Airport Strategic Stand Capacity Assessment Applied Through a Value-Focused Thinking Process

Master's Thesis

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Technische Universiteit Delft

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Airport Strategic Stand Capacity Assessment Applied Through a Value-Focused Thinking Process

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by

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TU Delft

Preface

Dear reader,

This report delineates my graduation project titled 'Airport Strategic Stand Capacity Assessment Applied Through a Value-Focused Thinking Process' as part of my graduation for the Master of Science in Aerospace Engineering at the Delft University of Technology. Over the past year, this project has led me to a more profound insight concerning airport operations and the power of mathematical optimisations. Furthermore, it has allowed me to get a better understanding and improve my knowledge with respect to operations research techniques.

I would like to express my sincere gratitude towards my supervisor Paul Roling for giving me this opportunity and his support and guidance throughout the challenging period during which this thesis project has been conducted. Furthermore, I would like to thank Alessandro Bombelli for his helpful feedback during the different review meetings.

As this thesis report and my colloquium marks the end of my journey at the Delft University of Technology, I would like to thank all the staff at the faculty of Aerospace Engineering for their dedication, knowledge base and openness towards their students. It was always fascinating to perceive the sparks of passion from all of you.

A special thanks to my family and friends for their support and encouragement throughout my student time. I want to contribute this thesis to my mother and father, Karima and Hassan. They have always been by my side and supported me throughout difficult times. No words can describe nor thank you for your encouragement and inspiration. Thank you for educating me with dedication and learning me to always work hard for my dreams and to never give up.

H. El Uamari
Delft, April 2021

Contents

List of Figures

List of Tables

Nomenclature

List of Abbreviations

ADG	Aircraft Design Group
APM	Adaptive policymaking
BB	Branch and Bound
BC	Branch and Cut
BIP	Binary Integer Programming
CC	Capital Cost
CPP	Clique Partitioning Problem
DDFS	Design day flight schedules
DSP	Dynamic strategic planning
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FSP	Flexible strategic planning
GAP	Gate Allocation Problem
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
KPI	Key Performance Indicator
LP	Linear Programming
MARS	Multi-Aircraft Ramp System
MILP	Mixed-Integer Linear Programming
MINP	Mixed-Integer Nonlinear Programming
NB	Narrow-Body
O&D	Origin and Destination traffic
OC	Operational Cost
PBB	Passenger boarding bridge
PLB	Passenger loading bridge
PO	Pareto Optimal
RON	Remain Overnight Stand
SAP	Stand Allocation Problem
SPL	Amsterdam Airport Schiphol
TT	Tow truck
WB	Wide-Body
WSM	Weighted Sum Method
WSS	Weight Space Search

Introduction

Stand capacity assessment is a key planning factor within airport development processes and is part of the demand and capacity analysis phase of an airport master plan. As the infrastructural and facility investments associated with airport stand capacity are substantial, airport stakeholders try to postpone or spread investments to mitigate associated risks. The area used is an important factor in airport design and planning. One of the core objectives is to minimise the land area used for developments and to take the needed area for future expansions into account. Different mathematical optimisation models are to be found aiding aviation decision-makers within tactical and operational time frames. However, not many of the frameworks consider the stand capacity assessment problem within a strategic time frame. As different factors influence the needed stand capacity and the fact that in a strategic time frame, the airport infrastructure is not defined yet, a clear gap exists. This gap concerns an optimisation framework that incorporates a trade-off between operational factors (robustness, flexibility, use of equipment), the use of specific stand types (e.g. remote, contact, MARS), and area limitations into a single optimisation framework.

Therefore, this research's main focus is developing a Mixed Integer Linear Programming optimisation model incorporating the above objectives through a value-focused thinking process. The decision-maker defines the optimisation objectives a priori, after which alternatives to comply with the set values are explored. The following research objective has been defined:

> To define recommendations to improve current practices of Airport Stand Capacity Assessment within a strategic time frame, by developing an optimisation framework incorporating a trade-off between stand types, operational factors (towing, robustness, flexibility) and area limitations through a value-focused thinking process.

The research scope will be on the development of a mathematical optimisation framework that enables a decision-maker to obtain results considering the objectives and factors mentioned above. Forecasting flight schedules and related demand is not part of this scope. Furthermore, the research will focus on applying mathematical techniques through a Mixed-Integer Linear Programming formulation, using exact algorithms to obtain solutions (which have proven to work for strategic stand capacity in other researchers work). Multi-objective optimisation is part of the research scope. It will be investigated how a trade-off between two objectives can be made.

The following research questions have been defined and form the backbone of the thesis process. Research questions 1 and 2 are answered through a literature study to support the research. Research question 3 relates to the defined optimisation framework.

RQ1: Which relevant factors in airport design and planning influence the stand capacity problem in a strategic time frame?
Sub1-RQ1: How is stand capacity embedded in airport (master) planning?
Sub2-RQ1: Which factors determine the characteristics of an aircraft stand?
Sub3-RQ1: Which airport systems influence the stand capacity?

RQ2: What are the relevant criteria and objectives for assessing the stand capacity of an airport in a strategic time frame?
Sub1-RQ2: Which (operational) factors influence the stand capacity assessment in a strategic time frame?
Sub2-RQ2: What are the objectives in stand capacity determination for strategic use?

RQ3: To what extent can strategic stand capacity assessment be aided by a framework allowing a decision-maker to make a trade-off between optimising for stand types, operational factors and area limitations?
Sub1-RQ3: Which methodologies and strategies can be distinguished for the modelling and optimisation of the stand capacity problem?
Sub2-RQ3: What are current industry practices regarding strategic stand capacity assessment?
Sub3-RQ3: What is the solution to a stand capacity problem after applying the optimisation framework?

The remainder of this thesis report is organised as follows: In Part I, the scientific paper is presented. Part II contains the relevant Literature Study that supports the research. Finally, in Part III, further elaboration on the thesis work is presented. In chapter A an extended description is given of the framework input, after which the architecture of the developed model is elaborated upon in Chapter B. The methodology followed for the model verification and validation is presented in Chapter C. The results of the model sensitivity analysis are discussed in Chapter D. An overview of the model data is given in Chapter E. Finally, some recommendations for further research are described in Chapter F.

I

Master of Science Thesis Paper

Airport Strategic Stand Capacity Assessment Applied Through a Value Focused Thinking Process

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Abstract

Stand capacity assessment is an essential factor in airport planning and design due to the large investments associated with airport development. Fulfilling anticipated demand while still considering future growth is key in airport master planning. In this paper, a mixed-integer linear programming optimisation model is proposed, which determines the stand mix and needed operational equipment through a value-focused thinking process. The decision-maker defines a priori the optimisation objectives (what to optimise for and the factors incorporated within the optimisation), after which different cases will be explored. The framework incorporates a trade-off between operational factors, different stand types, area limitations and flight frequency through two objectives: capital cost and operational cost. A trade-off between the two objectives is made through weight factors, which results in a Pareto curve. The model is validated through a case study performed using a design day flight schedule of Amsterdam Airport Schiphol. This paper shows the implications of the trade-off between capital cost and operational cost, the drivers for flight splitting, the use of swing stands, incorporation of area limitations and the implications of incorporating the weekly frequency of flights on the stand mix. It is recommended to apply the weighted sum method and the creation of Pareto curves to create a value-focused thinking process for a decision-maker. The availability of an optimisation framework, which allows airport stakeholders and decision-makers to get insights into implications of strategic decisions on stand capacity in the form of a trade-off between objectives and optimisation factors, will benefit the airport development process.

Keywords: Strategic Stand Capacity, Optimisation, MILP, Area Limitations, Airport Stands, Robust Scheduling, Stand Mix, Multiple Aircraft Receiving Stands, Flight Frequency

1. Introduction

Before the corona pandemic, which evolved during the first months of 2020 [1], the aviation industry was one of the fastest growing industries in the world. The expected yearly growth in demand was set to around 4.3% [2] [3]. Not only growth in air traffic demand was expected, but also an increase in the aircraft sizes was anticipated [4]. One of the main objectives in airport development is the minimisation of the land used while still enabling the fulfilment of forecast demand and leaving room for any future expansions [5]. This stresses out the importance of proper demand and capacity determination for any of the airport systems. The stand capacity assessment plays a key role in the airport planning and design process and is embedded in an airport master plan. Accurate planning and assessment of the capacity are of key importance to mitigate associated risks. The objective is to avoid disinvestments and to assure that developments are just in time. However, the process is generally associated with high risks due to the strategic time frame associated with the analysis.

To aid airport planners in determining the stand capacity within a strategic time frame, the need arises for optimisation frameworks that determine the needed stand-mix and its associated area use. The application of mathematical optimisation models for strategic stand capacity assessment is not well defined in the literature. Therefore, the following challenges with respect to stand capacity assessment within a strategic time frame are investigated in this paper:

1. Consideration of land area limitations: Minimisation of the land area is key in the airport development process but is not considered in existing optimisation frameworks.
2. Aid decision-makers in making a trade-off between optimising for different stand types, operational factors (towing, robustness and flexibility) and area limitations.
3. Adaptation of a value-focused thinking approach in the optimisation framework: since the objective in strategic stand capacity assessment is to proactively assess the implications of different decisions regarding the optimisation objectives; a value-focused thinking approach can be beneficial. In such an approach, the decision-maker defines the objectives (values), after which alternatives that comply with the set values are explored [6].

In this paper, an optimisation framework is proposed employing a Mixed Integer Linear Programming model that incorporates a trade-off between stand types, operational factors and area limitations. The objective of the proposed model is the determination of the number of stands (differentiated by type) which allows for the fulfilment of the expected air traffic demand and is optimised for user-specific objectives. Optimisation models that allow airport designers to make a trade-off between different optimisation objectives will help airport designers obtain quick insights and make strategic decisions.

The remainder of this paper considers the results from a literature study in Section 2, in which an analysis is performed concerning the existing optimisation frameworks in the field of mathematical optimisation modelling applied to stand capacity assessment. Furthermore, in Section 3, the research methodology is further elaborated upon. This consists of the conceptual framework, the model topology, the framework input, the mathematical model formulation and the resolution method. Section 4 describes the results of the proposed model through an analysis of a case study performed using data from Amsterdam Airport Schiphol. This paper is concluded in Section 5 with conclusions and recommendations.

2. Literature Survey

2.1. *Airport Master Planning*

The design and planning of airports is a very complex and time-consuming process without a single solution. Stakeholders involved in the decision-making process of airport planning make use of different guidelines stipulated by aviation organisations such as the International Civil Aviation Organisation (ICAO), the International Air Transport Association (IATA) and the Federal Aviation Administration (FAA). The different phases of airport planning are depicted in Figure 1.

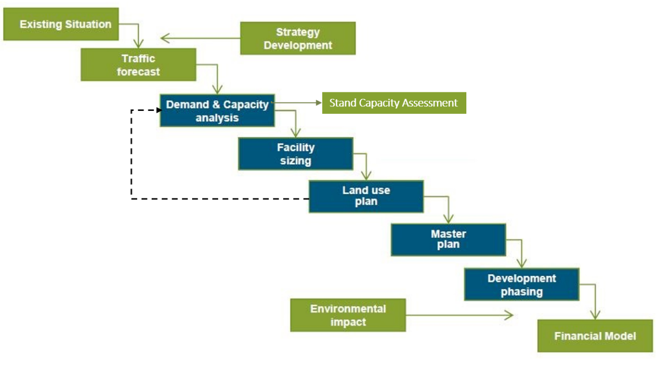


Figure 1: Airport Development Phases [4]

An airport master plan encompasses the airport planners' ultimate vision of the development of the airport [7]. A master plan can be developed for both new and existing airports. As described by de Neufville [8] a master plan should involve the following three factors: ultimate vision (a view of the long term future of the airport), development (i.e. physical facilities on the airside and landside such as runways and terminal buildings) and consider a specific airport (not the regional or national aviation system).

For the master planning process different international and national guidelines are to be used from e.g.: ICAO [9] [7], EASA (CS-ADR-DSN) [10], FAA (for the United States) [11] and IATA [12]. Airport planners and other stakeholders aim for good strategic thinking and flexibility in the master planning process to make sure that the developed plans assess a wide range of scenarios and possibilities and thus are robust for different future changes [8]. This objective can be realised by creating flexible and adaptable designs.

2.2. *Optimisation Frameworks in Literature*

Solving the assignment of aircraft to gates/stands is in the literature also known as the Gate Allocation Problem (GAP) or the Stand Allocation Problem (SAP). The first paper regarding GAP dates back to 1974 [13]. Throughout the last decades, multiple solutions are proposed. The programming formulation of the models depends on the objective variables (integer, binary, quadratic) and objective function (linear, non-linear).

The core objective of the SAP is the assignment of aircraft/flights to a stand while optimising for cost efficiency, passenger convenience and the operational efficiency of the airport operations [14]. Many methods are to be found regarding the modelling and optimisation of the problem. Bouras [14] performed an extensive literature review regarding the state-of-the-art in the field of GAP/SAP.

Lim et al. [15], Diepen et al. [16], formulated the problem as an Integer Linear Programming (ILP) model with the objective of minimising the passenger walking distance. The research of Lim et al. [15] showed that an ILP Solver (CPLEX) was outperformed in both running time and solution quality by heuristics.

A Binary Integer Programming (BIP) framework is used by Tang et al. [17] , Kumar and Bierlaire [18], Mangoubi and Mathaisel [19], Bihr [20], and Yan et al. [21]. These frameworks optimise either for the passenger walking distance or the cost of assigning an aircraft to a stand. Mixed Integer Linear Programming (MILP) models are defined among others in literature by Bolat [22] [23], Seker and Noyan [24], Neuman [25], Guepet [26], Deken [27], Kaslasi [28], and Boukema [29]. The objective functions of these MILP models are related to minimisation of the range of slack times (the time between the two successive assignments of flights to a stand), minimisation of the range of gate idle times, minimisation of buffer times, maximisation of aircraft assigned to contact stands and minimisation of towing movements.

Mixed-Integer Nonlinear Programming (MINP) models are defined by Li [30] and Bolat [22]. Li [30] defined a model in which the number of gate conflicts of any two adjacent aircraft assigned to the same stand is minimised. In the model of Bolat [22] the variance of gate idle times is minimised. For an extensive overview of these methods and the associated papers, the reader is referred to the overview as presented by Bouras [14] and Boukema [29].

Not much of the investigated literature regarding the SAP/GAP and stand capacity assignment considers the problem within a strategic time frame. Most of the research considers existing airport infrastructures. However, only two research papers are found which considered the stand capacity assessment problem within a strategic time frame.

Boukema [29] described the strategic stand allocation problem as a MILP model with the objective of minimising the capital cost and operational cost related to the use of certain stand types. Boukema defined a framework in which the stand capacity is determined for a design flight schedule, after which a stand allocation model is optimised to allocate the flights to individual stands. In this research, no explicit area limitations have been considered. However, the cost of a certain stand is based on its area, which is also minimised due to the objective's minimisation formulation. Kaslasi [28] also defined a stand capacity assessment model using a MILP formulation in which both infrastructure cost and allocation costs are minimised. The objective of the framework of Kaslasi is to minimise the number of stands and their size. This is done by incorporating the stand sizes in the objective function.

2.3. ***Resolution Methods***

Different resolution methods can be found in the literature on SAP/GAP. Resolution methods can be distinguished concerning the algorithmic method used to find a solution to the defined optimisation problem. The optimisation techniques applied in the stand capacity/allocation problem can be divided into three groups: exact algorithms, heuristics, and meta-heuristics. Exact algorithms yield an optimal solution [14] using different algorithms such as branch & bound, simplex, primal-dual and column generation. Heuristics are employed in case an optimal solution cannot be attained within reasonable time. Meta-heuristics are used to capture a known drawback of heuristics of reaching a local optimum and getting stuck.

Furthermore, to solve an optimisation model, a solver is needed. A solver is a software type applying different optimisation principles such as branch & bound to solve defined problems. In the literature regarding the stand allocation problem, commercial solvers such as CPLEX and Gurobi are mainly used. Research has revealed that CPLEX and Gurobi is able to solve MILP formulations of the stand allocation/capacity problem within reasonable time ([15], [31], [26], [29], [28], [25], [18]).

2.4. ***Multi-Objective Optimisation***

In the early developments of stand allocation and capacity assessment, the models were mainly formulated with a single objective (such as in Haghani [32]). Throughout the years, frameworks have been developed, which opened the need for multi-objective approaches to capture the problem's complexity. As different factors influence the assessment and allocation problem, the challenge of multi-objective optimisation is finding an optimal solution based on a trade-off between the different objectives (which might be conflicting). In the case of multi-objective optimisation, a Pareto Optimal (PO) solution should be sought. In a Pareto optimal solution no objective can be increased except by decreasing another one [33] [28].

Different methods for multi-objective optimisation are described by Miettinen [33]. These methods are grouped into four categories: no-preference methods, a posteriori methods, a priori methods and interactive methods. In no-preference methods, the decision-maker does not play a role. The decision-maker is presented a PO solution based on preset importance of the objectives. Multiple PO solutions are generated in a posteriori methods. These solutions are subsequently presented to the decision-maker. In a priori methods, the decision-maker defines the preferences regarding the objective. Interactive methods are highly-developed methods that require a high involvement from the decision-maker to direct the solution process [33]. These methods generate fewer solutions with no interest for the decision-maker, reducing the information load presented [33].

2.5. ***Theoretical Relevance***

The area used is an important factor in airport design and planning. The core objective is to minimise the land area used for developments and to take the needed area for future expansions into account [34] [5]. This objective is not found in almost any of the literature on stand capacity assessment and allocation frameworks.

Based on the performed literature study, in which the research field of stand capacity assessment is investigated, it is concluded that many frameworks can be used to model and solve the stand allocation problem. The chosen objective functions mainly define the programming formulation. Only two studies considered the SAP within a strategic time frame (in which the capacity was not predetermined). As different factors influence the needed stand capacity and the fact that in a strategic time frame, the airport infrastructure is not defined yet, a clear gap exists concerning an optimisation framework that incorporates a trade-off between operational factors (robustness, flexibility, use of equipment), the use of specific stand types (remote, contact, MARS etc.), and area limitations into a single optimisation framework. Consideration of these factors through a value-focused thinking process, in which the decision-maker defines the optimisation objectives a priori after which possible alternatives to comply with the set values are explored, might be beneficial for application within a strategic time frame framework.

3. Methodology

The proposed framework is based on a mixed-integer linear programming formulation. As described in Section 2, stand capacity assessment is known in the literature as the Stand Allocation Problem (SAP) or Gate Allocation Problem (GAP). The research methodology applied is depicted in Figure 2. Since this methodology is found throughout the paper, it will be elucidated before we dive into the specifics of the proposed framework. The methodology followed can be divided into four main blocks. The first block consists of desk research. The main objective of this was to assess the state of the art with respect to airport design and planning, stand capacity assessment procedures and modelling and optimisation techniques. The results of this part are already elaborated upon in Section 2. As part of the experiment, an optimisation framework is defined based on a mathematical model. The specifics of this mathematical model are defined in Section 3.4 along with a description of the proposed model topology in Section 3.2. Furthermore, the third block is centred around the validation of the proposed framework. This is done through a case study in which the model's performance is assessed along with a sensitivity analysis. These three research blocks formed the basis of the definition of conclusions and recommendations with respect to strategic stand capacity assessment.

In this section, first the conceptual framework will be elaborated upon in Section 3.1, followed by a description of the model topology in Section 3.2. The input of the framework will be discussed in Section 3.3. A description of the mathematical optimisation model will be described in Section 3.4, after which the section will be concluded with an elaboration on the resolution method used in Section 3.5.

Figure 2: Research Methodology followed

3.1. Conceptual Framework

In this research, a framework is proposed that is based on a mixed-integer linear programming formulation. The proposed framework is based on two important objectives within stand capacity assessment, being the capital cost of needed investments and the operational cost of flight handling. It is chosen to adapt these two as the model's main objectives due to the strategic time frame linked to the decisions that have to be made with respect to stand capacity in airport planning. Since the airport infrastructure is not defined yet, the most profound objective is the cost. These costs are related to other optimisation objectives (values) that are considered in the optimisation framework, such as the area of the stands, the use of equipment etc.

A clear distinction has to be made between model objectives and optimisation objectives in this paper. The model objectives relate to the objectives used in the objective function of the mathematical model implemented in the framework. On the other hand, the optimisation objectives refer to factors that are of importance to the decision-maker and that are considered in the framework.

The following optimisation objectives are part of the proposed framework:

1. Area Limitations: As described earlier, one of the key objectives in stand capacity assessment is the minimisation of the area used. To capture the dynamics of this optimisation objective, area limitations are considered in the proposed framework.
2. Robustness: Uncertainties characterise a strategic optimisation time frame with respect to the quantity of anticipated demand as well as the fulfilment of the anticipated demand. Robust scheduling is applied in frameworks to capture the dynamics of operations concerning delays. This is done in the proposed framework through the implementation of buffer times (at the choice of the decision-maker).
3. Operational Factors: To represent airport operations as accurately as possible different operational factors are considered in the proposed framework. Towing operations are used in airport operations to allow for efficient use of the infrastructure as described by Diepen [31] and Boukema [29]. This policy is also implemented by airports (such as Amsterdam Airport Schiphol [35]. Within the framework, splitting of flights into two phases (to capture the demand of sector switching flights) and three phases (to allow for efficient use of connected stand capacity) is implemented.

   Furthermore, the use of needed operational equipment is implemented in the framework to reflect real-life operations. The following equipment is implemented: narrow-body tow trucks, wide-body tow trucks, passenger busses and boarding stairs.
4. Stand Types Flexibility: Since the air traffic demand is characterised by different aircraft sizes, the need arises for the consideration of flexible stand use. Flexible stand use is achieved by implementing different stand types (with respect to size, aircraft handling type and terminal type) and the implementation of so-called multiple aircraft receiving stands (MARS).
5. Flight Frequency: In order to assess the implications of the consideration of the frequency of a flight in the demand flight schedule, the flight frequency is considered in the optimisation framework. The rationale behind this lies within the optimisation time

frame that is adopted. As the stand capacity assessment is performed by considering a design flight schedule of the peak day, the frequency of flight movements is not considered in the adopted cost. By incorporating the flight frequency in the objective cost, the hypothesis is that the stand mix will better represent the use of the airport infrastructure.

6. Stand Input: To aid a decision-maker in the decision process and for validation purposes, it is needed to be able to define the stand input a priori. This is implemented in two ways: the number of stands as a hard input or a minimal input.

3.2. *Model Topology*

The proposed mathematical model can be visualised through the conceptual schematic depicted in Figure 3. The schematic is divided into three parts. As described in Section 3.1, the decision-maker is facilitated with a few optimisation choices. These consist of the choice to include or exclude: the consideration of robustness through buffer times, area limitations, multi-case simulation (to create a Pareto curve with a trade-off between operational and capital cost), flight frequency and the stand input (either through a hard input or a minimal constraining case).

A mixed-integer linear programming formulation is adopted in the proposed framework due to the characteristics of the defined stand capacity assessment problem. The stand capacity assessment problem's objective is formulated as the determination of the needed stand-mix to fulfil the anticipated demand in a strategic time frame. Therefore, the model's output should be the number of stands per type (integer decision variable) and the assignment of a flight to a stand type (binary). As described in Section 3.1 the proposed framework also considers the equipment needed to fulfil the air traffic demand. This is done in the form of decision variables representing the number of needed tow trucks and busses. The proposed framework considers the capital cost of the investments, which are related to the stands (the area, terminal and passenger boarding bridges), the tow trucks (capital cost), the busses (capital cost) and the area limitations (induced cost due to exceeding the available area). Furthermore, the operational cost is considered in the form of the cost needed to handle a flight at a specific stand. This includes the cost of boarding stairs and the operational cost of tow truck operations and bussing operations. The framework is implemented in Python and optimised using the Gurobi optimiser. Upon literature research concerning the different optimisation solvers, it is found that CPLEX and Gurobi are the best-suited solvers for the stand capacity problem. Due to the convenient connection between Python and Gurobi, it is chosen to adapt Gurobi as the optimisation solver. Furthermore, it is chosen to model the framework in Python due to the open-source availability of the programming language.

The topology of the proposed framework is schematically depicted in Figure 4. Different blocks can be distinguished within the stand capacity assessment model. The main block consists of the optimisation unit. This unit consists of the mathematical optimisation model implemented through the objective function and the needed constraints. In order to be able to run an optimisation, the model needs input data. This input data consists of the design day flight schedule, the available stand types and their characteristics, and optimisation policies (such as the decision-makers choice to include or exclude an objective but also the parameters used in the optimisation). By using a design day flight schedule, not only peak hour characteristics are taken into account, but also the effective use of stands over a longer time frame is considered.

The input data is partly fed by a database consisting of three parts. The first part consists of the stand data (the different stand types and their characteristics), the aircraft data (consisting of the design group an aircraft type falls into) and airport data (consisting of the specifics of each airport in the world). The airport data is obtained from `https://ourairports.com/data/` and altered (addition of a Schengen, Non-Schengen designator)

All of this is processed in a data processing unit. This unit's objective is to read and store data, create operations from the flight schedule, assess conflicting operations, and create aircraft-stand compatibility data. After which, the optimisation is executed. The results of the optimisation are processed in the output unit in the form of solution dashboards, which the decision-maker can access.

The idea behind the defined topology and the conceptual framework is the incorporation of a value-focused thinking process in the optimisation framework. A value-focused thinking process can be distinguished in four steps described by Keeney [6]. The first step consists of the objective definition. In this step, the important objectives for the decision-maker(s) are defined, followed by a filtration step. In this second step, the goal is to assure that the defined objectives are actually objectives. Following this, the alternatives are created, after which the possible alternatives are assessed.

This process is implemented in the following way in the proposed framework: the decision-maker defines a priori the optimisation objectives (the values that are considered in the optimisation) and, for example, constraining factors. By implementing a weighted sum method between the two earlier defined objective parts (capital cost and operational cost), the model can generate multiple alternatives. These alternatives are run in a multi-case simulation, which implies a predefined range of factors, α_{CC} (ranging from 0 to 1), for the capital cost and factors $1 - \alpha_{CC}$ for the operational cost. This multi-case run is then processed in a visualisation dashboard which

Figure 3: Conceptual Overview of the Optimisation Model

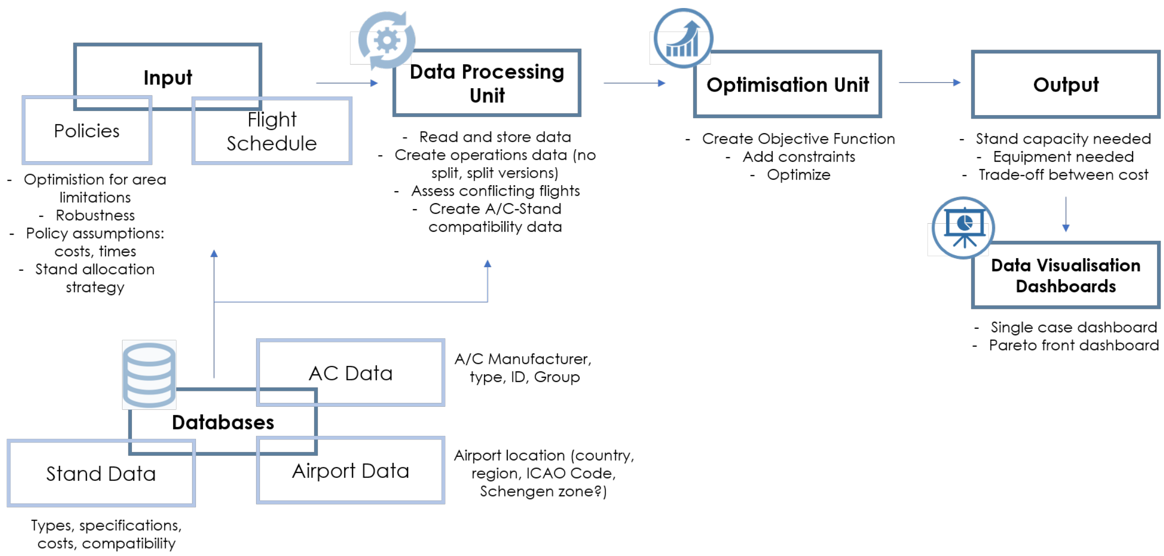


Figure 4: Model Topology

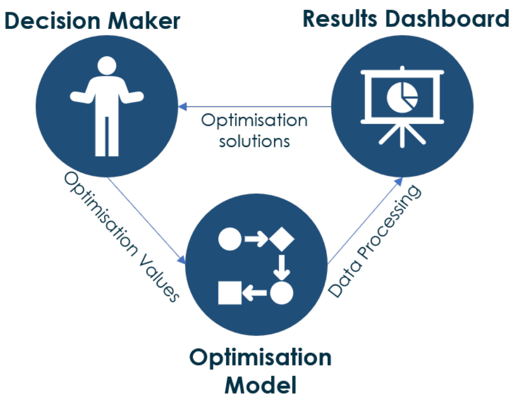


Figure 5: Schematic overview of the interactions between the decision maker and the optimisation model

depicts the Pareto curve (trade-off between capital and operational cost) and the characteristics of a chosen specific alternative. The decision-maker can then decide on a specific alternative, which can be further analysed through a single case run (obtain extensive output data for a single choice of α_{CC}). The interactions between the decision-maker and the optimisation model are simplified in Figure 5.

3.3. *Framework Data*

As described in Section 3.2, the defined framework uses different data sets, such as the different stand types, the different cost factors used in the optimisation and the policies implemented (such as stand allocation principles).

3.3.1. *Stand Types*

Within the framework, 35 different stand types are considered. A differentiation is made with respect to three factors: the handling type, terminal type and the stand size. Five types can be distinguished concerning handling type: contact stands (connected handling of passengers using a passenger boarding bridge), non-contact stands (stands close to the terminal without connected handling of passengers), remote operational stands, remote non-operational stands (used for the parking of aircraft) and multiple aircraft receiving stands (MARS). MARS stands are capable of handling two narrow-body aircraft simultaneous or a single wide-body aircraft.

Three different terminal types are considered within the framework: domestic (Schengen), international (Non-Schengen) and swing terminals. Large airports experiencing flights with different origins and destinations require efficient handling of flights flying to different areas (with different customs and immigration regulations). Swing stands are a versatile solution to this problem. These stands can accommodate flights with different origins and destinations (domestic and international), through a multi-level terminal design, which allows the separation of passenger flows on different levels through sterile corridors [36]. These stands allow for efficient use for sector switching flights and cross utilisation of the available infrastructure (use for a specific sector during peaks).

To allow for a distinction with respect to aircraft type, four different stand sizes are considered: C, D, E and F. These are linked to the aircraft design groups (ADGs) as defined by ICAO [9]. The characteristics of the 35 different stand types are depicted in Table A.3.

3.3.2. Cost Factors

The proposed framework considers two main objectives: the capital cost of investments and the operational cost associated with the assignment of flights to a compatible stand.

Capital Cost

The capital cost implemented can be split into three main parts: the investment cost associated with the stands, the equipment needed and the cost for exceeding the area limitation. The capital cost of the stands consists of the need for passenger boarding bridges, the stand area and the terminal needed. The area of a stand is modelled by incorporating the terminal area, the aircraft parking area and the taxiway area. The cost are based on literature research ([29], [37], [38]) and the analysis of policies implemented at reference airport ([35]. In the definition of the areas, the following requirements have been implemented: wingtip clearances [36], nose to building clearances [36] and the taxi lane to object clearance [36]. The definition of the underlying capital costs of the different stand types is depicted in Table A.4 in AppendixAppendix A. The stands' capital cost is determined using a depreciation period of 20 years [39].

As described above, the cost of busses and tow trucks is considered within the optimisation framework. An overview of the capital cost of the equipment is depicted in Table B.5 in AppendixAppendix B. The capital cost of the equipment is determined using a depreciation of 10 years.

Operational Cost

The operational cost is linked to the cost associated with the assignment of a flight operation to a specific stand. The operational cost can consist of the cost for boarding stairs, busses and tow trucks. The operational cost is defined through three main factors: the electricity/fuel, the personnel and maintenance cost. An overview of the operational cost factors is depicted in Table B.6 in Appendix Appendix B.

3.3.3. Allocation Principles

The compatibility of a flight to a stand is determined based on three aspects: the aircraft size (limiting the compatible stand size), the origin airport and the destination airport (defining the flight sector and the compatible terminal). One would expect that an aircraft is compatible with any stand size larger than the aircraft design group of the aircraft. However, this is not the case for the contact stands. Due to restrictions concerning the slope of passenger boarding bridges [40], a type C aircraft is only compatible with type C and D contact stands.

As described in Section 3.1, flight splitting is implemented in the framework to allow for the efficient allocation of flights to stands. Two types of flight splitting are considered. The first type is a two-split (arrival and departure part) for aircraft with a turnaround time of minimum 120 minutes. The second implemented type is a three-split (arrival, parking and departure part) version. Flights are eligible for a three split if the turnaround time is minimum 170 minutes. These policies are determined upon analysis of the principles implemented at Amsterdam Airport Schiphol [35]. To assure the model performs no unnecessary two splits, the towing cost of non-sector switching flights is penalised by a factor of two. In line with the policy behind flight splitting, the assignment of split phases of a flight to remote stands is prohibited within the model. The parking phase of a three split operation can be assigned to a remote operational stand or a remote non-operational stand (which can only be used for flight parking).

Furthermore, busses are needed for passenger transporting to and from remote stands. The capacity of the busses is set to 55 passengers per bus (based on analysis of reference airport). Furthermore, an assumption had to be made regarding the task scheduling time (the time a bus is occupied with a specific flight operation). This is set to 20 and 30 minutes for narrow-body and wide-body aircraft, respectively. For the arrival part, busses are assigned at the scheduled arrival time of a flight, while for the departure part, busses are assigned 45 minutes before the scheduled departure time. Due to the complexity associated with the assignment of busses to departure parts of a flight (passengers are not at the same time at the same place), it is decided to penalise the assignment of busses to departure parts of a flight by a factor of 1.5. This is also based upon other research performed in the field of strategic stand capacity assessment [29],

Tow trucks are needed for the departure pushback of aircraft as well as the towing of flights that are split. In case of a two split, the following policy is implemented: aircraft are towed away 40 minutes after departure to a second stand. In case of a three split, an aircraft is towed to a remote parking stand 60 minutes after arrival and is towed back to an operational stand 60 minutes before departure. Also, for the tow trucks, an assumption had to be made regarding the task scheduling time of tow trucks (the time a tow truck is occupied with a task). This is set to 15 minutes for narrow-body aircraft and 20 minutes for wide-body aircraft. The implication of this assumption will also be analysed through a sensitivity analysis.

For full cargo flights, it is chosen not to implement dedicated cargo stands, but to handle these flights at remote operational stands. This policy is chosen due to a lack of developed airport plans associated with the strategic time frame of this framework.

3.4. **Mathematical Model Formulation**

The proposed optimisation framework is implemented through a mathematical model definition. This mathematical model is defined around decision variables and sets, an objective function and the necessary constraints.

3.4.1. **Decision Variables and Sets**

As described in Section 3.1, the defined framework is centred around two main objectives: the capital cost of investments and the operational cost.

Sets

$O = \{1, .., i\}$: Set of operations
$O_2 = \{1, .., i\}$: Set of operations eligible for a two split
$O_3 = \{1, .., i\}$: Set of operations eligible for a three split
$T = \{1, .., t\}$: Set of unique arrival times of all the operations
$T_B = \{1, .., t_B\}$: Set of unique start times of bussing operations
$T_T = \{1, .., t_T\}$: Set of unique start times of towing operations
$O_t = \{1, .., i\}$: Set of operations i which are conflicting at time t
$O_{t_f} = \{1, .., i\}$: Set of operations i in phase f which are conflicting at time t
$O_{t_{BA}} = \{1, .., i_{BA}\}$: Set of arrival bussing operations i_{BA} which are conflicting at time t_B
$O_{t_{BD}} = \{1, .., i_{BD}\}$: Set of departure bussing operations i_{BD} which are conflicting at time t_B
$O_{tTD_p} = \{1, .., i_T\}$: Set of departure towing operations i_{TD} which are conflicting at time t_T for tow truck type p
$O_{tT2T_p} = \{1, .., i_T\}$: Set of two split towing operations i_{T2T} (towing to departure stand) which are conflicting at time t_T for tow truck type p
$O_{tT3T_p} = \{1, .., i_T\}$: Set of three split towing operations i_{T3T} (towing to parking stand and departure stand) which are conflicting at time t_T for tow truck type p
$S = \{1, .., j\}$: Set of stand types
$S_i \in S$: Set of stand types compatible with operation i
$S_M \in S$: Set of MARS type stands
$S_{NM} \in S$: Set of Non-MARS type stands
$S_B \in S$: Set of stands that need bus operations
$F = \{Nosplit, A2, D2, A3, P3, D3\}$: Set of phases (no split, arrival two split, departure two split, arrival three split, parking three split, departure three split)
$F_{BA} = \{Nosplit, A2, A3\}$: Set of bus arrival phases (no split, arrival two split, arrival three split)
$F_{BD} = \{Nosplit, D2, D3\}$: Set of bus departure phases (no split, departure two split, departure three split)
$F_{TD} = \{Nosplit, D2, D3\}$: Set of departure push-back phases (no split, departure two split, departure three split)
$F_{T3T} = \{P3, D3\}$: Set of three split tow phases (three split parking, three split departure)
$P = \{NB, WB\}$: Set of tow trucks (narrow-body, wide-body)

Decision Variables

X_{ij}: Binary decision variable representing if operation i is assigned to stand type j
X_{i2Aj}: Binary decision variable representing if the arrival part of the two split version of operation i is assigned to stand type j
X_{i2Dj}: Binary decision variable representing if the departure part of two the split version of operation i is assigned to stand type j
X_{i3Aj}: Binary decision variable representing if the arrival part of the three split version of operation i is assigned to stand type j
X_{i3Pj}: Binary decision variable representing if the parking part of three the split version of operation i is assigned to stand type j
X_{i3Dj}: Binary decision variable representing if the departure part of three the split version of operation i is assigned to stand type j
Y_j: The number of stands needed of type j (Integer)
B: The number of busses needed
TT_{NB}: The number of narrow-body tow trucks needed
TT_{WB}: The number of wide-body tow trucks needed
AC_1: The area assigned to block 1 of the area limit optimisation (Integer)
AC_2: The area assigned to block 2 of the area limit optimisation (Integer)
AC_3: The area assigned to block 3 of the area limit optimisation (Integer)
$V1_i$: Binary decision variable defining the choice for the no split version of operation i
$V2_i$: Binary decision variable defining the choice for the two split version of operation i
$V3_i$: Binary decision variable defining the choice for the three split version of operation i

Parameters

oc_{ij}: The operational cost of assigning operation i to stand type j
oc_{i2Aj}: The operational cost of assigning the arrival part of the two split version of operation i to stand type j
oc_{i2Dj}: The operational cost of assigning the departure part of the two split version of operation i to stand type j
oc_{i3Aj}: The operational cost of assigning the arrival part of the three split version of operation i to stand type j
oc_{i3Pj}: The operational cost of assigning the parking part of the three split version of operation i to stand

type j
oc_{i3Dj}: The operational cost of assigning the departure part of the three split version of operation i to stand type j
cc_j: The capital cost of stand type j
c_B: The capital cost of the busses
cc_{TTNB}: The capital cost of a narrow-body tow truck
cc_{TTWB}: The capital cost of a wide-body tow truck
c_1: The cost induced for the available area (which is 0)
c_2: The cost induced for the available area at the cost of pavement
c_3: The cost induced for the available area at the cost of pavement and land area purchasing
a_i: MARS stand parameter, 0.5 for a narrow-body aircraft and 1 for a wide-body aircraft
$area_j$: The area of stand type j
Bus_{i_A}: The number of busses needed for the arrival part of operation i
Bus_{i_D}: The number of busses needed for the departure part of operation i

3.4.2. *The objective*

The model's objective function is centred around minimising the capital cost (CC) and operational cost (OC). Since research within the field of strategic stand capacity assessment has revealed that the choice regarding the stand mix implemented at an airport is based on a trade-off between these two, it is decided to implement these two costs through a multi-objective perspective. This is done by the assignment of a factor α_{CC} to the capital cost and subsequently the assignment of a factor $1-\alpha_{CC}$ to the operational cost as depicted in Equation 1.

$$min[\alpha_{CC} \cdot CC + (1 - \alpha_{CC}) \cdot OC] \tag{1}$$

The terms of the capital cost are depicted in Equation 2. This consists of the capital cost of the stands (the first term), the capital cost of the narrow-body and wide-body tow trucks (the second and third term, respectively) and the cost for exceeding the area limitation (the fourth term).

$$\begin{aligned} CC = (\sum_{j\in S} cc_j \cdot Y_j) + (c_B \cdot B) + (c_{TTNB} \cdot TT_{NB}) \\ + (c_{TTWB} \cdot TT_{WB}) + \\ (c_1 \cdot AC_1 + c_2 \cdot AC_2 + c_3 \cdot AC_3) \end{aligned} \tag{2}$$

As described earlier in this paper, the operational cost is considered through the cost implied by assigning an operation to a stand type. This is further divided into the cost for the two and three split versions of an operation. The mathematical formulation of this objective is depicted in Equation 3.

$$\begin{aligned} OC = [\sum_{i\in O}\sum_{j\in S_i} oc_{ij} \cdot X_{ij} \\ + \sum_{i\in O_2}\sum_{j\in S_i} (oc_{i2Aj} \cdot X_{iA2j} + oc_{i2Dj} \cdot X_{iD2j}) + \\ \sum_{i\in O_3}\sum_{j\in S_i} (oc_{i3Aj} \cdot X_{iA3j} + oc_{i3Pj} \cdot X_{iP3j} + oc_{i3Dj} \cdot X_{iD3J})] \end{aligned} \tag{3}$$

3.4.3. *Constraints*

In order to represent real life operations and restricting factors, different constraints are implemented to constrain the defined optimisation model. These will be elaborated upon in the following subsections.

