research could address this sphere by addressing the question, how much allocation efficiency is being "lost" in today's solution, and how much efficiency can be "gained", implementing a slot coherent approach. A further topic to address is the determination of airport capacities. We underline that airports' and airlines' perspectives and intentions in the context of slot allocation differ substantially. Therefore, it will be relevant to quantify these differences and to develop a solution further addressing both sides of the process. A further point is seen in the balance and interaction of strategic and operational slot scheduling. Given today's procedure, strategic slot allocation occurs in timely advance to the execution of a flight and in advance of operational scheduling of a flight. For further research, it can be relevant to quantify and address this "mismatch" between strategic and operational slot scheduling, especially given the fact that at major hubs, a significant amount of flights is being operated off slot times ([Zografos et al., 2012](#)). A combined solution could include estimations on traffic and passenger numbers (e.g., improved estimations on terminal infrastructure utilization) or improved estimations on applicable weather conditions. To summarize, today's slot allocation mechanism remains a single-point optimization that includes many manual interactions (e.g., bi-annual IATA slot conferences) and that follows in large parts the exact same pattern established in 1974. The implications of this lead to drawbacks and deficits, pointed out in the beginning of this study, and the resulting implications for air transport research.



## 6 Appendices

### A Appendix to Chapter 2: Analytic Hierarchy Process (AHP)

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
<b>C1 Competition</b>	0	0	1	1	1	0	1	0	1	1
<b>C2 Punctuality</b>	84.5%	69.0%	68,8%	78.2%	83.5%	84.0%	79.7%	81.4%	69.6%	85.7%
<b>C3 CO2 Emissions</b>	2,169 kg	2,570 kg	4,610 kg	5,449 kg	13,048 kg	6,362 kg	10,624 kg	8,072 kg	6,829 kg	10,944 kg
<b>C4 Passenger Satisfaction</b>	Rank 19	Rank 7	Rank 29	Rank 54	Rank 1	Rank 13	Rank 100	Rank 5	Rank 40	Rank 15
<b>C5 Overbidding Rate</b>	1.1	1.2	1.4	1.8	1.7	1.2	1.1	1.6	1.5	1.3
<b>C6 Location Investments</b>	7.77	10.95	4.82	17.99	5.24	2.68	1.62	4.09	4.73	2.66
<b>C7 Route Network</b>	1	0	1	1	1	0	0	0	0	1
<b>C8 Retail Business</b>	\$ 20,760	\$ 23,617	\$ 24,702	\$ 37,903	\$ 24,703	\$ 20,293	\$ 11.884	\$ 16,699	\$ 1,043	\$ 24,147
<b>C9 Effective Waiting Period</b>	0	1	0	0	1	1	1	1	0	1
<b>C10 Service Type Code</b>	1	0	0	1	1	0	0	1	1	0

Figure A1: Considered entry parameters and model assumptions in categories C1, C5, C7, C9 and C10

