Aircraft Stand Capacity Model for Strategic Airport Planning

A Schiphol Airport case study

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by

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TU Delft

Preface

This thesis is the result of my research into strategic stand capacity planning for NACO Netherlands Airport Consultants. In the duration of this project I have had the opportunity to combine my interest in optimisation problems and strategic airport planning. Also the case study of Amsterdam Airport Schiphol has been a great application of complex strategic planning and greatly sparked my interest in airport development.

I would like to thank Paul Roling, my supervisor at the TUDelft, for his positive attitude and guiding me through the world of airport operations. I would also like to thank Emanuel for his guidance during his project. The collaboration with NACO has given me an exciting insight in the world of airport planning. The time spend in the The Hague office has been great in terms of research but also as a positive work environment. Our meet-ups have always delivered fruitful discussions.

This research could never have been conducted without the support of people in my personal environment. I would like to thank my family Ruud, Ingrid, Hans, Renske, Jack, James, Robbert and Danieke for their love and dedication, and letting me finish my stories even though everyone lost track. Special gratitude to my mother who is always manages to motivate me and to pursue my dreams. Also my boyfriend Bing Steup for his never-ending support and for always challenging me in discussions about algorithms, web-development, mathematics and programming. Lastly I would like to thank Kek at the Voldersgracht for giving me infinite inspiration by pouring me the best coffee in Delft.

Marijke Boukema
Delft, February 2018

Summary

The main objective of a Master Plan is to develop an integral long-term development plan to guide the future of an airport. The plan should be compatible with the larger framework of regional and national transport and economic plans. All of this while being sustainable, protecting and enhancing the environment around the airport. One important element is the capacity analysis as a first step in strategic airport planning. Capacity is defined as the maximum sustainable throughput: "How many aircraft operations can an airfield reasonably accommodate in a given period of time?[1]". The research commissioned by NACO is boiled down to the main research objective:

"*To contribute to the development of Strategic Stand Planning for airports, by finding an optimal required Stand Capacity using mathematical optimisation techniques.*"

To give answer to this question a model developed which is called the Strategic Stand Capacity Model. A software framework is created around two main optimisation models: firstly a stand capacity optimisation and secondly a stand allocation optimisation. As the main result the model provides a range of optimal solutions as a trade-off between operational cost and capital cost to support decision making in strategic airport planning. A web-based supporting tool is developed as part of this research project to make practical application possible.

As a case study Schiphol Airport is selected. Historic data is used as input and to validate the results of the model. The impact of expansions at A-pier and H-pier are analysed. The Strategic Stand Capacity Model is then expanded with a strategic airline division feature which allows for insight in shared usage of stands by different demand segments.

The result of the model is not a single solution of stand capacity but a range of optimal solutions of different capital investment. This creates the opportunity for airport planners to make a data-driven trade-off between optimising many performance indicators, such as stand utilisation, bus movements, towing and remote parking. The results of this study will allow airport planners at NACO to develop a flexible master plan with respect to changing demand, and will support decision making to achieve the required stand capacity.

The mathematical optimisation model at heart of the Strategic Stand Capacity Model can be described as a set of two classic linear optimisation problem, integrated in a larger software architecture. The model consists of two optimisation models, one for stand capacity and one for stand allocation. The goal of first optimisation model is to determine the exact amount of stands required for a certain flight schedule. The goal of the second model is to create insight in solution characteristics by providing Gantt visualisations of the solution found in the first optimisation.

For the main optimisation model the main objective is to minimise cost. The cost can be divided in two sources: operational cost and capital cost. To mathematically describe the problem a Mixed Integer Linear Problem formulation is used. In the objective function the two types of cost are both given a weight to allow for a trade-off between these two. Using constraints the complex allocation rules are added to the problem. Two important constraints are defined that model the behaviour at the airport. The stand allocation constraint ensures that only one version of flight splitting is selected, complying with stand size and sector. The second constraint for variable capacity makes sure enough stands are added while ensuring that no flights are overlapping.

The goal of the second optimisation model is to create insight in solution characteristics. This second model is a classic stand allocation problem which uses the amount of stands calculated by the first optimisation model as a hard input. Another input of this model are the results of the first model about flight-standtype combinations: for each standtype a set of flights that are allocated to that standtype. These two are used as input for the second optimisation model. The objective of this model is to allocate flights to individual

stands while minimising the amount of stands used. The formulation style of the second optimisation model is a Binary Problem formulation. Two constraints are used to model the rules of stand allocations. Firstly a hard constraint guarantees that each flight is allocated to a stand. A second constraint ensures that no flights are overlapping.

The resolution method is based on extensive literature research into algorithms applied for stand allocation models. For both models the primal simplex algorithm is used to search for the optimal solution. A trade-off is made between available optimiser tools where IBM CPLEX is selected, which will be integrated in a python framework. Both optimisation models are solved using the Dynamic Search Algorithm in CPLEX. The version of CPLEX used is 12.7.1.0, which is integrated in a python framework. This framework is extensively described in the software architecture.

The main result of optimisation model 1 is the stand capacity required for the flight schedule of peakday 7th of August of 2017. By developing a Pareto optimal range of solution the model provides strong trade-off possibilities between capital and operational cost. These show for Schiphol that a minimum of 131 stands are required, with standmix depending on the solution selected by the decision maker.

The result of the second optimisation model is Gantt chart which visualises that the utilisation per stand varies strongly. This is validated on historic stand utilisation data which also shows a great variance in air traffic movements handled per stand. In strategic airport planning it should therefore be taken into account that it is typically not possible to achieve the maximum stand utilisation on all stands.