Constraint set 1 - Flight Assignment to Stand

The first set of constraints relates to the assignment of each operation to a single stand. As described in Section 3.1 the flights with a long turnaround time can be split into two or three phases. To assure that only one of the three possible versions of a flight is chosen and that each of the phases of the version is assigned to a stand, the following sets have been defined. First of all, Equation 4 defines that only one of the version of operation i is used. Furthermore, Equation 5 restricts the assignment of operation i to a compatible stand if the no split version is chosen. The same logic is applied for the two split and three split versions. Equations 6 assure that both the arrival and departure part of operation i are assigned to compatible stands, while Equations 7 do the same for the three split versions.

It has been chosen to define the aforementioned restrictions through multiple equations instead of a single equations upon the literature study that has been performed as part of this research. It has been proven that a single equation formulation results in a longer run time compared to the restrictions as imposed by the multiple equations [29].

$$\begin{gathered} V_{1i} + V_{2i} + V_{3i} = 1 \\ \forall i \in O \end{gathered} \tag{4}$$

$$\begin{gathered} \sum_{j\in S_i} X_{ij} - V_{1i} = 0 \\ \forall i \in O \end{gathered} \tag{5}$$

$$\begin{gathered} \sum_{j\in S_{iA2}} X_{iA2j} - V_{2i} = 0 \\ \sum_{j\in S_{iD2}} X_{iD2j} - V_{2i} = 0 \\ \forall i \in O_2, O_3 \end{gathered} \tag{6}$$

$$\sum_{j \in S_{iA3}} X_{iA3j} - V_{3i} = 0$$
$$\sum_{j \in S_{iP3}} X_{iP3j} - V_{3i} = 0$$
$$\sum_{j \in S_{iD3}} X_{iD3j} - V_{3i} = 0 \quad (7)$$
$$\forall i \in O_3$$

Constraint 2 - Overlap of Operations and Dynamic Stand Capacity

The second set of constraints has two objectives: assuring that there is no overlap between operations assigned to a stand and that a sufficient number of stands is acquired.

To assure that there is no overlap between the assignment of flights to stands, the assignment of conflicting operations to the same stand has to be restricted. This is where the time factor has to be considered. Within the literature on stand capacity/allocation assessment, two methodologies are to be found. In single-time slot models conflicting flights are defined, after which the model is constrained to only allocate a single flight from a set of conflicting flights [41] [42]. Multiple-time slot models consider the entire time-frame of flights by defining a fixed number of time slots [42]. A drawback of multiple-time slots is the influence on stand utilisation and the fact that these models are less exact compared to the single-time slot models. Furthermore, due to the increase in decision variables in multiple-time slot models, the running time of the models also increases rapidly. Research performed by Deken [27] revealed that the running time for a multiple-time slot model is double the time for a single-time slot model.

Therefore, it has been chosen to adapt the following methodology (which can be linked to the single-time slot models): first the unique arrival times of all the operations within the flight schedule are defined, from which for each unique arrival time conflicting operations are assessed. This is done for each phase $\mathbf{f} \in F$. The conflicting sets are linked to these phases ($O_{t_\mathbf{f}}$). In the definition of this constraint, it is constrained that sufficient stands are acquired for each of the unique arrival times (based on the number of conflicting operations assigned to the same stand type). Lastly, a distinction has been made regarding non-MARS Stands (Equation 8), and MARS Stands (Equation 9), due to the policy implemented for MARS stands. These stands are capable of handling two narrow-body aircraft or a single wide-body aircraft at the same time. Therefore, an alternative formulation is implemented for the MARS stands consisting of a parameter (a_i), which defines each narrow-body aircraft as 0.5. Since no half stands can be built, the number of needed stands is rounded up.

$$\sum_{\mathbf{f} \in F} \sum_{i \in O_{t_\mathbf{f}}} X_{i\mathbf{f}j} - Y_j \leq 0 \quad (8)$$
$$\forall t \in T, j \in S_{NM}$$

$$\sum_{\mathbf{f} \in F} \sum_{i \in O_{t_\mathbf{f}}} a_i \cdot X_{i\mathbf{f}j} - Y_j \leq 0 \quad (9)$$
$$\forall t \in T, j \in S_M$$

Constraint 3 - Area Limitation

To consider imposed area limitations separately, it is chosen to model these through the addition of an additional set of constraints. Area limitations are considered through a split into three parts. The first part is linked to the integer decision variable AC_1, representing the area available at no penalty cost. The limit to this area is constrained through the second equation in Equation set 10. The same policy is implemented for the area available at the cost of pavement (AC_2, with a cost c_2 of 110 euro/m^2 based on an average cost for pavement in airport development [43]) and the area available at the cost of purchasing (set to 150 euro/$m2$) and pavement (AC_3). To assure that the area assigned to AC_1, AC_2 and AC_3 is equal to the total area of the assigned number of stands per type, the first equation of Equation set 10 is defined.

$$AC_1 + AC_2 + AC_3 - \sum_{j \in S} area_j \cdot Y_j = 0$$
$$0 \leq AC_1 \leq 100000$$
$$0 \leq AC_2 \leq 100000 \quad (10)$$
$$0 \leq AC_3 \leq 100000$$

Note:

The decision-maker defines if this constraint set is used in the optimisation model or not. The implications of consideration of this constraint are assessed in the case study of this research.

Constraint 4 - Bussing Operations

Bussing operations are needed for aircraft assigned to remote stands. The number of busses needed for the arrival and departure parts is predetermined through Bus_{iA} and Bus_{iD}. Bus operations are created based on the arrival and departure times of a flight, considering the policy described in 3.3. This constraint set aims to assure a sufficient number of busses is acquired in the model by considering conflicting bus operations and dynamic bus capacity. Therefore, the same policy as for the aircraft stands (constraint set 2) is implemented to consider the time factor to ensure no overlap between bus operations.

From the created bus operations, all the unique starting times are obtained. For each of the unique starting times, it is analysed which bus operations are conflicting. For each of the unique starting times, a constraint is added consisting of all the conflicting operations at the specific time. The number of busses is linked to the maximum number of assigned conflicting bus operations. This is considered through the decision variable $X_{if_{BA}j}$. The f_{BA} and f_{BD} parts refer to the considered phase from the bus arrival and bus departure phases.

Equation 11 depicts the mathematical form of the bus constraint. It considers the arrival and departure operations for each of their specific phases that are conflicting at all the unique starting times ($t \in T_B$) of the assigned bus operations.

$$\sum_{\mathbf{f_{BA}} \in F_{BA}} \sum_{O_{t_{BA}}} \sum_{j \in S_B} Bus_{i_A} \cdot X_{i\mathbf{f_{BA}}j} + \sum_{\mathbf{f_{BD}} \in F_{BD}} \sum_{O_{t_{BD}}} \sum_{j \in S_B} Bus_{i_D} \cdot X_{i\mathbf{f_{BD}}j} - B \leq 0 \qquad \forall t \in T_B \tag{11}$$

Constraint 5 - Towing Operations
To facilitate departure pushbacks and aircraft towing, sufficient tow trucks must be considered in the optimisation model. The same policy as adapted for the busses and stands is implemented for the tow trucks. The difference lies within the two sets of tow trucks (narrow-body and wide-body tow trucks). Equation 12 depicts the constraint's mathematical formulation, assuring sufficient tow trucks are considered within the framework.

As for the busses, tow truck operations have been created, from which all the unique starting times are obtained. These times ($t \in T_T$) are used to define the conflicting operations. For each of the times, a constraint is added for each of the tow truck types ($p \in P$). This constraint consists of three parts. The first part considers all the departure pushback operations (which apply for the departure tow phases $f_{TD} \in F_{TD}$) that are conflicting (O_{tTD_p}) at time $t \in T_T$ for tow truck type $p \in P$). The second part consists of the towing operations of two splits to the departure stand. The third part considers the three split tows, consisting of two phases (tow to parking and tow to departure stand).

$$\sum_{\mathbf{f_{TD}} \in F_{TD}} \sum_{i \in O_{tTD_\mathbf{p}}} \sum_{j \in S} X_{i\mathbf{f_{TD}}j} + \sum_{i \in O_{tT2T_\mathbf{p}}} \sum_{j \in S} X_{iD2j} + \sum_{\mathbf{f_{T3T}} \in F_{T3T}} \sum_{i \in O_{tT3T_\mathbf{p}}} \sum_{j \in S} X_{i\mathbf{f_{T3T}}j} - TT_\mathbf{p} \leq 0 \qquad \forall t \in T_T, \forall \mathbf{p} \in P \tag{12}$$

Constraint 6 - Stand Capacity Hard Input
It is desirable to be able to assess the results of real-life implemented cases through a fixed stand mix. A hard input of the stand mix for a known case can also be used to fine-tune the optimisation model's parameter settings (to obtain the parameter set that represents the real-life case best). Furthermore, in order to be able to perform a case study to assess how a real-life case performs compared to the model results, it is necessary to be able to use the stand mix as hard input. Therefore, the constraint as depicted in Equation 13 is defined in the optimisation model. To also facilitate a minimum stand capacity case (a minimum number of stands of a specific type), the constraint as depicted in Equation 14 is also implemented.

$$Y_j - cap_j = 0 \qquad \forall j \in S \tag{13}$$

$$Y_j - \min cap_j \geq 0 \qquad \forall j \in S \tag{14}$$

Note:
The decision-maker defines if this constraint set is used in the optimisation model. The implications of considering this constraint are assessed in the case study of this research.

Flight Frequency Unit
A flight frequency unit is implemented in the developed model to assess the effect of incorporating the weekly flight frequency on the stand mix within the framework. This unit can be turned on or off. It incorporates the weekly flight frequency in the operational cost assigned to an operation as depicted in Equation 15. $OC_{FrequencyCost}$ is the operational cost incorporating the weekly frequency of the operation, f the weekly frequency of a flight movement and OC_{cost} the daily operational cost.

It has to be noted that a weekly time frame is used for the operational cost in this unit. To make sure that the capital cost also reflects a weekly time frame, the capital cost is increased to a weekly cost (multiplication by 7).

$$OC_{FrequencyCost} = f \cdot OC_{cost} \tag{15}$$

3.5. Resolution Method

The mathematical model defined in Section 3.4 is implemented in Python and solved through the Gurobi Optimizer. The performed literature study has revealed that the stand capacity problem can be modelled and solved differently. Research performed by Bouras [14] showed that a binary integer formulation could be best solved using the primal simplex algorithm. This is also validated in the research performed by Diepen and Hoogeveen [16], Boukema [29] and Kaslasi [28]. As described in Section 2 (Resolution Methods), when the primal simplex algorithm is not sufficient to solve a defined problem within a reasonable time, heuristics can be employed.

Within the optimisation toolbox of Gurobi, different building blocks are used to solve an optimisation problem. The first method used by the Gurobi optimiser is an LP Presolve. This method aims to reduce the problem size to speed up linear algebra during the solution process. This is done through the reduction of redundant constraints and substitution. The second method explored is the LP relaxation. In this method, the integrality constraint is relaxed.

Within the literature on operations research techniques, the branch-and-bound algorithm is well-known. Within branch-and-bound subproblems are assessed by dropping the integrality constraint, after which a solution tree is created. Solutions are explored until there are no better solutions considering all the set constraints [44]. Furthermore, cutting planes can be used to reduce the feasibility region without compromising any feasible solutions. The goal of the branch-and-bound and cutting planes methods is to reduce the needed time to obtain an optimal solution.

The Gurobi optimiser [45] employs a hybrid method that combines both the branch-and-bound and cutting planes methods. This is called the branch & cut method. The cutting planes approach is applied before the branching step in the branch-and-bound algorithm. Within the cutting plane method, cutting plane constraints are generated (through, e.g. Gomory cuts, Flow cover cuts, Lift-and-project cuts and zero-half cuts [45]) and added to the LP relaxation, in which fractional optimal solutions of the root problem are explored while keeping all integer solutions intact. By applying this method, the algorithm computes the gap between the lower and upper bound. Optimality is proven once these have the same value (and thus, a gap of 0% is found).

4. Results

The following section will dive into the results of the research. It is kicked off with a description of the verification and validation methodology used in Section 4.1, followed by an analysis of the used input data in Section 4.2. Furthermore, in Section 4.3 the results of the performed case studies will be presented, after which the model performance will be analysed in Section 4.4.

4.1. ***Verification and Validation Methodology***

The proposed framework is verified in the following way: quality control (by assessment of the efficiency and clarity of the code), code verification (verification of parts of the code using numerical cases with a known output) and system verification (verification of the framework through a numerical case). For an extensive overview of the verification cases and their results, the reader is referred to the accompanying thesis report.

In order to assess the performance and results of the proposed optimisation framework, a case study has been set up. The goal of the case study was to validate the capabilities of the proposed framework to define the anticipated stand-mix for an airport based on a design day flight schedule.

As described in the methodology part of this paper, the optimisation framework uses a flight schedule to determine the needed stand-mix and equipment. To test the model for an existing airport, it is chosen to use Amsterdam Airport Schiphol as the case study airport. This airport has been chosen due to the availability of flight data, stand data and the short line of connection between the Delft University of Technology and the airport.

The raw input data for the case study consists of two parts: flight movement data as obtained from the OAG database for the year 2018 and the stand mix. The flight movement data is analysed for the number of movements per week for the year 2018 as well as for the peak day. According to the analysis performed, week 21 was the peak week in 2018. From the peak week, the peak day is obtained. This resulted in the definition of Monday 21 May as the peak day for the year 2018. This is validated using flight data obtained from Amsterdam Airport Schiphol.

The peak day is represented by 1583 flight movements as obtained from the OAG database. Using an in-house developed flight movement pairing model (which matches arrival and departure flight movements amongst others based on the turnaround time, aircraft type, and airline), pairings are created for the flight movements. This resulted in 769 pairings (of which 80 are overnight pairings). These pairings have been validated using a developed pairing algorithm.

The case study has been performed through three steps. First, the input data is analysed to understand the specifics of the input design day flight schedule. An analysis of different predefined cases follows this. In each of the cases, different parts of the optimisation model are tested or compared. The case study is concluded with a sensitivity analysis.

4.2. ***Data Analysis***

4.2.1. ***Input Flight Schedule***

As described in Section 4.1, a design day flight schedule has been created based on the peak day flight movements at Amsterdam Airport Schiphol in 2018. This resulted in 769 pairings (1583 flight movements). The number of arrivals and departures throughout the day are depicted in Figure 6. The flight schedule is characterised by alternating arrival and departure peaks. In the morning, most of the transatlantic flights arrive between 06:00 and 08:00, while the short-haul flights arrive between 08:00 and 09:00. The peak between 09:00-10:00 is due to the the departing transatlantic and short-haul flights (this is also the largest departure peak of the day).

Figure 7 depicts the air traffic demand throughout the day with differentiation in aircraft size. It is visible that at the start of the day, the large aircraft (ICAO Aircraft Design Group E) arrive. It can be seen in Figure 8 that these flights arrive from Non-Schengen destinations and depart to Non-Schengen destinations. Furthermore, it can be seen that the most significant part of the flight movements is operated by type C aircraft. Around 22% of the flights switch between sectors from their arrival to their departure.

4.2.2. ***Stand Data***

To assess the performance of the model based on the operations at Amsterdam Schiphol Airport (SPL), the available stands are needed. The available stand types

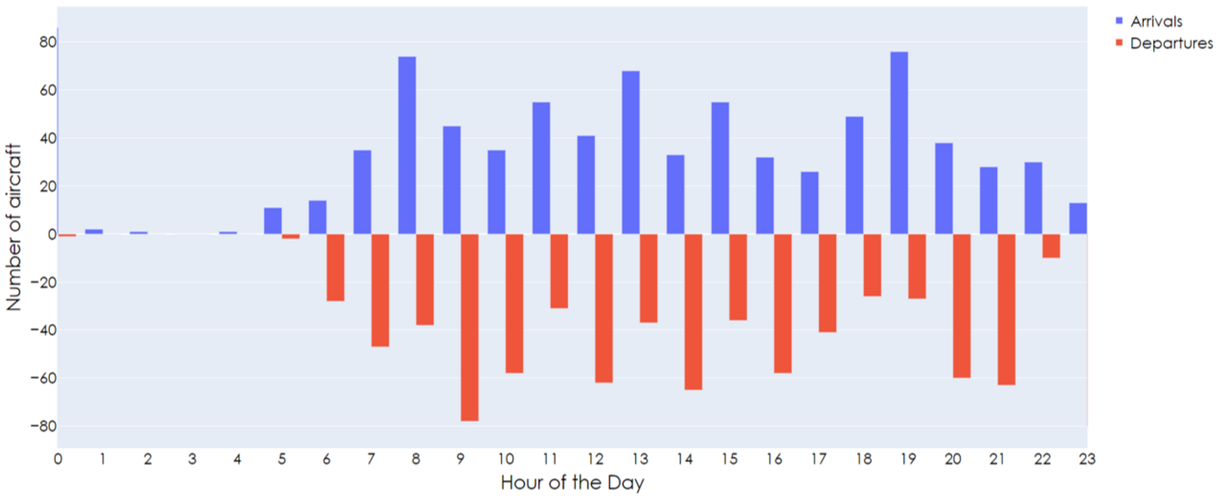


Figure 6: Number of arrivals and departures throughout the day of the input flight schedule

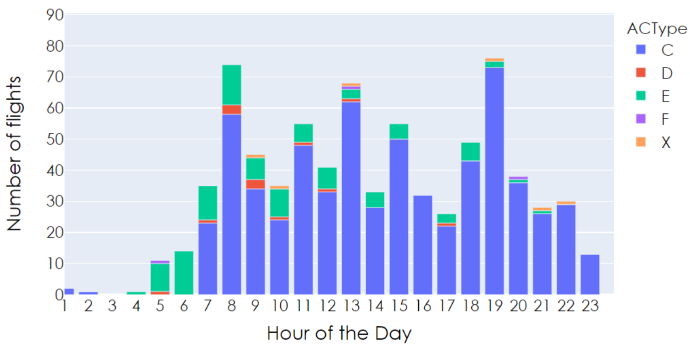


Figure 7: Case study flight schedule air traffic demand throughout the day with a differentiation in aircraft size

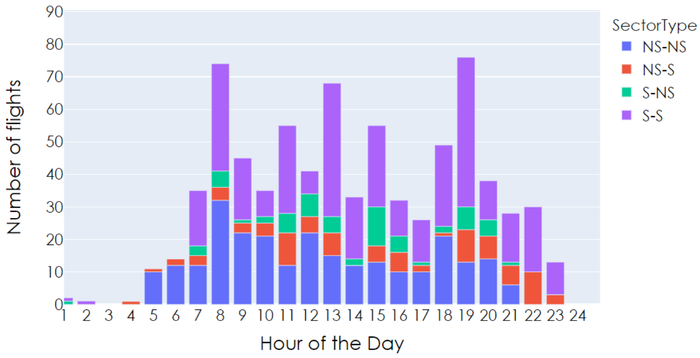


Figure 8: Case study flight schedule air traffic demand throughout the day with a differentiation in flight sector (NS: Non-Schengen, S: Schengen, first part is the origin sector, the second part is the destination sector)

are obtained from Amsterdam Airport Schiphol (SPL) and translated back to the stand types implemented in the proposed framework. For this, some assumptions have been used. First of all, SPL uses ten aircraft categories for their stands. These categories have been adapted to stand sizes C, D, E and F. Furthermore; the airport uses dedicated cargo stands for full cargo flights. These are modelled as remote operational stands in the case study analysis. Lastly, an assumption has been made regarding the sector usability of the stands (B and C piers: Schengen, E-G piers: Non-Schengen, D/H-M piers: Swing).

4.3. Model Results & Analysis

The developed optimisation model is assessed through a set of cases developed. The results of these cases will be described in the following section.

4.3.1. Pareto Multi Case Results - Base Case

First, the model is run for the design day flight schedule by varying the factors assigned to the capital cost and operational cost in the objective function. In this first case, no additional units are considered (no robustness, no area limitations, no flight frequency). The factor assigned to the capital cost, α_{CC}, is altered from 0.05-0.99 in 19 steps. The results of the trade-off between operational and capital cost is depicted in Figure 9. Each of the points depicts a solution for a specific α_{CC}. It can be seen that an increase in capital cost allows for a decrease in operational cost.

Stand Mix:
Figure 10 depicts a boxplot of the number of stands per type built in the multi-case run. It can be seen that the contact stands and remote operational stands have the largest spread. The highest number of contact stands is chosen for $\alpha_{CC} = 0.05$ (132 contact stands). At this α_{CC}, the highest number of total stands is built (142). This can be explained by the fact that at this choice, the operational cost is dominant. Since contact stands do not induce any operational cost in the defined framework, these stands are chosen. This is also visible in Figure 12 in the number of busses (4) used in this solution. As the α_{CC} increases, the number of contact stands decreases, and more remote operational stands are used (at the cost of more busses). The total number of stands doesn't vary very much after $\alpha_{CC} = 0.05$

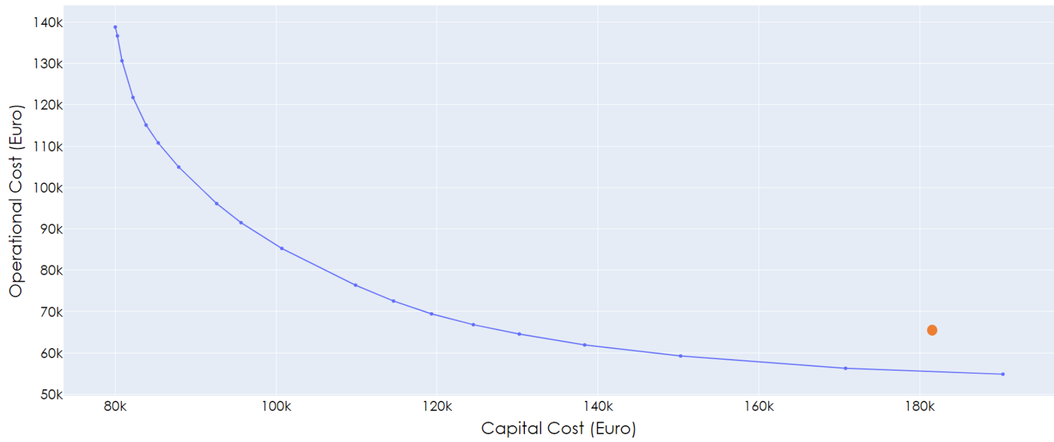


Figure 9: Pareto curve for the base case

(variance of 0.28).

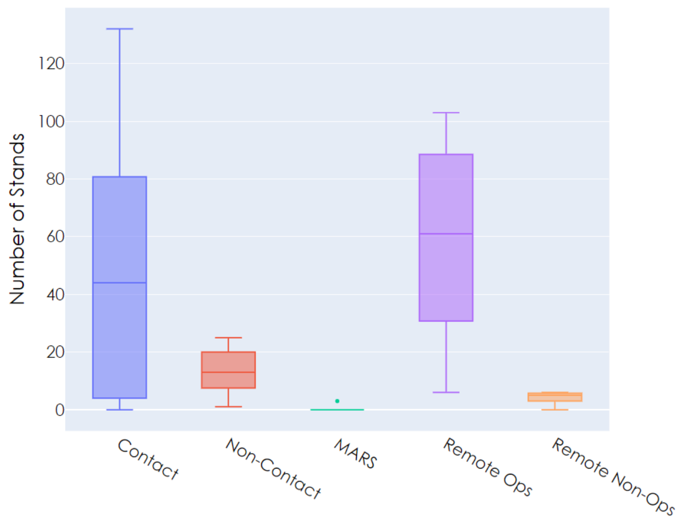


Figure 10: Boxplot graph of the number of stands per type for the base case. Ops = Operational

It turns out that MARS stands are only used in the case $\alpha_{CC} = 0.05$. A MARS stand is not very cost-efficient. The capital cost is 4.5 times higher than a contact swing stand (for ADG C). Therefore, a use case in which a MARS stand is used for handling two type C aircraft simultaneously followed by handling a type E aircraft without the need to build an additional stand would make it viable. Having an in-depth look at the design day flight schedule reveals that the demand is insufficient to employ such solutions. At the start of the day, the demand consists mainly of type E aircraft, after which the portion of type E aircraft reduces.

To test the implications of the flight schedule, a test case has been produced. A schedule has been created with the same number of flight movements as the input schedule. However, this schedule consists of alternating peaks of type C and type E arrivals. In this case MARS stands are indeed used up to $\alpha_{CC} = 0.18$. The percentage of MARS stands (out of the total number of stands per run case) ranges from 4.9% ($\alpha_{CC} = 0.15$) to 43% ($\alpha_{CC} = 0.05$).

From the output results, it is seen that as the α_{CC} increases, more flights are split into three phases until $\alpha_{CC} = 0.31$ when the maximum of 10 flights is reached. This is due to the implemented policy for flight splitting in the framework. Assignment of flight splits to remote stands is not allowed due to the inefficiency associated with such a solution and as the number of remote operational stands increases by an increase in the α_{CC} the number of flights split into three phases reduces which each step of increase.

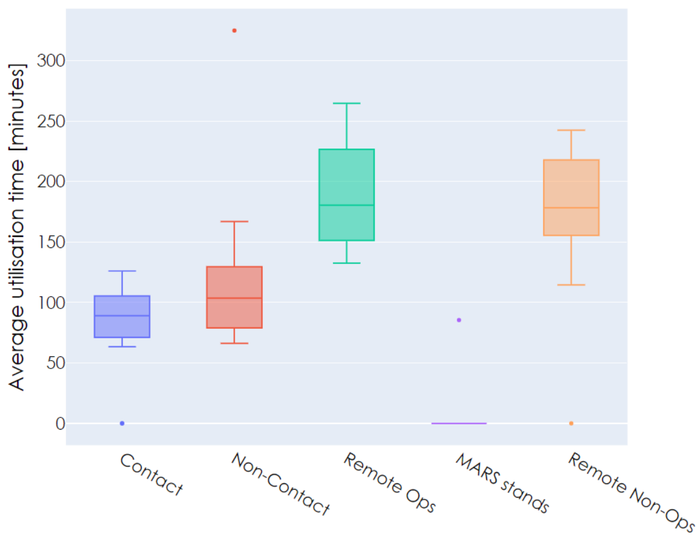


Figure 11: Boxplot graph of the average stand utilisation (in minutes) for the base case. Ops = Operational

Figure 11 depicts boxplots of the average utilisation time for each stand type. It can be seen that the remote operational and non-operational stands have the highest average stand utilisation time. Since only the parking phase of a three split can be assigned to a remote non-operational stands, this is logical. Furthermore, upon further analysis of the solutions it can be seen that around 50% of the overnight flights is assigned to remote operational stands, which also increases the stand utilisation time.

Use of Equipment:
It can be seen in Figure 12 that there is no variation in the number of tow trucks. This can be explained because a tow truck is needed for the pushback for any of the stands. The splitting of flights into two or three phases does not impact the number of tow trucks. The visible variation in the number of busses is related to the increase in the number of remote handling operations due to an increase in the α_{CC}. The validity of the large number of busses for an existing airport will be considered in Section 4.3.2.

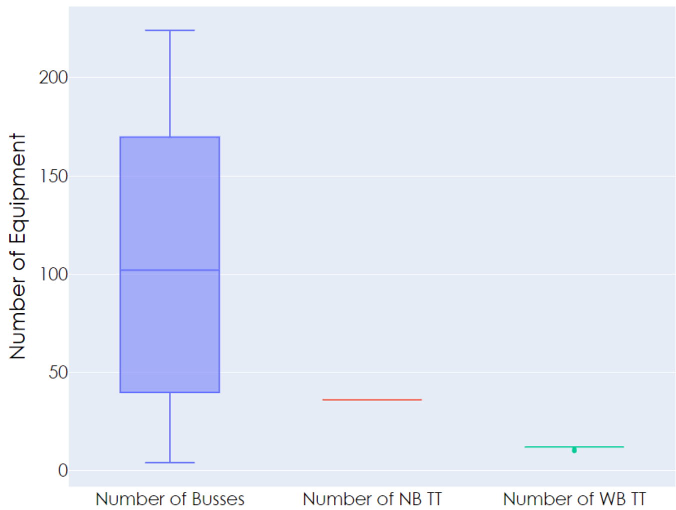


Figure 12: Boxplot graph of the number of equipment for the base case. NB = Narrow-Body, WB = Wide-Body, TT = Tow Truck

Area Limitations:
Since being able to assess area limitations is one of the key aspects of the proposed framework, the total area for each of the case runs is analysed. Figure 13 depicts the total area for each of the α_{CC} cases that have been run. It can be seen that through the choice for an α_{CC}, a trade-off can be made regarding the total area used. The largest area refers to the lowest considered α_{CC} in which 93% of the stands are contact stands, while the lowest area is represented by full remote handling of flights.

Utilisation of Swing Stands:
From the model output, the use of swing stands is further analysed. The case $\alpha_{CC} = 0.1$ is chosen from the Pareto curve since this is the first solution in which almost all flights are handled at connected stands. As described in Section 3.3, swing stands are efficient for sector switching flights as well as for cross use during peaks of a specific sector. From the analysis, it is obtained that around 50% of the flights assigned to swing stands are

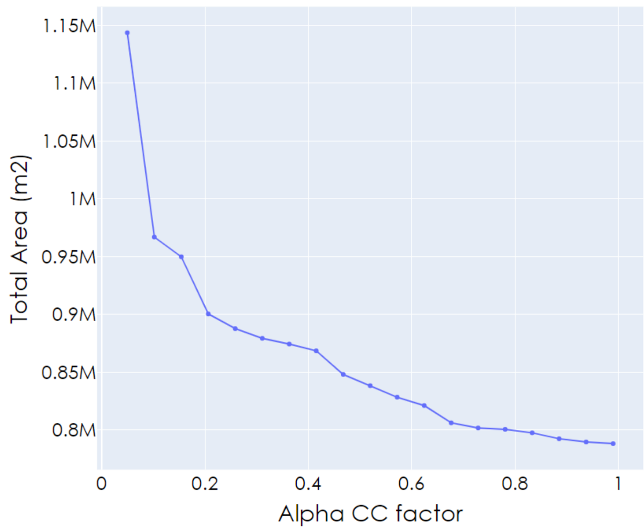


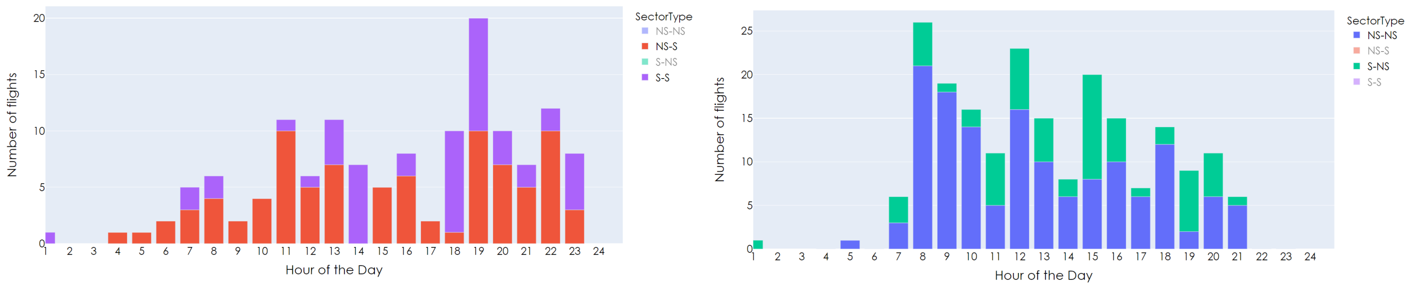
Figure 13: Total area used for different α_{CC} values along the Pareto curve

sector switching flights. Figure 14a depicts the demand on the swing stands of flights departing to Schengen destinations, while Figure 14b depicts the demand on swing stands of flights departing to Non-Schengen destinations. It can clearly be seen that the swing stands are cross utilised for both types of flights and that the demand is captured by alternating peaks, which validates the policy for these stands.

4.3.2. Validation using Amsterdam Airport Schiphol Data

The real case performance at Amsterdam Airport Schiphol compared to the model output is also analysed. In this part of the case study, the stand data described in Section 4.2.2 is implemented in the model as a hard input. Furthermore, the capital cost and operational cost in the objective function are equally taken into account (no consideration of an α_{CC} factor). The orange dot in Figure 9 depicts the position of the solution in which the number of stands at Schiphol Airport is used as hard input. The result is a capital cost of 181,865 euro and an operational cost of 65,608 euro. It can be seen that the solution is not optimal. Apparently, the airport uses more stands than needed. Based on the developed model and through interpolation, it is found that the operational cost could be reduced by around 15%. However, this gap could be expected as stand capacity assessment is not only driven by a peak day analysis. The proposed framework determines the minimum number of stands, which does not incorporate general aviation flights and emergencies.

It has to be noted that only the stands are modelled as hard input in this analysis. The needed equipment is not restricted. The model assigns the number of busses needed to operate the aircraft assigned to a remote stand. This is independent of the number of remote stands built. The number of busses needed for the design day flight schedule based on Amsterdam Airport



(a) Demand on swing stands for flights departing to Schengen destinations (case $\alpha_{CC} = 0.1$)

(b) Demand on swing stands for flights departing to Schengen destinations (case $\alpha_{CC} = 0.1$)

Figure 14: Demand on swing stands for the case $\alpha_{CC} = 0.1$

Schiphol's stand mix is 31. Upon analysis of the available number of busses at the airport (around 35 busses), it is validated that the developed model is accurate in reflecting the actual operations.

4.3.3. ***Consideration of Weekly Flight Frequency***

As described in Section 3 the consideration of the flight frequency is also implemented in the developed framework. To analyse the implications of incorporation of the flight frequency on the model output, the same case study has been performed as described in Section 4.3.1. However, the flight frequency unit has been turned on in this analysis. Therefore, the weekly frequency of flight operations is now also included in the optimisation.

Figure 15 depicts boxplots of the number of stands for the multi-case runs of the model without flight frequency (NF) and with flight frequency (WF). The same range of 123-125 for the total number of stands built is obtained if the model is run with the flight frequency unit (if the first case $\alpha_{CC} = 0.05$ is excluded from the analysis). Furthermore, there are no significant variations with respect to the number of equipment in the two runs (for the tow trucks, there is no variation at all). However, it is clear from Figure 15 that a different variation of stands is used if the flight frequency is considered. Flights are handled more remotely in this case (fewer contact stands and more remote operational stands).

The variation in stands is also visible from the total area used in both the runs. Figure 16 depicts the area used in both case runs 1 and 2 for a variation in the α_{CC} factor. It can be clearly seen that turning on the consideration of the flight frequency results in a lower area compared to the base case (without the flight frequency). The flight frequency run results in an area reduction from 0.1% up to 6.5% compared to the base case. This leads to a cost reduction between 15% and 20%. This percentage gets lower and lower as the α_{CC} is increased. The lower area is a result of the reduction in contact stands and increase in the number of remote stands. Upon further analysis of the results, it is found that the percentage of aircraft assigned to a stand with an equivalent stand size (instead of a larger size) reduces as the α_{CC} increases for both the run with and without flight frequency. However, if the flight frequency is considered on average 0.5% fewer flights are assigned to an equivalent stand size compared to the case without flight frequency.

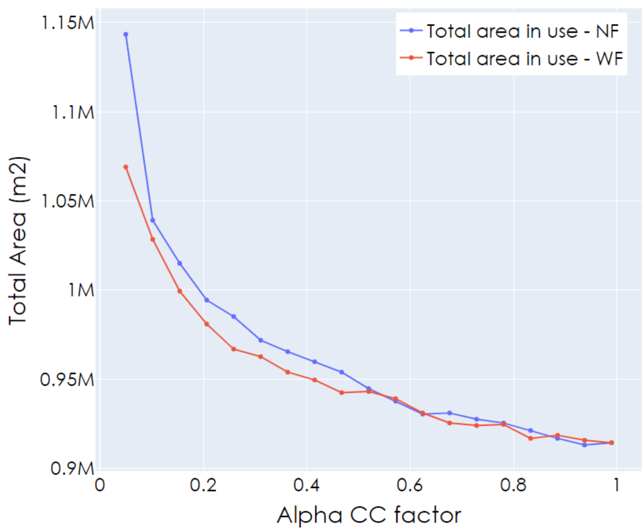


Figure 16: Total area used as a function of α_{CC} for the base case (NF) and the case including flight frequency (WF)

4.3.4. ***Consideration of Area Limitations***

To test the implications of the area limitations unit, a third case study has been set up. As described in Section 3, the area limitations are considered in three blocks: a block of the available area, the second block of the area available at the cost of pavement and a third block containing the area available at the cost of pavement and purchasing. In this case study the available area at no cost is set to 960,000 m^2 (the average area used by the model in case 1), the area at cost of pavement to 300,000 m^2 and the area at the cost of pavement and purchasing to 100,000 m^2. As with the other two multi-case runs, the α_{CC} is varied from 0.05 to 0.99 in 19 steps.