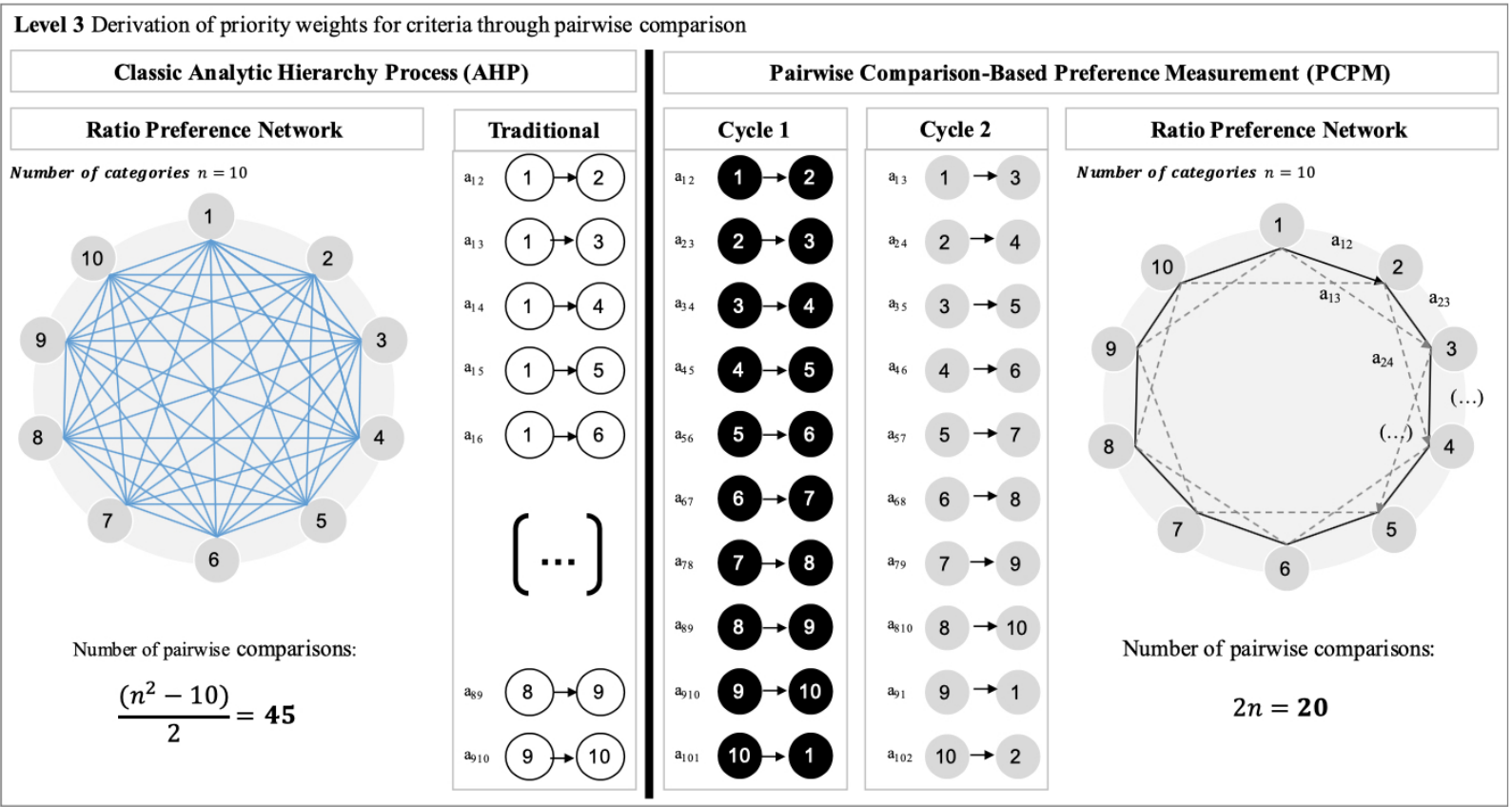


Figure A2: Derivation of criteria weightings according to classic AHP (Saaty, 1980) and PCPM applied in this study (Scholz et al., 2010)