As part of validation the model is checked on operational effects such as cross-utilisation in stand-flight combinations. This is investigated for aircraft size and for aircraft sector. By applying cross-utilisation the capacity can be used more optimally because peaks between different sizes or sectors are absorbed. These effects are visualised using coloured stack-line charts. Based on these charts the conclusion can be drawn that the model strongly captures cross-utilisation. By capturing these effects, the stand-mix can be determined most optimally.

Observations in these utilisation charts confirm the two drivers for swing stands stated to be:

1. To increase stand utilisation when peaks of Schengen flights and non-Schengen flights are such that a common share using a swing stand is preferable (peaks are not occurring at the same time)

2. To prevent operational cost of bussing passengers or towing aircraft that have international origins and domestic destinations (or vice versa).

The current capacity offered by Schiphol is forced into the model to investigate it's optimality. The results are close the optimal solution curve, but there is room for improvement. The amount of stands needed with the current stand capacity is a 100% match with the total stands needed on the entire Pareto optimal curve. No conclusion can be made about the amount of contact stands versus remote stands, because it is a ratio depending on the trade-off that a decision maker desires. However, the current solution offered by Schiphol is proven to be sub-optimal in terms of standmix where for the capital cost spend a reduction of 18% in operational cost is possible.

A validation on airport tow operations is performed. The rules on stand allocations are confirmed to be captured by the model. The Strategic Stand Capacity Model models operational rules closely, with a 98% match on tow movement observed in historic stand allocation data.

The future expansion at the H-pier and A-pier has proven to induce a reduction in operational cost by 24% by adding a new set of contact stands. It can be concluded that the new expansion shows improvements in stand allocation, but is still unable to handle all demand at contact stands. Even though 7 extra contact stands are added for the capacity, there is still room for capacity improvement in the morning peak.

The Strategic Stand Capacity model provided a range of solutions for All Other Airline(AOL) demand segment. The minimum amount of stands needed to converge to a solution are 43 stands. The stand-mix can be chosen along a range of optimal solutions. Special attention is paid to the solution which requires the lowest capital investment while handling all passengers at contact stands. This solution requires 38 contact stands of which 27 narrowbody stands and 11 widebody stands. A combination of 3 remote narrowbody and 3 remote widebody stands is needed. Due to the fact that 100% of passengers are handled at contact stands the level-of-service is high. However, the selection of a solution on the trade-off curve is up to the individual decision maker.

When separating the AOL demand from Skyteam demand a problem is observed concerning overnight flights. Demand for Schengen stands is driven on overnight demand, however, there is not enough demand during the day to utilise these stands. In the traditional current combination with Skyteam and AOL a higher utilisation can be achieved, because demand peaks of these groups are at different times of day such that a common share of stands enhances efficient utilisation for the flight demand characteristics at Schiphol Airport. It can be concluded that a separation of demand will therefore result in a decrease of overall utilisation. This is proven by applying the Strategic Stand Capacity Model on both demand segments, which shows that a separation of demand increases the minimum amount of stands required by 14%. It is therefore decided to add an extra feature to the strategic stand capacity model where the model can optimise the strategic division in airlines.

For a strategic airline division the strategic stand capacity model is changed slightly. The split in demand is defined as follows. Skyteam, The main alliance of Schiphol, is allocated to segment A together with airlines that codeshare with KLM. The other alliances Star Alliance and Oneworld Alliance are allocated to segment B. The remaining 26 airlines are free to move between the two segments. A hard split in demand resulted in a total of 151 stands needed when all these airlines are allocated to segment B. When these 26 airlines are variable and the model can chose an airline division, the total amount of stands needed can be reduced to 136, which is a reduction of 10 % in stand capacity needed. The model already reaches the most optimal amount of stands of 136 by shifting 9 airlines to segment A. It can be concluded that a hard split in airlines results in an inefficient combination of airlines. It should be noted that for the flight schedule used for this model the results showed that a total amount of stands of 131 can be achieved, which implies that the division chosen will never reach the same efficiency as a combined usage in stands.

Concluding, the model has proven to optimise stand capacity while following rules of airport operations and stand allocations. There is no one solution for stand capacity, but a range of solutions where the decision maker can select the best solution.

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Abbreviations

AAS	Amsterdam Airport Schiphol
AOL	All Other Airlines
ATM	Air Traffic Movement
DOY	Day Of Year
GAP	Gate Assignment Problem
HOD	Hour Of Day
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
KLM	Koninklijke Luchtvaart Maatschappij
LCC	Low Cost Carrier
MARS	Multi-Aircraft Ramp System
MILP	Mixed Integer Linear Programming
NACO	Netherlands Airport Consultants
PBB	Passenger Boarding Bridge
RASAS	Regulations Aircraft Stand Allocation Schiphol
RON	Remain OverNight
SAP	Stand Allocation Problem

Symbols

$A_{2,i}$	binary variable to assign arrival part of 2-split parking option
$A_{3,i}$	binary variable to assign arrival part of 3-split parking option
α	weight for operational cost
$c1_j$	capital cost to build a stand of standtype j
$c2_{ij}$	operational cost of assigning operation i to standtype j
$D_{2,i}$	binary variable to assign departure part of 2-split parking option
$D_{3,i}$	binary variable to assign departure part of 3-split parking option
i	set of flight operations
j	set of different stand types
$P_{3,i}$	binary variable to assign non-operational parking part of 3-split parking option
B	Set of separation buffer times
Cap_j	Set of predetermined number of stands of standtype j
S_i	Set of compatible stands for operation i
O	Set of operations
O_t	Set of conflicting operations at time t
S	Set of standtypes
T	set of unique arrival times
W_i	Set of tow times depending on operation i and stand j
V_{1i}	binary variable for full parking option
V_{2i}	binary variable for 2-split parking option
V_{3i}	binary variable for 3-split parking option
x_{ij}	binary variable of assignment of an operation i to a standtype j
y_j	integer variable defining the amount of stands