From the model results, no significant differences are found between the model output for the base run (case run 1) and the area limitation case. A lower maximum number of contact stands is observed if the

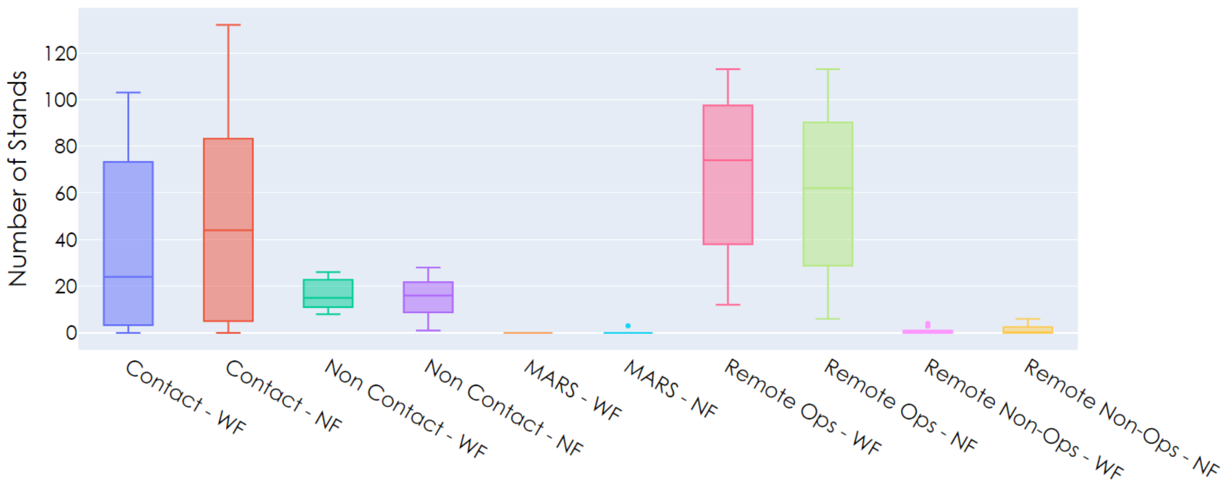


Figure 15: Boxplot graph of the number of stands per type for the base case (NF) and case including flight frequency (WF)

area limitation unit is used.

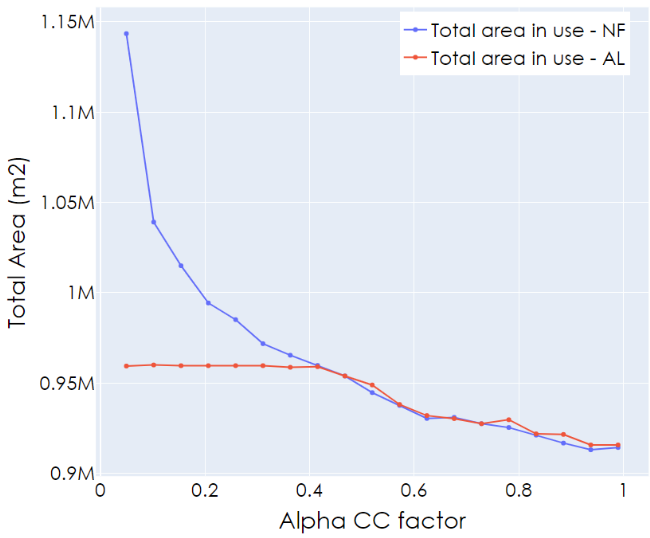


Figure 17: Total area used as a function of α_{CC} for the base case (NF) and the case with area limitations (AL)

Interesting conclusions can be drawn upon analysis of the area used for this case study run. Figure 17 depicts the area used as a function of α_{CC} for the base run (without area limitations) and the run with area limitations (AL). It can be seen that the area limitation case results in a lower area due to the set restrictions. Upon analysis of the solution characteristics, it is found that the model splits more flights into three phases until the point of the set area is reached, after which the graphs are almost equal. The minor deviations between the two lines once the 960,000 m^2 is reached at $\alpha_{CC} = 0.42$ can be linked to the optimisation cut-offs, the optimisations of the area limitation run are not optimised until a 0% gap, but are at some points cut off between a 0% and 1% gap.

From the results, it can be said that the base model (without the area limit run) already allows for a trade-off with respect to the area used. However, the area limitation unit in the proposed framework is useful for a single case study in which a decision-maker assesses what the implications on the stand mix and cost are by implying area restrictions. As can be seen in Figure 17 the unit reduces the area up to the set threshold for the same α_{CC} factor.

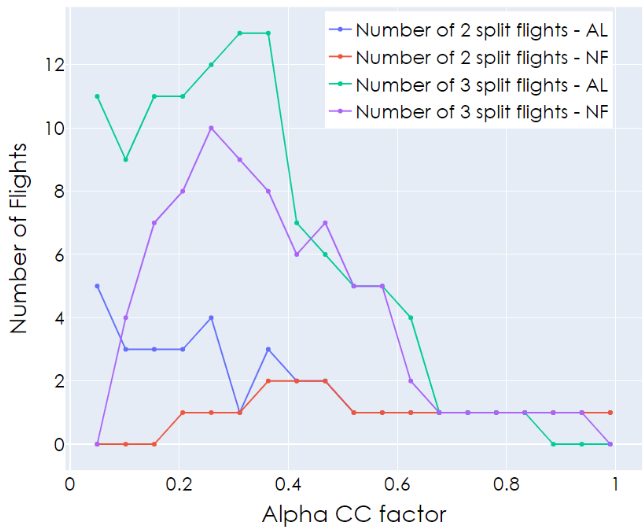


Figure 18: Number of flights split into two or three phases as a function of α_{CC} for the base case (NF) and the case with area limitations (AL)

4.3.5. *Implications of Flight Splitting Policy*

To test the implications of flight splitting, a small case study has been performed in which the operational cost for split phases is lowered. In the base definition of the model, the operational cost for the split phases is the same as for the no split versions of a flight (thus, if a flight is split, the operational cost is induced twice or thrice). For this analysis, the operational cost of the split phases is reduced to 50%. This is done to push the model towards the employment of flight splitting.

Tables 1 and 2 depict the results of this analysis. It can be seen in Table 2 that the number of busses is reduced as the cost is reduced. The total number of stands in both runs is 123. There is a small variation in the number of stands per type. From the results, it is obtained that an increase in the number of flights split results in a higher service level (more flights are assigned to contact stands). Furthermore, this also results in a lower number of busses needed (less remote operations).

The described policy for flight splitting was adapted after the validation performed using the case study data. It was found that the model also executed unnecessary tows due to the lower stand occupation time. If a flight is towed away, the stand occupation time is lowered due to the needed towing time during which the flight does not occupy a stand. Therefore, two split tows of non-sector switching flights is penalised by a factor of 2 and three split tows are restricted to be assigned to non-remote stands (to assure that these will only be used if it results in efficient use of the infrastructure).

Run	Capital Cost (Euro)	Operational Cost (Euro)
Base	103,568	82,225
50% decrease in split cost	105,027	78,934

Table 1: Capital cost and operational cost results of the flight splitting analysis

Run	Number of Busses	Number of Narrow-Body Tow Trucks	Number of Wide-Body Tow Trucks
Base	84	36	12
50% decrease in split cost	77	36	12

Table 2: Number of equipment results of the flight splitting analysis

4.3.6. *Model Sensitivity*

The sensitivity of the defined parameters on the model output has been assessed through a sensitivity analysis. This analysis is performed around three categories: cost factors, time factors and robust scheduling.

The capital cost of the stands is more dominant than the operational cost associated with operating boarding stairs, tow trucks and busses. Altering the capital cost of the stands results in a change of the number of stands per type through more contact handling of flights, which is linked to the number of busses needed. For analysis in which the capital cost of the stands is reduced in 5 steps from 5% to 25%, the number of contact stands increases on average with 8%, the number of remote stands is reduced by 6% and the number of busses is reduced with 8% (all relative to a 5% reduction in the capital cost). The total number of stands does not vary. The capital cost of the equipment is not a dominant factor.

As described, the framework also incorporates the ability to create robust schedules through the addition of buffer times. An analysis has been performed in which the buffer times have been increased from 0-20 minutes in steps of 4 minutes (2 minutes subtracted from the scheduled arrival times and 2 minutes added to the scheduled departure time of flights). It is found that the total number of stands increases on average by 3% for every 4 minutes of buffer time.

4.3.7. *Decision Maker Dashboards*

Interpretation of output data can be cumbersome for a decision-maker or stakeholder. As described in Section 4, the proposed framework is extended with solution dashboards to aid a decision-maker in interpreting the model output and making decisions. The features of the visualisation dashboards are depicted in Figure 19. Two minimum viable products (MVP) of analysis dashboards have been developed. The first version refers to the left branch in Figure 19 and consists of data visualisations for a single case (a run for a single choice of α_{CC} and α_{OC}). This encompasses the input schedule analysis by means of the analysis of the traffic demand throughout the day with respect to differentiation in size and sector and the analysis of the model output. This analysis of the model output consists of the stand mix, equipment and stand utilisation. A screenshot of this dashboard can be found in Figure C.22.

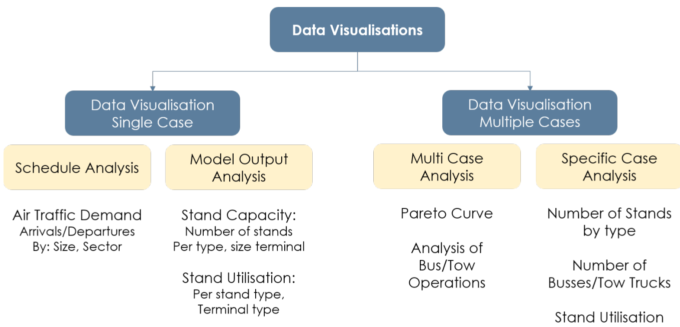


Figure 19: Schematic overview of the dashboard features

The second developed dashboard aids a decision-maker in the interpretation of results and decision making for a multi-cases run. This dashboard depicts the Pareto curve, the area for each of the cases and the bus/tow operations as is depicted in Figure C.23. Based on these graphs, the decision-maker can investigate the characteristics (stand mix, equipment, stand utilisation time) of a specific solution, as shown in the right part of Figure C.23. These MVPs allow for an easily accessible and interactive interface for a decision-maker to interpret the model output.

4.4. Model Performance

The model performance is assessed through the performed case studies as described in Sections 4.3.1, 4.3.3 and 4.3.4. The developed model has been tested using a laptop with:

- Processor: Intel Core i7-8550U CPU 1.80GHz, 2001 MHz, 4 CPU Cores, 8 threads.
- Python 3.7
- Gurobi Optimizer version 9.1.1 build v9.1.1rc0

The developed mathematical optimisation model consists of 11,102 rows and 46,116 columns
The computational time for each of the three runs: base (1), consideration of flight frequency (2) and consideration of area limitations (3) is depicted in Figure 20 as a function of the α_{CC} factor (the computational time of each of the individual case runs). Figure 21 depicts the computational times of the base case and the case with the flight frequency consideration.

Note: The computational times depicted in Figures 20 and 21 consist of the computational time needed by Gurobi to solve each of the α_{CC} cases.

The total computational time needed to run 19 cases of α_{CC} for the base case, and the flight frequency is around 7 minutes (of which 4 minutes are needed for the Gurobi optimisation). A single case is performed within a minute, including the output set up (graphs, etc.). The Gurobi optimizer solves the defined optimisation problem using the methodology described in Section 3.5. The developed mathematical optimisation model consists of 11,102 rows and 46,116 columns. First, the presolve module is used, which removed 5631 rows and 28075 columns and reduced the problem to 5471 rows and 18,041 columns. This is followed by root relaxation, after which the branch & cut algorithm is used. Three cutting plane methods are used for the base runs or runs with the flight frequency unit (Gomory, MIR and Zero half).

As can be seen in Figure 20, the area limit unit rapidly increases the computational time. To investigate how this can be reduced, the single case at $\alpha_{CC} = 0.57$ is further analysed. The running time of the model with the area limitation unit was initially around 52 minutes. Upon further inspection of the solution it is found that the definition of the α_{CC} and α_{OC} factors as floats increases the solution time. By altering these factors to 2 digits, the model's running time with the area limitations (for 19 cases) is lowered by around 50%.

Furthermore, no time limit or gap limit is imposed within the framework as an average optimisation time of 11 seconds (the time needed by the Gurobi optimiser) for a case is deemed as acceptable. The results have been obtained. However, it is analysed how the running time for the area limitation unit can be improved. The objective bound is moving slowly in some of the cases in which the area limitation constraint is included. For these cases, the high-level solution strategy can be changed using the Gurobi parameter "MIPFocus" [46]. For the runs with the area limitation unit, the MIP Focus has been set to focus on the bound.

Figure 20: Computational time of the multi case runs per run case (α_{CC})

Figure 21: Computational time of the base case and the case with flight frequency consideration per run case (α_{CC})

5. Conclusion & Recommendations

In this research paper, a mathematical optimisation model capable of determining the needed stand mix and equipment for a design day has been developed. The proposed framework combines the incorporation of area limitations, robust scheduling, operational factors, different stand types and flight frequency within a single framework. It has been proven that there is no one answer to such a problem. Within the proposed framework, the trade-off is made between operational cost and capital cost using weight factors to the objectives (α_{CC} for the capital cost and $1 - \alpha_{CC}$ for the operational cost), after which a Pareto curve is created. This allows a decision-maker to make a trade-off between the level of service (through connected stands), the number of needed equipment and area use. For this, a value-focused thinking process is employed. The decision-maker defines a priori the optimisation objectives (what to optimise for and the factors incorporated within the optimisation), after which different cases will be run. These cases will be presented to the decision-maker, after which a decision can be made. Furthermore, the decision-maker can also decide to further analyse a specific solution through a single run. Data visualisation dashboards have been developed to aid a decision-maker in this process. The proposed framework has been modelled within Python 3.7 and optimised using the Gurobi optimiser. To validate the model, a case-study analysis has been performed. This case study has been performed by defining a design day flight schedule for the peak day of 2018 (using OAG data), which has been validated using data obtained from Amsterdam Airport Schiphol.

From the case study, it became clear that the total number of stands does not vary very much along the Pareto curve. The variation lies within the number of specific stand types and the needed equipment. MARS stands are not used within the framework (except for the case $\alpha_{CC} = 0.05$) due to the high cost associated with these stands and the relatively low demand of aircraft belonging to aircraft design group E within the design day flight schedule. As the α_{CC} is increased, the model shifts towards the use of remote stands, which lowers the total needed infrastructural area. The implemented area limitations unit within the model has proven to lower the needed area for specific solution cases successfully. Furthermore, the model is validated using the available stands at Amsterdam Airport Schiphol in 2018. This showed that the model accurately reflected the operations (the need for 31 busses, while the airport had 35 busses available). However, the solution turned out to be sub-optimal. A reduction in the operational cost by around 15% could be gained by employing a solution along the Pareto curve.

Two specific implemented policies have been validated: flight splitting and the use of swing stands. Flight splitting is employed within the framework to allow for optimal use of the infrastructure by towing long stay aircraft to a remote stand to free up connected stand capacity. It has been validated that an increase in splitting flight increases the number of connected handled flights. Furthermore, the use of swing stands is centred around demand from sector switching flights as well as capturing sector peaks (to Schengen or Non-Schengen destinations).

The effect of incorporating the weekly flight frequency has also been assessed within the research. It turns out that the cost can be reduced by around 15%-20% compared tot the base case. This is due to the adaptation in the stand mix employed by the optimisation model. The model reduces the number of connected handled flights (at contact or non-contact stands), which allows for a reduction in the area used up to 6.5%.

The proposed framework contributes to the body of knowledge and the assessment tools available for decision-makers within strategic airport planning. Upon the research results, it is recommended to apply the weighted sum method along with the creation of Pareto curves to create a value-focused thinking process for a decision-maker. Practical optimisation models for strategic stand capacity assessment are scarce within the literature. Furthermore, no framework exists that incorporates operational factors, the use of different stand types, area limitations and flight frequency within a single framework. The developed model captures this by providing the backbone and MVP dashboards for a decision-making tool, allowing a decision-maker to analyse a best-fit solution through a value-focused thinking process.

For further research within the domain of strategic stand capacity assessment it firstly recommended to further analyse the implications of anticipated demand and its implications on the stand mix. In this research, a design day schedule has been developed using OAG data which is not perfect (it contains both scheduled and executed flights). The proposed framework could be used to perform scenario analysis and to incorporate multiple air traffic demand scenarios (e.g. for multiple time spans within the strategic time frame). E.g. this can be used to consider investments based on the anticipated demand now and in X years. Moreover, to reflect actual airport operations, it is desired to tune the made operational assumptions through collaborative research with airport stakeholders. Furthermore, as the proposed framework is aimed at a strategic development time frame, the physical airport layout is not considered. Therefore, it is interesting to analyse the effects of different factors related to the physical layout on the stand mix (such as placement of roads, handling of aircraft, and stand adjacency constraints). Lastly, as the proposed model defines the needed equipment, it could be extended to include the needed workforce for the operations (passenger and aircraft handling) and how this could be used within a strategic time frame.

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Appendix A. Stand Type Information

Nr	Type	Size	Terminal	Area (in m^2)	Capital Cost per day (in EUR)	Bussing	Boarding Stairs
1	Contact	C	Domestic	5000	771	No	No
2	Contact	C	International	5000	771	No	No
3	Contact	C	Swing	5000	1045	No	No
4	Contact	D	Domestic	9277	943	No	No
5	Contact	D	International	9277	943	No	No
6	Contact	D	Swing	9277	1217	No	No
7	Contact	E	Domestic	14840	2383	No	No
8	Contact	E	International	14840	2383	No	No
9	Contact	E	Swing	14840	3150	No	No
10	Contact	F	Domestic	19656	3120	No	No
11	Contact	F	International	19656	3120	No	No
12	Contact	F	Swing	19656	4107	No	No
13	Non-Contact	C	Domestic	5000	702	No	Yes
14	Non-Contact	C	International	5000	702	No	Yes
15	Non-Contact	C	Swing	5000	976	No	Yes
16	Non-Contact	D	Domestic	9277	929	No	Yes
17	Non-Contact	D	International	9277	929	No	Yes
18	Non-Contact	D	Swing	9277	1203	No	Yes
19	Non-Contact	E	Domestic	14840	2246	No	Yes
20	Non-Contact	E	International	14840	2246	No	Yes
21	Non-Contact	E	Swing	14840	3013	No	Yes
22	Non-Contact	F	Domestic	19656	2915	No	Yes
23	Non-Contact	F	International	19656	2915	No	Yes
24	Non-Contact	F	Swing	19656	3901	No	Yes
25	Remote Operational	C	NA	4298	132	Yes	Yes
26	Remote Operational	D	NA	8368	344	Yes	Yes
27	Remote Operational	E	NA	12709	609	Yes	Yes
28	Remote Operational	F	NA	16979	814	Yes	Yes
29	MARS	NA	Domestic	16350	3455	No	No
30	MARS	NA	International	16350	3455	No	No
31	MARS	NA	Swing	16350	4688	No	No
32	Remote Non-Operational	C	NA	4298	103	No	No
33	Remote Non-Operational	D	NA	8368	287	No	No
34	Remote Non-Operational	E	NA	12709	522	No	No
35	Remote Non-Operational	F	NA	16979	698	No	No

Table A.3: Overview of the different stand types and their specifics

Stand	**C**	**D**	**E**	**F**	**C NC**	**D NC**	**E NC**	**F NC**	**MARS**	**Remote C NOP**	**Remote D NOP**	**Remote E NOP**	**Remote F NOP**	**Remote C OP**	**Remote D OP**	**Remote E OP**	**Remote F OP**
Nr PBB	1	2	2	3	0	0	0	0	3	0	0	0	0	0	0	0	0
PBB Cost	500,000	50,000	500,000	500,000	500,000	500,000	500,000	500,000	500,000	0	0	0	0	0	0	0	0
Total PBB Cost	500,000	100,000	1,000,000	1,500,000	0	0	0	0	1,500,000	0	0	0	0	0	0	0	0
Area																	
Area Cost (EUR/m2)	225	300	350	350	225	300	350	350	350	175	250	300	300	225	300	350	350
Area m2	5,000	9,277	14,840	19,656	5,000	9,277	14,840	19,656	16,350	4,298	8,368	12,709	16,979	4,298	8,368	12,709	16,979
Total Area Cost	1,125,000	2,783,100	5,194,000	6,879,600	1,125,000	2,783,100	5,194,000	6,879,600	5,722,500	752,063	2,092,075	3,812,640	5,093,568	966,938	2,510,490	4,448,080	5,942,496
Terminal Cost																	
Layers	2	2	2	2	2	2	2	2	2	0	0	0	0	0	0	0	0
Swing Layers	3	3	3	3	3	3	3	3	3	0	0	0	0	0	0	0	0
Width [m]	50	50	70	90	50	50	70	90	90	0	0	0	0	0	0	0	0
Depth [m]	10	10	20	20	10	10	20	20	25	0	0	0	0	0	0	0	0
Building Area Cost (EUR/m2)	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	0	0	0	0	0	0	0	0
Cost single sector terminal	4,000,000	4,000,000	11,200,000	14,400,000	4,000,000	4,000,000	11,200,000	14,400,000	18,000,000	0	0	0	0	0	0	0	0
Cost swing terminal	6,000,000	6,000,000	16,800,000	21,600,000	6,000,000	6,000,000	16,800,000	21,600,000	27,000,000	0	0	0	0	0	0	0	0
Total single sector cost	5,625,000	6,883,100	17,394,000	22,779,600	5,125,000	6,783,100	16,394,000	21,279,600	25,222,500	752,063	2,092,075	3,812,640	5,093,568	966,938	2,510,490	4,448,080	5,942,496
Total swing terminal cost	7,625,000	8,883,100	22,994,000	29,979,600	7,125,000	8,783,100	21,994,000	28,479,600	34,222,500	0	0	0	0	0	0	0	0
Depreciation per day (EUR)	771	943	2,383	3,120	702	929	2,246	2,915	3,455	103	287	522	698	132	344	609	814
Depreciation per day swing (EUR)	1,045	1,217	3,150	4,107	976	1,203	3,013	3,901	4,688	0	0	0	0	0	0	0	0

Table A.4: Distinction between capital cost of the different aircraft stands based on stand size, the use of a PBB and terminal layers. NC = Non-Contact stand, NOP = Non-Operational, OP = Operational.

Appendix B. Cost Factors

Equipment	Capital Cost (Euro)	Depreciation per day (Euro)
Bus	500,000	137
Boarding Stairs	32,000	9
NB Tow Truck	200,000	55
WB Tow Truck	500,000	137

Table B.5: Overview of the capital cost of the implemented equipment

Equipment	Fuel/Electricity Cost	Maintenance Cost	Personnel Cost
Bus	0.32 Euro/km (Electricity)	0.40 Euro/km	5 Euro/operation
NB Tow Truck	44 Euro/operation (Fuel) [1]	8 Euro/operation [2]	9 Euro/operation [3]
WB Tow Truck	65.5 Euro/operation (Fuel) [1]	13 Euro/operation [2]	9 Euro/operation [3]

Table B.6: Overview of the operational cost of the equipment implemented in the model (NB: Narrow-body, WB: Wide-body)

[1] Based on: a daily cost of 655 euro for fuel (6,152,726 MJ/year [43], an energy content of 36 MJ/liter for diesel [47], an average price of 1.40 euro/liter for diesel [47]) which is translated back to a cost per operation based on an assumption of the average movements per day for narrow-body trucks (15 movements) and wide-body trucks (10 movements).

[2] Based on: an average maintenance cost of 25 euro/hour [43] and an assumption of 5 hours for the in use time of the tow trucks. This is translated back to a cost per movement upon an assumption of the average movements per day as for the fuel

[3] Based on: an assumption of the average gross salary of personnel (50,000 euro per year)

Appendix C. Decision Maker Dashboards

Figure C.22: Single Case Dashboard

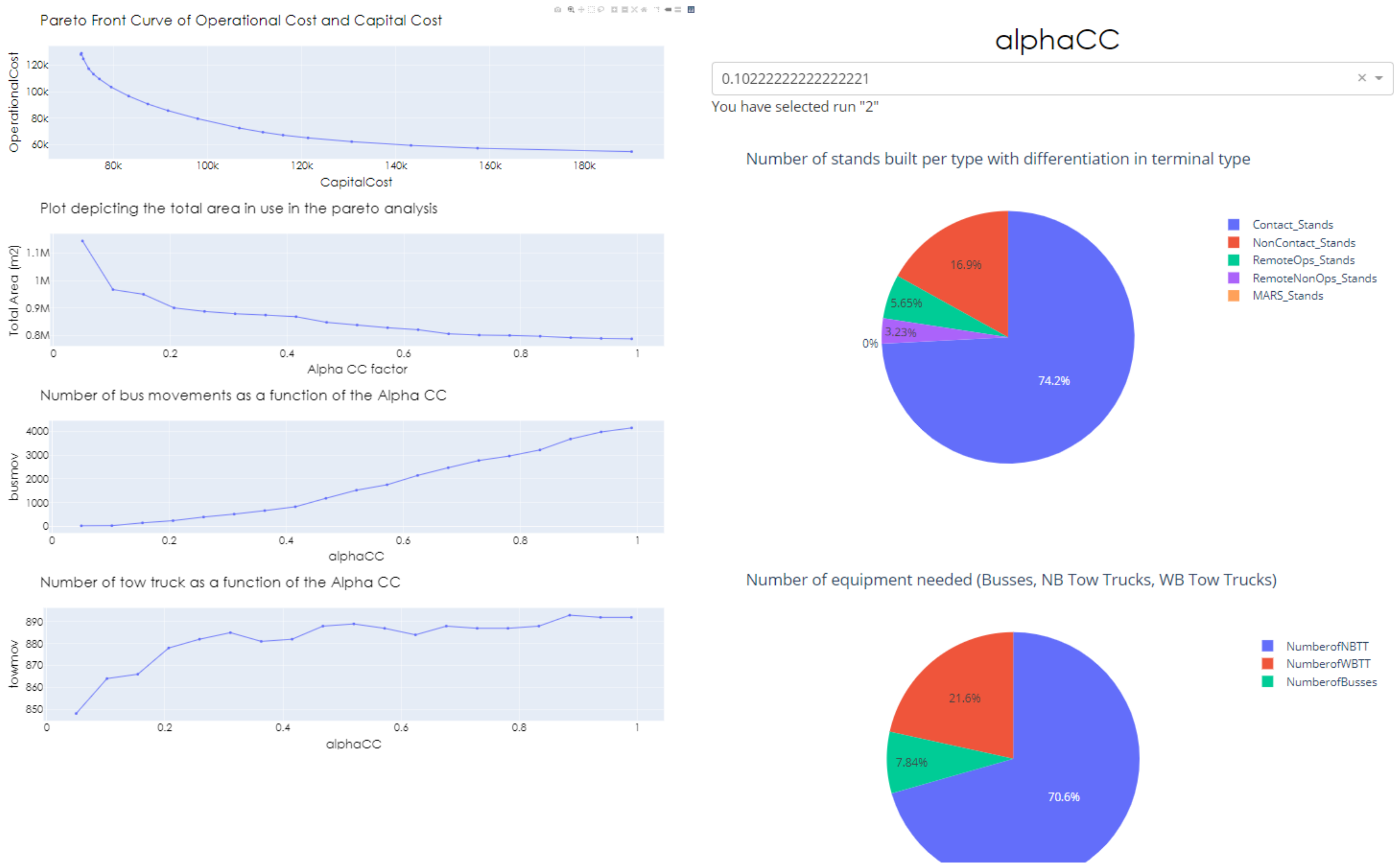

Figure C.23: Dashboard to analyse multiple cases

II

Literature Study (previously graded under AE4020)

1
Literature Study Introduction

Airport design and planning is an iterative process in which significant investments are to be considered. One of the key objectives in airport design and planning is the minimisation of the land used while still anticipating for additional needed capacity in the future. Assessing the implication of different scenario choices on the needed stand capacity in a strategic time frame will help airport planners determine the required land area with more precision. It will result in in-depth insights regarding the factors defining the needed capacity. Furthermore, it allows decision-makers to obtain results based on their own choices regarding stand types, operational factors and the area used.

The following chapters describes the results of a literature study regarding airport stand capacity assessment within a strategic time frame. This literature study is performed as part of an MSc. graduation project at the Delft University of Technology. The objective is to analyse the research field and to find a gap within the literature. This encompasses applying mathematical modelling to solving gate and stand assignment problems, the underlying objectives and consideration of the strategic time frame. Although the focus is on the analysis of stand types, factors of influence, assessment policies and optimisation frameworks, the report also contains a review of the literature regarding airport planning & design and forecasting to assure the broader context in which airport stand capacity fits, is also understood. It has to be noted that forecasting stand demand is out of scope.

The literature study has been performed in two phases. First, a general search is performed to get acquainted with the different concepts related to stand capacity assessment and stand allocation. Three high-level concepts have been defined from the first phase: airport design and planning, stand capacity assessment and modelling & optimisation techniques. These concepts formed the foundation of the second phase. In this phase, the literature regarding these topics has been investigated and analysed. Based on the performed literature study, the following research objective is defined:

> "To define recommendations to improve current practices of Airport Stand Capacity Assessment within a strategic time frame, by developing a mathematical optimisation model which allows a trade-off between optimising for stand types, operational factors and area limitations".

.

The report starts with an introduction into airport planning and design in Chapter 2, in which the different development phases are described along with the characteristics of airport master planning. Chapter 3 contains the review of stand capacity assessment within airport designs. It encompasses subjects as forecasting, the apron system and different stand types. Following this, the factors of influence, analytical assessment policies and performance indicators are described in Chapter 4. Furthermore, Chapter 5 contains a literature review of the modelling and optimisation frameworks for stand capacity assessment. Based on the performed literature study, the research scope and objective are defined. The literature study is concluded with a conclusion in Chapter 6.

2
An Introduction to Airport Planning & Design

The objective of the following chapter is to establish a profound introduction regarding airport planning and design. This will act as the basis for the remainder of the literature study. It starts with a description of the phases in airport development in Section 2.1, followed by a description of conventional master planning and adaptive planning in Sections 2.2 and 2.3, respectively. The chapter is ended with a conclusion in Section 2.4.

2.1. Airport Development Phases

The design and planning of airports is a very complex and time-consuming process without a single solution. Stakeholders involved in the decision-making process of airport planning make use of different guidelines stipulated by aviation organisations such as the International Civil Aviation Organisation (ICAO), the International Air Transport Association (IATA) and the Federal Aviation Administration (FAA). Before diving into the specifics of master planning, the different phases of airport planning are described.

Figure 2.1 depicts the different airport development phases from top to down. Every airport planning process starts with an analysis of the current situation. This can be a situation where there is no traffic yet (a new to be build airport) or the case in which an existing infrastructure needs to be expanded.

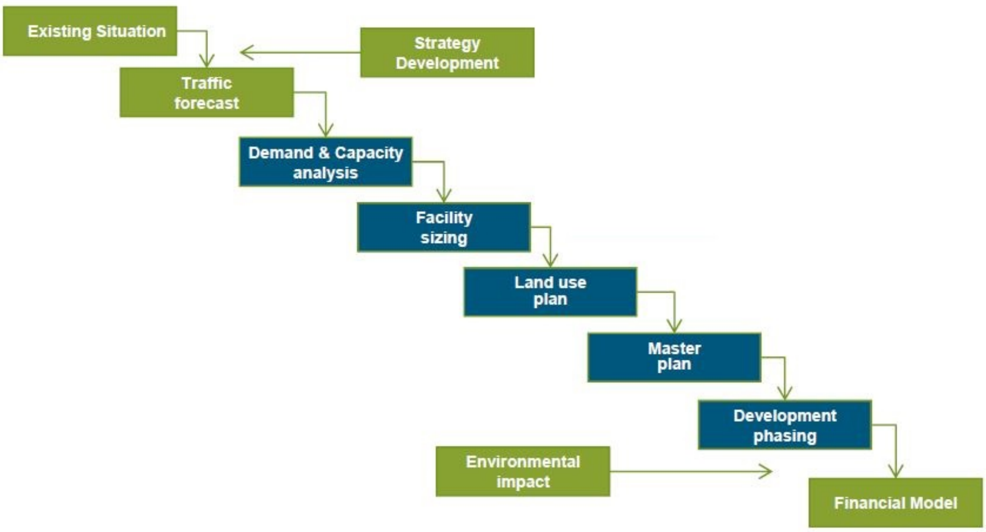

Figure 2.1: Airport Development Phases [68]

The definition of a clear vision through strategy development is crucial for the next phase: traffic forecasting. Traffic forecasting is conducted by analysing both market demand, and airline capacity [40]. Multiple factors should be taken into account, such as the airline industry, national and international economies and socioeconomic conditions within the airport catchment area [40].

Before the facilities can be sized, a thorough analysis of the current infrastructure needs to be performed using the forecasts of the earlier phase [68]. The required capacity needs to be assessed concerning the fulfilment of the demand. Once a decision is made on how to assess the demand and the strategy to fulfil the demand (peak demand, design day etc.), the facilities can be sized. Facility sizing consists of the airside and landside infrastructure. However, if the development concerns a new airport, the new airport sites must first be selected and evaluated. This evaluation can be based on operational capability (weather, airspace), the capacity potential (the available land), ground access (to assess the location of the airport concerning the anticipated catchment area for demand), development costs, and environmental impact [38].

From the facility sizing phase, a land-use plan can be created. A land-use plan is a high-level plan of the allocation of the airport facilities and airside infrastructure [68] and determines the land acquisition. A land-use plan should be flexible, find the most efficient placement of the airport's most important functional areas, and be cost-effective.

The main functional areas which should be taken into account in the land use plan are airside infrastructure, the passenger terminal, air cargo facilities, aircraft maintenance facilities, military facilities (if applicable), support facilities, and landside access [68]. By developing multiple options and through evaluation, the best option can be selected.

Now that a high-level overview of the needed land and the position of different facilities is known, the master plan can be created. This is the objective of the next phase. The master plan defines the aforementioned functional areas in the land use plan to the level of individual elements of infrastructure. A master plan should encompass the planners' vision of the ultimate development potential of the airport. Furthermore, a master plan should entail how the capacity may proceed over both short term (0-5 years) and long term (6-10 years) [40]. The time horizon of a master plan is not preset. However, generally, a time horizon of 20 years is used [31].

The next phase in airport planning consists of the development phasing. This is to define the different stages needed to obtain the defined objectives in the master plan. It is vital to integrate the master plan objectives with daily airport operations to facilitate traffic growth [40]. Assessing the environmental impact of the defined development plan is of key importance to ensure acceptance of the master plan. In the assessment procedure, both the environmental effects of the defined developments and possible mitigation procedures should be defined [40].

The final phase in airport development consists of financial analysis. Although considering the financial side of investments is an important factor throughout all development phases discussed before, proving that the development's financial side is in line with the defined strategy at the start of the first development phase will ensure acceptance of the master plan. Conventionally, the breakdown of costs for the defined master plan is more detailed for the first years of the plan than for the periods after that [40]. It is much more difficult to predict traffic growth, movements, passengers/cargo movements and inflation for long periods.

The steps mentioned above cover the most widely applied phases in the aviation industry by airport associations and consulting firms [68] [40]. Once the development process has been finished, the airport stakeholders' aim shifts towards commercialisation and optimisation [40]. To ensure the literature study to be specific and condensed, these phases will not be discussed because they are out of scope for the research topic as described in the introduction to the literature study.

2.2. Conventional Master Planning

As described in Section 2.1, an airport master plan encompasses the airport planners' ultimate vision of the development of the airport [43]. A master plan can be developed for both new and existing airports. As described by de Neufville [15] a master plan should involve the following three factors: ultimate vision (a view of the long term future of the airport), development (i.e. physical facilities on the airside and landside such as runways and terminal buildings) and consider a specific airport (not the regional or national aviation system).

For the master planning process different international and national guidelines are to be used from e.g.: ICAO [45] [43], EASA (CS-ADR-DSN) [26], FAA (for the United States) [31] and IATA [40]. In conventional master planning, it is assumed that the planners only consider a single forecast. Multiple factors influence future traffic, and thus no single scenario can be developed. Furthermore, by considering only a single forecast, future growth potential risks are neglected, which is a big flaw in conventional master planning.

Therefore, airport planners and other stakeholders aim for good strategic thinking and flexibility in the master planning process to ensure that the developed plans assess a wide range of scenarios and possibilities and thus are robust for different future changes [15]. This objective can be realised by creating flexible and adaptable designs.
Airport Master Plans are developed by application of a linear process as described by de Neufville [15]:

- Analysis of existing conditions.

- Forecast creation of future demand.
- Identification of facility requirements.
- Development and evaluation of alternatives to fulfil the defined demand.
- Choice of an alternative and further translation into a master plan.

A schematic overview of a flowchart to prepare an airport master plan is defined by Horonjeff [38] and is depicted in Figure 2.2.

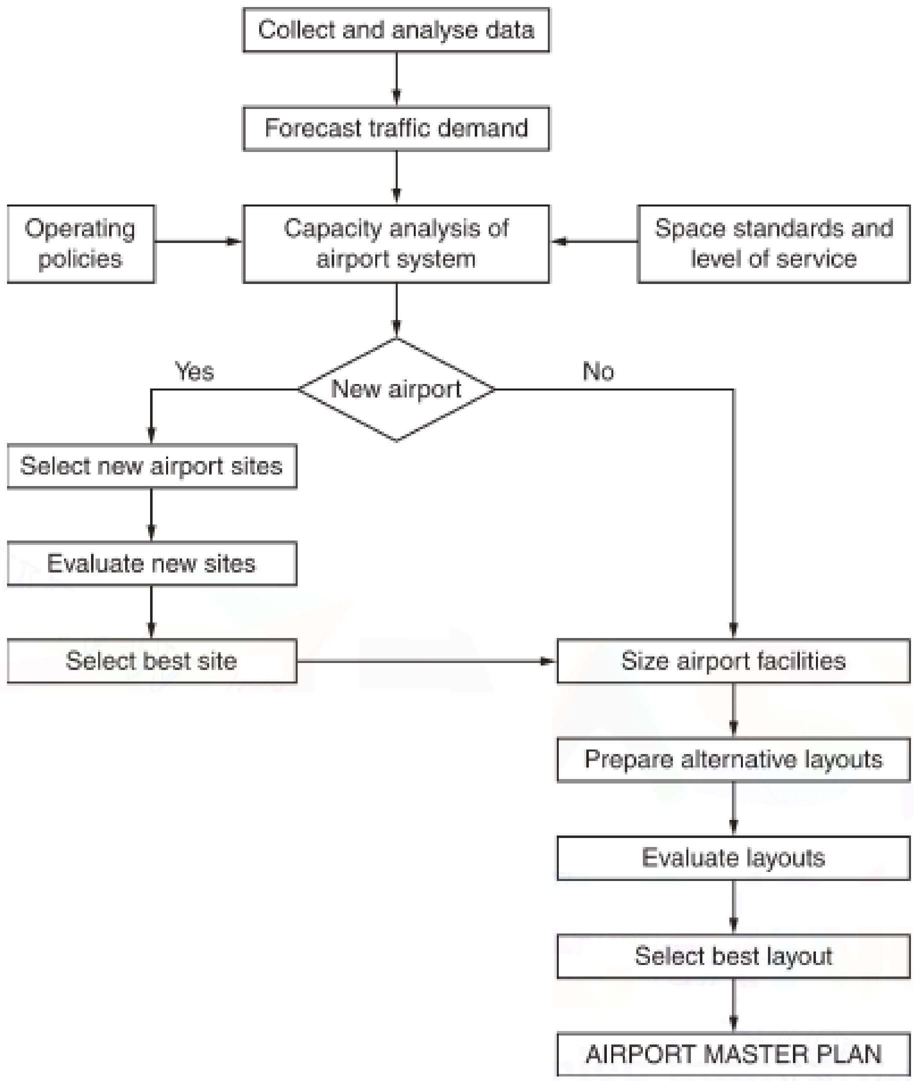

Figure 2.2: Flowchart of steps to be followed to obtain an airport master plan [38]

The drawbacks of conventional master planning became painfully evident in the development of Amsterdam Airport Schiphol. A plan developed in 1995 for the airport became obsolete only four years after the first development due to the unanticipated rapid growth of the aviation demand [55]. This plan was initially developed to cover a period of 20 years. Another example is the development of Denver Airport. The developed master plan for this research ended up not representing the actual traffic at the airport. The airport ended up with fewer air transport movements than anticipated for [17].