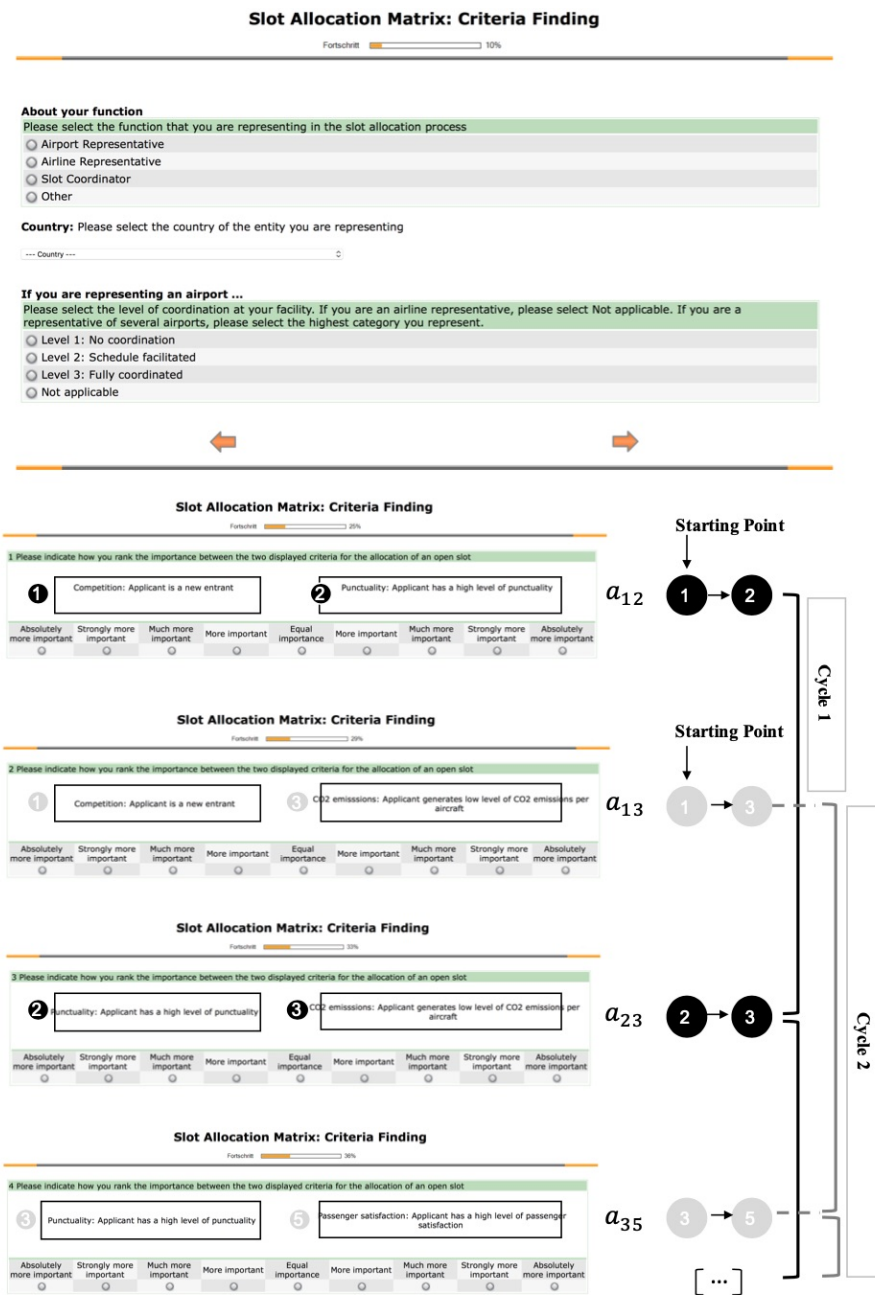


Figure A3: PCPM including pairwise comparisons of criteria in two cycles (Schlereth and Skiera, 2012)