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1 Introduction

Advances in technology in aviation industry and economic growth in the last years have led to a steady increase in air travel. ICAO suggests that this growth can be projected into the foreseeable future [1]. This growth goes hand in hand with the need for ever increasing airport capacity. NACO gives an answer to these worries by developing Airport Master Plans for over 600 airports around the world, for both existing and future airports. Being ready for an unlimited number of future scenarios asks for great flexibility and detailed long-term guidance.

One of the bottlenecks in airport capacity are aircraft stands, the physical parking places for aircraft which can be both connected to terminals as well as remote stands. The research published in this document focuses on the strategic design of aircraft stands, a crucial element of airport master planning. In airport design the stands are the physical parking spaces of aircraft. Many different types of stands exist with various design options to make sure each aircraft can operate at the airport as optimally as possible. As part of the Airport Master Plan the stand capacity has to be designed to optimally fulfil future demand, in terms of stand quantity but also location and specific type of stands. The research commissioned by NACO is boiled down to the main research objective:

"*To contribute to the development of Strategic Stand Planning for airports, by finding an optimal required Stand Capacity using mathematical optimisation techniques.*"

Scientific literature does not show any evidence of a stand allocation model that can determine the most optimal stand capacity. On the other hand no stand capacity tools exist that take stand allocation rules into account. Therefore, a strategic tool that models stand allocations while having variable capacity will be a significant improvement. The theoretical relevance of this project is to design an optimisation model which optimise stand capacity while integrating aircraft allocation rules. To create such a model first the technical real-life problem should be mathematically formulated, after which a resolution method has to be applied to converge to an optimal solution.

The model developed is called the Strategic Stand Capacity Model. A software framework is created around two main optimisation models: firstly a stand capacity optimisation and secondly a stand allocation optimisation. As the main result the model provides a range of optimal solutions as a trade-off between operational cost and capital cost to support decision making in strategic airport planning. A web-based supporting tool is developed as part of this research project to make practical application possible.

As a case study Schiphol Airport is selected. Historic data is used as input and to validate the results of the model. The impact of expansions at A-pier and H-pier are analysed. The Strategic Stand Capacity Model is then expanded with a strategic airline division feature which allows for insight in shared usage of stands by different demand segments.

[1] https://www.eurocontrol.int/sites/default/files/content/documents/official-documents/reports/201307-challenges-of-growth-summary-report.pdf

The result of the model is not a single solution of stand capacity but a range of optimal solutions of different capital investment. This creates the opportunity for airport planners to make a data-driven trade-off between optimising many performance indicators, such as gate utilisation, bus movements, towing and remote parking. The results of this study will allow airport planners at NACO to develop a flexible master plan with respect to changing demand, and will support decision making to achieve the required stand capacity.

1.1. Background: Strategic Airport Planning

Caves book named Strategic Airport Planning describes a Master Plan as crucial preparation for future of an airport [2]. The design of an airport is a complex piece of engineering where many requirements have to be met. Not only design and engineering, but also project management and finance is part of an Airport Master Plan. In this section a short introduction is given to airport design with a special focus on stands.

The main objective of a Master Plan is to develop an integral long-term development plan to guide the future of an airport. The plan should be compatible with the larger framework of regional and national transport and economic plans. All of this while being sustainable, protecting and enhancing the environment around the airport. Stakeholders, both public and private, have to be informed and enabled to participate in planning. This way as many uncertainties as possible are removed.

Besides these project management objectives, also the physical planning of terminals, airspace, airfield, landside and all necessary facilities. The location should be analysed on restrictions for potential expansions in the future. This also includes project finance, such as capital investment planning and economic planning of cost and revenue streams. Also environmental impact should be assessed and mitigation strategies should be proposed. All these steps combined are visualised in a flow chart in Figure 1.1.

In the strategic development in Figure 1.1 the block of capacity analysis is seen. The Evaluating Airport Manual by FAA states the following definition of airport capacity is as the most use-full because it compares capacity with demand.

> **Capacity** defined as the maximum sustainable throughput: "How many aircraft operations can an airfield reasonably accommodate in a given period of time when there is a continuous demand for service during that period?[1]"

The word sustainable reflects the fact that this capacity can be exceeded however not for an entire hour. In this block of capacity calculations also the optimal stand capacity calculations are performed. As an input of these calculations a flight schedule is needed. However, this flight schedule is not always available and therefore visualised as a light-blue block. The Strategic Stand Capacity Model is designed to fit in this capacity analysis block, having a flight schedule as input and having facility sizing as the next step. This means that at this point in the design phase the terminal is not yet designed and thus the location of stands is not known.

At the core of all these aspects lies the forecast of aviation activity, especially for detailed capacity planning. According to Caves the biggest uncertainty in airport planning is future demand. Therefore, the model should be flexible and easily rerun when changes occur in expected flight demand, this is done by applying demand management.