2.3. Adaptive Strategic Airport Planning

As described in Section 2.2 it is not convenient for airport planners to use single forecasts in the development process. Predictions always differ from reality and serve as a basis to build upon future developments. However, they inevitably add risk to the process. For example, no one could predict the corona crisis and its impact on the aviation industry (also affecting multiple airport master plans). To capture the dynamics of the future demand and allow for mitigation strategies, dynamic strategic planning can be applied [15].

The core objective of dynamic planning is flexibility. Assessing multiple forecasts makes it easier for the decision-maker to assure that the developed plan is at least flexible to changes in the forecasts, which are inevitable. It directs decision-makers towards assessing the performance of the developed plan upon the different forecasts and the performance in different scenarios. The airport planner needs to consider the developed plans' effect, as the traffic load applied to a development plan can easily block future changes. For example, if an airport terminal is designed specifically for low-cost carriers, future changes to facilitate network carriers might not be possible.

Key in dynamic planning is identifying the starting position, which allows for an effective response to changing conditions. The objective is not necessarily to develop a plan that will always work out for any future scenario but rather an adaptable plan.

Different methodologies for dynamic/adaptive strategic planning can be distinguished in literature. Kwakkel et al. [55] assessed three of the different methods described in the literature: dynamic strategic planning, adaptive policy-making and flexible strategic planning.

Dynamic strategic planning (DSP) is based on forecasting a range of future traffic along with different scenarios and developing facility requirements along with various alternatives for the range of scenarios defined at the start. This should be followed by selecting the first-phase development, which enables appropriate responses to changes in the demand forecast [15].

Adaptive policymaking (APM) is defined as a generic approach to deal with uncertainties. It is based on the notion that a fixed policy is likely to fail and that a decision-maker learns more about reducing uncertainties over time. The process is divided into two phases, namely a thinking phase and an implementation phase. During the thinking phase, a basic form of the policy is defined and further analysed for the possible vulnerabilities. The most certain ones are taken into account by defining mitigation procedures in the basic policy. Furthermore, actions are prepared for uncertain exposures once these take place. The thinking phase is followed by the implementation phase, during which events are monitored and measures are taken if needed. If it turns out that the defined policy is not on track to achieve the intended objectives, a reassessment is necessary.

Burghouwt [12] defines flexible strategic planning (FSP) as an alternative for traditional airport master planning. In short, FSP builds upon DSP and adds pro-active planning and contingency planning to the process. FSP is based on the assessment of real options, contingency planning, monitoring, experimentation, and diversification [55]. However, FSP lacks a detailed explanation of the application in practice.

Although all the three methods differ in their descriptions, they all have the same objective of achieving master plans or decision-making, which is robust for unexpected future changes. They differ primarily in consideration of robustness, flexibility and planning process. Concerning the consideration of robustness, only DSP doesn't explicitly consider robustness in the process. Furthermore, ADP and FSP both explore a more extended consideration of the flexibility of the plan. They both consider flexibility by some kind of contingency planning by pre-specification of responses. Lastly, the three approaches can be distinguished based on their planning process. Only the FSP does not have a straightforward process specified.

Although different policies can be found in literature, their core objective is the same: establishing a continuing planning process to monitor the defined plan and the conditions to be able to adjust the plan based on the circumstances.

2.4. Conclusion

It can be concluded that airport development is a versatile process prone to different uncertainties about the future. Airport planners and designers try to follow predefined distinct phases to ensure well-defined plans. However, traditional master planning is prone to flaws due to considering single forecasts and developing strategies that are not robust enough for the dynamic world. Recent research in this field focuses on the development of dynamic master planning processes.

Although different policies regarding dynamic master planning can be found in literature, their core objective is the same: establishing a continuing planning process to monitor the defined plan and the conditions to adjust the plan based on the circumstances. Considering a hybrid combination of the different approaches will be the most beneficial for decision-makers.

3

Review on Stand Capacity Assessment within Airport Design

It is important to clearly understand the definitions of capacity to assess stand capacity to define strategic decisions. This encompasses how capacity can be measured and how the demand can be obtained using forecasting techniques. Although the thesis work will not be dedicated solely to forecasting demand, it helps to understand the broader context in which stand capacity assessment fits. Furthermore, before a framework can be defined, the different aircraft stands in airport development need to be investigated and their characteristics, pros and cons.

This chapter follows the aforementioned steps. It starts with an introduction into strategic planning and capacity evaluation in Section 3.1, followed by a description of forecasting techniques used within airport development in Section 3.2. After this, the context of stand capacity assessment within airport development is defined in Section 3.3. Following on this, a description of the apron system and the different aircraft stands is given in Sections 3.4 and 3.5, respectively. The chapter ends with a conclusion in Section 3.6.

3.1. Introduction into Strategic Planning and Capacity evaluation

As described in the introduction to this report, this research's context lies within the field of stand capacity assessment in strategic airport design. As a starting point, first, the term "strategic" will be outlined, followed by a description of capacity within aviation.

3.1.1. Strategic Planning

To start with, it is vital to understand the meaning of "strategic" in the context of airport planning. In general, strategic planning constitutes the steps followed by any organisation in which its future is defined through a plan to get the organisation from its current state to its objective vision [78].

Strategic airport planning relates to the long-term future developments of an airport. The applicable period can differ from 3-5 years up to 20 years [78]. A general overview of the strategic planning framework and the different objectives is depicted in Figure 3.1. A master plan (as described in Chapter 2) is a result of the strategic development phase and is generally accompanied by a communications and monitoring plan [78]. The communications plan aims to serve as a means to inform the involved stakeholders and receive feedback from them. It contains the details on how the communication and interaction between the stakeholders should take place. On the other hand, the monitoring plan contains a description on the evaluation policy of the defined strategic plan.

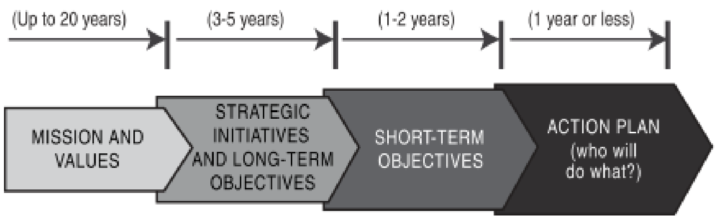

Figure 3.1: Strategic planning framework [78]

3.1.2. Capacity within Airport Development

Capacity is defined by Janic (2013) as: "the maximum number of units of demand, which can be accommodated during a given period of time under given constraints" [49]. The International Air Transport Association (IATA) defines capacity as: "the quantitative measure for the supply of service of a processing facility to accommodate sustained demand over a specified period of time, under given service conditions" [40]. These descriptions are similar and boil down to defining capacity as a system's capability of fulfilling the demand presented to it.

The capacity of a system can be assessed using different measurements. IATA defines the following measurements for capacity [40]: dynamic, static, sustained, maximum and declared capacity. Dynamic capacity relates to the maximum processing of demand through a system per unit of time. On the other hand, static capacity is defined by the maximum demand that a facility can withstand at any moment in time depending on the chosen level of service [39]. The sustained capacity is represented by the demand, which can be sustained by the system per time unit without negatively impacting the service's objective level.

The measurements explained in the above paragraph serve as a means to define and assess the capacity of the different airport systems. Within the airside infrastructure, this can relate to runways, taxiways, aprons and stands. For the landside infrastructure, a capacity assessment relates to the processing (passenger and baggage transactions), holding (waiting areas), and circulation facilities (movement between subsystems) [40].

Demand and capacity imbalance is a clear reason stressing out the importance of capacity assessment in airport planning and balancing demand and capacity. An imbalance between the two factors will lead to delays. The objective in strategy planning is not necessarily to avoid any delays, as a trade-off needs to be made between many factors such as the costs of delays and the costs of capacity addition.

3.1.3. Stand Capacity Measurements

In strategic stand capacity assessment, the objective is to determine the number of stands (differentiated by type), which satisfies the requirements defined in the airport stakeholders' vision. If the measurements for capacity as described in Subsection 3.1.2 are projected onto stand capacity assessment, the following distinctions can be made.

First of all, the static stand capacity can be described as the available number of stands (in any form) per aircraft type [49]. This can also be seen as the maximum number of aircraft that can be parked simultaneously at the apron complex. Seen in a broader context, an apron complex's ultimate capacity should also incorporate the facility interface's ability to fulfil effective transfer of passengers, baggage and freight between the aircraft and the airport terminal [49]. However, this literature study will not elaborate upon this, as this part of the assessment is out of the research scope.

The other form by which the stand capacity can be defined is the dynamic stand capacity. The dynamic capacity can be seen as the maximum number of aircraft that can be facilitated during a particular time at the apron complex [49]. This capacity is influenced by the number of stands (the static capacity), the aircraft mix, and the demand distribution in time by aircraft category. Furthermore, the flight type is also a critical factor. The flight type relates to the origin and destination of a flight. The following flight types can be distinguished: domestic, international, originating, terminating, and transit.

3.2. Forecasting

For any airport development process, airport planners have to rely on traffic forecasts to define their policies. As it is impossible to predict the future perfectly, the objective of forecasts is to provide airport development stakeholders information concerning traffic scenarios, which can be used to evaluate uncertainties about the future [42]. for stand capacity assessment, airport planners have to rely on forecasts as input data for their assessment methods. The following section describes a brief background on forecasting for airport developments, followed by an explanation of the forecast data used for stand capacity assessment.

It is chosen to limit the description in the following subsections to a description of the idea behind forecasts, a brief overview of the techniques, and how forecasting fits within stand capacity. This to assure that the literature study remains in line with the overall research objective as introduced in the introduction to this report. Developing traffic forecasts is not part of this objective. However, one can argue that a brief discussion aids the researcher in having a broader context and understanding possible relations between the research objective results and processes at the base of capacity assessment, such as forecasting.

3.2.1. Forecasting within Airport Development

Two levels of forecasting can be distinguished in general, aggregate forecasting and disaggregate forecasting. Aggregate forecasts consider the region's total aviation activity (country, metropolitan area) of the considered airport.

Variables related to aggregate forecasts are the number of enplaned passengers, total revenue passenger-kilometres, and aircraft operations. Disaggregate forecasts assess the aviation activity at a specific airport. Some of the variables considered in disaggregate forecasts are the number of enplaned passengers, air traffic movements, passenger origin-destination traffic characteristics and the number of origins and destinations. [38]

The International Air Transport Association defines in the airport development reference manual different forecasts for the various development phases [40].

The scale and timing of facility development or expansion are based on annual traffic forecasts embedded in the Airport Master Plan. Furthermore, estimates of peak hour passenger movements are appropriate for the sizing of the different subsystems such as check-in counters, baggage reclaim areas and immigration desks. Lastly, the airside capacity and runway requirements should be based on the forecasting of air traffic movements. However, since forecasts are generally "wrong" [15], forecasts should be based on appropriate techniques, be supported by information in the defined study and should justify defined development policies.

As described earlier, each subsystem or part of the airport development process should rely on its appropriate forecasting method. So what are these forecasting methods? Different forecasting techniques can be distinguished, each with its specifics. The International Civil Aviation Organisation (ICAO) divides forecasting methodologies into quantitative and qualitative methods in their Manual on Air Traffic Forecasting [41]. It is chosen to use this description of the forecasting methodologies for the remainder of this subsection. The overview presented by ICAO is much more extensive and follows a clear division between the different methods.

Figure 3.2 schematically depicts the main forecasting techniques as described by ICAO.

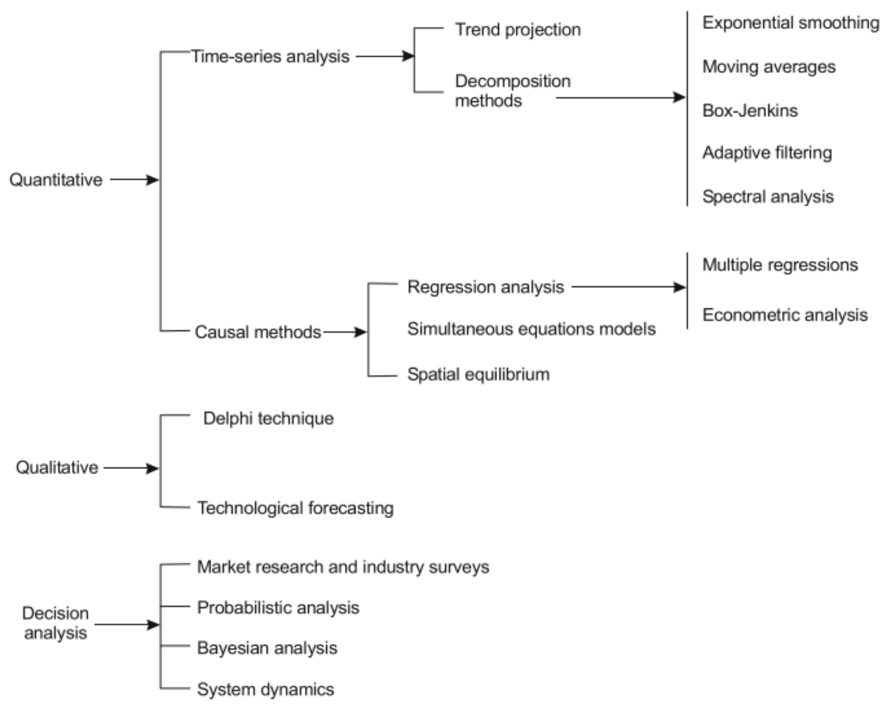

Figure 3.2: Overview of forecasting methods [41]

Quantitative forecasting methods can be subdivided into time-series analysis and causal methods. Time-series analysis relies on historical data and assumes historical patterns to continue. Trend projection is a form of time-series analysis. The available historical data is studied, from which a trend is determined. The main assumption in this is that the factors which have driven past developments will continue to drive future traffic. Therefore, these forecasting techniques heavily rely on stability in past developments. The result of trend projection is a graph with the dependent variable (e.g. traffic) on the vertical axis and the independent variable (e.g. time) on the x-axis. The obtained graph can be characterised by a trend curve, which can be represented by different mathematical relations, such as linear, exponential, parabolic and Gompertz. [41]

An other type of time-series analysis methods is the decomposition methods. These methods break the forecasting problem down into multiple components. In case of strong seasonality in the historical data or other repeating patterns, these methods can identify the following aspects of the data pattern: the trend factor, the seasonality factor and the cyclical factor if applicable [41]. The characteristics and the specifics of the different methods will not be elaborated upon in this literature study, as the main objective of this part is understanding the objective of forecasting and obtaining an idea of the methods. The goal is not to understand the specifics of all the different forecasting methods to conduct forecasts. For further information regarding these methods, the reader is referred to the ICAO Manual on Air Traffic Forecasting [41].

As described earlier, the second type of quantitative forecasting methods is the causal methods. Causal methods are based on the incorporation of causal relations which affect the forecast variables. These causal relations can relate to economic, operational and social conditions. The idea behind causal methods is assessing the significance of the dependent variable's mathematical relationship to the independent variables upon changes in these variables [41]. One of the most widely used causal methods in the forecasting of aviation demand is regression analysis. The core objective of regression analysis is to consider other variables defined as having a causal relation to the historical values. Simultaneous equations models are another type of quantitative forecasting methods. These methods involve more than a single equation. The name of this methods is derived from the fact that these models' variables simultaneously satisfy all the defined equations. The main advantage of simultaneous equations models is that the model itself contains the variables which explain the obtained results. The last causal method, as described by ICAO, is spatial equilibrium models. These models' core objective is to establish a relationship describing the movement of traffic between two centres or regions. These techniques are mainly used to determine air traffic distributions between certain regions and are based on the proportionality of a region's traffic to its size and inverse proportionality to the region's distance. [41]

If historical data or a profound understanding of the underlying patterns is lacking, qualitative forecasting methods are applied. These methods are mainly based on expert judgement. The Delphi technique is a qualitative forecasting method based on the combination of the different prospects of the future. It uses the judgement of experts to determine the most probable course of development. Technological forecasting is another qualitative forecasting method. Technology forecasting can be executed by assessing future conditions based on the current knowledge of a specific variable. Another way of technological forecasting is to determine needed developments based on the assessment of future goals and objectives. [41]

As described earlier in this subsection, there are many different forecasting methods to be distinguished. Quantitative methods rely on the availability of historical data and data on the underlying influencing variables, while qualitative methods are based on the qualitative judgement of developments based on, e.g. expert judgements. As the research's objective doesn't incorporate the forecasting of variables, it is still decided to add a small background to the different techniques to assure that the broader context of airport development and the possible input of stand capacity assessment (which can be a forecast) is understood.

3.2.2. Forecasting for Stand Capacity Assessment

After a brief introduction regarding the general forecasting methods used in aviation forecasting, the following subsection will describe how forecasting is used within stand capacity assessment.

The air traffic demand needs to be known to assess the required stand capacity of an airport. The specifics of this demand can differ per assessment method/framework used. The stand demand can be determined from forecasts of high-level airport systems, such as the runway system. This can result in obtaining the aircraft fleet mix, and the peak demand on the apron [80]. The peak demand can be the hourly peak demand [38], which indicates the number of aircraft to be parked simultaneously. This can be translated to the needed apron facility requirements. By also incorporating the aircraft mix into this, the stand mix can be determined. Using the peak demand, the aircraft mix, and turn around times is also the current policy used within airport consultancy firms [68].

ICAO defines two methodologies for predicting the peak hour passenger aircraft movements in their Airport Planning Manual [42]. Figure 3.3 depicts these two methodologies schematically. The main difference between the two methodologies is the use of annual forecast data in method A and an aircraft peak day ratio to end up at the movements on a day level, from which a peak hour passenger aircraft movement by aircraft type is obtained. Method B relies on a forecast of the peak hour passenger volume, from which the peak hour passenger aircraft movements are determined using a peak hour average load factor and a forecast of the aircraft mix. ICAO also acknowledges the difficulty of forecasting a future aircraft mix. This difficulty can be tackled by analysis of trends in the world regarding aircraft mix and consultation of the airlines that will make use of the airport.

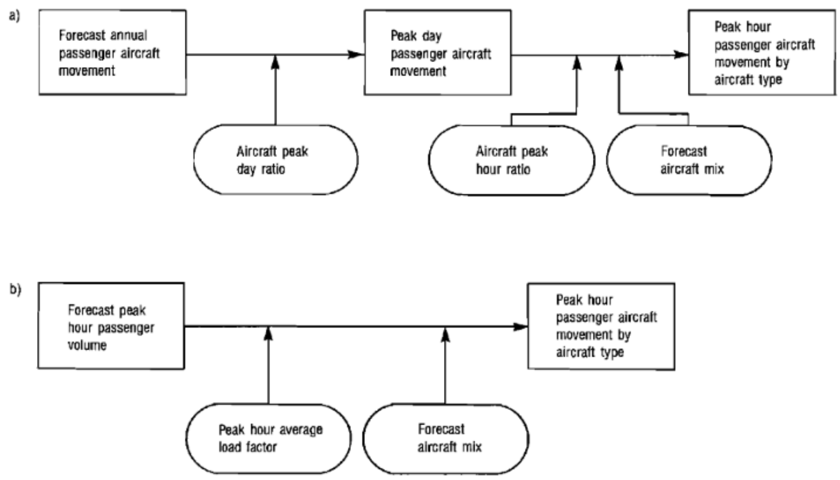

Figure 3.3: Peak hour passenger aircraft movements forecasting methodologies [41]

The necessity for peak period forecasts in use for determination of demand lies within the objective of the to be designed facilities. The developed facilities' design level should assure that they aren't underutilised or overused [40].

In case of the need for extensive assessments of demand for the sizing of facilities (both passenger and aircraft handling facilities), design day flight schedules (DDFS) can be developed for a design day [40]. These flight schedules contain detailed information regarding the scheduled flights, flight types, aircraft types, seating, origins and destinations, and arrival/departure times. This level of detail is beneficial to estimate the volumes of passengers throughout the terminal (for terminal design) and the volume of aircraft. The latter is mainly useful for stand capacity assessment as it contains all the necessary data needed to determine the needed capacity with a level of detail, enabling the airport planner/designer to assess multiple scenarios.

3.3. Stand Capacity Within Airport Development

Now that an introduction has been given concerning airport capacity and forecasting, the following section will identify where stand capacity assessment fits within the broader context of airport development.

One of the main objectives in airport development is the minimisation of the land used while still enabling the fulfilment of forecast demand and leaving room for any future expansions [49]. This stresses out the importance of proper demand and capacity determination for any of the airport systems. Mirkovic [62] and Janic [49] identify the runway system as the primary airport capacity constraint. The development of the runway system is a large project in terms of the involved investment costs and the determination of the airport operational capacity (the number of aircraft movements/operations which can be facilitated per hour). Although the runway characteristics (size and number) are driving the capacity of an airport, being able to assess the implication of the area used for the stands will aid the airport planners in determining the needed land area with more precision, as the stand mix (number and size) also determines the apron size as well as the terminal configuration [42].

In strategic stand capacity assessment, the objective is to determine the number of stands (differentiated by type), i.e. the stand-mix, which satisfies the expected air traffic demand [62] [3]. Figure 3.4 depicts where stand capacity assessment fits within airport development phases as described in Chapter 2. The stand capacity is assessed as part of the apron complex capacity. The definition of the apron complex will be elaborated upon later in this chapter. As described earlier in this chapter, the stand capacity is based on the expected air traffic demand.

The stand demand is primarily related to the type of user. These users are airlines, cargo carriers, general aviation, and helicopters [80]. Each airline flies its fleet mix, routes (domestic, international or mixed) and has its own service needs (requirements of aircraft and passenger handling). Based on forecasting techniques, as described in Section 3.2.2, the air traffic demand is determined. This can be a peak demand of air traffic movements [68] or a design day flight schedule. From this demand, the capacity needed is assessed, from which the land area required can be determined. This is an iterative process in which multiple solutions exist, all affecting the related airport systems.

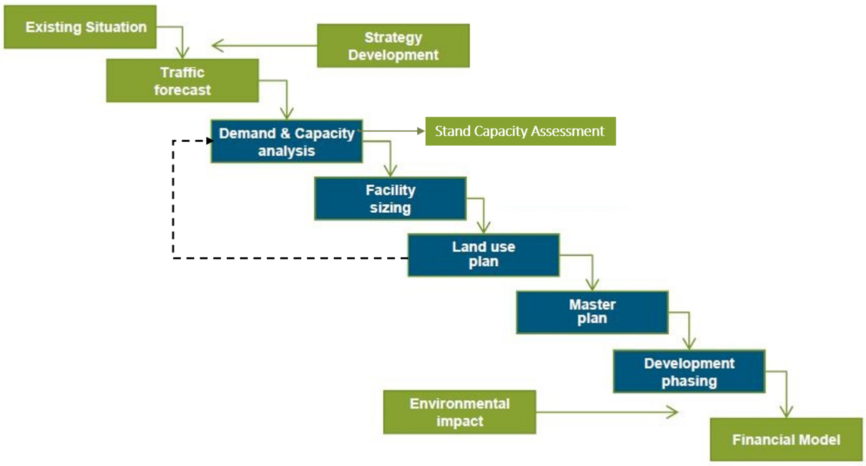

Figure 3.4: Strategic planning framework [68]

3.4. The Apron System

The airport system comprises different subsystems. These subsystems are in literature generally grouped into two components, namely airside and landside. Figure 3.5 depicts the different airport systems categorised by these two groups schematically.

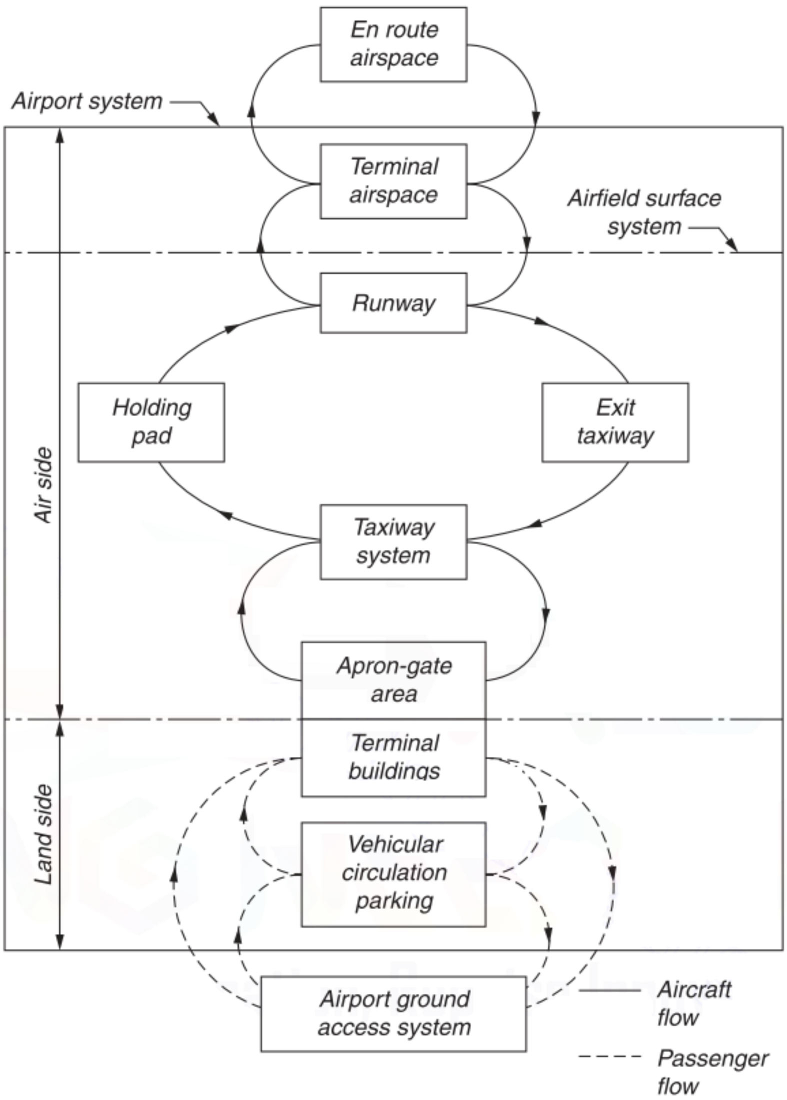

Figure 3.5: Overview of airport systems [38]

Aircraft stands are part of a more extensive system, called the apron system. The apron is defined as: "a defined area intended to accommodate aircraft for purposes of loading and unloading passengers, mail or cargo, fuelling and parking or maintenance " [44]. The apron system consists of the aircraft stands/gates (for parking aircraft, passenger embarking/disembarking and maintenance of aircraft), holding pads, de-icing pads and the taxiway system [62] [80].

3.5. Aircraft Stands

As described in Section 3.4, aircraft stands are part of the apron system. The following section will dive into the characteristics of airport stands and their designs, starting with a discussion on the different ways an aircraft can be parked, followed by a description of the methods of aircraft handling, and concluding with an elaboration concerning how the sizes of aircraft stands are determined or influenced.

Figure 3.6 depicts the general layout of an aircraft stand and its elements. It contains the physical area for parking of the aircraft, dedicated spaces for servicing equipment and the passenger loading bridges to enplane and deplane the passengers. The thick red line below the aircraft's tail defines the border between the aircraft stand and the apron taxi area.

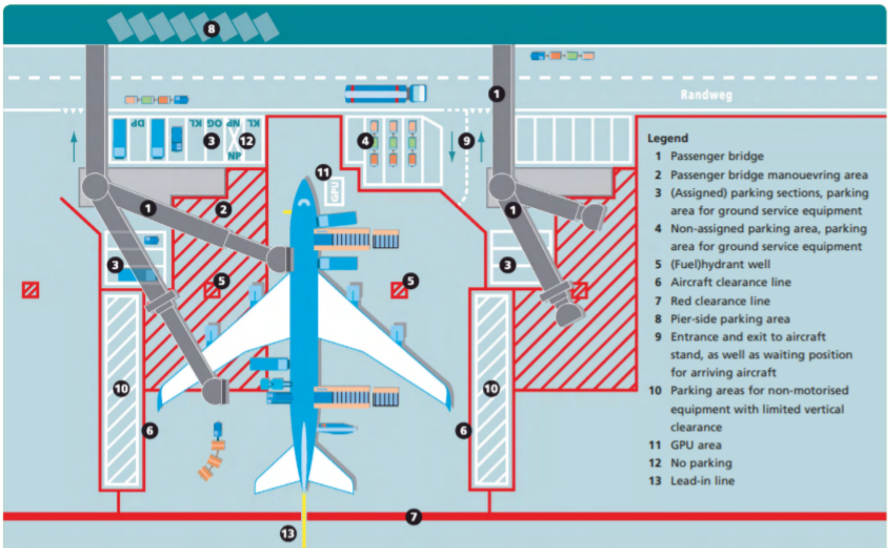

Figure 3.6: Overview of a general airport stand and its elements [71])

3.5.1. Parking an Aircraft

Aircraft can enter and leave stands in different ways. The manoeuvres can be performed either using the power of the aircraft or with the help of towing vehicles. These procedures are largely determined by the terminal design. Four different methods of aircraft parking can be distinguished in literature.

The first method is called angled nose-in parking, as depicted in Figure 3.7. In this apron design, the aircraft is parked at an angle with respect to the terminal building. The aircraft enters and leaves the stand using its power. Figure 3.8 depicts the angled nose-out method. The obvious difference between this method and the angled nose-in is the opposite placement of the aircraft nose.

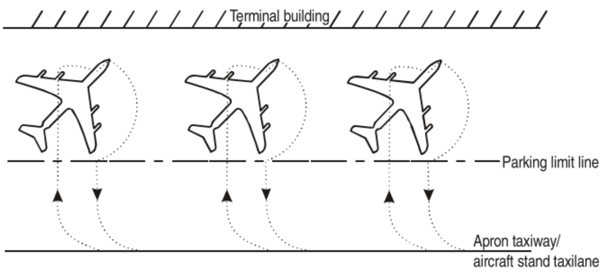

Figure 3.7: Angled nose-in parking [44]

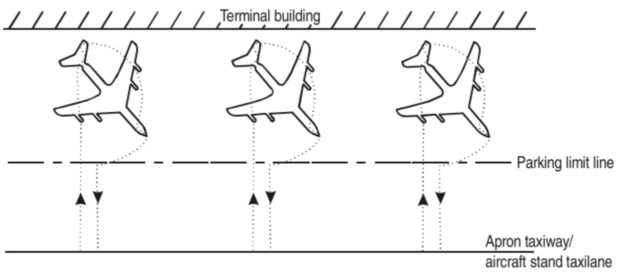

Figure 3.8: Angled nose-out parking [44]

Figures 3.9 and 3.10 depict the parallel parking and the taxi-in/push-out parking methods, respectively. In the parallel parking method, also the aircraft's power is used. However, in this method, the aircraft is parked parallel with respect to the terminal building. The taxi-in/push-out method is the most conventional parking method applied in the world's busiest airports [44], in which the aircraft is parked perpendicular to the terminal building. In this method, the aircraft's power is used during the taxi-in and is assisted by a towing vehicle during the taxi-out. The parallel parking method is the easiest method concerning the manoeuvres needed to taxi-in and out of the stand. However, this method also implies the largest stand area needed out of the four methods described. The angled nose-in and nose-out methods are second regarding the stand area needed, while the taxi-in/push-out method needs the least area [44].

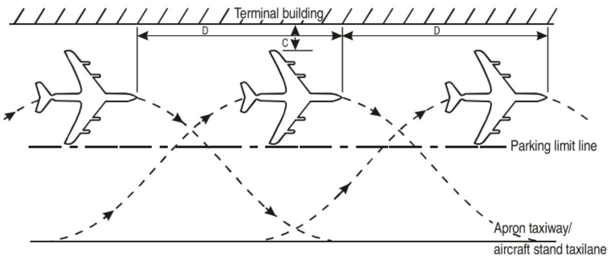

Figure 3.9: Parallel parking [44]

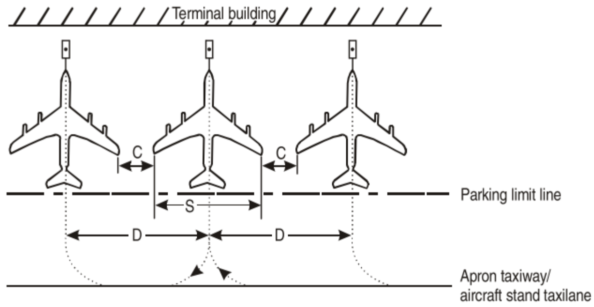

Figure 3.10: Taxi-in, push-out parking [44]

Terminal Design
The apron design (including the positioning of stands) is related to the terminal layout applied in the airfield design, which is again related to the parking methods used. Different layouts can be used in the design of a terminal. The most simple layout is the simple concept. This concept is characterised by a simplistic layout in which the aircraft is parked angled nose-in or nose-out to ease the operations. This concept is most widely applied at low traffic airports [44]. A representation of this concept is depicted in Figure 3.11.

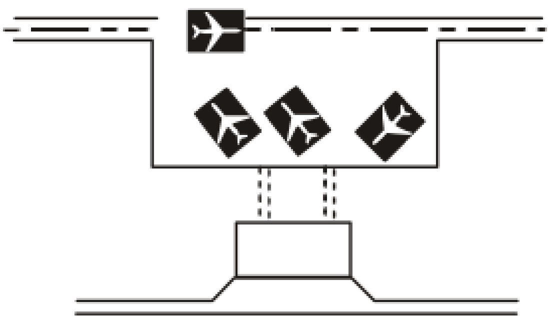

Figure 3.11: Representation of the simple concept in terminal design [44]

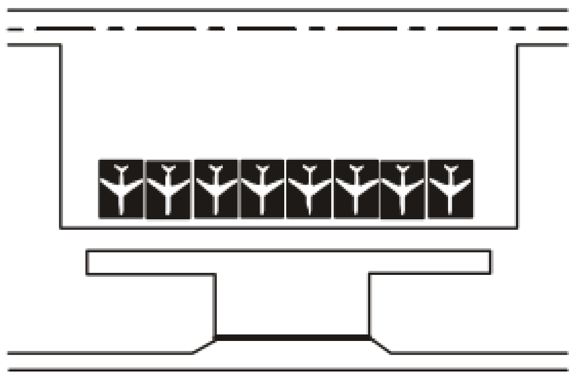

Figure 3.12: Representation of the linear concept in terminal design [44]

The linear concept may be seen as an extended form of the simple concept. It is characterised by a linear positioning of the aircraft with respect to the terminal. Furthermore, the aircraft can be parked parallel or using the taxi-in/push-out method. A representation of this concept is depicted in Figure 3.12. Figure 3.13 depicts the pier concept. This layout consists of several linear concepts joined together, resulting in a pier design. The pier design allows for aircraft parking on both sides of the concourse [44]. The aircraft can be parked in several ways, either taxi-in/push-out, parallel or angled. This is based on the terminal design.

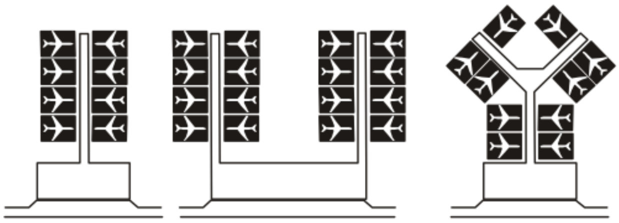

Figure 3.13: Representation of the pier concept in terminal design [44]

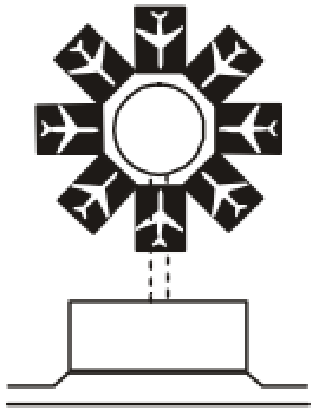

Figure 3.14: Representation of the satellite concept in terminal design [44]

Another possible terminal design is the transporter concept, as depicted in Figure 3.15. This concept is also known as a remote apron or open apron concept. The apron (and thus the aircraft stands) is located remotely from the terminal building, making it necessary to exploit any form of transportation of the passengers, luggage, and cargo. This concept's benefit is to be found within the close location of stands to the runway, leading to short taxiing times. The final design is the hybrid concept. As the name would suggest, this concept might contain elements of other concepts resulting in a hybrid design.

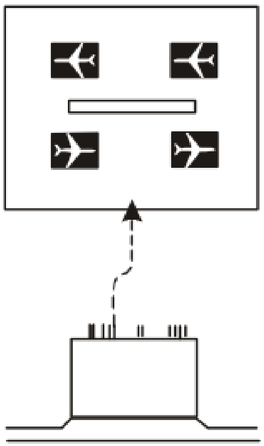

Figure 3.15: Representation of the transporter concept in terminal design [44]

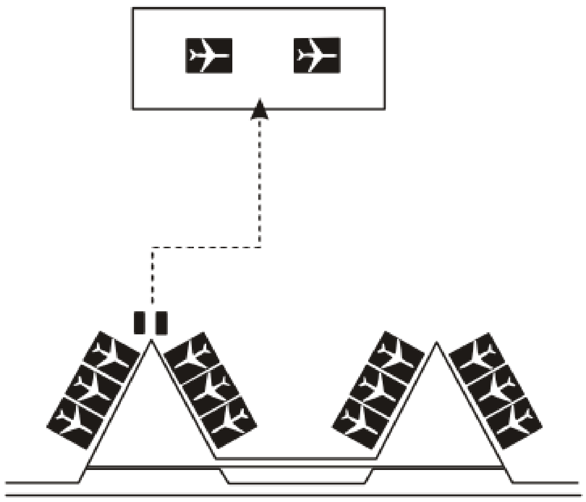

Figure 3.16: Representation of the hybrid concept in terminal design [44]

3.5.2. Methods of Aircraft Handling

Different types of aircraft stands can be distinguished based on the parking method of the aircraft and the methods used for handling of the aircraft and passengers. The following section will dive into the difference of aircraft stands based on their handling of flights.

Contact Stands

An aircraft can be handled at so-called contact stands. These stands connect the terminal building and the aircraft seamlessly, which can be accessed directly from the terminal without the need for passenger bussing [40]. The availability of fixed servicing equipment characterises these stands and the availability of a passenger loading bridge (PLB) [80]. The PLB is a corridor connecting the terminal and aircraft door to enable enplaning and deplaning of passengers. Two different types of PLBs can be distinguished from literature: stationary loading bridges and apron drive loading bridges [80] [44]. A stationary loading bridge is characterised by a fixed link from the terminal concourse to a pedestal on the stand. The bridge has very limited manoeuvrability and supports minor variations between the terminal and the aircraft's main deck [44]. A schematic representation of a stationary PLB design is depicted in Figure 3.17.

On the other hand, apron drive loading bridges are manoeuvrable around the stand and can adapt to different aircraft types and even provide over the wing servicing. Figure 3.18 depicts the design and use of an apron drive loading bridge. The advantage of stationary loading bridges is the reduced area needed on the stand compared to apron drive loading bridges. However, this comes with a reduction in the usability of the bridge for different aircraft types.