B Appendix to Chapter 3: Slot coherency model

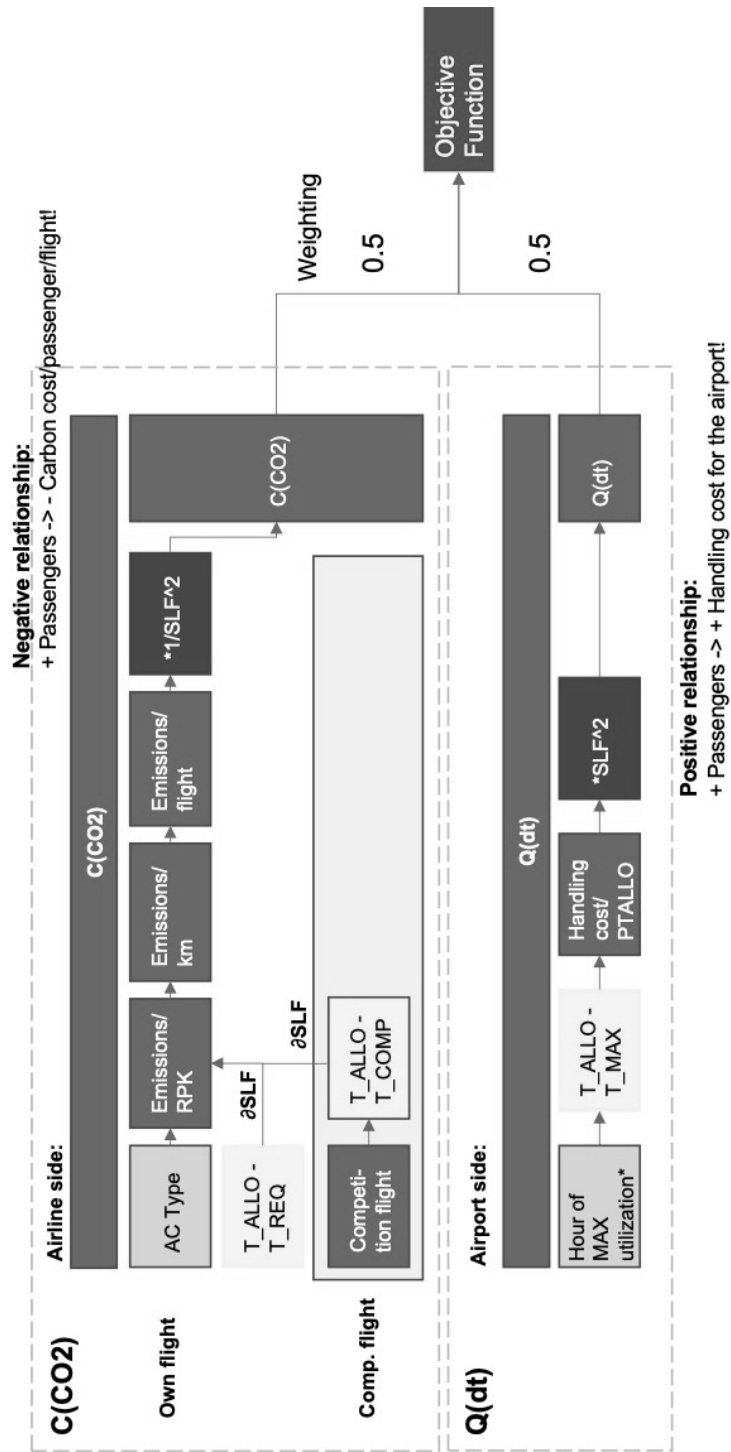


Figure A4: Development of objective function for allocation model, note: term  $SLF^2$  in handling cost function without application in solution of this study