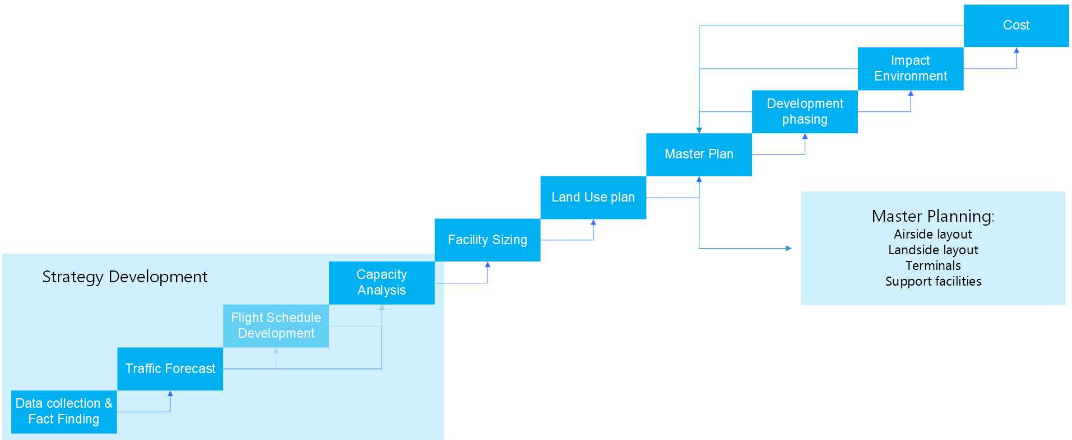


Figure 1.1: Master Planning phases

1.2. Research Questions

The objective of this research is to contribute to the development of Strategic Stand Planning for airports, by finding an optimal required Stand Capacity using mathematical optimisation techniques. Besides this central theme of the research, two important sub-goals are investigated in this project. The first sub-goal is to create meaningful intelligence from the model to support decision making in strategic airport development. Not only the required number of stands should be provided but also sensitivity analysis and implications for different scenarios should be presented. It is important to track the feasibility of creating fit-for-purpose data-driven business intelligence for airport design at NACO while also contributing to the body of scientific knowledge in this field. The second sub-goal is to determine the optimal time interval for the flight schedule, whether this is an hour, a day, a year or a complete optimisation for multiple years. To reach these project goals a set of research questions are formulated. Four fields of interest are identified to group the research questions: the technical design of aircraft stands, assessment of stand capacity, mathematical modelling and flight demand forecasting. Each question is divided in several sub-questions:

1. What are the relevant criteria and objectives for the planning of aircraft stands?
   (a) What are the relevant stand planning objectives and how are they prioritised?
   (b) What are the relevant stand planning constraints?
   (c) How should a strategic stand capacity model represent its results to support decision making?
2. How is the capacity of aircraft stands currently assessed?
   (a) What is the current stand capacity planning procedure and its quality?
   (b) On which airport elements/systems is stand capacity dependent?
   (c) What is considered as an efficient and successful stand capacity?
   (d) What is the optimal time interval of a stand capacity analysis?
3. What mathematical optimisation methods exist for the strategic stand capacity model?
   (a) How can a stand allocation schedule be mathematically modelled?
   (b) What is the best mathematical formulation to define the stand capacity problem?
   (c) What is the best mathematical optimisation resolution algorithm to solve the stand capacity problem?
   (d) How can a trade-off between all objectives be represented?

To give answer to the main objective of this research a set of steps have to be defined. In Figure 1.2 the research framework can be seen. The theoretical basis of the research can be seen in the first column, which correspond to the four topics of interest stated in the above section. These topics are covered in the literature review written parallel to this project proposal. The methodology is to continuously investigate these theories throughout all modules of the model development. The second column shows the model development where the experiment is modelled. The third and fourth columns are the steps that need to be taken are to process the results and create recommendations.

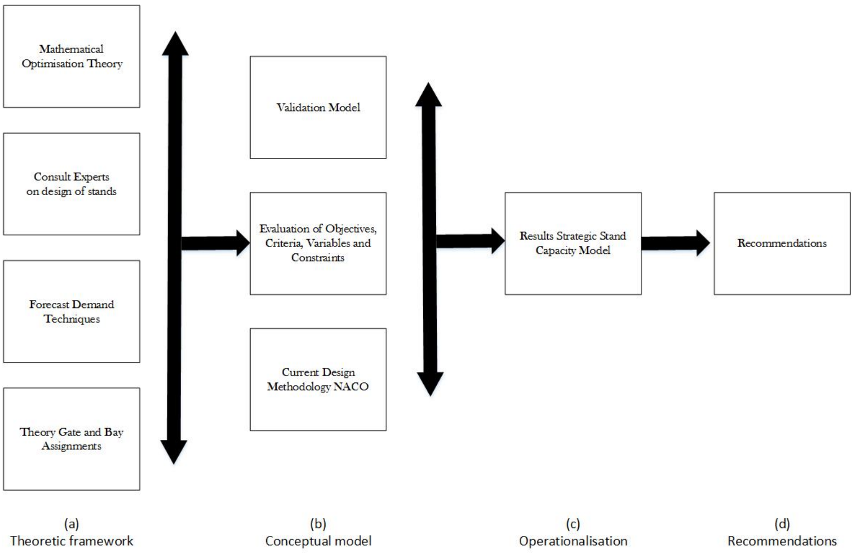


Figure 1.2: Research Framework

The current body of knowledge on mathematical optimisation theory for stand allocation problem will be used to answer the objective of this research and thus to find an optimal solution for the stand capacity problem. The methodology is to apply linear optimisation techniques. This implies that the stand problem should be converted into a quantified model using expert knowledge to define all variables. According to stand allocation literature the computation times might run up to several hours, which required further investigations into appropriate heuristic or meta-heuristic algorithms. In the literature research performed prior to this thesis these are investigated.