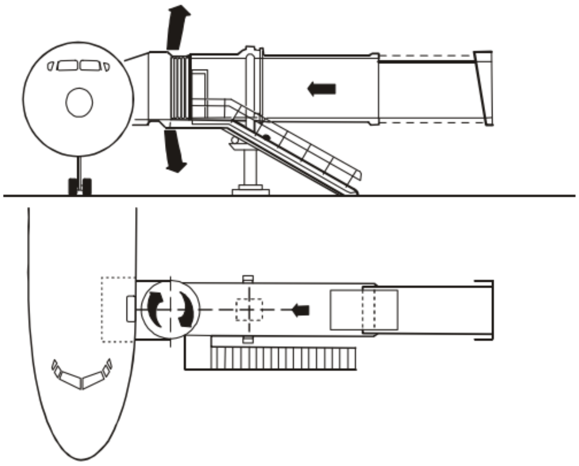

Figure 3.17: Schematic representation of a stationary passenger loading bridge [44]

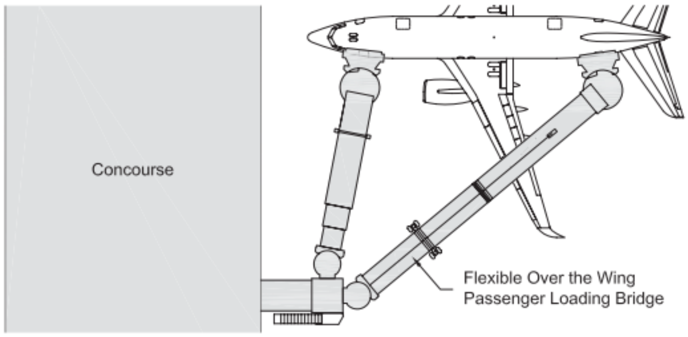

Figure 3.18: Schematic representation of an apron drive passenger loading bridge [80]

Non-Contact Stands
Non-contact stands are related to contact stands. Non-contact stands are also located close to the terminal building. The difference between contact and non-contact stands is the use of stairs, mobile stairs or aircraft stairs to enplane and deplane passengers [80]. Non-contact refers to the lack of a direct link between the terminal and the aircraft.

Non-contact stands offer a lower level of service and are mainly used by low-cost airlines seeking short turnarounds and a reduction in the service level provided to their passengers.

Remote Stands
Remote stands are located away from the terminal building and can require bus operations to transport the passengers to the aircraft. Remote stands are characterised by mobile servicing equipment, and the use of (mobile) staircases [44]. Furthermore, remote stands are used for overnight parking of aircraft, assuring no scarce contact positions are taken by aircraft with long layovers. The stands used for overnight parking are also called RON (Remain Overnight) stands [80].

Remote stands provide a lower service level to passengers due to transportation operations from the terminal to the remotely located aircraft stands. On the other hand, remote stands also have some benefits, such as the flexible use of the available area. Furthermore, remote stands can accommodate a broad range of aircraft with a relatively simple infrastructure, and they require lower investment costs than contact stands. However, remote stands do imply operational costs for the transportation of passengers. [79]

Swing Stands
Large airports experiencing flights with different origins and destinations require efficient handling of flights flying to other areas (with different customs and immigration regulations). Swing stands are a versatile solution to this problem. These stands can accommodate flights with different origins and destinations (domestic, international, Schengen, Non-Schengen). The flights all have other requirements regarding customs and immigration. Swing stands are equipped with a multi-level terminal design to facilitate these flights, which allows the separation of passenger flows on different levels through sterile corridors [80]. These stands are, in essence, contact or non-contact stands, with additional functionality. Figure 3.19 depicts an example of the use of swing stands at Melbourne International Airport. The use of swing stands results in the efficient use of the available land area and infrastructure and omits the need for flight-specific dedicated terminals and stands.

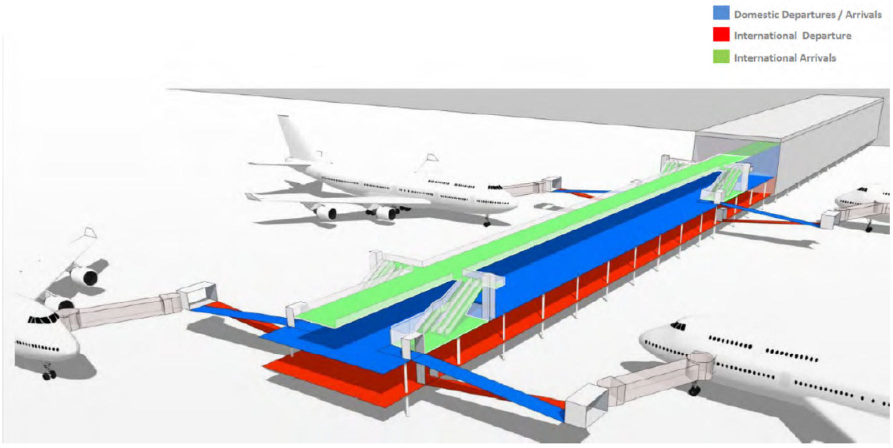

Figure 3.19: Example of swing stands at Melbourne International Airport [77])

MARS Stands
To assure efficient use of the infrastructure at busy airports, with different traffic waves across the day, so-called Multi-Aircraft Ramp System Stands (MARS) can be used. These stands can accommodate two narrow-body aircraft, or a single wide-body aircraft [40] within the same area footprint. This results in the flexible use of the airport infrastructure as well as flexibility in the planning. Furthermore, MARS stands increase the stand utilisation and reduce the infrastructure cost [40]. Figure A.1 depicts the design of a MARS stand.

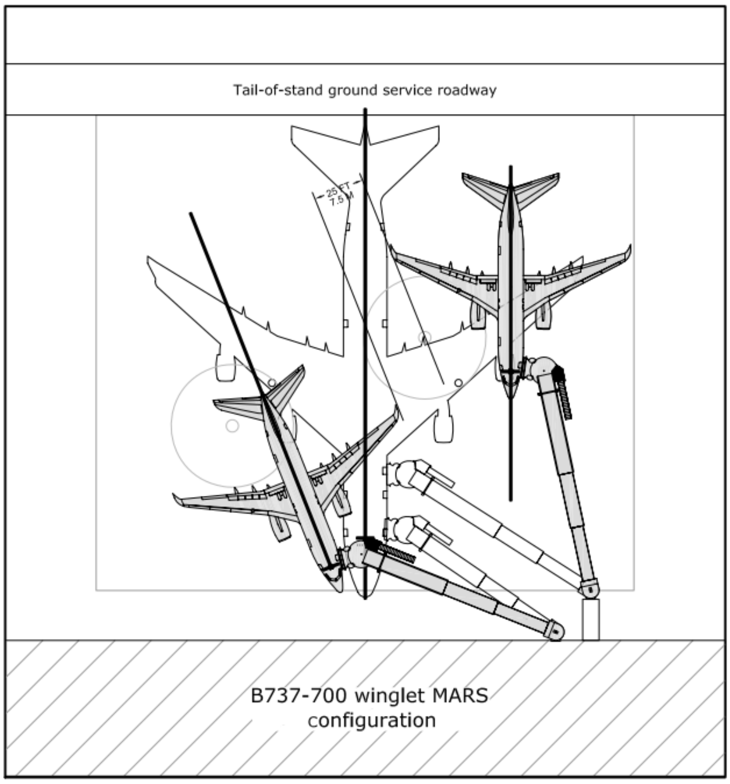

Figure 3.20: Design of a MARS stand [79]

3.5.3. Stand Sizes
The size of a stand is influenced by multiple factors, such as the dimensions of the aircraft to be accommodated, the type of stand (use of equipment such as a PLB influence the needed area), the aircraft parking method (based on the terminal layout) and separation requirements.

Aircraft Design Groups
ICAO has grouped aircraft in different Aircraft Design Groups (ADGs), based on aircraft wingspan. The ADG is used to determine the aerodrome reference code [45], which defines the type of aircraft an airport can accommodate. Table

A.1 depicts the different groups along with the wingspan requirements. Furthermore, the table also contains an example of aircraft for each of the defined groups. Group A consists of general aviation aircraft, which are generally handled at non-contact stands [80]. Group B consists of regional jets, while group C is defined by narrow-body aircraft. Groups D, E and F, consist mainly of wide-body aircraft. However, it has to be noted that the descriptions provided here are arbitrary, as there are some exceptions. An example of such an exception is the Boeing 757-200 with a wingspan of 38 meters [6]. This aircraft belongs to design group D based on its wingspan, while it is labelled as a narrow-body aircraft.

Aircraft Group	**Wingspan (meter)**	**Example Aircraft**
A	<15	Cessna 172, Cessna 525 Citation Jet, Piper PA-28 Cherokee
B	15 <24	Bombardier CRJ100/200/700, Embraer ERJ-135/140/145
C	24 <36	Airbus A318/A319/A320/A321, Boeing 737 (All Models), Bombardier CRJ705/900/1000, Embraer E-170/-190 (All Models), McDonnell Douglas, MD-80/-90 (All Models)
D	36 <52	Boeing 757 (All Models), Boeing 767 (All Models)
E	52 <65	Airbus A340 (All Models), Boeing 747-400, Boeing 777 (All Models), Boeing 787 (All Models)
F	65 <80	Airbus A380, Boeing 747-8

Table 3.1: Aircraft Design Groups as defined by ICAO [45] [80]

The Federal Aviation Administration (FAA) also defined a set of six aircraft design groups [30] similar to the groups as defined by ICAO. Since the criteria as defined by the FAA are almost equal to the definition of ICAO, these are omitted from the report.

Furthermore, the FAA defined guidelines for five gate types in terms of sizing and the required clearances. These guidelines are summarised in Table 3.2.

Gate Type	**FAA Design Group**	**Criteria**
A	III	Wingspan between 24 m and 36 m
B	IV	Wingspan between 36 m and 52 m AND fuselage length less than 49 m
C	IV	Same wingspan as for gate type B, fuselage length larger than 49 m
D	V	Wingspan between 52 m and 60 m
E	VI	Wingspan between 65 m and 80 m

Table 3.2: Guidelines for gate types as defined by FAA [2]

Aircraft Clearances and Separations

Sufficient separation between aircraft of adjacent stands is essential to avoid collisions between wingtips or other movable parts of the aircraft. Table 3.3 depicts the recommended wingtip clearances per aircraft design group as stipulated by ICAO. These clearances also influence the stand sizes. It can be clearly seen that the bigger an aircraft, the larger the recommended wingtip clearance.

ICAO Aircraft Code	**Clearance (meters)**
A	3.0
B	3.0
C	4.5
D	7.5
E	7.5
F	7.5

Table 3.3: Wing tip clearances of different aircraft design groups as recommended by ICAO [80]

The needed wingtip clearance is also affected by the airport planner/designer's vision concerning the design of access of the stands. Having a vehicle servicing road between stands requires additional separation between aircraft. The Transportation Research Board suggests an additional separation of 5 feet (1.5 meters) between the wingtip of a parked aircraft and the edge of vehicle road in case of vehicle road between stands [80].

3.6. Conclusion and Reflection

A clear understanding of the broader context of stand capacity assessment within airport development is the basis of this chapter. Stand capacity represents the quantitative supply of service to accommodate the service's demand, as defined by IATA [40]. Different measurements can be distinguished, such as static and dynamic capacity. However, the literature study did not elaborate on other measurements such as ultimate capacity and consideration of transfer of passengers and baggage between the aircraft and terminal. This is defined as out of scope.

The anticipated demand is needed to assess stand capacity. Different forecasting methods are used for this. Based on available forecasts of, e.g. the runway system and the fleet mix, the peak demand can be obtained. This can be used to obtain the hourly or peak hour demand for the stand capacity assessment process. However, forecasting of schedules is defined as out of scope for the research project. Furthermore, design day flight schedules can be used to determine the demand. The advantage of this is that not only peak hour characteristics are taken into account, but that the effective use of stands is taken into account over a day. Therefore, a design day flight schedule will be used in the research project.

Airport stands are part of the apron system, which is part of the airport system's airside part. Aircraft stands can be grouped into contact or remote stands. Contact stands offer a higher service level to passengers due to a short (fixed) connection between the terminal and aircraft through a passenger loading bridge. Furthermore, a distinction can be made regarding passenger servicing (swing stands) and aircraft servicing (MARS stands). Swing stands allow efficient use of airport infrastructure due to the ability to serve aircraft with multiple customs and immigrations requirements based on the origin and destination. This is done by a multi-level terminal. Furthermore, the use of MARS stands, which enable facilitating two narrow-body or a single wide-body aircraft simultaneously, also influences the effective use of infrastructure. Therefore, it is chosen for the thesis work to consider different stands (contact, remote, swing, and MARS stands) and their influence on the needed stand capacity in the framework.

4

Review on Stand Capacity Assessment Procedures

Before the literature is analysed regarding existing optimisation frameworks and models, it is chosen to take a step back and consider the different factors influencing stand capacity assessment in Section 4.1. Furthermore, some of the analytical assessment policies in literature will be touched upon along with the industry practices in Sections 4.2 and 4.3, respectively. Lastly, the performance indicators in stand capacity assessment will be reviewed along with a conclusion in Sections 4.4 and 4.5, respectively.

4.1. Factors of influence

It is essential to understand the influencing factors on stand capacity assessment before a proper theoretical framework can be established to contribute to the field. Therefore, the objective of the following section is to discuss these factors. To make sure that the description is structured to a certain extent, the different factors are grouped in the following three groups, which also define the different subsections of this section: Economical/Operational Factors are discussed in Section 4.1.1, Technical Factors in Section 4.1.2 and Safety Factors in Section 4.1.3.

4.1.1. Economical/Operational Factors

The users of an airport, i.e. airlines, operators, and ground handling agents, define the characteristics of the available airport infrastructure to a certain extent. The influence is represented by the user requirements regarding the level of service to be provided. The Level of Service an airport offers in the form of, e.g. contact stands, terminal layout (walking times of passengers), and other facilities is determined by the airline community making use of the specific airport [40]. The negotiated level of service between an airport and the airline community using the airport facilities is noted down in a so-called service level agreement between the two parties [39].

A distinction can be made regarding the agreements made between the airport users and the airport operator in exclusive, preferential and common-use agreements [80]. Exclusive use agreements refer to airlines having the sole right granted to operate a certain gate or stand. If other airlines are also allowed to use stands that are granted solely to an operator, this is referred to as preferential use agreements. In common-use agreements, there is no primary user of stands. This adds much more flexibility to the planning process for airport operators compared to the other two agreements. Preferential and common-use agreements are characterised by higher average utilisation due to the dynamic use of the stands by different airlines [80].

Even if an airport is equipped with stands defined under common use agreements, airlines might still prefer the type of stand, based on the level of service an airline aims to provide to its passengers. A low-cost airline with short turnaround times might prefer non-contact stands, due to the lower costs [73]. This airline preference can be a **constraining factor** in stand capacity assessment.

The stand demand is described by the flights arriving at and departing from an airport. The flight schedule operated at an airport defines the spatial time peaking of aircraft demand. The gate occupancy time or turnaround times also influence the needed stand capacity [68] and one of the factors determining the peak aircraft demand. The turnaround time (gate occupancy time), which can be extracted from the flight schedule, is a **factor of influence**, to be taken into account in stand capacity assessment.

The gate occupancy time is dependent on the aircraft type, the flight turnaround characteristics (is the flight originating, a turnaround or a through flight), the number of passengers on the flight and correspondingly the amount of baggage and cargo, and lastly, the efficiency and productivity of the servicing/handling operations (the planning, productivity of personnel) [2].

4.1.2. Technical Factors

A factor not described in subsection 4.1.1 is the aircraft mix making use of the airport infrastructure. This aircraft mix is deduced from the flight schedule operated by the different carriers. As described in Section 3.5.3 the aircraft sizes determine the needed stand area. Since not all stand sizes can accommodate all the different aircraft groups (e.g. stand type D can accommodate all aircraft up to aircraft design group D, while the opposite is not true), the aircraft mix is a **factor of influence**.

Consideration of the airport site is an important factor throughout the airport design and planning process. This also holds for stand capacity assessment. Site constraints might be in place regarding the physical area available for the infrastructure, ground flow operating configurations, critical surfaces, and environmental considerations [80]. If applicable, this should be considered a **constraining factor** in the stand capacity assessment.

4.1.3. Safety Factors

Assuring the safety and well-being of both passengers and aircraft is of key importance in the airport design process. As described in Section 3.5.3, to avoid collisions between aircraft on the apron area, *separation requirements* are defined as a recommended practice. These requirements have to be taken into account as **constraining factors** in the stand capacity assessment process.

Furthermore, national/international regulations impose requirements regarding the separation of passengers based on their origin and destination to assure flight safety. Passengers flying domestically have less strict customs and immigration requirements imposed on them during their travel, compared to, e.g. passengers flying internationally. Customs and immigration requirements might be translated into the separation of passenger flows by using different terminals (and thus dedicated stands per flight type) or by having mixed stands (swing stands) that can be used by specific O&D traffic. These are **constraining factors** which have to be taken into account by the airport planner and incorporated in the design.

Several options and policies can be distinguished to facilitate customs and immigration requirements: the first possibility is using dedicated terminals for domestic and international flights. In this case, the stands corresponding to the terminals are only to be used by the specific flight types, which can be accommodated in the respective terminal [62]. The second option is using mixed terminals and swing stands (as described in Section 3.5.3. These terminals allow for vertical separation between the different passenger flows (domestic and international). An example of an airport in which separation of passenger flows is achieved through vertical separation is Amsterdam Airport Schiphol. This airport has been reconstructed to facilitate these operations in a three-level pier design [2]. A schematic overview of such a pier design is depicted in Figure 4.1. In the case of mixed flights, i.e. aircraft with a mix of domestic and international rotations, these can only be handled at mixed terminals. The design choice influences the capacity assessment process in the form of additional constraints regarding the stand mix.

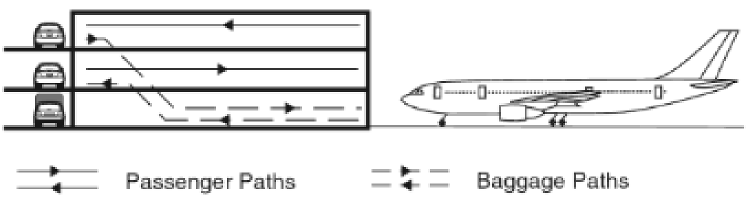

Figure 4.1: Schematic overview of a three-level pier design [2]

European airports have to deal with another factor regarding the separation of passenger flows. A free movement of passengers within all countries belonging to the Schengen area in the European Union is agreed upon, consisting of both EU and non-EU states [29]. Therefore, European airports have to deal with the separation of passengers travelling within the Schengen area and the passengers travelling from or/to the non-Schengen and intercontinental area [62].

4.2. Analytical Stand Capacity Assessment Policies

Different analytical methods to analyse or assess stand capacity are to be found in the literature. These methods are based on the high-level assessment of capacity based on the expected traffic demand and averages for the gate occupancy times and the traffic mix. The following section will describe two of the analytical methods found in the literature: the numerical capacity assessment methods as described by EUROCONTROL [28] and Ashford et al. [2].

EUROCONTROL Capacity Assessment

EUROCONTROL defines in their Airport Capacity Assessment Methodology Manual (ACAM Manual) [28] three steps of airside capacity assessment. These steps are related to the airport development phases. During the macro strategic time frame, structural airside capacity is assessed. At this point in time, the stand capacity is assessed at a macro level, not imposing constraints concerning aircraft stand compatibility. However, it must be noted that the described steps of capacity assessment assume an already existing airport. Incorporating these constraints in a strategic time frame for new airports will help the airport stakeholders determine the needed capacity with much more precision.

The second step, as described by EUROCONTROL [28] is the determination of the planned airside capacity. This should be calculated 18 months before the actual operations. This is in line with the strategic-tactical time frame in airport planning. During this assessment, the average turnaround time for aircraft should be incorporated as well as gate compatibility, overnight parking and towing operations.

As defined by EUROCONTROL in their ACAM Manual, the last step is the definition of operational capacity. This is the most detailed capacity assessment before the actual day of operation. During this assessment, detailed weather scenarios should be incorporated as well as ground handler constraints, landside capacity, the actual scheduled fleet mix and known overnight parking and towing operations [28].

Ashford et al. Analytical Assessment

Ashford et al. describe in the book "Airport Engineering" [2] two analytical methods to determine the stand capacity for the case in which each stand is available to all users and the case in which airlines have exclusive rights to use stands.

In both cases, the input data needed is the traffic mix divided over a set of aircraft classes and the average service time per aircraft class (which can also be classified as the turnaround time). Equation 4.1 depicts the formula to calculate the stand capacity in aircraft per hour.

$$C = Gc = G\frac{1}{\text{weighted service time}} \tag{4.1}$$

In which C is the stand capacity, G the number of available gates and c the inverse of the weighted gate occupancy time. The weighted service time is determined by multiplying the average stand occupancy time of an aircraft class by the percentage of aircraft belonging to the aircraft class.

In case of stands that are to be used exclusively by an airline, Ashford et al. defined Equation 4.2 to determine the stand/gate capacity of a system with exclusive use of stands by a specific aircraft group or class.

$$C = min_{\text{all i}}\left[\frac{G_i}{T_i M_i}\right] \tag{4.2}$$

In which C is again the stand capacity, G_i the number of stands that can accommodate aircraft of class i, T_i the mean gate occupancy time of aircraft of class i and M_i the fraction of aircraft class i demanding service. In this method, an additional input variable is needed compared to the all use case: the number of stands that can accommodate a certain aircraft class. Equation 4.2 can also be seen as the determination of the capacity per aircraft class i and then taking the minimum capacity as the system capacity. In the case of exclusive use, the system capacity is not just the sum of the capacities of the different subgroups.

This simplistic analytical method's clear drawback is that the number of stands has to be known beforehand, while it is desirable for strategic assessment of stand capacity to have the number of stands needed as the dependent variable. Furthermore, average gate occupancy times are used in the method as well as fractions of the different aircraft types expected, which might not always accurately represent the actual traffic.

Reflection and Conclusion

Also, other numerical stand capacity assessments are defined by other researchers and institutions. ICAO defined an assessment method based on a formula in which the needed stand capacity is based on a peak hour passenger forecast, the gate occupancy time per aircraft group and the number of arriving aircraft during the peak hour per aircraft group. Other analytical methods are amongst others defined by the following researchers: Janic (2001) [48], Newell and Edwards (1969) [27], Steuart (1974) [74], and Mirkovic [62].

The analytical methods described in this section are used for the first-order assessment of needed stand capacity. They have many drawbacks, such as considering average stand occupancy times and only considering peak hour demand (which does not consider stand utilisation over the day). Using a peak hour demand does not capture all demand characteristics and influencing factors such as the influences of runway capacity, as described by Mirkovic [62]. Furthermore, these methods do not consider the use of different stand types and do not optimise the stand-mix for cost and efficiency. Therefore, they are not considered in the remainder of the project.

4.3. Industry Methods

Decision-makers can use different industry tools within airport planning and design. These tools are either in-house developed or attained through partners (e.g. consultancy firms). The tools are capable of allocating aircraft to stands/gates based on specific objectives and constraining factors. An example of these tools is CAST Stand & Gate Allocation, developed by Airport Research Center [1].

These tools are suitable for allocations within a tactical or operational time frame, in which the airport infrastructure is already known. For stand capacity assessment within a strategic time frame, these industry programs are not suitable due to the need for optimisation trade-offs between different objectives. This is mainly because of multiple existing solutions for the problem.

4.4. Stand Capacity Assessment Performance Indicators

To assess, analyse and interpret any results obtained from a framework, it is important to define key performance indicators (KPIs), which can be assessed for different scenarios and changes in variables. The following section will describe some of the key performance indicators found in the literature regarding stand capacity assessment.

Operational Efficiency

Many factors are related to operational efficiency, such as infrastructure availability, design and safety. The different factors influence the traffic flows at the airport, which inherently influences how servicing and stand demand is met [80].

One of the KPIs related to operational efficiency is the utilisation rate of stands, representing the utilisation per stand over a specifically defined time frame. This can be the percentage of time during which the stand is used. Furthermore, another KPI is the number of aircraft handled (per stand type) over the defined time frame [37]. The maximum number of occupied stands per type (simultaneously) related to the total number of stands per type can also be used to determine the efficiency. The stand idle time also represents the operational efficiency. It depicts the time between two consecutive assignments of flights to a stand.

Flexibility and Robustness

The flexibility of an airport infrastructure determines its ability to react or cope with the dynamic airport world. Airline schedules are not static. The same applies to the aircraft fleets [80]. Having a flexible infrastructure is represented by the stand-mix's ability to fulfil changes in demand or allowing cross usage of stands. This can be assessed by analysing the change in the resulting stand mix by changing the aircraft fleet in the flight schedule (larger aircraft). This is represented by the allocation rate to a stand type (the percentage of the flights handled at each stand type) for different scenarios.

Robustness is related to the ability of the designed allocation schedule to cope with unexpected changes in the schedule. These changes can be delays in the scheduled arrival or departure times. A KPI related to robustness is the number of reassignments needed due to a change in the flight schedule, as described by Deken [16].

4.5. Conclusion

Understanding the factors influencing stand capacity assessment is of key importance in defining a framework to assess stand capacity assessment since these factors define the physical constraints and the factors which have to be taken into account. Different factors can be distinguished. These can be grouped into economic/operational factors, technical factors and safety factors.

Concerning economic/operational factors, airline level of service can be a constraining factor since it limits the assignment of stands to aircraft and also influences the resulting stand-mix. Furthermore, an influencing factor from an operational perspective is the turnaround time. However, this will be considered during the thesis as part of the robustness analysis. From a technical perspective, the aircraft mix as part of the flight schedule is another factor of influence. This will be considered as part of a sensitivity analysis, as the flight schedule is the input of the to be defined framework. Another important factor is the available land area, which will be considered one of the framework's key factors. Furthermore, physical safety factors are implied to assure the safety of passengers and aircraft. These factors range from separation requirements between aircraft to factors regarding the use of specific stands based on the origin and destination of a flight.

Analytical methods for stand capacity assessment are found in literature, which provides a high-level estimate. These methods will not be used in the definition of a framework due to their drawbacks. These methods are based on multiple assumptions regarding the gate occupancy time of aircraft (averages are used) and the expected aircraft mix. Furthermore, these methods are generally defined around peak hour demands. This does not allow the decision-maker to consider all demand characteristics (throughout the day).

Decision-makers within the aviation industry (e.g. airport planners) might use in-house developed optimisation frameworks for stand capacity assessment. These tools are not well-suitable for application within a strategic time frame since multiple assumptions have to be made regarding factors such as the expected traffic and turnaround times.

Performance indicators are needed to analyse any defined framework. It is decided to use performance indicators regarding operational efficiency and flexibility/robustness. An important indicator is stand utilisation as well as the idle time between consecutive assignments. However, these indicators will also follow once a framework is defined and developed.

5

Review on Modelling and Optimisation Frameworks

The following chapter will describe the literature review results regarding modelling and optimisation frameworks in the field of (strategic) stand capacity assessment. It starts with a description of the found frameworks in Section 5.1, followed by a description of the objectives used in frameworks in Section 5.2. Since in every optimisation model, certain constraints are needed, Section 5.3 will elaborate on this. Section 5.4 will dive into the resolution methodologies applied to solve stand capacity and allocation models, followed by a description of multi-objective optimisation in Section 5.5. The chapter is concluded with a conclusion in Section 5.6.

5.1. Optimisation Frameworks in Literature

Solving aircraft assignment to gates/stands is in the literature referred to as the Gate Allocation Problem (GAP) or the Stand Allocation Problem (SAP). Different frameworks using different formulations can be distinguished. As described by Dorndorf et al. [22], the research field can be divided into two main research streams. The first stream concerns mathematical programming techniques, while the second stream considers rule-based expert systems. The following section will describe the different frameworks found.

Static and Dynamic Models

Cheng et al. [13] classified the GAP/SAP into two types: static and dynamic models. Static models are characterised by time-independence. Dynamic models, on the other hand, are time-dependent and have internal memory. Dynamic models are further classified into stochastic and robust models. Stochastic models are based on probabilistic uncertainty (e.g. flight delays). Robust models are based on the assumption that the uncertainty is deterministic (e.g. known flight delays).

Mathematical Programming Techniques

The core objective of the SAP is the assignment of aircraft/flights to a stand while optimising for cost efficiency, passenger convenience and the operational efficiency of the airport operations [11]. Many methods are to be found regarding the modelling and optimisation of the problem. Bouras [11] performed an extensive literature review regarding the state-of-the-art in the field of GAP/SAP. The first paper regarding GAP dates back to 1974. In this paper, Steuart [74] proposed a stochastic model to assess the behaviour of flights relative to their schedule and proposed a method for estimating the number of required gates. Throughout the last decades, multiple solutions are proposed. The models' programming formulation depends on the objective variables (integer, binary, quadratic) and objective function (linear, non-linear).

The GAP is, in essence, a Quadratic Assignment Problem, which is an NP-hard problem as proven by Obata [67]. Lim et al. [58], Diepen et al. [18], formulated the problem as an Integer Linear Programming (ILP) model to minimise the passenger walking distance. The research of Lim et al. [58] showed that an ILP Solver (CPLEX) was outperformed in both running time and solution quality by heuristics.

A Binary Integer Programming (BIP) framework is used by Tang et al. [75] and Kumar and Bierlaire [69], Mangoubi and Mathaisel [60], Bihr [4], and Yan et al. [84]. These frameworks optimise either for the passenger walking distance or the cost of assigning an aircraft to a stand. Mixed Integer Linear Programming (MILP) models are defined among others in literature by Bolat [9] [7], Seker and Noyan [85], Neuman [66], Guepet [35], Deken [16], Kaslasi [52], and Boukema [10]. The objective functions of these MILP models are related to minimisation of the range of slack times (the time between the two successive assignment of flights to a stand), minimisation of the range of gate idle times, minimisation of buffer times, maximisation of aircraft assigned to contact stands and minimisation of towing movements.

Mixed-Integer Nonlinear Programming (MINP) models are defined by Li [57] and Bolat [9]. Li [57] defined a model in which the number of gate conflicts of any two adjacent aircraft assigned to the same stand is minimised. In the model of Bolat [9] the variance of gate idle times is minimised.

Other formulations found in literature defined the SAP as a clique partitioning problem (CPP), a stochastic model, a scheduling problem, and a network representation. For an extensive overview of these methods and the associated papers, the reader is referred to the overview as presented by Bouras [11] and Boukema [10].

Rule-Based Expert Systems
Rule-based expert systems are based on a set of predefined rules regarding decision making based on human expertise. These rules are ordered by importance and are used in optimisation decision making. An example of rule-based systems for the allocation of stands to flights is described by Hamzawi [37]. Advantages of these systems are that human expertise is taken into account in decision making, and the systems can continuously be improved [14]. The drawbacks of these systems as described by Cheng [14] are the inefficiency of the systems regarding running time (comparing the different rules is time consuming), the systems often only represent a selection of a domain, and these systems are not suited for solving numerical multi-objective optimisation problems efficiently.

Strategic Time Frame Optimisations
Not much of the investigated literature regarding SAP/GAP and stand capacity assignment considers the problem within a strategic time frame. Most of the research considers existing airport infrastructure. However, two research papers are investigated, which considered the stand capacity assessment problem within a strategic time frame.

Boukema [10] described the strategic stand allocation problem as a MILP model with the objective of minimising the capital cost and operational cost related to the use of certain stand types. Boukema defined a framework in which the stand capacity is determined for a design flight schedule, after which a stand allocation model is optimised to allocate the flights to individual stands. In this research, no explicit area limitations have been considered. However, the cost of a specific stand is based on its area, which is also minimised due to the minimisation formulation of the objective. Kaslasi [52] also defined a stand capacity assessment model using a MILP formulation in which both infrastructure cost and allocation costs are minimised. The objective of the framework of Kaslasi is to minimise the number of stands and their size. This is done by incorporating the stand sizes in the objective function.

Conclusion
Based on a literature review, it can be concluded that many frameworks can be used to model and solve the stand allocation problem. The programming formulation is mainly defined by the chosen objective functions. Only two studies considered the SAP within a strategic time frame (in which the capacity was not predetermined). Based on research performed by Bouras [11] it can be said that a formulation using a binary or an integer model formulation along with the application of a linear programming tool is preferred in terms of modelling complexity and running time [11] [10].

5.2. Optimisation Objectives

As described in Section 5.1 different objectives can be distinguished in the literature regarding the SAP/GAP. The following section will describe the different optimisation objectives.

Cost-Benefits

Cost is not considered often in definitions of the SAP and GAP. One of the cost factors used in the stand allocation problems in literature is capital cost and operational cost. Capital costs are associated with the needed investments (e.g. PLBs, area cost, building cost, pavement) to build the stands along with the related servicing equipment, the maintenance of the stands and depreciation costs [3] [80] [10]. On the other hand, operational costs are related to the costs induced by operating specific stands. The operational costs consist of passenger transportation costs, equipment transportation, costs for leasing busses, and the aircraft towing costs. One might argue why these operational costs have to be included in analysing the stand capacity process. The reason for this is simply that the overall cost and benefits of a specific stand decision are not only related to the needed capital cost. If only the capital cost were to be included, there would be no need, e.g. for contact stands (due to the higher cost compared to remote stands). However, remote stands induce additional operational costs, which contact stands do not induce.

The application of the cost as an objective is found in the research of Boukema [10]. Boukema [10] defined the capital and operational costs per stand type based on expert knowledge. The capital cost is determined to incorporate the cost for a passenger loading bridge, the area cost, the building costs per square meter, utilities, and depreciation cost. Furthermore, Boukema considered the depreciation costs of the investments over a time frame of 20 years for the stands. The useful life used by airport stakeholders for depreciation of aprons (stands) is 24-60 years [64] [70].

On the other hand, the operational cost is defined by Boukema to include the cost for busses, boarding stairs and depreciation cost. Since the trade-off between capital and operational cost is different for every airport and dependent on the stakeholders' vision, Boukema considered weighting factors in the objective to make sure that a trade-off can be made between the two costs based on the stakeholder interest.

Equations 5.1 and 5.2 depict the objective functions as defined by Boukema for the operational costs and capital costs, respectively.

$$MIN \quad \alpha \sum_{i \in O} \sum_{j \in S_i} c2_{ij} x_{ij} \qquad [10] \tag{5.1}$$

$$MIN \quad (1-\alpha) \sum_{j \in S_i} c1_j y_j \qquad [10] \tag{5.2}$$

In which α is the weight factor given to the operational cost in the objective function, $c2_{ij}$ being the operational cost of assigning operation i to stand type j, y_j the number of stands of a particular stand type j, and $c1_j$ the capital costs to build stand type j.

Kaslasi [52] adopted a cost objective based on the cost of a stand type, terminal complexity and the cost of allocating a flight to a stand type (based on the handling preference, terminal area preference and the size fit).

Efficient use of stands can be reached by planning long stay aircraft at multiple stands, of which an remote stand is used for intermediate parking to free capacity at operational stands. This policy is already incorporated by airports, such as Amsterdam Airport Schiphol, as described by Diepen and Hoogeveen [19]. This flight splitting is found in research performed amongst others by Boukema [10], Kaslasi [52] and Prem Kumar [69]. Based on a defined time interval, aircraft turnarounds are split into two or three segments (of which an intermediate parking phase).

Maintenance Cost
The maintenance cost of a stand depends on the infrastructure, the equipment (e.g. loading bridges), and the pavement (concrete or flexible pavement) [80]. The maintenance cost tends to increase with the lifetime of the infrastructure [80]. No research has been found in which the stand allocation problem incorporated the maintenance costs of a stand. Beudeker [3] did mention this in his research, however with lack of a proper definition on how to incorporate maintenance costs into the objective.

Robustness

As described in Subsection 3.1.1, the strategic time frame refers to multiple years before the actual day of operations. Therefore, considering operational delays is not possible (since the flight schedule is not flown yet). However, it is possible to assess the robustness of the obtained results by adding buffer times (to the scheduled arrival and departing time), simulating changes during the day of operations [22]. These buffer times will simulate the effect of delays on the capacity. Optimising a model for robustness is mainly performed for tactical and operational time frames.

Deken [16] proposed a robust scheduling methodology for the robust allocation of stands/gates to aircraft. Other research work in this field is performed amongst others by Bolat [8], Dorndorf et al. [22] and Kaller [51].

Prem Kumar [69] presented a mathematical framework in which robustness in a gate allocation problem is included using a so-called minimum gate rest. This gate rest represents the idle time between two successive assignments of aircraft to a gate. The objective of this addition is to be able to cope with delays in the flight schedule.

Land Area Minimisation

The area used is an important factor in airport design and planning. The core objective is to minimise the land area used for developments and take into account the needed area for future expansions [38] [49]. This objective is not found in almost any of the literature on stand capacity assessment and allocation frameworks. Boukema [10] and Kaslasi [52] considered the land use in their frameworks through the cost function in the objective function. The cost of assigning an aircraft to stands is based on the stand size in these studies. In the research of Boukema [10], the land area used is minimised by the cost objective (a larger and more complex stand also has a higher cost). The same principle is applied by Kaslasi [52], in which the number of stands and size are minimised. This is done by taking into account the size of stands in the objective function.

Level of Service

The level of service can also be the objective in stand capacity assessment instead of only a constraining factor. Most of the early developed frameworks on SAP and GAP use a form of modelling the level of service as an objective. Minimising the passenger walking distance is a widely used objective ([60], [84], [4], [83], [25]). Another used objective is the maximisation of the assignment of flights to their preferred stand ([25]) or the minimisation of the aircraft allocated to remote stands ([35], [33], [58], [69]).

Airport Operational Efficiency

Some of the models in the literature use objectives in which operational efficiency is considered. The objectives found are: the minimisation of the number of towing operations [25], [23], [24], minimisation of the number of stand conflicts between flights [20], maximisation of the idle times [18] [24] [23], and minimisation of the waiting time for a flight allocation to a stand [58].

5.3. Optimisation Constraints

Operational and physical restrictions are modelled through constraints in modelling frameworks. The following section will describe the different constraints found in the literature on stand capacity/allocation frameworks. It first starts with a description of the essential constraints in Section 5.3.1, followed by a description of user-specific constraints in Section 5.3.2.

5.3.1. Essential Constraints

Many of the earlier described optimisation frameworks apply constraints based on the objective of the model. However, there are some constraints that any developed model or mathematical formulation should obey. Drexl and Nikulin defined two necessary constraints: only a single aircraft can be assigned to a stand simultaneously, and every operation should be only assigned to a single stand [25]. Dorndorf et al. defined an additional constraint regarding space and service restrictions of adjacent stands [22].

Single Stand per Aircraft

The most obvious and most important constraint is the stand processing constraint. This constraint represents the physical constraint that only one stand can be assigned to handle/service an aircraft. This constraint is modelled in all the literature found using different variables. However, the idea behind this constraint is the same and boils down to the formulation as depicted in Equation 5.3. If x_{ij} is the binary variable expressing the assignment of operation i to stand type j with S_i the set of stands compatible for operation i, this constraint assures that the sum of all possible assignments to operation i is 1. This is equivalent to only assigning one of the compatible stand types to an aircraft.

$$\sum_{j \in S_i} x_{ij} = 1 \quad \forall i \in O \qquad [10] \tag{5.3}$$

One Aircraft per Stand

To assure no overlapping between the assignment of operations/aircraft to the same gate, a time variable has to be taken into account in the modelling of stand capacity assessment. If this is not constrained, multiple operations or aircraft might be allocated to the same stand. Different definitions of this constraint can be found in the literature regarding stand/gate allocation.