c Appendix to Chapter 4: Hub-and-spoke allocation model

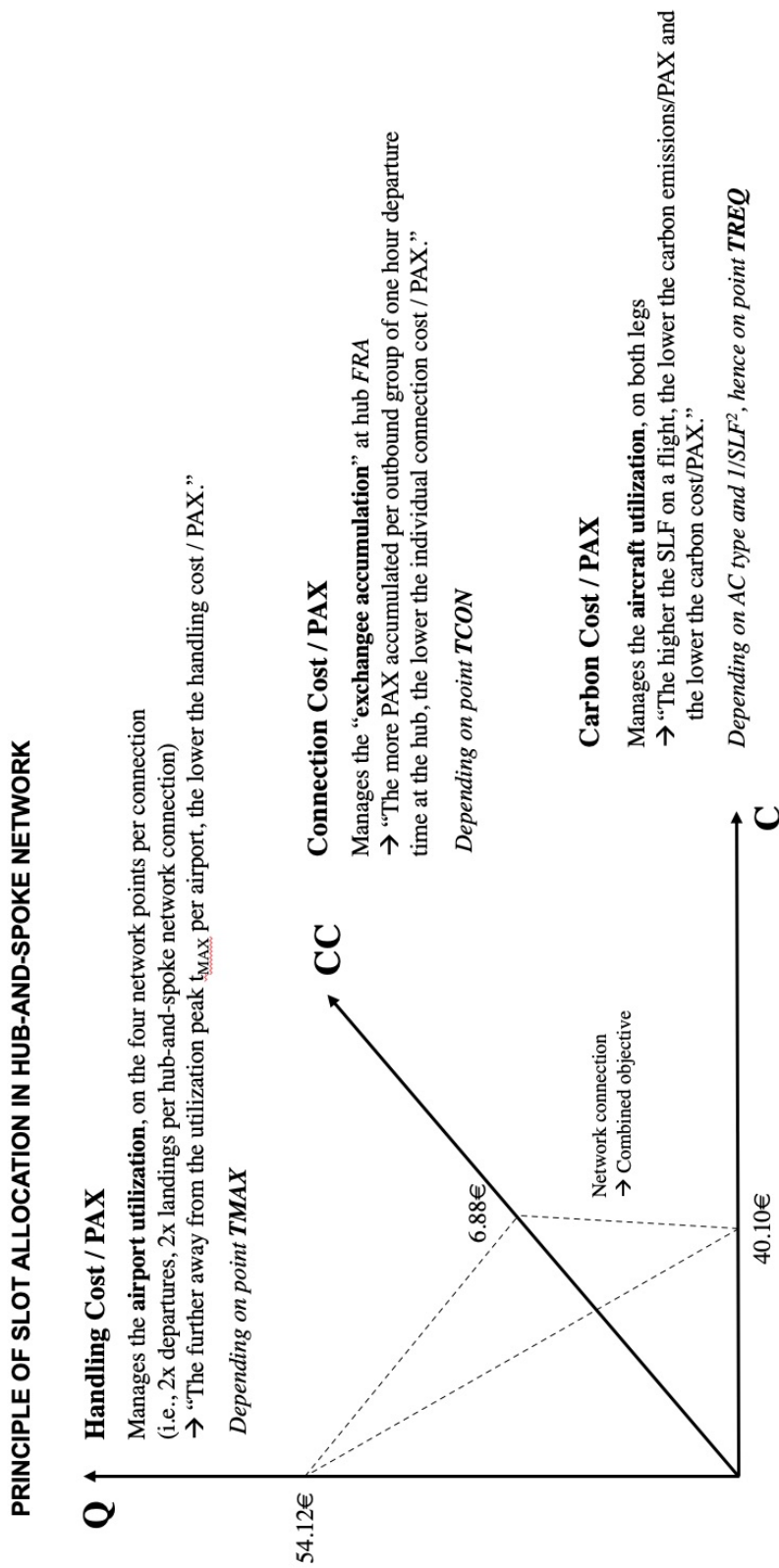
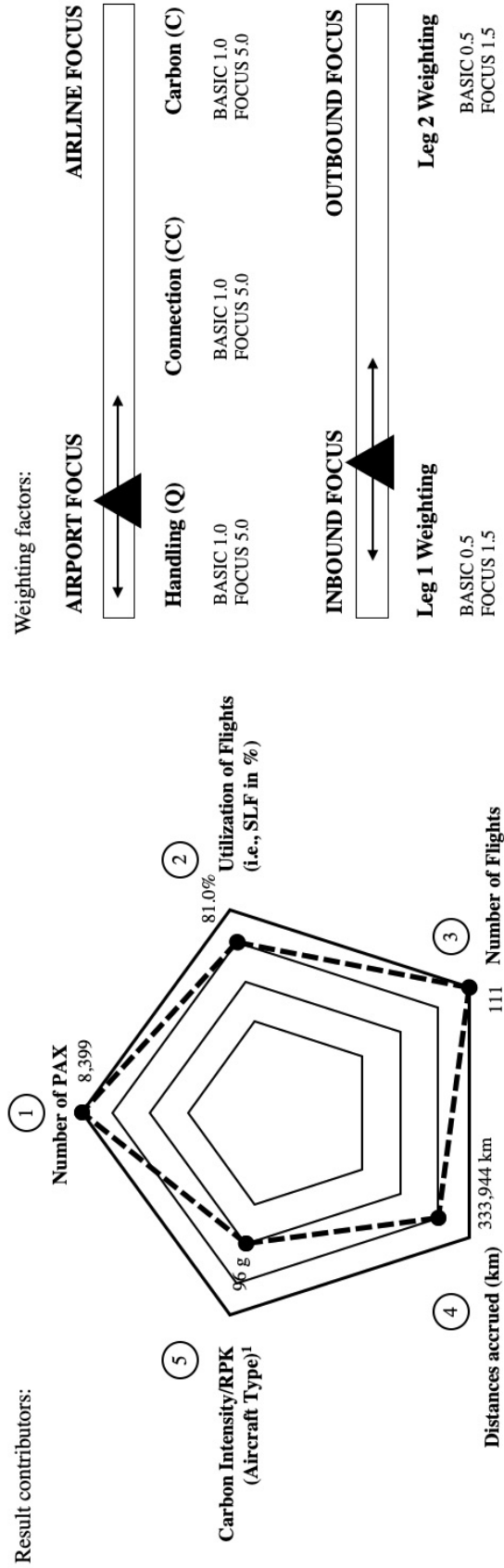


Figure A5: Principle of slot allocation applied in this study

**RELATIONSHIP OF RESULT CONTRIBUTORS AND WEIGHTING FACTORS FOR INCLUSION OF STAKEHOLDER INTERESTS**



<sup>1</sup>Graver et. al (2020), CO<sub>2</sub> Emissions from Commercial Aviation 2013, 2018 and 2019, ICCT.

Figure A6: Five result contributors to objective function and five weighting factors

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