Consults with experts at NACO is needed to define all the parameters and variables in the mathematical model. Expert knowledge is needed to assign an affinity value between particular combinations of aircraft types to aircraft stands. This affinity variable will allow to model that certain aircraft will fit a particular stand type, but it is not the most desired and most efficient solution in airport operations. Also historic data can be used to assign values to parameters. Examples are average idle times between aircraft that operate at a single stand, or average turn around times per aircraft type.

In the second column the conceptual model is defined in three modules, namely the Pre-Processing Module, the Forecasting Module and the Optimisation Module. In the Pre-processing module the parameters and variables of the model are generated, based on the particular scenario to be investigated. Then in the second module, the forecast is generated for that particular scenario, which will deliver a flight schedule. In the third module the model the flight schedule is optimised for the required number of stands. This solution is then used in the third column. In the third column the results are validated and post-processed. In the post-processing the results are used to develop performance metrics by going through an extensive sensitivity analysis. As shown in the fourth column, the last step is to give recommendations on these results by looking at the bigger picture of airport master planning.

1.3. Methodology

The methodology behind the development of the Strategic Stand Capacity Model can be described as a set of two classic linear optimisation problem, integrated in a larger software architecture. The model consists of two optimisation models, one for stand capacity and one for stand allocation. The goal of first optimisation model is to determine the exact amount of stands required for a certain flight schedule. The goal of the second model is to create insight in solution characteristics by providing Gantt visualisations of the solution found in the first optimisation.

For Strategic Stand Capacity Model the physical problem has to be translated in a mathematical model. An optimisation model consist of an objective function, which is the equation that drives the solution to a certain business goal. The constraints define the rules of the game - what is allowed, what is preferred and what is absolutely not allowed. The algorithm then searches the solution space for an optimal solution by varying the decision variables. The Strategic Stand Capacity Model consists of two optimisation models, where the first optimises the stand capacity and the second allocates aircraft to individual stands to create a planning based on this capacity.

An extensive research into stand allocation and gate assignment research is used as a guide to determine the best methods of mathematical formulation of the objective, constraints and optimisation techniques. The two optimisation models differ slightly in optimisation formulation methods, which will be described in the next two sections.

For the first and main optimisation model the main objective is to minimise cost. The cost can be divided in two sources: operational cost and capital cost. To mathematically described the problem a Mixed Integer Linear Problem formulation is used. In the objective function the two types of cost are both given a weight to allow for a trade-off between these two. Using constraints the complex allocation rules are added to the problem. Two important constraints are defined that model the behaviour at the airport. The stand allocation constraint ensures that only one version of flight splitting is selected, complying with stand size and sector. The second constraint for variable capacity makes sure enough stands are added while ensuring that no flights are overlapping.

The goal of the second optimisation model is to create insight in solution characteristics. This second model is a classic stand allocation problem which uses the amount of stands calculated by the first optimisation model as a hard input. Another input of this model are the results of the first model about flight-standtype combinations: for each standtype a set of flights that are allocated to that standtype. These two are used as input for the second optimisation model. The objective of this model is to allocate flights to individual stands while minimising the amount of stands used. The formulation style of the second optimisation model is a Binary Problem formulation. Two constraints are used to model the rules of stand allocations. Firstly a hard constraint guarantees that each flight is allocated to a stand. A second constraint ensures that no flights are overlapping.

The resolution method is based on extensive literature research into algorithms applied for stand allocation models. For both models the primal simplex algorithm is used to search for the optimal solution. A trade-off is made between available optimiser tools where IBM CPLEX is selected, which will be integrated in a python framework. Both optimisation models are solved using the Dynamic Search Algorithm in CPLEX. The version of CPLEX used is 12.7.1.0, which is integrated in a python framework. This framework is extensively described in the software architecture in chapter 4.

The results of the model are validated using a Schiphol case study. A Pareto optimal front is created where the stand capacity solutions along the Pareto optimal front can be investigated. Then, the solution offered by Schiphol is forced into the model to investigate how the current capacity at Schiphol performs. A sensitivity analysis is done on cost and time parameters, after which the historic allocation data of Schiphol is used to validate the model. After this validation, the model is applied for strategic airline division where demand is divided in segments to optimise stand capacity.

1.4. Conclusion on Research Methodology

In this chapter the main research object was presented to be:

"*to contribute to the development of Strategic Stand Planning for airports, by finding an optimal required Stand Capacity using mathematical optimisation techniques.*"

As a guide throughout this project a research framework is developed and a list of research questions is provided. The background of Strategic Airport planning and Mathematical Modelling form the theoretical foundation of this model.

To give answer to the research objective a Strategic Stand Capacity Model is developed, being a set of two classic linear optimisation problem, integrated in a larger software architecture. The goal of first optimisation model is to determine the exact amount of stands required for a certain flight schedule. The goal of the second model is to create insight in solution characteristics by providing Gantt visualisations of the solution found in the first optimisation. As a case study the AAS is investigated. For both models the primal simplex algorithm is used to search for the optimal solution. Both optimisation models are solved using the Dynamic Search Algorithm in IBM CPLEX.