Within the literature on stand capacity/allocation assessment, two types of time modelling methodologies can be distinguished. In single-time slot models conflicting flights are defined, after which the model is constrained to only allocate a single flight from a set of conflicting flights [25] [22]. Multiple-time slot models consider the entire time frame of flights by defining a fixed number of time slots [22]. A drawback of multiple-time slots is the influence on stand utilisation and the fact that these models are less exact compared to the single-time slot models. Furthermore, due to the increase in decision variables in multiple-time slot models, the models' running time also increases rapidly. Research performed by Deken [16] revealed that the running time for a multiple-time slot model is double the time for a single-time slot model.

Stand Compatibility

As described in Section 3.5.3 stand sizes are defined based on the aircraft design group an aircraft falls into. Therefore, in stand capacity optimisation, not every stand type can be assigned to an aircraft. The compatibility of a stand with a specific aircraft operation needs to be taken into account in the model's definition. Deken [16] formulated a constraint that assures that the number of assigned stands for an aircraft is equal to 1 by checking a matrix containing binary information regarding a flights compatibility with a specific stand. Boukema defined a set of compatible stand types S_i for an operation, from which a stand is chosen in the optimisation framework.

Variable Stand Capacity
In the literature on stand/gate allocation, capacity is generally a fixed variable. Most of the literature solves the stand allocation problem in a tactical or operational time frame. Research performed by Boukema [10] and Kaslasi [52] defined stand capacity as a variable instead of a fixed number.

Boukema combined the variable stand capacity constraint with the earlier described "one aircraft per stand" constraint (which assures only a single operation is allocated to a stand simultaneously). Different strategies are found in the literature regarding the modelling of this constraint. The definition of this constraint should be carefully considered as it might influence the model's running time significantly [10] [16]. This possible significant influence is founded by the introduction of time. A check has to be performed, which assures that for every moment in time (second, minute etc.), there is no overlap in the allocation for every aircraft for every stand, which increases the number of variables depending on the definition.

An efficient formulation is defined by Boukema [10] based on the single-time slot formulation as described earlier in the description of the "one aircraft per stand" constraint. Conflicting sets of operations are defined for each unique arrival time. For each aircraft selected in a conflicting set, an additional stand must be added due to the constraint. The definition of this constraint assures that no aircraft are overlapping and that the stand capacity is variable, as depicted in Equation 5.4.

$$C(10, j, t): \quad \sum_{i \in O_t} x_{ij} \leq y_j \qquad \forall t \in T, \quad \forall j \in S_i \qquad [10] \tag{5.4}$$

Note: It might be desirable to fix the stand capacity (of all the stand types or a single stand type) to be able to assess the performance of a solution. In such a case, an additional constraint needs to be modelled, limiting the addition of stands of a specific type up to a defined capacity level.

5.3.2. User Specific Constraints

The second set of constraints found in the literature is specific to the defined model and objective defined by a researcher. A selection of these constraints will be elaborated upon below. The focus will be on the constraints which are important for strategic stand capacity assessment.

Flight Splitting
Flight splitting concerns long stay aircraft which are assigned to multiple stands (up to three) to ensure that the available infrastructure is not occupied by non-operational aircraft. Flights with a long turnaround time can be first assigned to a contact stand to allow the passengers to disembark, followed by an assignment to a remote stand, after which it can be assigned again to an operational stand for the next flight. In this way, the available capacity can be used more efficiently.

Boukema defined three types of flight splitting. The first type considers no flight splitting. In this case, a flight is handled at a single stand. In the second type, an aircraft is handled at two different stands with an arrival part and a departure part. Finally, the third type is the most extended type considered in the research of Boukema. It considers a three-split of a flight in an arrival phase, a parking phase and a departure phase. This three-split is beneficial for long-stay aircraft, as it assures that scarce and valuable contact stands are not blocked by non-operational flights opening up the capacity for other flights. Furthermore, it increases the flexibility of scheduling operations [10].

The mathematical formulation of the flight splitting as defined by Boukema is depicted in Equation 5.5. Boukema altered the set of operations O based on the turnaround time of a flight. Based on flight eligibility for a two or three-split, two or three operations are added to the set of operations. To assure that only a single version of a flight can be chosen, constraint 5.5 is defined. In which V_{1i}, V_{2i} and V_{3i} define the selection of the no-split, two-split or three-split version, respectively (binary variable). Based on the selected split version, additional constraints are formulated.

$$C(1, i): \quad V_{1i} + V_{2i} + V_{3i} = 1 \quad \forall i \in O \qquad [10] \tag{5.5}$$

Equation 5.6 defines the assignment of a single stand for a no-split flight from the set of compatible stands S_i. In the case of a two-split flight, Equation 5.7 defines the allocation of both the arrival and departure phase of the flight to a compatible stand. Variables $A_{2,i}$ and $D_{2,i}$ define the allocation of a stand to the arrival and departure phase of a two-split flight, respectively. Constraints 5.8 and 5.9 assure that only a single stand is assigned to the two phases.

$$C(2, i): \quad V_{1i} = \sum_{j \in S_i} x_{ij} \quad \forall i \in O \qquad [10] \tag{5.6}$$

$$C(3,i): \quad 2\dot{V}_{2i} = A_{2,i} + D_{2,i} \quad \forall i \in O_2 \qquad [10] \tag{5.7}$$

$$C(4,i): \quad A_{2,i} = \sum_{j \in S_i} x_{ij} \quad \forall i \in O_2 \qquad [10] \tag{5.8}$$

$$C(5,i): \quad D_{2,i} = \sum_{j \in S_i} x_{ij} \quad \forall i \in O_2 \qquad [10] \tag{5.9}$$

The same set of constraints are defined for a three-split version of a flight. Equation 5.10 defines that the arrival, parking and departure phase are all assigned to a stand. The Equations 5.11, 5.12 and 5.13 constrain the different phases to be assigned to exactly one stand.

$$C(6,i): \quad 3\dot{V}_{3i} = A_{3,i} + P_{3,i} + D_{3,i} \quad \forall i \in O_3 \qquad [10] \tag{5.10}$$

$$C(7,i): \quad A_{3i} = \sum_{j \in S_i} x_{ij} \quad \forall i \in O_3 \qquad [10] \tag{5.11}$$

$$C(8,i): \quad P_{3i} = \sum_{j \in S_i} x_{ij} \quad \forall i \in O_3 \qquad [10] \tag{5.12}$$

$$C(9,i): \quad D_{3i} = \sum_{j \in S_i} x_{ij} \quad \forall i \in O_3 \qquad [10] \tag{5.13}$$

Examining the constraints above, one might argue the need for so many constraints in the definition of an optimisation framework. In the research of Boukema, clear reasoning is provided for the choice of 9 constraints, namely a decrease in the running time of the model. Boukema describes a decrease by a factor 8 in the model's running time with the earlier described constraints compared to the use of a single more complex constraint [10]. An example of a single flight splitting constraint in literature is found in the research of Deken [16].

MARS Stand Constraints
As described in Section 3.5.3, MARS stands can accommodate a single wide-body aircraft or two narrow-body aircraft simultaneously. In the earlier defined constraints, the model is limited to only assigning a single aircraft operation to a stand, which is conflicting. To solve this conflict and model the allocation of aircraft to MARS stands correctly, Kaslasi defined additional constraints for MARS stands [52]. Two types of constraints can be distinguished for the modelling of MARS stands. The first type concerns the modelling of two narrow-body stands by assuring the number of narrow-body stands being twice the number of wide-body stands. The other type concerns the "blocking" of the narrow-body positions of a MARS stand in case of occupation by a wide-body aircraft.

Stand Sector Compatibility / Level of Service
Based on the origin and destination of a flight, certain customs and immigration requirements are imposed [62]. These requirements are translated into the separation of passenger flows through separate terminals or multi-level terminals [2]. The division can be made in domestic (e.g. Schengen), international (Non-Schengen) or swing stands (both domestic and international flights). This has to be constrained. The same applies to the user-specific level of service constraints, such as assigning certain flights to a specific type of stand.

Another user-specific constraint is sector compliance. In the case of airports in which a clear division has to be made between different sectors (domestic, international, Schengen, Non-Schengen), aircraft operations to certain stands have to be constrained.

5.4. Resolution Methods

Different resolution methods can be found in the literature on SAP/GAP. Resolution methods can be distinguished concerning the algorithmic method used to find a solution to the defined optimisation problem. Furthermore, a distinction can be made regarding the solver applied. The following section will describe the state-of-the-art concerning the methods and solvers used in stand capacity/allocation assessment.

5.4.1. Methods

The optimisation techniques applied in the stand capacity/allocation problem can be divided into three groups: exact algorithms, heuristics, and meta-heuristics. These methods will be described below.

Exact Algorithms
Exact algorithms yield an optimal solution [11] using different algorithms such as branch & bound, simplex, primal-dual and column generation. The branch and bound (B&B) algorithm is based on a search of the solution space by defining subproblems. Different solutions are explored. Instead of exploring all the possible solutions, the algorithm explores branches of a created tree (with the candidate solutions) that result in a better solution [10]. Another example is the branch and cut (B&C) algorithm. The B&C algorithm is based on the same principle as B&B. However, B&C adds a cutting-plane method, in which the feasible set of solutions is refined using cuts (linear inequalities) [51]. The drawback of the B&C algorithm is the inability to deal with symmetrical solution branches. However, the BC and BB algorithms can also use heuristics to, e.g. determine an upper bound [56] (therefore, they are sometimes classified as heuristics).

The core of column generation is considering variables and resources in an optimisation framework only if they influence the result positively. Therefore, certain "columns" (which might depict the choice for a certain resource) are not considered at all, reducing the running time significantly [18]. Mangoubi and Mathaisel [60] defined an ILP model for minimising the total passenger walking distance. The integrality was relaxed, and the relaxed model was solved using column generation. Bihr [4] used a primal-dual simplex algorithm to find an optimal solution and was successful in finding one. Yan and Huo [83], Bolat [7] [8], and Wang [81] applied branch and bound to solve their developed models.

Heuristic Algorithms
Obata [67] described in his research the gate allocation problem as a quadratic assignment problem, which is an NP-Hard problem. Therefore, different researchers have proposed different heuristic algorithms to solve the NP-Hard problem. Since it can be impossible to obtain an optimal solution in a reasonable time frame in some formulations, heuristics and meta-heuristics are applied [10]. Ding et al. [20] [21] used a greedy algorithm to solve the gate assignment problem with an objective of minimising the number of ungated flights. Lim [58] also used a greedy algorithm along with approaches with an "insert move algorithm" and an "interval exchange move algorithm". A drawback of heuristic algorithms is that they do not always provide an optimal solution due to reaching a local optimal solution and getting stuck [11].

Guépet et al. [35] analysed the difference between exact algorithms (applied using the commercial solver CPLEX) and the use of heuristic algorithms. The following algorithms were compared: decomposition methods, the ejection chain algorithm and the greedy algorithm. The performance of the different methods was assessed using real-case data of two major European airports. The results of this research showed that for a stand allocation formulation, the exact algorithms yield better results compared to using heuristics at the cost of a longer running time (dependent on the number of operations). The greedy algorithm outperformed all the other algorithms in terms of computational time. However, it also compromised the optimality of the solution the most. This can be explained based on the foundation of the greedy algorithm. It chooses the most optimal solution available at the current stage of the solution search by considering the local optimum rather than the global optimum, as described in Neuman [65].

Meta-Heuristic Algorithms
To capture the aforementioned drawback of heuristic algorithms, meta-heuristics have been developed. Meta-heuristics are often also labelled as modern heuristics. The difference between meta-heuristics and heuristics is the introduction of systematic rules in meta-heuristics which result in an ability of the algorithms to move out from local optima [11]. This is done by allowing solutions that result in a worse objective function result. Different meta-heuristic algorithms can be found in literature, such as the genetic algorithm (Gu and Chung [34], Bolat [9]) and tabu search (Lim et al. [58], Xu and Bailey [82]).

Xu and Bailey [82] analysed the performance difference between an exact algorithm (branch and bound) and a meta-heuristic (tabu search). They concluded that both approaches yield optimal solutions. However, the tabu search algorithm outperformed the branch and bound algorithm with respect to CPU time. Cheng et al. [13] have performed a study on the performance difference between several meta-heuristic algorithms. They analysed the genetic algorithm, tabu search, simulated annealing, and a hybrid form of simulated annealing and tabu search [11]. The tabu search algorithm outperformed simulated annealing and the genetic algorithm. However, the hybrid method was better than the tabu search algorithm concerning the solution quality.

Conclusion and Reflection
Different optimisation techniques can be distinguished from the literature on stand/gate capacity assessment and stand allocation frameworks. Exact algorithms are used to obtain optimal solutions, if possible, within a reasonable time frame. If due to the problem formulation it takes a lot of time to converge to a solution, heuristics and meta-heuristics can be applied. Heuristics tend to converge to local optima, which is avoided in meta-heuristics.

A detailed overview of the different techniques applied within this research field with many more research papers can be found in the research performed by Bouras [11]. Boukema added some other literature to the overview of Bouras from the years 2015-2017 [10]. It has to be noted that the conclusions of the different researchers regarding the performance of different optimisation techniques do not necessarily hold for alterations in the definition of the optimisation models (alterations in the objective function and constraints). The only thing which can be stated with certainty is that their conclusions hold for their specific defined optimisation frameworks.

Since not much research is done in the application of stand capacity assessment within a strategic frame, the research work of Boukema [10] and Kaslasi [52] is used as a basis to define the framework and justify the choices regarding the formulations and optimisation methods. The choice for a resolution method is based on their research and encompasses the use of exact algorithms to solve the strategic stand capacity assessment problem.

5.4.2. Solvers

A solver is needed to solve an optimisation model. A solver is a software type applying different optimisation principles such as branch and bound to solve defined problems. In the literature regarding the stand allocation problem, commercial solvers such as CPLEX and Gurobi are mainly used. Research has revealed that CPLEX is able to solve MILP formulations of the stand allocation/capacity problem within reasonable time ([58], [19], [35], [10], [52], [66], [69]).

A research study performed by Mittelmann [63] regarding benchmarks of optimisation solving software (simplex LP solvers) revealed that commercial software outperforms free versions. The following optimisation software was analysed in the benchmark of October 2018: CPLEX 12.8, Gurobi 8.1, Mosek 8.1, FICO Xpress 8.5, Coin-OR CLP 1.16.11, Google-GLOP, SOPLEX 4.0, LP Solve 5.5.2, GLPK 4.64, MATLAB R2018a, and SAS-OR 14.3. The results showed that Gurobi outperformed the other two commercial software, CPLEX and FICO Xpress. The best free optimisation tool in terms of running time was Coin-OR CLP 1.16.11, which CPLEX in the benchmark study slightly outperformed.

A similar study has been performed regarding the performance of the solvers for mixed-integer linear programming models [63]. These results show that the commercial tools Gurobi, CPLEX and FICO Xpress outperform the other free ones concerning running time.

Note: In 2019, the commercial companies FICO and CPLEX withdrew themselves from the benchmark results of Mittelmann, after which also the results of Gurobi have been omitted. Therefore, it has been decided to include the latest benchmark results in which the commercial solvers are taken into account in this literature study.

Conclusion

Based on the analysis of the benchmark results of Mittelmann [63], and the availability of a Gurobi license for students at the Delft University of Technology, it has been decided to use Gurobi as the optimisation tool in the course of the thesis work. The results of research performed by Diepen and Hoogeveen [18] [19], Kaslasi [52], and Boukema [10] revealed that the use of CPLEX (which has comparable performance as Gurobi) along with the use of a simplex algorithm successfully solved stand capacity and stand allocation problems.

5.5. Multi-Objective Optimisation

In the early developments of stand allocation and capacity assessment, the models were mainly formulated with a single objective (such as in Haghani [36]). Throughout the years, frameworks have been developed, which opened the need for multi-objective approaches to capture the complexity of the problem. As different factors influence the assessment and allocation problem, as is described in the earlier sections. The challenge of multi-objective optimisation is finding an optimal solution based on a trade-off between the different objectives (which might be conflicting). In the case of multi-objective optimisation, a Pareto Optimal (PO) solution should be sought. In a Pareto optimal solution, none of the objectives can be improved without decreasing another objective. [61]

Different methods for multi-objective optimisation are described by Miettinen [61]. These methods are grouped into four categories: no-preference methods, a posteriori methods, a priori methods and interactive methods.

In no-preference methods, the decision-maker does not play a role. The decision-maker is presented a PO solution based on the preset importance of the objectives. Multiple PO solutions are generated in a posteriori methods, which are then presented to the decision-maker. A posteriori methods are computationally expensive. In a priori methods, the decision-maker defines the preferences regarding the objective. However, defining the preferences can be difficult due to underlying correlations if the decision-maker does not well understand the problem. Interactive methods are highly-developed methods that require a high involvement from the decision-maker to direct the solution process. These methods generate fewer solutions with no interest for the decision-maker, reducing the information load presented [61].

One of the a posteriori methods is the Weighted Sum Method (WSM). This method requires the assignment of weights to the different objectives, representing the objective's priority. An example of the use of a Pareto Front analysis (in a posteriori setting) is to be found in the research of Boukema [10]. The weight of a weight factor (α), related to the weight given to the optimisation for operational cost in the objective function, is determined using a Pareto Front analysis in which the decision-maker decides on the solution point for a specific $alpha$. In this Pareto analysis, the results of the trade-off between the capital and operational cost are assessed (based on the choice for certain weight factors). The analysis conducted by Boukema [10] was extended by investigating the influence of the weight choice on KPIs (such as the number of tow movements and bus movements).

A drawback of WSM is the ambiguity associated with the assignment of weights to objectives. Correlations and non-linear effects might be overseen. A variant of WSM is lexicographic ordering (a priori method), in which a hierarchy is defined for the objectives, which is subsequently translated into the weight factors. The drawback of this is the lack of a trade-off between the objectives. Furthermore, objectives with a lower ordering might have no chance to influence the solution, since the method stops if the current objective in the hierarchy has a unique solution [61].

Földes [33] applied the posteriori WSM through a Weight Space Search (WSS) algorithm for an objective function consisting of 5 objectives. Many solutions were created with different weight factor settings, which were then clustered into unique weight ranges that resulted in comparable objectives using the k-means clustering method. Földes concluded that the individual weights of the objectives do not represent the value of the Pareto optimal objective value, but the weight combinations do. This reveals the disadvantage of a priori methods. If the decision-maker does not well understand the objectives and their correlations, this can result in unexpected results.

Deken [16] assigned weights to the objectives in a priori setting. The importance of objectives is defined in advance by objective hierarchy. The weights linked to the objectives are determined using the maximum achievable value of an objective part.

Decision Making Process

The a posteriori methods as described earlier, in which the decision-maker improves the desired solution by controlling the importance of the objectives, can be seen as a form of alternative-focused thinking [53]. However, it might be desirable to first define the objectives (values) of the stand capacity assessment problem, after which possible alternatives to comply with the set values are explored. This process is also known as value-focused thinking [53]. Since the objective in strategic stand capacity assessment is to proactively assess the implications of different decisions regarding the optimisation objectives, a value-focused thinking approach is beneficial.

Keeney [53] described four steps in a value-focused thinking framework. The first step is the identification of objectives. This can be achieved through a discussion between the involved stakeholders. After objectives have been identified, they have to be structured. This step assures that every objective defined is a fundamental objective (instead of e.g. alternatives, constraints and criteria). The next step consists of creating alternatives to the defined problem, followed by the final step, which consists of defining decision opportunities. A value-focused thinking approach is successfully applied by Földes [33] in his research on tactical stand capacity assessment.

Conclusion

Different objectives are involved within stand capacity assessment, which might be conflicting. Multi-objective optimisation captures the optimisation complexity of problems through different assessment methods: no-preference methods, a posteriori methods, a priori methods and interactive methods. Based on the application of these methods within research, different pros and cons can be defined. Research performed by Boukema [10] concerning strategic stand capacity assessment revealed that multi-objective optimisation using a posteriori methods provides a comprehensive insight into the problem. However, it requires engagement from the decision-maker to choose a specific solution based on the generated solutions. Furthermore, a posteriori methods tend to have the highest computational times [61]. On the other hand, a priori methods provide less insight into the problem than a posteriori methods but require less user engagement and have a lower computational time [61]. However, defining the weights of objectives in a priori methods can be ambiguous and require the decision-maker to have a well-defined understanding of the possible correlations between objectives. If not, unexpected results can be obtained [52].

The optimal solution in multi-objective optimisation can be a trade-off between conflicting objectives. This means that a solution can not be further improved without lowering one of the objectives. Therefore, Pareto Optimal solutions are found in the literature, in which a decision concerning a solution is made using, e.g. a graphical representation of the relation between two objectives.

Enabling a decision-maker to decide through a value-focused thinking process can be beneficial to proactively assess the implications of decisions and obtain solutions based on the desired objectives and values. The thesis aims to investigate the added value of value-focused thinking in strategic stand capacity assessment. This will be linked to the multi-objective optimisation method to be used (either a posteriori or a priori method).

5.6. Conclusion and Reflection

Optimisation frameworks are essential in the assessment of complex mathematical problems such as stand capacity assessment. The different frameworks, objectives, constraints, resolution methods, and multi-objective optimisation methodologies are described in this chapter based on a literature review.

Both static and dynamic models can be distinguished in literature. The difference between the two is the time-dependency in dynamic models. Furthermore, the research field can be divided into mathematical programming techniques and rule-based expert systems. Much of the research concerning the stand capacity and stand allocation problem concerns mathematical programming techniques. Different formulations are to be found for the problem. However, not much research is found in which stand capacity assessment is addressed within a strategic time frame. Based on research performed, it is concluded that mixed-integer programming formulations and applying a linear programming tool are preferred in terms of complexity and running time.

The objectives used in formulations of the stand allocation problem differ from passenger-oriented (minimisation of the passenger walking distance) to airport efficiency-oriented (maximisation of the use of stands, minimisation of idle times between stand assignments, minimisation of towing operations). Furthermore, land area minimisation is generally not considered explicitly in optimisation frameworks. However, the stand sizes and area are minimised using cost objectives. Therefore, consideration of area limitations either through an objective or constraints is defined as a gap in the literature, which is assessed in the thesis work. No research is found which considered robustness in strategic stand capacity assessment. Therefore, the aim of the thesis will be the definition of a framework which allows the assessment of the influence of different stand types, operational factors (towing operations, robustness, flexibility) and area limitations (either through an objective or constraints). The prior research performed by Boukema [10] and Kaslasi [52] form the basis of this, as the frameworks have proven to be able to assess stand capacity assessment within a strategic time frame.

To represent the physical world in mathematical formulations, constraints have to be modelled. These constraints impose that solutions meet requirements such as only a single aircraft is assigned to a stand, only a single stand is assigned to an aircraft, and the assigned stand is compatible with the aircraft type. Furthermore, some user-specific constraints are found in literature based on the modelling objectives (such as incorporating flight splitting to ensure efficient use of stands). These constraints will be assessed during the thesis work and applied if deemed necessary. However, some of the essential constraints have to be modelled in any formulation.

Different resolution methods can be distinguished in literature, such as exact algorithms, heuristic algorithms and meta-heuristic algorithms. Exact algorithms yield an optimal solution. Heuristic and meta-heuristic algorithms are used if it is impossible to obtain an optimal solution within a reasonable time. Based on research in the field, it is concluded to apply exact algorithms to solve the strategic stand capacity assessment problem. Exact algorithms have proven to yield better results than heuristics [35]. However, the running time has to be considered carefully. Furthermore, it is decided to use Gurobi to solve the framework due to its availability and good benchmark results as obtained from the literature.

Stand capacity and allocation problems can be defined as multi-objective problems. In a Pareto Optimal solution, none of the objectives can be increased without decreasing another objective. Different methods can be applied in multi-objective optimisation, such as no-preference methods, a posteriori methods, a priori methods and interactive methods. The choice for one of the methods depends on the running time, desired insights and user engagement. Both a priori and a posteriori methods have been applied to solve the strategic stand capacity assessment problem in the past. For the course of the thesis, the choice for a method will be based on the desire to obtain a framework based on value-focused thinking (which is linked to a priori and a posteriori methods). Therefore, weighting methods might be used both in a priori or a posteriori settings to assess the difference.

6 Conclusions

Stand demand is one of the key parameters in airport planning and design. It influences the needed facilities and, subsequently, the land area needed. Based on anticipated stand demand, stand capacity is assessed by decision-makers as part of an airport development process. Stand capacity represents the quantitative supply of service to accommodate the demand for the service. There is no single answer to define stand capacity for an airport. It depends on the stakeholders' strategic vision, as the stand capacity problem can be optimised for different objectives and consider multiple constraints.

This part of the report consists of the results of a literature study performed regarding stand capacity assessment within a strategic time frame as part of an MSc. graduation project at the Delft University of Technology. The literature study is focused on best practices and the current state of the art regarding modelling and optimising stand capacity assessment. However, to assure that the broader context in which stand capacity assessment fits is understood, it also contains a review on airport development and forecasting methods. It has to be noted that forecasting of stand demand is out of the scope of the research.

Different factors influence stand capacity assessment. These factors range from economic, operational to technical and safety factors. Some of the factors have to be considered as constraining factors, such as the aircraft stand compatibility and immigration requirements (regarding the separation of passenger flows).

Based on the performed literature study, it can be concluded that the stand assignment problem is widely discussed within the literature. However, the research's focus is generally on the application within a tactical or operational time frame. Not many research studies have been found considering the stand capacity problem within a strategic time frame. Furthermore, to be able to perform a well-defined trade-off between different optimisation strategies, optimisation models and frameworks are needed. Analytical methods are not suited for this purpose, as these methods are based on assumptions such as gate occupancy times and the expected traffic mix. Furthermore, these methods generally consider peak hour demand, which does not capture all demand characteristics over a period.

The chosen objective defines the mathematical definition of a model, which subsequently defines the resolution methods which can be used. Different resolution methods can be distinguished in literature, such as exact algorithms, heuristic algorithms and meta-heuristic algorithms. Exact algorithms yield an optimal solution. Heuristic and meta-heuristic algorithms are used if it is impossible to obtain an optimal solution within a reasonable time frame. Strategic stand capacity assessment models are formulated in literature as mixed-integer linear programming optimisation models and solved using exact algorithms. These algorithms have proven to yield better results compared to heuristics, as is proven by Guepet [35].

A clear gap can be defined within the research field. This gap relates to the definition of an optimisation framework allowing a decision-maker to consider a trade-off between different stand types, operational factors (robustness, flexibility) and area limitations through value-focused thinking. As the effectiveness of the use of a mixed-integer linear programming model and an exact algorithm modelled through the optimiser CPLEX is proven by Diepen and Hoogeveen [19], Kaslasi [52] and Boukema [10], a framework will be based on this. Therefore, the thesis's scope will be on the development of a mathematical optimisation framework that incorporates the aforementioned gap. This will contribute to the body of knowledge in the field of airport planning and design and aid decision-makers in their airport planning process.

III

Further elaboration on thesis work

A
Extended Framework Input

The following chapter contains an extended description of the framework input, complementary to the thesis paper. First, the different used stand types are described in Section A.1, followed by the considered stand sizes and terminal types in Section A.2. Furthermore, the stand compatibility and allocation principles are discussed in Section A.3. An in-depth overview of the capital cost and operational cost definitions is described in Sections A.4 and A.5, respectively.

A.1. Stand Types

Aircraft stands are part of a larger system, called the apron system. The apron is defined as: "a defined area intended to accommodate aircraft for purposes of loading and unloading passengers, mail or cargo, fuelling and parking or maintenance" [44].

The apron system consists of the aircraft stands/gates (for parking aircraft, passenger embarking/disembarking and maintenance of aircraft), holding pads, de-icing pads and the taxiway system [62] [80].

Different types of aircraft stands can be distinguished not only based on the aircraft's parking method but also on the methods used for handling the aircraft and passengers. The following stand types are implemented in the framework.

Contact Stands
An aircraft can be handled at so-called contact stands. These stands connect the terminal building and the aircraft seamlessly, which can be accessed directly from the terminal without the need for passenger bussing [40]. The availability of fixed servicing equipment and a passenger loading bridge (PLB) [80] characterises these stands. The PLB is a corridor connecting the terminal and aircraft door to enable enplaning and deplaning of passengers.

Non-Contact Stands
Non-contact stands are related to contact stands. Non-contact stands are also located close to the terminal building. The difference between contact and non-contact stands is the use of stairs, mobile stairs or aircraft stairs to enplane and deplane passengers [80]. Non-contact refers to the lack of a direct link between the terminal and the aircraft.

Non-contact stands offer a lower level of service and are mainly used by low-cost airlines seeking short turnarounds as well as a reduction in the service level provided to their passengers.

Remote Stands
Remote stands are located away from the terminal building and can require bus operations to transport the passengers to the aircraft. Remote stands are characterised by mobile servicing equipment, and the use of (mobile) staircases [44]. Furthermore, remote stands are used for overnight parking of aircraft, assuring no scarce contact positions are taken by aircraft with long layovers. The stands used for overnight parking are also called RON (Remain Overnight) stands [80].

Remote stands provide a lower service level to passengers due to the need for transport operations from the terminal to the remotely located aircraft stands. On the other hand, remote stands also have some benefits, such as the flexible use of the available area. Furthermore, remote stands can accommodate a broad range of aircraft with a relatively simple infrastructure, and they require lower investment costs than contact stands. However, remote stands do imply operational costs for the transportation of passengers [79]. Two types of remote stands are implemented within the proposed framework, being: operational and non-operational stands. Non-operational stands are not used for embarking/disembarking of passengers, but only for intermediate parking of aircraft with a long turnaround time.

MARS Stands
To assure efficient use of the infrastructure at busy airports, with different traffic waves across the day, so-called Multi-Aircraft Ramp System (MARS) [40] stands can be used. These stands can accommodate two narrow-body aircraft, or a single wide-body aircraft [40] within the same area footprint. This results in the flexible use of airport infrastructure as well as flexibility in the planning. Furthermore, MARS stands increase the stand utilisation and reduce the infrastructure cost [40].

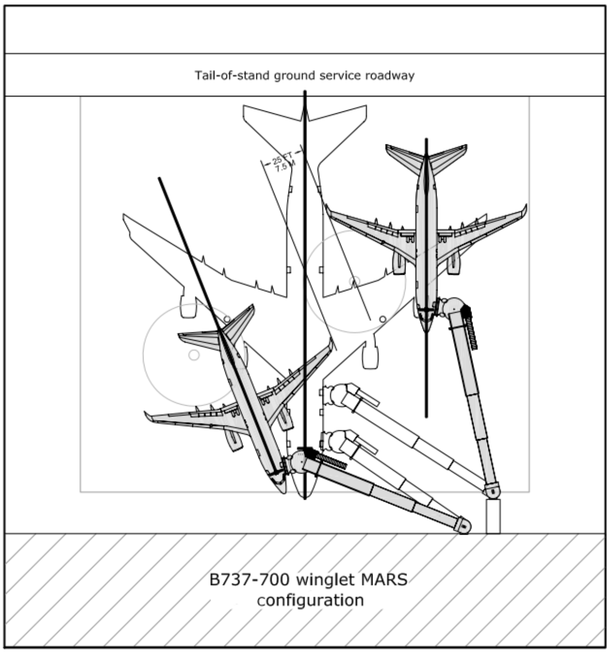

Figure A.1: Design of a MARS stand [79]

A.2. Stand Sizes and Terminal Types

In determining the different stand types, a differentiation is made concerning stand sizes and terminal types. This is an added layer to the aforementioned sets of stands that are differentiated regarding handling type.

Stand Sizes
The defined stand types are based on the Aircraft Design Groups (ADGs) as defined by ICAO. The ADG is used to determine the aerodrome reference code [45], which defines the type of aircraft an airport can accommodate. Table A.1 depicts the different groups along with the wingspan requirements. Furthermore, the table also contains an example of aircraft belonging to each of the defined groups. Group A consists of general aviation aircraft, which are generally handled at remote stands [80]. Group B consists of regional jets, while group C is defined by narrow-body aircraft. Groups D, E and F, consist mainly of wide-body aircraft. However, it has to be noted that the descriptions provided here are arbitrary, as there are some exceptions. An example of such an exception is the Boeing 757-200 with a wingspan of 38 meters [6]. This aircraft belongs to design group D based on its wingspan, while it is labelled as a narrow-body aircraft. In the proposed framework, the following stand sizes are defined: C, D, E and F. These stand sizes all refer to the aircraft design groups from Table A.1. Groups A and B are not considered since the aircraft in these groups do not limit the stand capacity in the framework proposed.

Aircraft Group	**Wingspan (meter)**	**Example Aircraft**
A	<15	Cessna 172, Cessna 525 Citation Jet, Piper PA-28 Cherokee
B	15 <24	Bombardier CRJ100/200/700, Embraer ERJ-135/140/145
C	24 <36	Airbus A318/A319/A320/A321, Boeing 737 (All Models), Bombardier CRJ705/900/1000, Embraer E-170/-190 (All Models), McDonnell Douglas, MD-80/-90 (All Models)
D	36 <52	Boeing 757 (All Models), Boeing 767 (All Models)
E	52 <65	Airbus A340 (All Models), Boeing 747-400, Boeing 777 (All Models), Boeing 787 (All Models)
F	65 <80	Airbus A380, Boeing 747-8

Table A.1: Aircraft Design Groups as defined by ICAO [45] [80]

Terminal Types
Large airports experiencing flights with different origins and destinations require efficient handling of flights flying to different areas (with different customs and immigration regulations). Swing stands are a versatile solution to this problem. These stands can accommodate flights with different origins and destinations (domestic, international, Schengen, Non-Schengen) through a multi-level terminal design, which allows the separation of passenger flows on different levels through sterile corridors [80]. These stands allow for efficient use for sector switching flights and cross utilisation of the available infrastructure (use for a specific sector during peaks). Therefore the following three terminal types are defined: domestic, international and swing.

A.3. Stand Compatibility and Allocation Principles

The compatibility of a flight to the stand types is determined in the "Data Processing Unit" of the framework, as explained in Section 3.2 of the paper. This is determined based on three aspects: the aircraft size, the origin airport and the destination airport. The aircraft size determines the compatibility concerning the stand size. On the other hand, the origin and destination airports define the sectors a flight falls into (Schengen, Non-Schengen/International or a combination), limiting the terminal type. The compatible terminal type also depends on if a flight is split.

The stand compatibility of contact and non-contact stands is depicted in Table A.2. In principle, this stand compatibility is straightforward; a stand can handle all aircraft up to the respective ADG. However, there is an essential consideration in the story, being the passenger boarding bridges. Due to passenger boarding bridge slope requirements [32], a C-type aircraft cannot be handled at an E and F stand. This is validated upon analysis of reference airport, such as Amsterdam Airport Schiphol [72].

ADG	**Handling Type**	**Compatible Stand Size**
C	Contact	C, D
D	Contact	D, E, F
E	Contact	E, F
F	Contact	F
C	Non-Contact	C, D, E, F
D	Non-Contact	D, E, F
E	Non-Contact	E, F
F	Non-Contact	F

Table A.2: Stand compatibility of contact and non-contact stands

Stand Compatibility Policy Flight Splitting
Aircraft with long turnaround times can be split into two or three parts to create efficient schedules or free up connected stand capacity. Within the framework, the following restrictions are implemented. If a flight is split into two phases, the split parts can only be assigned to contact or non-contact stands. The same applies to the arrival and departure parts of a three-phase split flight. The parking part of a three split can be assigned to either a remote operational or remote non-operational stand (not used for passenger processes). The reason for this lies within the policy behind the implementation of the split versions, as described in the thesis paper. A flight can be split into two phases if it results in efficient use of the infrastructure (e.g. for sector switching aircraft). Furthermore, a flight can be split into three phases if it frees up connected stand capacity. These policies are validated upon research of the policies

implemented at Amsterdam Airport Schiphol.

To assure no unnecessary two splits are performed by the model, towing of non-sector switching aircraft is penalised by a factor 2. This is done through the analysis of the turning point at which no unnecessary tows are performed.

Allocation Principles Remote Stands and Cargo Flights
Two restrictions are imposed within the framework. The first restriction concerns the remote non-operational stands. These stands are only compatible with the parking phase of the three split version of a flight. Furthermore, full cargo flights are always assigned to remote operational stands. These decisions have been validated upon analysis of policies implemented at Amsterdam Airport Schiphol [72].

Allocation Principles Towing and Bussing Operations
In order to be able to use remote stands, busses are needed for the transportation of passengers from the terminal to the aircraft. Therefore the number of needed busses is implemented in the model. A few decision had to be made regarding the policies for bussing operations. First of all, the busses' capacity is set to 55 passengers per bus (based on analysis of reference airport). Furthermore, an assumption had to be made regarding the task scheduling time (the time a bus is occupied with a particular flight operation). This is set to 20 and 30 minutes for narrow-body and wide-body aircraft, respectively. The implications of this choice are assessed through a sensitivity analysis, as described in Chapter D. Busses are assigned both for the arrival and departure part of a flight. For the arrival part, busses are assigned at the scheduled arrival time of a flight, while for the departure part, busses are assigned 45 minutes before the scheduled departure time. Due to the complexity of assigning busses for departure parts of a flight (passengers are not at the same time at the same place), it is decided to penalise the assignment of busses to departure parts of a flight by a factor of 2.5, upon other research performed in the field of strategic stand capacity assessment [10].

Furthermore, the number of tow trucks is modelled. Tow trucks are needed for the departure pushback of aircraft as well as the towing of flights that are split. A distinction has been made concerning narrow-body and wide-body tow trucks. In case of a two split, the following policy is implemented: aircraft are towed away 40 minutes after departure to a second stand. In case of a three split, an aircraft is towed to a remote parking stand 60 minutes after arrival and is towed back to an operational stand 60 minutes prior to departure. Also, for the tow trucks, an assumption had to be made regarding the task scheduling time of tow trucks (the time a tow truck is occupied with a task). This is set to 15 minutes for narrow-body aircraft and 20 minutes for wide-body aircraft. The implication of this assumption is also analysed through a sensitivity analysis in Chapter D.

A.4. Capital Cost

The objective of the proposed framework is the minimisation of the capital and operational cost. The definition of the different cost factors will be elaborated upon below.

Stands
Each stand type's capital cost is based on three aspects: the stand area, the terminal, and the need for a passenger boarding bridge. The stand area is defined around three parts: the terminal area, the area for the aircraft parking and the taxiway area. The terminal cost is considered through the building cost (based on the number of layers). The cost factors for a PBB, area cost and building cost are based on a literature search ([10], [3], [5]) and the analysis of policies implemented at reference airport ([72]. In the definition of the areas, the following requirements have been implemented: wingtip clearances [80], nose to building clearances [80] and the taxi lane to object clearance [80].

In the definition of the different areas, a few assumptions have been made. The area cost per m^2 is higher for E and F stands due to the increased complexity associated with a larger stand (such as an increase in the number of passenger boarding bridges). The same cost is adapted for MARS stands. Furthermore, the area cost of remote stands is lower than operational stands of the same type due to the decrease in stand complexity (e.g. no need for underground systems). The same policy is adopted for the area cost of remote non-operational stands, as these stand types require no operational equipment (they are only used for remote parking). The capital cost is deduced to a cost per day by adopting a depreciation period of 20 years [46].

Area Limitations
The proposed framework is capable of incorporating area constraints on the optimisation problem. This can be done in multiple ways, such as constraining the available area for the optimisation problem or by incorporating the area in the objective function. Due to the nature of the strategic stand capacity assessment problem in which the cost is the predominant factors, it is chosen to adopt the following policy. An area limitation block is implemented consisting of three parts: the freely available area (this consists of the area that is available for the optimisation case at no induced cost), the area available at the cost of paving and the area that is available at the cost of acquisition and pavement. By

adopting this policy, there is no interference between objective functions due to the adopted KPI (the area limitation is implemented as a cost induced in the objective function as a penalty in the minimisation problem). The pavement cost is set to 110 euro/m^2 based on an average cost for pavement in airport development [47]. Furthermore, the cost of land acquisition is primarily set to 150 euro/$m2$. This is based on the land cost per m^2 in the Netherlands with an added factor to represent the degree of how constraining it is having to use any area within the third "block" of available land area.