The structure of this thesis is as follows. In chapter 2 the background of Schiphol Airport is given to provide as a basis of understanding of airport operations and specific characteristics of Schiphol. Then, the physical problem is translated in a mathematical model in chapter 3. Around this mathematical model a software framework is developed, which is explained in chapter 4. As input of the Strategic Stand Capacity Model a flight schedule and a few databases are used, which are provided in chapter 5. Then, the results and validation of the model are given in chapter 6. As an application the model is used for a research in strategic airline division in chapter 7. Lastly, a chapter with conclusions and recommendations is provided.

2

Schiphol and Current Capacity

Schiphol aspires to develop into Europe's Preferred Airport for both passengers and airlines. The overall business strategy for 2016-2020 is focused on reinforcing the current competitive position of Schiphol being a strong intercontinental hub [3]. In terms of its connecting network, Schiphol competes in the top of European airports together with Frankfurt, Paris and London. Currently Schiphol holds the number one position in terms of flights handled per year [3]. However, to hold this position, future demand requires strategic capacity planning for today. Strategic planning at Schiphol in the last years resulted in the capacity expansions of a new A-pier and connected terminal which will be delivered in phases from 2019 till 2025. Due to political reasons at Schiphol currently maximum capacity is set on 500.000 ATM till 2020.

Because the strategic stand capacity model takes many airport-specific patterns of particular flights into account, it is important to first introduce these concepts at Schiphol and why they influence stand utilisation. In this chapter these influences at Schiphol are introduced, which will then be taken into account in the strategic capacity model. By validating and calibrating the model on these details of the Schiphol case study, it can then be applied for different scenario's of strategic combinations of airlines.

The structure of this chapter is as follows. To create a basis of understanding firstly the current airport layout, location and stand capacity are described. Secondly, Schiphol's network of connected destinations is set out. In the third section the main players at the airport are introduced, from both airline and alliance perspective. After that, the aircraft operating at Schiphol and their influences on stand capacity are explained. Fourthly, the aircraft and stand sizes are explained. Lastly, an overview of stand capacity is provided.

2.1. Airport Layout

Before diving in demand characteristics it is important to form a basis of understanding of the context of this airport. Firstly, a short introduction is given on the location of the airport and the design specifics of the terminal. Then, the runways and their capacity specifics are provided and their influence on airport capacity.

2.1.1. Location

Schiphol airport is located near Amsterdam, the capital of the Netherlands. Holding the competitive position it currently holds is also of interest of the government and is one of the main priorities of the dutch Ministry of Infrastructure, Public Works and Water Management. Specifically, the increase of capacity is listed as high priority on the action-list published in 2016 [4].

2.1.2. Terminal Configuration

The layout of Schiphol as of 2017 can be seen in Figure 2.1. The airport holds about 2.787 hectare. The airport has a single-terminal concept where one large terminal is split into multiple departure halls. It is possible to walk between from pier to pier, in either the Schengen or the Non-Schengen area. These divisions can have large influences on airports and stand allocation planning because both direct and transfer passengers need to able a gate within minimum connecting time.