Equipment
Another essential factor in stand capacity assessment is the use of equipment, such as busses and tow trucks and their implications on the stand mix. Therefore, the number of needed busses and tow trucks are implemented as part of the decision variables. The capital cost of busses is set to 500,000 euro (based on analysis of bus prices) for a passenger bus with a capacity of 55 passengers. This implies a capital cost of 146 euro with a depreciation of 10 years [47] (including the cost of boarding stairs).

For the tow trucks, a distinction is made between narrow-body and wide-body tow trucks. The capital cost of a narrow-body tow truck is set to 200,000 euro [47] (55 euro with a depreciation of 10 years). The investment cost of a wide-body tow truck is based on the price of a narrow-body tow truck as obtained from literature and is set to 500,000 euro (137 euro per day) with a depreciation of 10 years.

As described in the discussion regarding the capital cost of busses, boarding stairs have also been added to the busses' respective capital cost. However, the number of boarding stairs is not implemented as a decision variable in the proposed framework because these are partly linked to the busses (the needed number of boarding stairs can partly be deduced from obtained bus decision variable) and the lack of a clear added value to the stand capacity assessment problem within a strategic time frame.

A.5. Operational Cost

The second main objective of the proposed framework is the operational cost. The operational cost comprises the cost induced by the use of equipment (busses, tow trucks and boarding stairs). For the boarding stairs, the operational cost comprises the investment cost (this is not considered in the capital cost part of the objective as is done for the busses and tow trucks), the personnel cost, cost for fuel and maintenance cost. This is set to 6 euro per boarding stairs operation for narrow-body aircraft and to 12 euro for wide-body aircraft (due to assignment of two boarding stairs). This policy has been validated upon reference research [10].

For the tow trucks and busses, the operational cost consists of three parts: fuel/electricity cost, maintenance cost and personnel cost. The following assumptions are made for the operational cost of bus operations. The operational cost of a bus is set to 15 Euro per operation. This is based on an electricity cost of 0.32 Euro/km [50], a maintenance cost of 0.40 Euro/km [76] and personnel cost of 5 Euro per operation.

The operational cost of the tow trucks is centred around the same three main factors as for the busses. The operational cost for narrow-body tow trucks is set to 60 euro per operation and 88 euro per operation for wide-body tow trucks. This based on:

1. A daily cost of 655 euro for fuel (6,152,726 MJ/year [47], an energy content of 36 MJ/liter for diesel [54], an average price of 1.40 euro/liter for diesel [54]) which is translated back to a cost per operation based on an assumption of the average movements per day for narrow-body trucks (15 movements) and wide-body trucks (10 movements).

2. An average maintenance cost of 8 euro for narrow-body tow trucks and 13 euro for wide-body tow trucks per operation. This determined based on average maintenance cost of 25 euro/hour [47], an assumption of 5 hours for the in-use time of the tow trucks. This is translated back to a cost per movement upon an assumption of the average movements per day as for the fuel.

3. Personnel cost of around 9 euro per movement. This based on an assumption of the average gross salary of personnel (50,000 euro per year).

B

Model Architecture

The following chapter will describe the architecture of the developed model. The model can be found in the file **stand_capacity_model.py**. A flow diagram of the model is presented in Figure B.1. It consists of multiple parts, which will be explained below. The designators in the figure (top left of each block) refer to specific labels in the model code.

P0 - Read Input Data: In this part of the model, the input data is read. The input data consists of four databases stored through Excel sheets, **inputSchedule.xlsx** (containing the design day flight schedule), **actypes.xlsx** (containing the compatibility of all the aircraft types), **input_stands.xlsx** (containing the stand data: costs, areas, operational costs) and **airport.xlsx** (containing geographical information of all the worldwide airports).

P1 - Set Optimisation Goals: The first part consists of the unit switches through which the optimisation goals are defined: to (not) consider area limitations, flight frequencies, stand hard input, stand minimal input, multi cases (to create a Pareto), limit the running time or robust scheduling.

P2 - Set Optimisation Parameters: In this part, the different optimisation parameters are defined, such as the cost of the equipment and the times for towing and bussing operations.

P3 - Functions: To assure a efficient use of the model some functions have been defined, which are used multiple times throughout the code. Functions have been created to convert datetime strings to minutes for arithmetical operations and the other way around, assess if two flights are conflicting, and obtain unique times from a list (used for the definition of conflicting operations).

P4- Process Input Data: After the optimisation parameters have been set, the data is processed to obtain: the needed number of busses per flight, split eligibility of flights, bussing and towing operations, conflicting flight sets, flight to stand compatibility data.

P5 - Optimisation Unit: Once all the data is processed, the optimisation model is created (P5A) in which the decision variables are added, the objective is set, and the constraints are added (P5B), after which the Gurobi optimisation parameters are set (max running time, Focus etc.).

P6 - Store Results and create output files: If an optimal solution is found, the optimisation results are stored and further processed into, e.g. graphs.

P7 - Decision Maker Dashboards: The output data is store in the so-called spydata format. These are used in two separate files to obtain interactive decision-maker dashboards, which are modelled through the DASH framework. **Dasboard.py** can be used to obtain a dashboard in which a single case run can be analysed, while **Dasboard_MR.py** can be used to obtain a dashboard in which multi cases can be analysed.

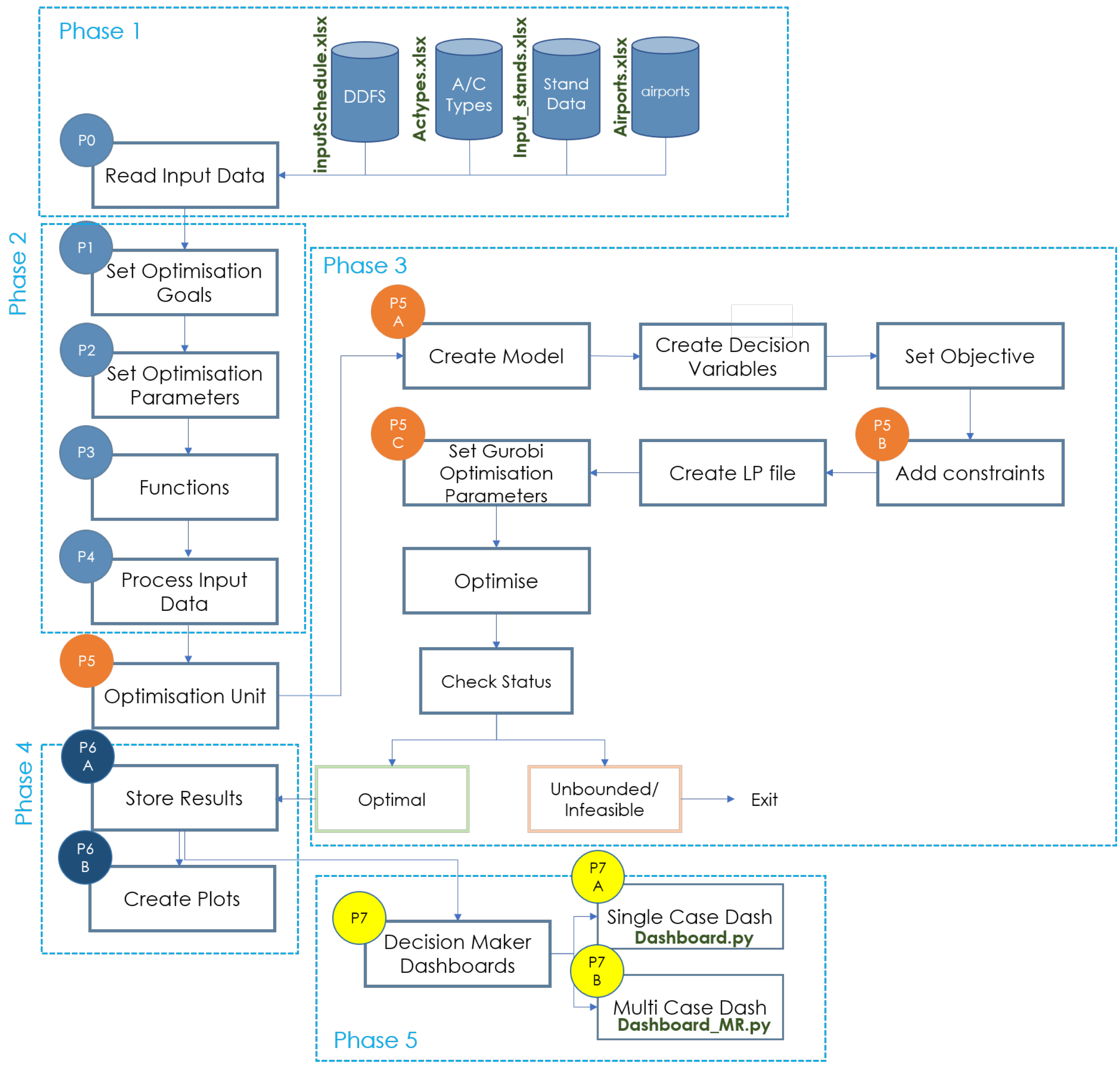

Figure B.1: Schematic representation of the model architecture

Needed Python Packages:
gurobipy
openpyxl (load_workbook)
math
numpy
datetime
plotly.express
pandas
matplotlib
matplotlib.pyplot
plotly.subplots
plotly.io
pio.renderers.default='browser'
dash
dash_core_components
dash_html_components
dash_bootstrap_components
plotly.graph_objects
timeit

C

Model Verification & Validation

The following chapter will describe the verification and validation strategy employed. Verification has been performed in three ways: quality control (by assessment of the efficiency and clarity of the code), code verification (verification of parts of code using numerical cases) and system verification (verification of the framework through a numerical case). The validation and model performance is described in the paper in Part I of this thesis report. The following chapter will summarise part of the performed system verification of the developed mathematical model in Section C.1. Furthermore, the methodology followed for the validation will be elaborated upon in Section C.2 after which some data is presented to support the defined results and conclusions in Section C.3.

C.1. Verification

C.1.1. Test Schedule

To verify the capabilities and results of the developed optimisation model, a verification study has been performed. A test schedule has been created consisting of four international flights. The flight schedule is depicted in Table C.1. It is chosen to adapt a simple schedule of which the solutions are also easily computed by hand.

Flight Nr 1	Flight Nr 2	Arrival Time	Departure Time	Origin	Destination	A/C Type	Passengers Arrival	Passengers Departure	Weekly Frequency
UA20	UA21	09:00:00	12:00:00	IAH	IAH	738	189	189	7
XC21	XC802	09:00:00	12:00:00	AYT	AYT	738	189	189	2
AM25	AM26	11:30:00	13:30:00	MEX	MEX	789	274	243	7
DL46	DL47	13:30:00	15:00:00	JFK	JFK	76W	226	226	6

Table C.1: Flight Schedule used for the Verification Runs

C.1.2. Verification Results

The input schedule as described in Section C.1.1 is used in the developed model. The model is run for a single cost in which both the operational and capital cost are equally taken into account (no trade-off between the two). The results of the optimisation are depicted in Table C.2. The table shows the costs and the number of equipment for three runs: the base run (in which the model is ran without any additions), the MARS run (in which the MARS stands are verified) and the flight splitting run (in which the splitting of flights is verified).

Run	Base	MARS stands	Flight Splitting
Objective Function Value:	3,726	1,660	1,119
Capital Cost:	3,231	1,376	847
Operational Cost:	4,901	280	268
Number of busses:	5	0	0
Number of NB Tow Trucks:	2	2	2
Number of WB Tow Trucks:	1	1	1

Table C.2: Verification results for the test schedule

Base Run

As described, in the base run the model is optimised for a single case in which both the operational and capital cost were taken into account equally. Table C.3 depicts the assignments of the flights to stands. This is graphically depicted in Figure C.1 through a GANTT chart. For the base run, the model builds three stands. This is sufficient for the schedule.

The assigned stands are all compatible with the flight sectors of the aircraft. From the results, it can be seen that all flights are assigned to compatible stands (based on size). This verifies constraint set 1 and 2. Furthermore, only one of the flights is assigned to a larger stand (flight 2). In this solution, two narrow-body tow trucks are needed (flights 1 and 2 are conflicting) and a single wide-body tow truck (for flight 4). Since only flight 3 is assigned to a remote operational stand, five busses are needed (274/55) for passenger transportation. Both the number of tow trucks and busses is verified with the model results, as shown in Table C.2 (this verifies constraints 4 and 5).

Flight	**Stand**	**Type**	**Stand Size**
Flight1	14	Non-Contact	C
Flight2	5	Contact	D
Flight3	27	Remote Operational	E
Flight4	5	Contact	D

Table C.3: Assignments of the flights to stands in the base run

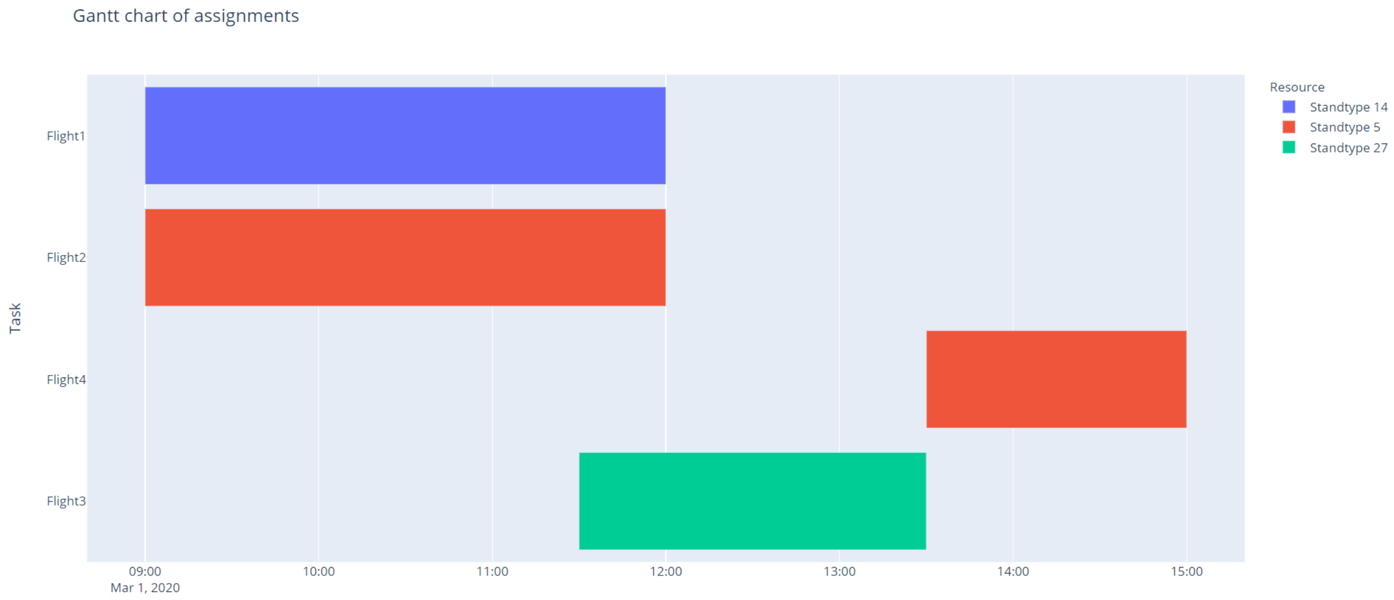

Figure C.1: Schematic overview of the flight assignments to stands in the base run. The colours depict the stand types

MARS Constraint

As described in the paper, the framework also incorporates so-called MARS stands. These stands can handle two type C aircraft simultaneously or a single type E aircraft. Within this run, the MARS constraint (assignment of flights to MARS stands) of the model is verified. Since these stands are more expensive than "regular" stand types, the cost of these stands is lowered to 100 Euros during this verification run.

The results of this run are depicted in Table C.4 and graphically in Figure C.2. The model builds three stands (two MARS stands and a non-contact stand). This is an expected result, due to the lower cost. Flights 1 and 2, both type C, are assigned to one of the MARS stands. Flight 3 (a type E) aircraft is assigned to the second MARS stand. No busses are assigned, which is also correct (no remote handling of flights in the solution). This verified the capabilities of the model in the assignment of the MARS stands.

Flight	Stand	Type	Stand Size
Flight1	31	MARS	NA
Flight2	31	MARS	NA
Flight3	31	MARS	NA
Flight4	17	Non-Contact	D

Table C.4: Assignments of the flights to stands in the MARS run

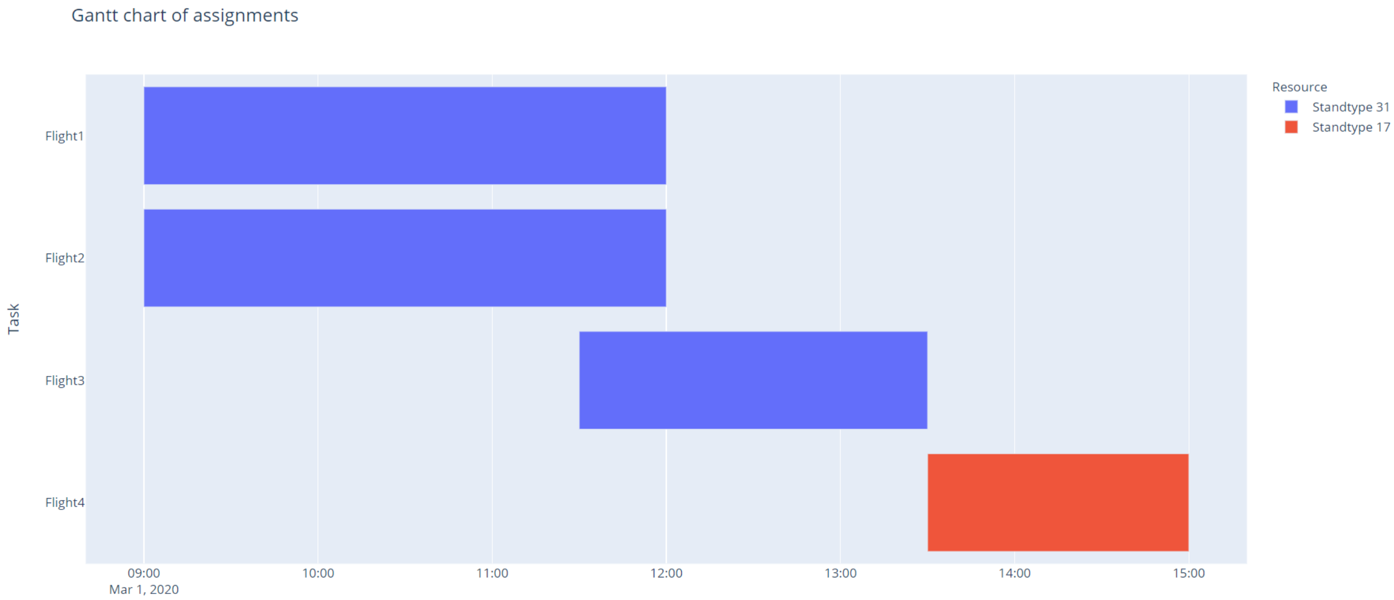

Figure C.2: Schematic overview of the flight assignments to stands in the MARS run

Flight Splitting

Lastly, the developed model is verified concerning the ability to split flights and correctly assign them to a stand (the flight splitting constraints from constraint set 1). To trigger a solution in which the flights are split, the contact stands' capital cost is lowered, and the operational cost of flights that are split is set to zero. The results of this run are depicted in Table C.5 and graphically in Figure C.3.

The model builds five stands (three contact stands and two remote non-operational stands). Flight 1 and 2 are split into three phases (turnaround time longer than 170 minutes). The remote non-operational stands are needed for the parking phase of flights 1 and 2. Furthermore, every phase of the splits is assigned to a single stand, and no busses are needed. With this the flight splitting capabilities of the framework are verified.

Flight	Stand	Type	Stand Size
Flight1A	6	Contact	D
Flight1P	32	Remote Non-Operational	C
Flight1D	3	Contact	C
Flight2A	3	Contact	C
Flight2P	32	Remote Non-Operational	C
Flight2D	6	Contact	D
Flight3	9	Contact	E
Flight4	6	Contact	D

Table C.5: Assignments of the flights to stands in the flight splitting run

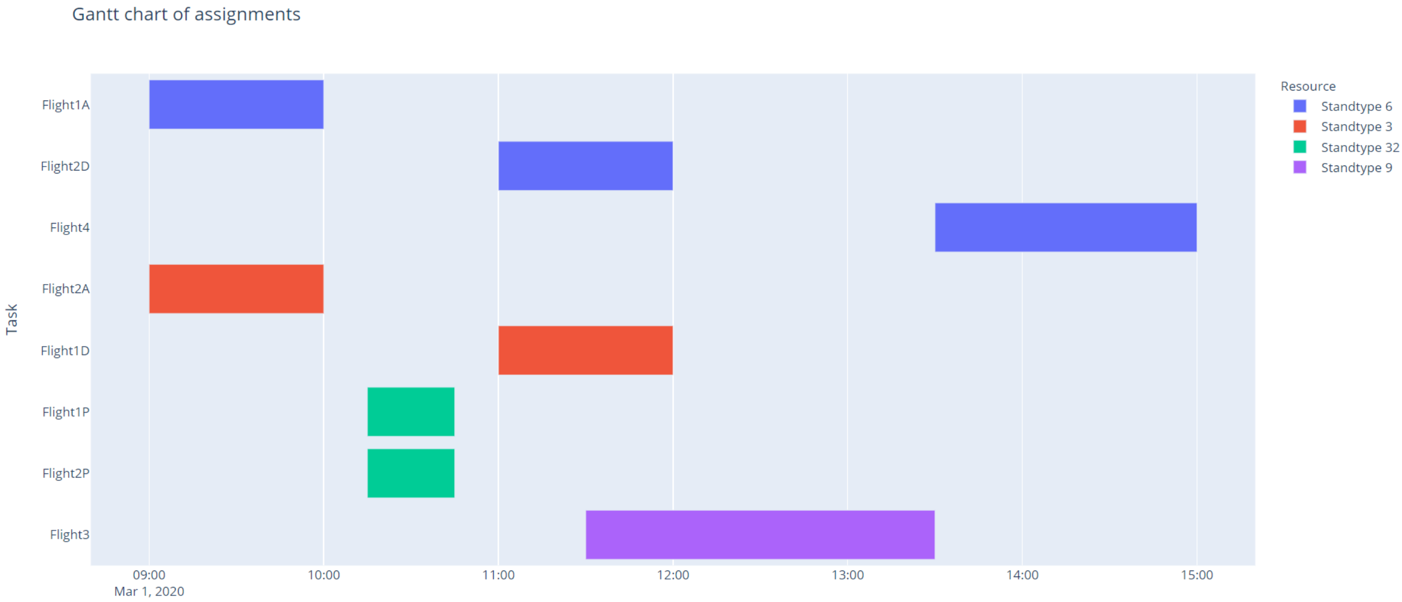

Figure C.3: Schematic overview of the flight assignments to stands in the flight splitting run

C.2. Validation Strategy

A case-study has been set up to validate the developed model. The goal of the case study is to validate the model's capabilities to define the anticipated stand-mix for an airport and its performance concerning defined KPIs. A schematic overview of the methodology followed is depicted in Figure C.4.

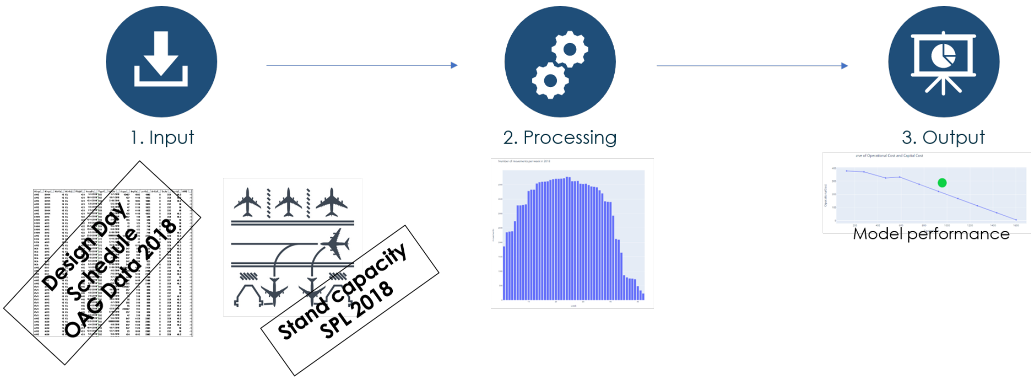

Figure C.4: Schematic overview of the case-study set up

A design day flight schedule is needed to apply in the framework. It is chosen to use Amsterdam Airport Schiphol as the case study airport due to the available data and the short line of connection between the Delft University of Technology and the airport. The case study is performed using flight movement data of the year 2018 (obtained from the OAG database used by the faculty of Aerospace Engineering at the Delft University of Technology) and the airport's capacity data in 2018 (consisting of the available stands).

Before a design day flight schedule could be created, the peak day had to be obtained. The strategy followed is depicted in Figure C.5. First, the number of flight movements per week is obtained, from which the peak week is obtained. From the peak week, the peak day is obtained. All the flight movements which occurred during the peak day were then obtained and stored for further processing. This is modelled in Python.

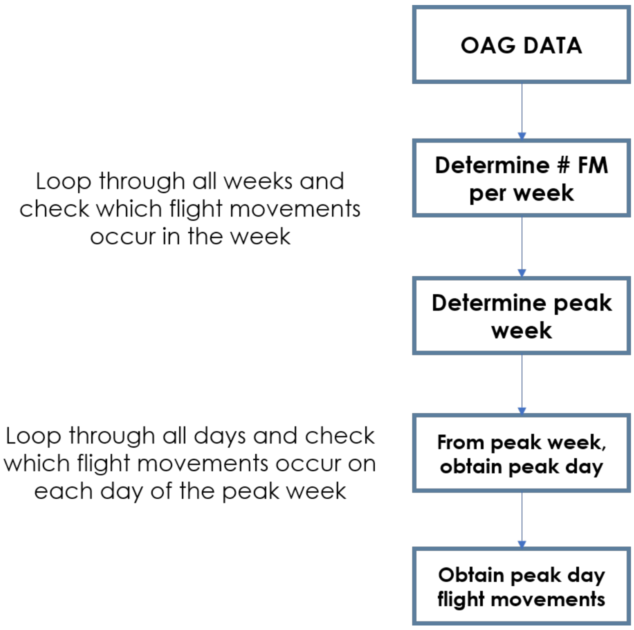

Figure C.5: Topology of the code to obtain the peak day flight movements

It is obtained that week 21 was the peak week in 2018, as can be seen in Figure C.6. Furthermore, Monday was the peak day, as shown in Figure C.7. From this analysis, Monday 21 May is defined as the peak day in 2018. This has been validated through the executed flight movement data as obtained from the airport (confidential data). This analysis has led to 1583 flight movements. From these flight movements, a schedule had to be created by pairing the individual flight movements. For this, an in-house developed optimisation framework from ir. P.C. Roling is used. This optimisation framework pairs different flight movements by considering, amongst others, the airline, aircraft type, turnaround time, origin and destination. The obtained pairings have been validated through a check with respect to viability (same airline and turnaround times). All the non-viable pairings have been removed. This resulted in 769 pairings, which are then used in the case study analysis to assess the model performance and characteristics.

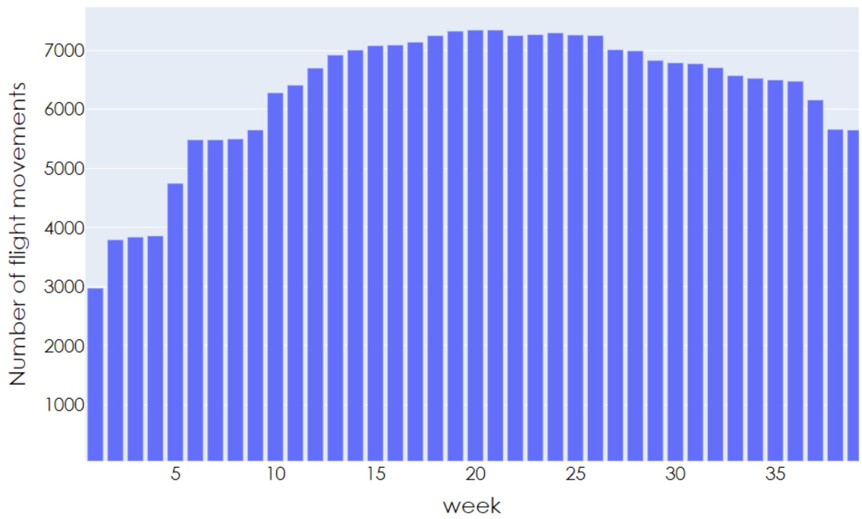

Figure C.6: The number of flight movements per week in 2018 operated at Amsterdam Airport Schiphol as obtained from the OAG data

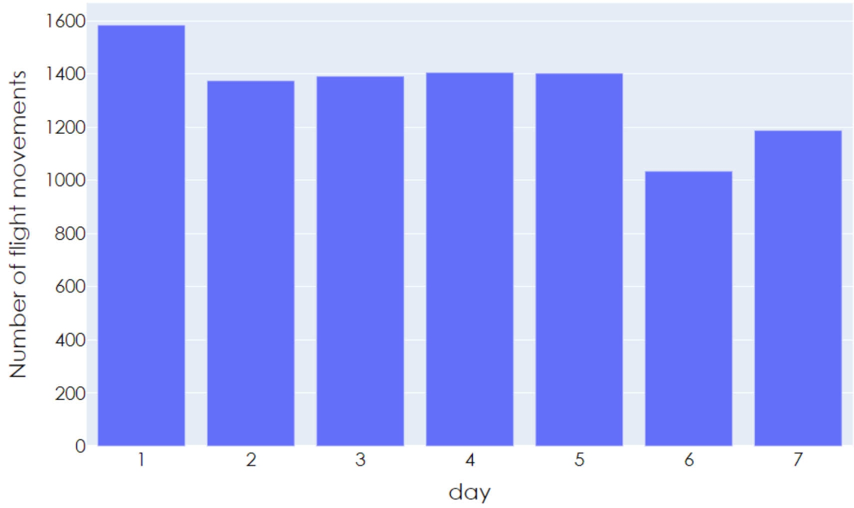

Figure C.7: The number of flight movements per day in week 21 (2018) operated at Amsterdam Airport Schiphol as obtained from the OAG data

C.2.1. Discussion

The OAG data used to create a design day flight schedule did show some deficiencies. The data consists of a mix between scheduled and actual operated flight movements. The data is characterised by a multitude of double entries related to alterations in the scheduled time of a flight movement for a specific period in the year or change in the operated aircraft type. Therefore, the data had to be filtered and sorted. This still resulted in some flight movements that could not be paired with other flights. Upon an in-depth analysis, it is found that the main reason for this is the fact that some airlines operate a specific flight movement using multiple aircraft types throughout the year. This drawback is captured in the pairing creations by allowing some pairings with different aircraft types operated by the same airline and a viable destination.

These discrepancies are known but were not leading, since the developed flight schedule still represents the expected traffic waves at the airport. Furthermore, these were deemed acceptable since the goal of the validation part was the assessment of the model performance and its characteristics, rather than perfectly reflecting a real-life airport case.

C.3. Validation Results

The following section depicts some additional results related to the Thesis Paper in Part 1 of this report. This data gives the reader an in-depth view and supports the defined results. First, the obtained model results for the base case are defined in Tables C.6, C.7, C.8 and C.9. Secondly, the model results for the cases in which the flight frequency are considered are defined in Tables C.10, C.11, C.12 and C.13. Lastly, two graphs are presented which allow a quick comparison between the two results sets in Figures C.8 and C.9.

Pareto Multi Case Results - Base Case

α_{CC}	Capital Cost (Euro)	Operational Cost (Euro)	Number of Stands	# Contact Stands	# MARS Stands	# Non-Contact Stands	# Remote Ops Stands	# Remote Non-Ops Stands
0.05	190,362	54,847	142	132	3	1	6	0
0.10	170,793	56,266	125	98	0	21	6	0
0.15	150,284	59,241	124	90	0	16	12	6
0.21	138,356	61,922	123	85	0	12	21	5
0.26	130,231	64,560	123	81	0	9	29	4
0.31	124,514	66,822	123	80	0	6	34	3
0.36	119,313	69,432	123	80	0	3	37	3
0.42	114,586	72,537	123	70	0	7	45	1
0.47	109,870	76,382	123	57	0	14	51	1
0.52	100,706	85,265	123	44	0	17	62	0
0.57	95,629	91,505	123	30	0	23	70	0
0.62	92,602	96,108	123	27	0	20	76	0
0.68	87,888	104,941	123	17	0	23	83	0
0.73	85,336	110,787	123	8	0	27	88	0
0.78	83,827	115,102	123	4	0	28	91	0
0.83	82,198	121,778	123	4	0	22	97	0
0.89	80,831	130,653	123	3	0	17	103	0
0.94	80,262	136,678	123	0	0	15	108	0
0.99	79,998	138,821	124	0	0	11	113	0

Table C.6: Number of stands per type for the base case in which the α_{CC} is altered from 0.05-0.99 in 19 steps. Ops = Operational

α_{CC}	Number of Busses	Number of NB TT	Number of WB TT	Busmovements	Towmovements
0.05	4	36	12	26	848
0.10	4	36	12	26	854
0.15	16	36	12	128	862
0.21	25	36	12	251	865
0.26	36	36	12	367	867
0.31	42	36	12	473	870
0.36	52	36	12	623	866
0.42	59	36	12	770	862
0.47	67	36	12	923	864
0.52	92	36	12	1,358	859
0.57	107	36	12	1,616	859
0.62	120	36	12	1,857	857
0.68	144	36	12	2,281	851
0.73	154	36	12	2,509	851
0.78	161	36	12	2,694	851
0.83	177	36	12	3,050	851
0.89	195	36	12	3,515	851
0.94	211	36	12	3,829	851
0.99	224	36	12	4,145	849

Table C.7: Number of equipment and movements for the base case in which the α_{CC} is altered from 0.05-0.99 in 19 steps. NB = Narrow-Body, WB = Wide-Body, TT = Tow Truck

α_{CC}	**Contact (Min)**	**Non - Contact (Min)**	**Remote - Ops (Min)**	**MARS (Min)**	**Remote Non-Ops (Min)**
0.05	126	293	229	96	0
0.10	120	186	212	0	0
0.15	116	167	230	0	209
0.21	108	165	270	0	179
0.26	106	144	256	0	157
0.31	106	114	251	0	117
0.36	105	123	239	0	113
0.42	100	147	227	0	103
0.47	94	146	218	0	82
0.52	90	127	200	0	0
0.57	79	121	194	0	0
0.62	77	117	186	0	0
0.68	72	101	179	0	0
0.73	63	88	174	0	0
0.78	63	80	170	0	0
0.83	64	77	160	0	0
0.89	63	74	150	0	0
0.94	0	69	146	0	0
0.99	0	67	141	0	0

Table C.8: Average utilisation of the different stand types in minutes for the base case in which the α_{CC} is altered from 0.05-0.99 in 19 steps

α_{CC}	**# 2 Split Flights**	**# 3 Split Flights**	**Total Area (m^2)**	**% flights assigned same size**	**% flights assigned larger size**
0.05	0	0	1,143,486	86	14
0.10	0	3	1,041,259	89	11
0.15	0	7	1,014,954	89	11
0.21	1	8	994,342	90	10
0.26	1	9	985,139	88	12
0.31	2	10	973,226	87	13
0.36	2	8	965,404	89	11
0.42	2	6	959,760	87	13
0.47	2	7	953,911	87	13
0.52	1	5	944,695	83	17
0.57	1	5	937,647	81	19
0.62	1	4	931,797	82	18
0.68	1	1	931,004	80	20
0.73	1	1	927,492	80	20
0.78	1	1	925,384	75	25
0.83	1	1	921,169	71	29
0.89	1	1	916,748	75	25
0.94	1	1	913,030	82	18
0.99	1	0	914,311	74	26

Table C.9: Number of flights split into 2/3 phases, the area used and the percentage of flights assigned to an equivalent stand size or to a larger stand size for the base case in which the α_{CC} is altered from 0.05-0.99 in 19 steps

Pareto Multi Case Results - Consideration of Flight Frequency

α_{CC}	**Capital Cost (Euro)**	**Operational Cost (Euro)**	**Number of Stands**	**# Contact Stands**	**# MARS Stands**	**# Non-Contact Stands**	**# Remote Ops Stands**	**# Remote Non-Ops Stands**
0.05	1,191,615	255,093	130	103	0	15	12	0
0.10	1,046,743	266,346	125	94	0	10	20	1
0.15	945,960	281,185	124	85	0	10	25	4
0.21	887,106	294,667	123	79	0	9	31	4
0.26	834,443	310,258	123	75	0	8	37	3
0.31	808,339	320,759	123	68	0	11	41	3
0.36	780,258	334,415	123	58	0	16	47	2
0.42	726,697	368,425	123	49	0	14	59	1
0.47	690,227	396,792	123	35	0	22	66	0
0.52	654,439	430,425	123	24	0	25	74	0
0.57	638,218	450,029	123	22	0	23	78	0
0.62	610,812	491,220	123	15	0	23	85	0
0.68	593,502	522,946	123	10	0	22	91	0
0.73	583,925	545,423	123	4	0	26	93	0
0.78	574,161	575,731	124	3	0	22	99	0
0.83	565,815	613,947	123	3	0	17	103	0
0.89	563,567	629,496	124	1	0	16	107	0
0.94	560,808	655,690	124	0	0	13	111	0
0.99	559,988	669,167	124	0	0	11	113	0

Table C.10: Model results for the case in which the α_{CC} is altered from 0.05-0.99 in 19 steps and the weekly flight frequency is considered. Ops = Operational

α_{CC}	**Number of Busses**	**Number of NB TT**	**Number of WB TT**	**Busmovements**	**Towmovements**
0.05	12	36	12	104	850
0.10	27	36	12	221	861
0.15	39	36	12	372	863
0.21	41	36	12	509	866
0.26	51	36	12	722	866
0.31	54	36	12	826	866
0.36	59	36	12	964	865
0.42	85	36	12	1359	864
0.47	98	36	12	1617	859
0.52	111	36	12	1941	853
0.57	123	36	12	2114	853
0.62	143	36	12	2491	851
0.68	161	36	12	2760	851
0.73	166	36	12	2917	851
0.78	179	36	12	3239	849
0.83	195	36	12	3628	851
0.89	204	36	12	3802	849
0.94	217	36	12	4078	849
0.99	224	36	12	4263	849

Table C.11: Number of equipment and movements for the case in which the α_{CC} is altered from 0.05-0.99 in 19 steps and the weekly flight frequency is considered

α_{CC}	Contact (Min)	Non - Contact (Min)	Remote - Ops (Min)	MARS (Min)	Remote Non-Ops (Min)
0.05	117	184	274	0	0
0.10	111	155	278	0	400
0.15	107	139	271	0	182
0.21	105	125	251	0	157
0.26	103	128	233	0	125
0.31	100	141	224	0	138
0.36	96	135	214	0	138
0.42	91	126	200	0	85
0.47	84	120	193	0	0
0.52	80	116	182	0	0
0.57	77	109	179	0	0
0.62	75	94	173	0	0
0.68	70	87	168	0	0
0.73	70	80	164	0	0
0.78	67	79	157	0	0
0.83	66	74	150	0	0
0.89	74	74	147	0	0
0.94	0	72	142	0	0
0.99	0	68	140	0	0

Table C.12: Average utilisation of the different stand types in minutes for the case in which the α_{CC} is altered from 0.05-0.99 in 19 steps and the flight frequency is considered

alphaCC	# 2 Split Flights	# 3 Split Flights	Total Area (m^2)	% flights assigned same size	% flights assigned larger size
0.05	0	1	1,069,026	88	12
0.10	1	6	1,026,258	89	11
0.15	1	7	997,226	89	11
0.21	2	8	980,876	88	12
0.26	2	8	966,833	87	13
0.31	2	8	962,594	87	13
0.36	3	7	961,518	88	12
0.42	2	7	949,504	83	17
0.47	1	5	942,432	82	18
0.52	1	2	943,042	83	17
0.57	1	2	939,009	78	22
0.62	1	1	931,028	81	19
0.68	1	1	925,384	82	18
0.73	1	1	923,979	77	23
0.78	1	0	924,558	78	22
0.83	1	1	916,748	72	28
0.89	1	0	918,526	79	21
0.94	1	0	915,716	81	19
0.99	1	0	914,311	72	28

Table C.13: Number of flights split into 2/3 phases, the area used and the percentage of flights assigned to an equivalent stand size or to a larger stand size for the case in which the α_{CC} is altered from 0.05-0.99 in 19 steps and the flight frequency is considered

Comparison Graphs

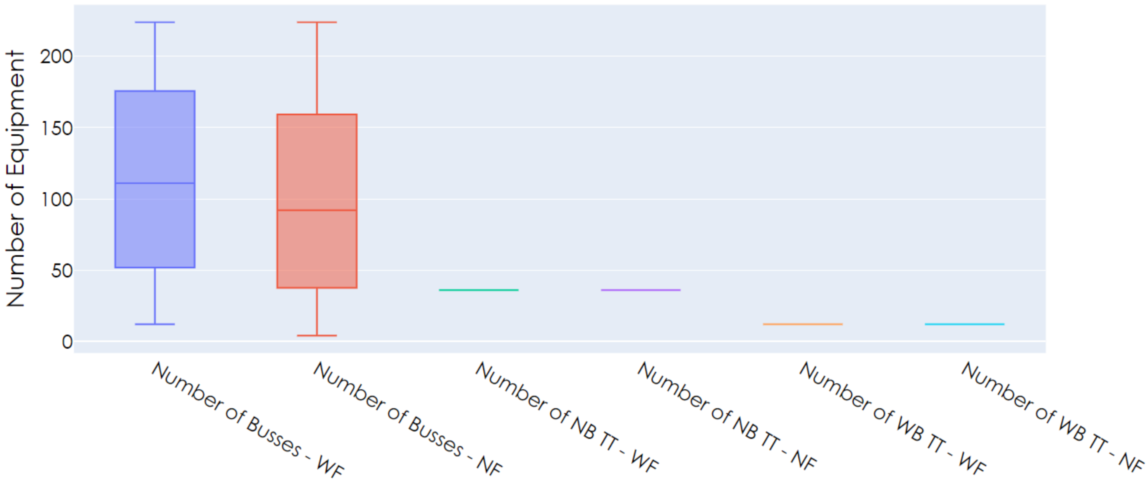

Figure C.8: Boxplots depicting the variations in the number of equipment for the different α_{CC} cases for the base cases (NF) and the cases in which the flight frequency is considered (WF)

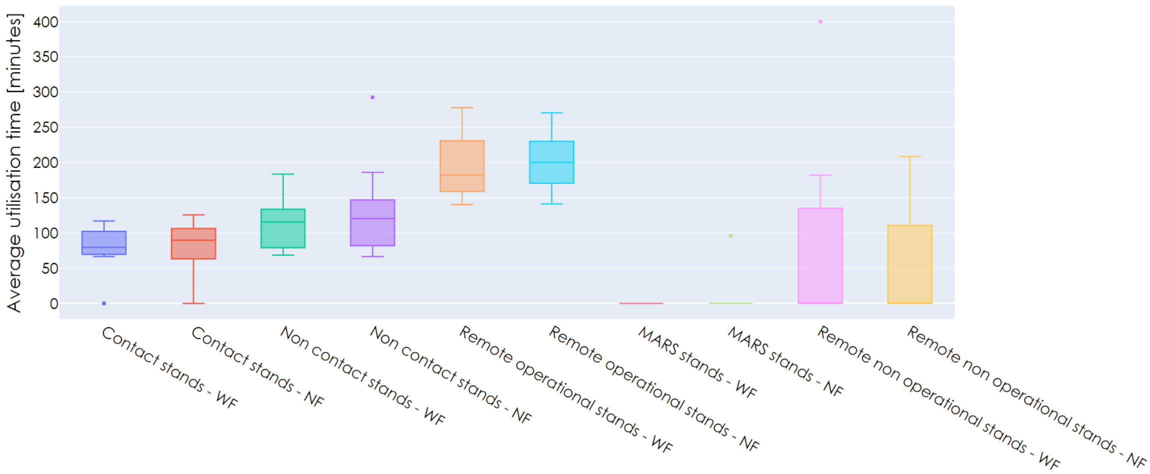

Figure C.9: Boxplots depicting the variations in stand utilisation times for the different α_{CC} cases for the base cases (NF) and the cases in which the flight frequency is considered (WF)

D
Sensitivity Analysis

A sensitivity analysis has been performed to assess the sensitivity of the model parameters used in the optimisation framework. This is centred around three main themes: cost factors, time factors and robust scheduling. Within the sensitivity analysis, the implications of altering specific parameters on the model output have been assessed. These are then compared with the base case. The base case refers to a single run in which the capital cost and operational cost are equally taken into account.