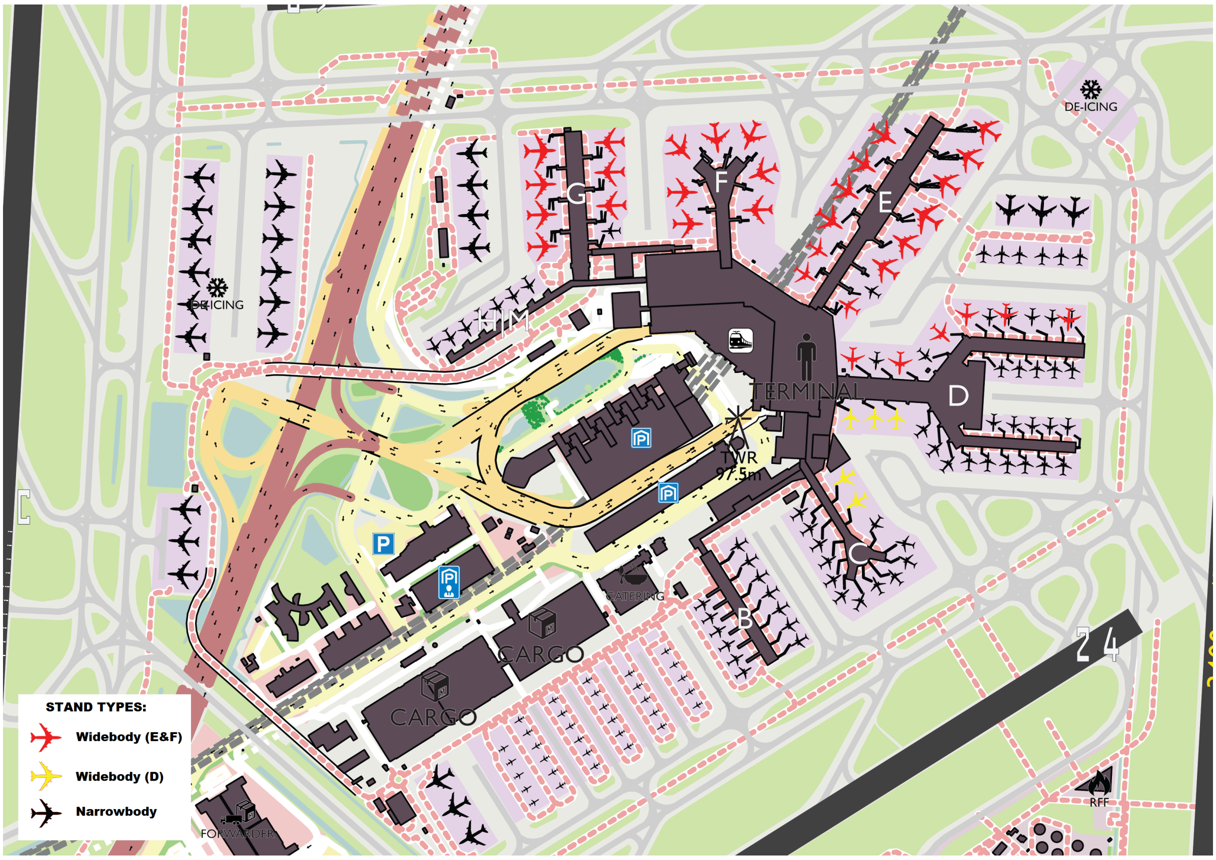


Figure 2.1: Layout of Schiphol with aircraft stands [5]

In Figure 2.2 different traditional terminal concepts can be seen. The layout of Schiphol is a pier configuration with exception of the A/B platform that is operated by bus, which is an open apron concept.

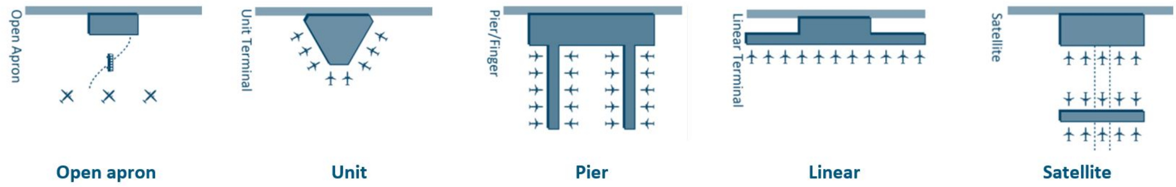


Figure 2.2: Types of terminal configurations as defined at NACO[6]

The A-field located south-side of Schiphol operates an open apron concept, where people use busses to get to the terminal. The strengths of this concept are short turnarounds and the fact that both Schengen and non-Schengen flights can operate there using busses to different bus gates [7]. However, using busses increase operational cost which implies that a careful trade-off is needed between capital investment cost and operational cost. It is also had weak hubbing functions for transfer passengers.
The B, C, D, E , F and G pier have traditional piers, build in a halve circle around the main terminal building. The strength of the pier concept is that the utilisation of the airport area is efficient. A plus of this layout is the hubbing function, however passenger walking distances can become an issue using this concept.

The influence of terminal design on stand utilisation is large, due to two reasons. Firstly, sectorisation (Schengen/Non-Schengen areas) inside the terminal influences the compatibility of a flight with a stand. When both sectors operate at one stand, an extra level has to be added to the terminal to assure that passengers can be separated and walk to the correct Schengen or non-Schengen area in the terminal. This is very important in terms of security and border control. Adding an extra level to the terminal is very convenient to simplify airside operational cost due to swing stand feature, however it increases capital cost of needing to build a double layer terminal. In the strategic stand capacity model a trade-off between these two is necessary.

The Schengen sector at Schiphol can be further divided into secure and non-secure. A non-secure Schengen flight is defined as high-risk destination and therefore require extra security. A list of non-secure Schengen destinations is used to assure correct separation. These destinations are often called unclean.

Secondly, the location of individual stands influences stand utilisation due to passenger walking distances. Hub airlines have strong preferences for stands that are located centrally in the terminal, which makes other stands underutilised. For Schiphol this is important due to the hubbing characteristics of this airport. For the strategic stand capacity model this effect can not be taken into account because this model is at a strategic level in the design phase of an airport, before facility sizing, and therefore it is not yet known where each stand will be located.

2.1.3. Runways

Schiphol airport has six runways, of which one is primarily used for general aviation. The influence of runway capacity on stand capacity is that the runway capacity has effects on flight schedules, which is the main input to determine stand capacity. Airports with certain peaking behaviour may have more difficulty reaching high stand utilisation due to complex demand characteristics with different types of peak throughout the day. It is therefore important for stand utilisation to perform at least a full day analysis instead of a peak hour analysis to capture the influences of this demand peaking behaviour.

2.2. Network connectivity

The main mission of Schiphol Group is Connecting the Netherlands[3]. Many destinations in and outside of Europe are already connected to Schiphol. These destinations can be divided into Schengen and non-Schengen. In this section the influence on stand capacity of sectorisation at Schiphol is explained.

2.2.1. Destinations

In historic flight data of 2017 January till November over 338 unique destinations are found (381 including frequency lower than 2 ATM per year), from 103 countries. When cargo flights are included even 373 destinations are found (453 including frequency lower than 2 ATM per year) from a grand total of 117 countries. The destinations change throughout the year, due to political unrest and commercial influences [3].

Due to this high connectivity the airport is utilised by many transfer passengers, in 2016 over 37.8 percent of passengers used Schiphol as a hub to their final destination. In Figure 2.3 a visualisation of Schiphol destinations is provided, which is available in the software Strategic Stand Capacity tool made during this research and works for any flight schedule provided to the tool[8].