D.1. Cost Factors

The developed model's main factors and parameters are based on costs, such as capital cost of stands and equipment. To assess the model output's sensitivity with respect to a change in any of the main factors, the following analysis has been performed.

Capital Cost Stands

First, the capital cost of the stands is reduced in 5 steps from 5% to 25% (while keeping all other parameters as defined). This is then compared to the base run (with the standard defined costs). The results of this analysis are depicted through the bar chart in Figure D.1. It can be seen that there is no variation in the total number of stands built. As the capital cost of the stands is increased, the number of contact stands increases while the number of remote operational stands decreases. This is also visible in the number of busses (which reduces by 8% on average per 5% reduction in capital cost. The total number of contact stands increases on average with 7.7% per 5% reduction in the capital cost of the stands. The number of remote stands is reduced with 6% on average per 5% reduction in the capital cost of the stands. There is no variation visible in the number of tow trucks nor the area used.

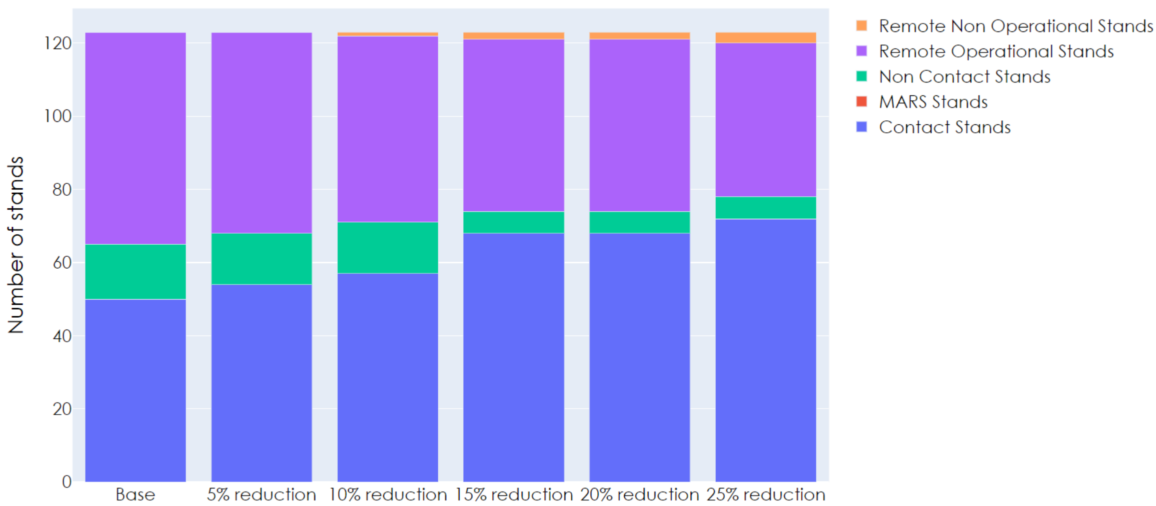

Figure D.1: Variation in the number of stands per type for the base case and the sensitivity analysis of the stand capital cost

Capital Cost Equipment

The second cost parameters that have been assessed are the capital cost of the tow trucks and busses. These cost parameters were also reduced in 5 steps from 5% to 25%. The results of this assessment are depicted in Figure D.2.

There is no difference in the number of stands per type, up to a reduction of 10%. From a 15% reduction in the operational cost, the number of remote stands increases by 7% and remains equal. The number of busses increases with 10% at a 15% reduction of the equipment cost and remains equal up to the 25% reduction.

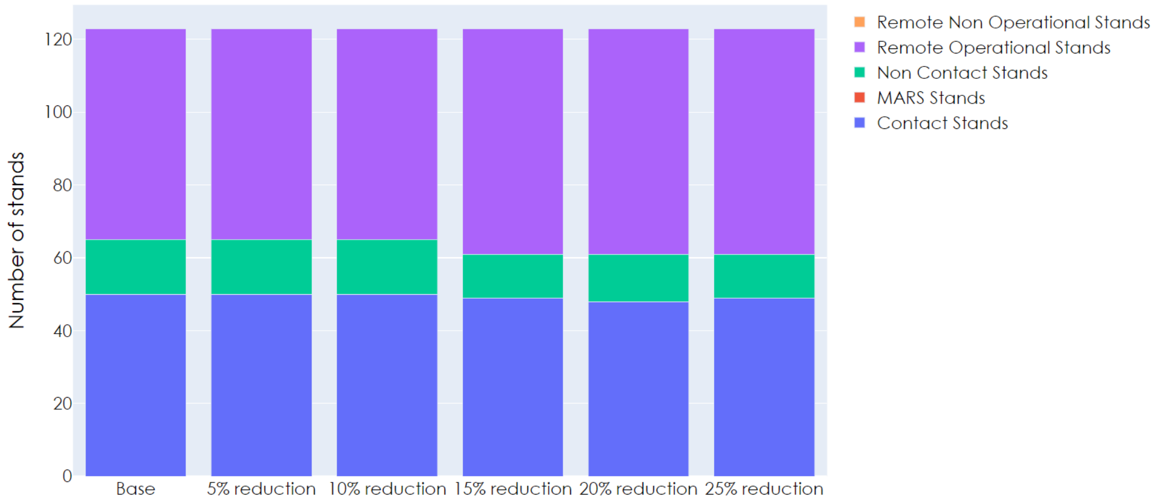

Figure D.2: Variation in the number of stands per type for the base case and the sensitivity analysis of the equipment capital cost

Operational Cost

The last cost parameters that have been assessed are the operational cost factors. These parameters relate to the cost associated with operating boarding stairs, busses and tow trucks. As with the other two analysed cost factor sets, the operational cost has been reduced in 5 steps from 5% to 25%, while keeping all the other parameters as defined originally. The results of this analysis are depicted in Figure D.3. As expected, the number of contact stands is reduced due to a reduction in the operational cost (more cost-efficient to operate remote stands). The number of contact stands is reduced with 10% on average for every 5% reduction in the number of contact stands, the number of remote stands increases with 4% on average (for every 5% reduction in the operational cost). Due to the increase in the number of remote stands, the number of busses increases. These increase on average by 5% for every 5% reduction in the operational cost.

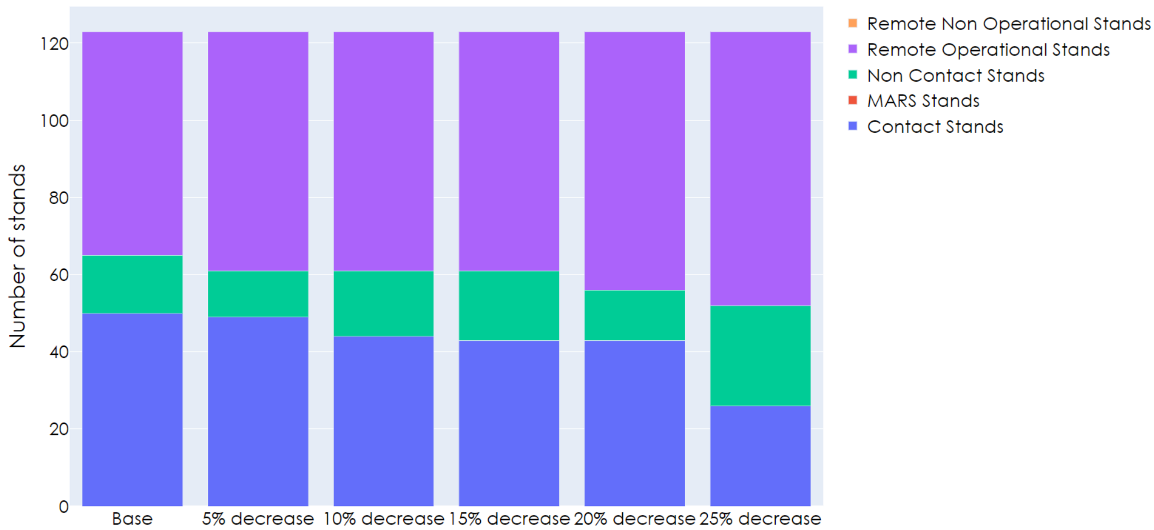

Figure D.3: Variation in the number of stands per type for the base case and the sensitivity analysis of the operational cost

D.2. Time Factors

In the second part of the sensitivity analysis, the implications of the time factors have been assessed. Within the framework, assumptions had to be made regarding the duration of bussing operations and towing operations. The implication of these assumptions have been tested through the following sensitivity analysis: the assumed operational times (for bussing and towing) have been increased in 5 steps with 5% to 25%. The results of this analysis are depicted in Figure D.4. As can be seen in the bar chart, there are no considerable variations visible.

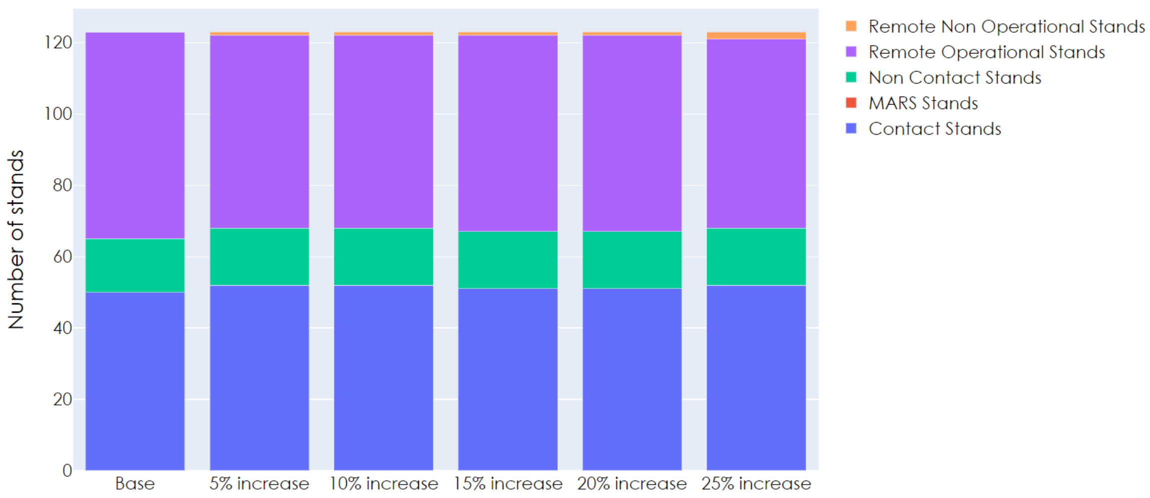

Figure D.4: Variation in the number of stands per type for the base case and the sensitivity analysis of the time factors of the bussing and towing operations

D.3. Robust Scheduling

Creating and assessing the implications of robust scheduling is important for operational and tactical time frames of airport planning. Incorporating buffer times in strategic stand capacity assessment allows decision-makers to obtain better insight into the needed stand capacity for different scenarios. To assess the implications of buffer times on the model output, the model is tested for multiple buffer time settings and compared with the base case. The buffer time is increased by steps of four minutes (aircraft arrival 2 minutes earlier than scheduled and a departure 2 minutes later than the schedule).

The results of this analysis are depicted in Figure D.5. As expected, the total number of stands increases as the buffer times are increased. These increase on average by 3% for every 4 minutes of buffer time. The model employs both more remote stands and contact stands which both increase on average with the same percentage. As the buffer times are increased, the number of busses is reduced (more flights are split into phases). The total area used increases on average with 2% for every 4 minutes of buffer time added.

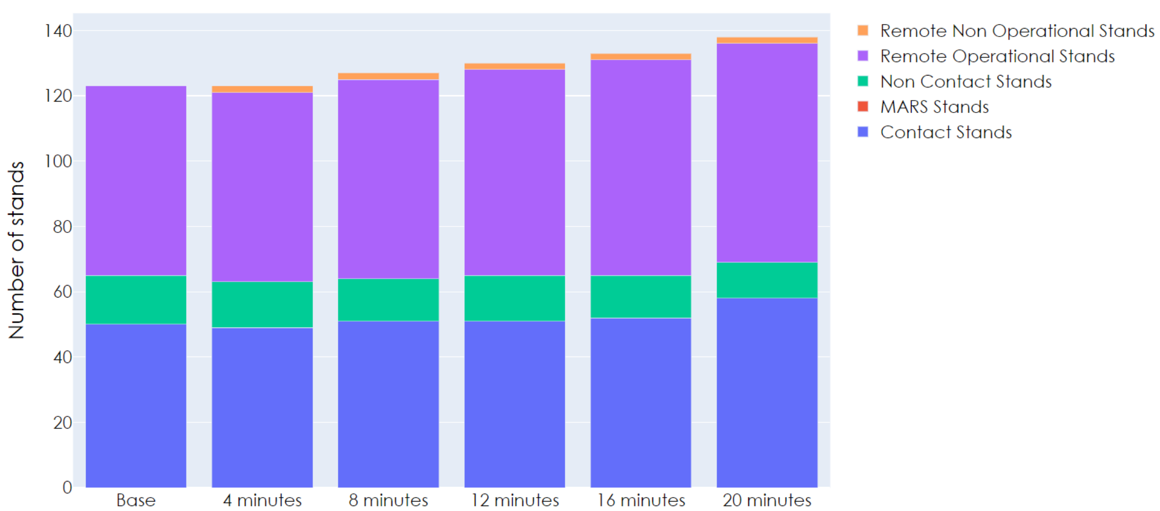

Figure D.5: Variation in the number of stands per type for the base case and the sensitivity analysis of the buffer times

E
Model Data

The following chapter contains the model data used within the thesis work. The following data can be distinguished:
- Aircraft Data in Section E.1: containing the categorisation of the different aircraft types to a design group. This data is obtained from Boukema [10].
- Stand Compatibility Data (Flight Sector) in Section E.2.1: containing the compatibility of every stand type to the flight sectors.
- Stand Compatibility Data (Aircraft Size) in Section E.2.2: containing the compatibility of every stand type to the different aircraft sizes.
- The design day flight schedule used for the validation in Section E.3.

E.1. Aircraft Data

Code	Manufacturer	Type	Compatible Stand
AT5	Aerospatiale/Alenia	ATR 42-500	C
ATR	Aerospatiale/Alenia	ATR	C
AT4	Aerospatiale/Alenia	ATR 42-300/320	C
AT7	Aerospatiale/Alenia	ATR 72	C
319	Airbus	A319	C
320	Airbus	A320-100/200	C
32A	Airbus	A320 sharklets	C
321	Airbus	A321-100/200	C
32S	Airbus	A318	C
318	Airbus	A318	C
32S	Airbus	A318/319/320/321	C
32B	Airbus	A321 sharklets	C
AN6	Antonov	An-26/30/32	C
A26	Antonov	An-26	C
A28	Antonov	An-28	C
A30	Antonov	An-30	C
A32	Antonov	An-32	C
A40	Antonov	An-140	C
A81	Antonov	An-148-100	C
AN4	Antonov	An-24	C
AN7	Antonov	An-72/74	C
AR8	Avro	RJ85 Avroline	C
AR8	Avro	RJ85 Avroliner	C
ARJ	Avro	RJ Avroliner	C
AR1	Avro	RJ100 Avroliner	C
AR7	Avro	RJ70 Avroliner	C
ARX	Avro	RJX	C
AX1	Avro	RJX100	C
AX8	Avro	RJX85	C
738	Boeing	737 800 pax	C
739	Boeing	737-900 pax	C
757	Boeing	757 all pax models	C

788	Boeing	787-800	C
733	Boeing	737-300 pax	C
734	Boeing	737-400 pax	C
735	Boeing	737-500 pax	C
73G	Boeing	737-700	C
73H	Boeing	737	C
73W	Boeing	737	C
721	Boeing	727-100	C
733	Boeing	737-300	C
737	Boeing	737	C
72B	Boeing	727-100 Combi	C
72F	Boeing	727 Freighter	C
72M	Boeing	727 Combi	C
72S	Boeing	727-200	C
72X	Boeing	727-100 Freighter	C
72Y	Boeing	727-200 Freighter	C
73C	Boeing	737-300	C
73E	Boeing	737-900ER	C
73J	Boeing	737-900WithWinglets	C
73N	Boeing	737-300Mixed Config	C
73Q	Boeing	737-400Mixed Config	C
73S	Boeing	737 Advanced	C
717	Boeing	717-200	C
722	Boeing	727-200	C
727	Boeing	727	C
731	Boeing	737-100	C
732	Boeing	737-200	C
735	Boeing	737-500	C
736	Boeing	737-600	C
72A	Boeing	727-200 Advanced	C
72C	Boeing	727-200 Combi	C
73A	Boeing	737-200/200C Advanced	C
73F	Boeing	737 Freighter	C
73G	Boeing	737-700	C
73H	Boeing	737-800WithWinglets	C
73M	Boeing	737-200 Combi	C
73P	Boeing	737-400 Freighter	C
73W	Boeing	737-700WithWinglets	C
73X	Boeing	737-200 Freighter	C
73Y	Boeing	737-300 Freighter	C
D92	Boeing/McDonnell Douglas	DC-9-20	C
D95	Boeing/McDonnell Douglas	DC-9-50	C
D9C	Boeing/McDonnell Douglas	DC-9-30 Freighter	C
M88	Boeing/McDonnell Douglas	MD-88	C
D3F	Boeing/McDonnell Douglas		C
D6F	Boeing/McDonnell Douglas	DC-6A/B/C Freighter	C
D91	Boeing/McDonnell Douglas		C
D93	Boeing/McDonnell Douglas	DC-9-30	C
D94	Boeing/McDonnell Douglas		C
D9F	Boeing/McDonnell Douglas	DC-9-40 Freighter	C
D9S	Boeing/McDonnell Douglas		C
D9X	Boeing/McDonnell Douglas	DC-9-10 Freighter	C
DC3	Boeing/McDonnell Douglas		C
DC6	Boeing/McDonnell Douglas	DC-6	C
DC9	Boeing/McDonnell Douglas		C
DCF	Boeing/McDonnell Douglas	DC-9 Freighter	C
M80	Boeing/McDonnell Douglas		C
M87	Boeing/McDonnell Douglas	MD-87	C
M90	Boeing/McDonnell Douglas		C
CR9	Bombardier	CRJ900	C

CS3	Bombardier	CS300	C
DH4	Bombardier	Q400	C
GLE	Bombardier	Global Express	C
142	British Aerospace	BAe 146-200	C
146	British Aerospace	BAe 146	C
14F	British Aerospace	BAe 146 Freighter	C
14X	British Aerospace	BAe 146-100QT/QC	C
B11	British Aerospace	BAC One Eleven	C
B12	British Aerospace	BAC One Eleven 200	C
B15	British Aerospace	BAC One Eleven 500	C
141	British Aerospace	BAe 146-100	C
143	British Aerospace	BAe 146-300	C
14Y	British Aerospace	BAe 146-200QT/QC	C
14Z	British Aerospace	BAe 146-300QT/QC	C
B13	British Aerospace	BAC One Eleven 300	C
B14	British Aerospace	BAC One Eleven 400	C
ATP	British Aerospace	ATP	C
CRK	Canadair	Regional Jet 1000	C
CR7	Canadair	Regional Jet 700	C
CRA	Canadair	Regional Jet 705	C
DHC	De Havilland Canada	DHC-4 Caribou	C
DH1	De Havilland Canada	DHC-8-100 Dash 8/8Q	C
DH2	De Havilland Canada	DHC-8-200 Dash 8/8Q	C
DH3	De Havilland Canada	DHC-8-300 Dash 8/8Q	C
DH7	De Havilland Canada	DHC-7 Dash 7	C
DH8	De Havilland Canada	DHC-8 Dash 8 All S.	C
E17	Embraer	170-200	C
E70	Embraer	170	C
E75	Embraer	175	C
E90	Embraer	190	C
E95	Embraer	195	C
EMJ	Embraer	170/190	C
EM9	Embraer	E190	C
F70	Fokker	70	C
GRJ	Gulfstream	G500	C
310	Airbus	all pax models	D
313	Airbus	A310	D
ABB	Airbus	A300-600ST Beluga	D
312	Airbus	A310-200	D
31F	Airbus	A310 Freighter	D
AB6	Airbus	A300-600	D
31X	Airbus	A310-200 Freighter	D
AB4	Airbus	A300B2/B4/C4	D
AB3	Airbus	A300	D
ABF	Airbus	A300 Freighter	D
ABX	Airbus	A300B4/C4/F4 Freighter	D
ABY	Airbus	A300-600 Freighter	D
31Y	Airbus	A310-300 Freighter	D
ANF	Antonov	An-12	D
752	Boeing	757-200	D
753	Boeing	757-300 pax	D
763	Boeing	767-300	D
752	Boeing	757-200 pax	D
75W	Boeing	757 200 pax	D
76W	Boeing	767-300	D
707	Boeing	707/720	D
70F	Boeing	707-300 Freighter	D
76F	Boeing	767 Freighter	D
B72	Boeing	720B	D
703	Boeing	707-300	D

762	Boeing	767-200	D
764	Boeing	767-400	D
70M	Boeing	707-300 Combi	D
75F	Boeing	757-200 Freighter	D
75M	Boeing	757-200 Combi	D
767	Boeing	767 all paxmodels	D
76X	Boeing	767-200 Freighter	D
76Y	Boeing	767-300 Freighter	D
D8M	Boeing/McDonnell Douglas	DC-8 Combi	D
D8Q	Boeing/McDonnell Douglas	DC-8-72	D
D8Y	Boeing/McDonnell Douglas	DC-8-71/72/73 Freighter	D
M83	Boeing/McDonnell Douglas	MD-83	D
D10	Boeing/McDonnell Douglas	DC-10	D
D11	Boeing/McDonnell Douglas	DC-10-10/15	D
D1C	Boeing/McDonnell Douglas	DC-10-30/40	D
D1F	Boeing/McDonnell Douglas	DC-10 Freighter	D
D1X	Boeing/McDonnell Douglas	DC-10-10 Freighter	D
D1Y	Boeing/McDonnell Douglas	DC-10-30/40 Freighter	D
D8F	Boeing/McDonnell Douglas	DC-8 Freighter	D
D8L	Boeing/McDonnell Douglas	DC-8-62	D
D8T	Boeing/McDonnell Douglas	DC-8-50 Freighter	D
D8X	Boeing/McDonnell Douglas	DC-8-61/62/63 Freighter	D
DC8	Boeing/McDonnell Douglas	DC-8	D
M11	Boeing/McDonnell Douglas	MD-11	D
M1F	Boeing/McDonnell Douglas	MD-11 Freighter	D
M1M	Boeing/McDonnell Douglas	MD-11 Combi	D
M81	Boeing/McDonnell Douglas	MD-81	D
M82	Boeing/McDonnell Douglas	MD-82	D
330	Airbus	A330 all models	E
342	Airbus	A340-200	E
343	Airbus	A340-300	E
359	Airbus	A359	E
340	Airbus	A340	E
332	Airbus	A330-200	E
333	Airbus	A330-300	E
345	Airbus	A340-500	E
346	Airbus	A340-600	E
330	Airbus	A330	E
351	Airbus	A350-1000	E
359	Airbus	A350-900	E
744	Boeing	747-400 pax	E
772	Boeing	777-200	E
777	Boeing	777 all pax models	E
787	Boeing	787	E
789	Boeing	787-9 pax	E
74E	Boeing	747-400 Combi	E
74F	Boeing	747 freighter	E
74Y	Boeing	747-400 freighter	E
74Z	Boeing	747	E
77W	Boeing	777-300	E
77X	Boeing	777-300	E
741	Boeing	747-100	E
74D	Boeing	747-300 Combi (including-200SUD)	E
74J	Boeing	747-400 Domestic	E
74M	Boeing	747 Combi	E
74T	Boeing	747-100 Freighter	E
74V	Boeing	747SR Freighter	E
74X	Boeing	747-200 Freighter	E
742	Boeing	747-200	E
743	Boeing	747-300 (including -100SUD and -200SUD)	E

747	Boeing	747	E
773	Boeing	777-300	E
74C	Boeing	747-200 Combi	E
74L	Boeing	747SP	E
74U	Boeing	747-300 Freighter	E
74N	Boeing	747-800 Freighter	E
77F	Boeing	777 Freighter	E
77L	Boeing	777-200LR	E
77W	Boeing	777-300ER	E
380	Airbus	A380	F
388	Airbus	A380 pax	F
38F	Airbus	A380 Freighter	F
A4F	Antonov	An-124 Ruslan	F
BH2	Bell Helicopters		X
H25	British Aerospace	(Hawker Siddeley) HS.125	X
J31	British Aerospace	Jetstream 31	X
J32	British Aerospace	Jetstream 32	X
J41	British Aerospace	Jetstream 41	X
JST	British Aerospace	Jetstream 31/32/41	X
HS7	British Aerospace	Hawker Siddeley HS748	X
CCX	Canadair	privejetCanadair Global Express	X
CRJ	Canadair	Regional Jet	X
CCJ	Canadair	Challenger	X
CR1	Canadair	Regional Jet 100	X
CR2	Canadair	Regional Jet 200	X
CNJ	Cessna	Citation	X
CNT	Cessna	twin turboprop engines	X
CN1	Cessna	single piston engine	X
CNA	Cessna		X
CNC	Cessna	single turboprop engine	X
DFL	Dassault	Falcon	X
EM2	Embraer	120	X
ER4	Embraer	RJ145 Amazon	C
ERJ	Embraer	Embraer RJ135 / RJ140 / RJ145	X
E55	Embraer	505 phantom	X
EMB	Embraer	EMB-110 Bandeirante	X
ER3	Embraer	ERJ-135 Regional Jet	X
ERD	Embraer	ERJ-140 Regional Jet	X
D28	Fairchild Dornier	Do-228	X
D38	Fairchild Dornier	Do-328	X
100	Fokker	100	X
F22	Fokker	F28 Fellowship 2000	X
F28	Fokker	F28 Fellowship	X
F50	Fokker	50	X
F21	Fokker	F28 Fellowship 1000	X
F23	Fokker	F28 Fellowship 3000	X
F24	Fokker	F28 Fellowship 4000	X
F27	Fokker	F27 Friendship/FairchildF27	X
AW1	Police Netherlands	helicopter	X
S20	Saab	Saab 2000	C
SF3	Saab	SF-340	X
SFB	Saab	SF-340B	X
TB7	Socata	TBM-900	X
SWM	Swearingen	Merlin twin prop	X

E.2. Stand Compatible Data

E.2.1. Stand Compatibility Flight Sector

The following table depicts the compatibility (1: compatible, 2: incompatible) of the 35 defined stand types with specific flight sectors (the last four columns). These columns depict the flight sector a flight belongs to. The first part refers to the sector a flight is arriving from, while the second part refers to the sector the aircraft is flying to. S = Schengen, NS = Non-Schengen.

Nr	Type	Size	Terminal	S-S	S-NS	NS-S	NS-NS
1	Contact	C	Domestic	1	0	0	0
2	Contact	C	International	0	0	0	1
3	Contact	C	Swing	1	1	1	1
4	Contact	D	Domestic	1	0	0	0
5	Contact	D	International	0	0	0	1
6	Contact	D	Swing	1	1	1	1
7	Contact	E	Domestic	1	0	0	0
8	Contact	E	International	0	0	0	1
9	Contact	E	Swing	1	1	1	1
10	Contact	F	Domestic	1	0	0	0
11	Contact	F	International	0	0	0	1
12	Contact	F	Swing	1	1	1	1
13	Non-Contact	C	Domestic	1	0	0	0
14	Non-Contact	C	International	0	0	0	1
15	Non-Contact	C	Swing	1	1	1	1
16	Non-Contact	D	Domestic	1	0	0	0
17	Non-Contact	D	International	0	0	0	1
18	Non-Contact	D	Swing	1	1	1	1
19	Non-Contact	E	Domestic	1	0	0	0
20	Non-Contact	E	International	0	0	0	1
21	Non-Contact	E	Swing	1	1	1	1
22	Non-Contact	F	Domestic	1	0	0	0
23	Non-Contact	F	International	0	0	0	1
24	Non-Contact	F	Swing	1	1	1	1
25	Remote Operational	C	NA	1	1	1	1
26	Remote Operational	D	NA	1	1	1	1
27	Remote Operational	E	NA	1	1	1	1
28	Remote Operational	F	NA	1	1	1	1
29	MARS	NA	Domestic	1	0	0	0
30	MARS	NA	International	0	0	0	1
31	MARS	NA	Swing	1	1	1	1
32	Remote Non-Operational	C	NA	0	0	0	0
33	Remote Non-Operational	D	NA	0	0	0	0
34	Remote Non-Operational	E	NA	0	0	0	0
35	Remote Non-Operational	F	NA	0	0	0	0

E.2.2. Stand Compatibility Aircraft Size

The following table depicts the compatibility of the different stand types with each aircraft design group (1: compatible, 2: incompatible).

Nr	Type	Size	Terminal	C	D	E	F	X
1	Contact	C	Domestic	1	0	0	0	0
2	Contact	C	International	1	0	0	0	0
3	Contact	C	Swing	1	0	0	0	0
4	Contact	D	Domestic	1	1	0	0	0
5	Contact	D	International	1	1	0	0	0
6	Contact	D	Swing	1	1	0	0	0
7	Contact	E	Domestic	0	1	1	0	0
8	Contact	E	International	0	1	1	0	0
9	Contact	E	Swing	0	1	1	0	0
10	Contact	F	Domestic	0	1	1	1	0
11	Contact	F	International	0	1	1	1	0
12	Contact	F	Swing	0	1	1	1	0
13	Non-Contact	C	Domestic	1	0	0	0	0
14	Non-Contact	C	International	1	0	0	0	0
15	Non-Contact	C	Swing	1	0	0	0	0
16	Non-Contact	D	Domestic	1	1	0	0	0

17	Non-Contact	D	International	1	1	0	0	0
18	Non-Contact	D	Swing	1	1	0	0	0
19	Non-Contact	E	Domestic	1	1	1	0	0
20	Non-Contact	E	International	1	1	1	0	0
21	Non-Contact	E	Swing	1	1	1	0	0
22	Non-Contact	F	Domestic	1	1	1	1	0
23	Non-Contact	F	International	1	1	1	1	0
24	Non-Contact	F	Swing	1	1	1	1	0
25	Remote Operational	C	NA	1	0	0	0	1
26	Remote Operational	D	NA	1	1	0	0	1
27	Remote Operational	E	NA	1	1	1	0	1
28	Remote Operational	F	NA	1	1	1	1	1
29	MARS	NA	Domestic	1	0	1	0	0
30	MARS	NA	International	1	0	1	0	0
31	MARS	NA	Swing	1	0	1	0	0
32	Remote Non-Operational	C	NA	1	0	0	0	1
33	Remote Non-Operational	D	NA	1	1	0	0	1
34	Remote Non-Operational	E	NA	1	1	1	0	1
35	Remote Non-Operational	F	NA	1	1	1	1	1

E.3. Design Day Flight Schedule

The design day flight schedule used in the thesis work can be found in the Gitlab MSc_Thesis page of the faculty of Aerospace Engineering.

F

Recommendations for Further Research

In this chapter, some recommendations for further research will be described. The following recommendations are defined:

- **Multi-Objective Optimisation:** The developed framework allows for a trade-off between two related objectives (both costs). It has been proven with this thesis that multiple objectives can play a role in decision making. These are mainly indirectly considered through the cost factors in the proposed optimisation framework (e.g. cost for exceeding area limitations). For further research, it is recommended to analyse and identify the critical objectives and how these can be considered explicitly through an optimisation framework. Assessment of the viability and usability is key in such research as the complexity increases rapidly with the addition of objectives (with, e.g. other metrics). Furthermore, such a research project can be used to investigate how the stakeholder (e.g. airports, airlines, alliances) interests can be reflected in a framework. Furthermore, it can be analysed how other multi-objective methods can be used in the strategic stand capacity assessment problem.
- **Demand Analysis:** Demand analysis was not included in the research objective of the project. The different techniques have been partly assessed in the accompanying literature study (to assure understanding of the full spectrum of stand capacity assessment). As part of the thesis work, a design day flight schedule has been created to test and validate the developed model's capabilities. For further research, it is recommended to investigate the implications of demand on the stand capacity. This can be done for single demand cases, which are then used to define the stand mix for changes in the anticipated demand. This can be used for scenario analysis and would aid decision-makers through an extra level of insights regarding the problem. Another interesting topic relates to the consideration of multiple demand time frames (e.g. demand now, demand in 5 years, 10 years etc.). This can be added as an extension to the developed optimisation model through which investments are placed in the demand horizon's perspective. E.g. if it is known that in 5 years, the demand will introduce the need for a specific number of stands, it can be wise to incorporate this in the first development phase already (taking into account the costs of the initial demand, the costs of having to remove stands and having to build new stands). Such a framework can also be used to adapt the framework to be dynamic. This can be achieved by incorporating policies to assess the implications of alterations in anticipated future traffic or creating robust schedules.
- **Reflection of real life airport operations:** Within the executed research, multiple assumptions had to be made regarding e.g. towing times of flights. To further tune the operational assumptions, it is recommended to perform collaborative research with the aviation industry (e.g. a consulting firm executing airport development processes for airport stakeholders). In this way, the developed framework can be validated to be used for different airport use cases (regional airport, hub and spoke etc.).
- **Consideration of Airport Layouts:** Traditionally airport layouts are considered in the land use plan and facility sizing phases of an airport master plan. However, since these decisions also impact the stand capacity it is desirable to consider the critical factors and design choices as early as possible; as this is linked to a strategic time frame, the level of detail should be tuned to this. It is recommended to investigate the impact of factors related to decisions concerning airport layouts (e.g. placement of service roads, runway placements, handling of aircraft etc.) on stand capacity and how these can be incorporated within a strategic time frame.
- **Integration with consecutive airport development stpes:** The defined framework defines not only the needed stand mix but also the needed equipment. It can be analysed how this framework can be further extended to be used in later development steps of an airport master plan, such as facility sizing and determination of the needed workforce (as the number of equipment is known). This can, e.g. be extended to consider the number

of ground staff. Furthermore, the viability and usability of linking/considering follow up processes in the stand capacity assessment process can be investigated.

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