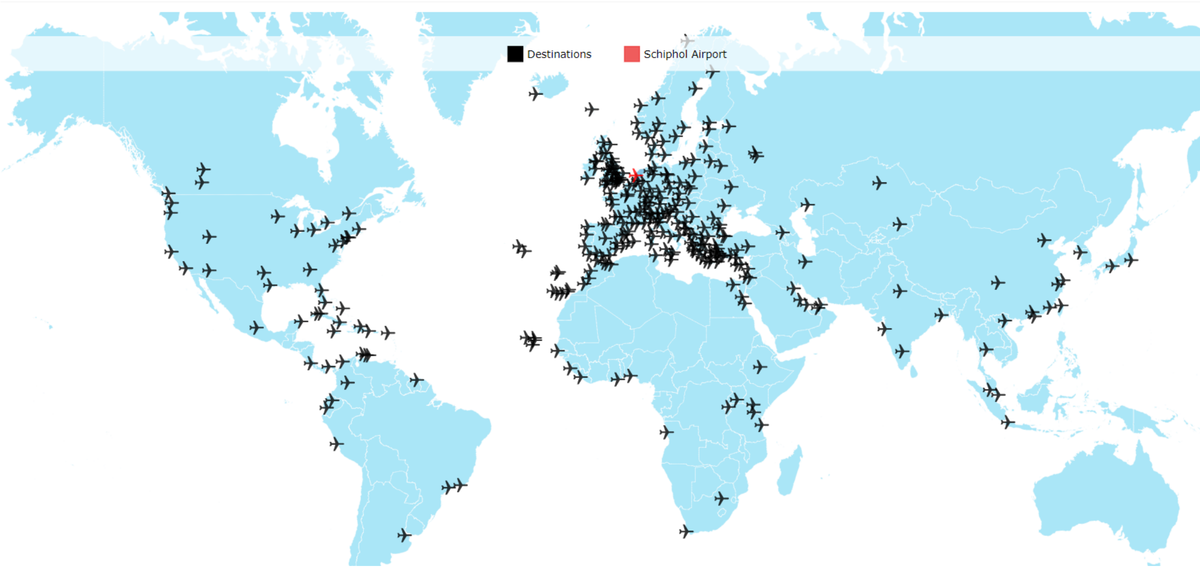


Figure 2.3: Destinations of Schiphol

The destinations are divided in two sectors Schengen and non-Schengen traffic due to restrictions of border control. In Figure 2.4 an overview is given of these areas. An interactive version of this visualisation is available in the software tool made as supportive tool for this research [8].

Schiphol separates passengers from particular destinations for an extra security check, these destinations are called unclean. For these stands another level is added to the terminal which creates extra costs. Therefore these stands are more expensive than conventional stands.

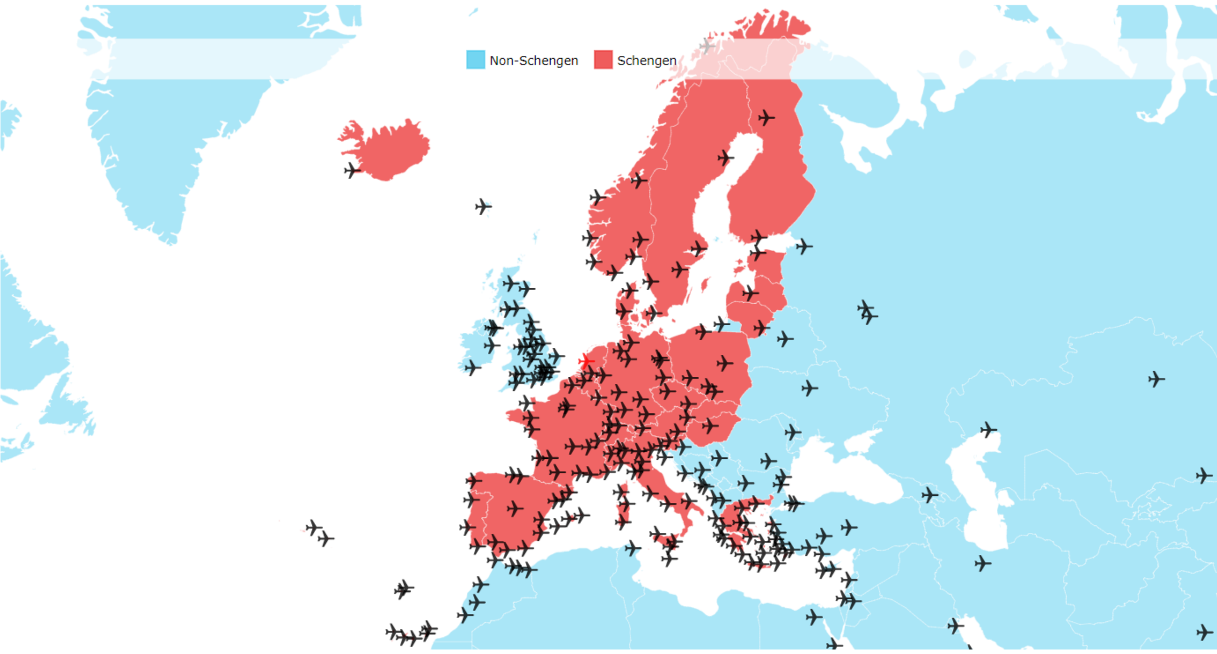


Figure 2.4: Sectorisation at Schiphol: Schengen and non-Schengen countries[5]

Schiphol is divided in a Schengen and non Schengen sector, which results in a complex design of passenger flow inside the terminal. The division in sectors can be seen visually in Figure 2.5. The D-pier has three floors to separate arriving non-Schengen, arriving & departing Schengen, and departing non-Schengen. In the H and M pier the segregation is done by a partition wall on the same floor. This solution requires a higher initial capital investment, but reduces operational cost by reduction of bus movements.

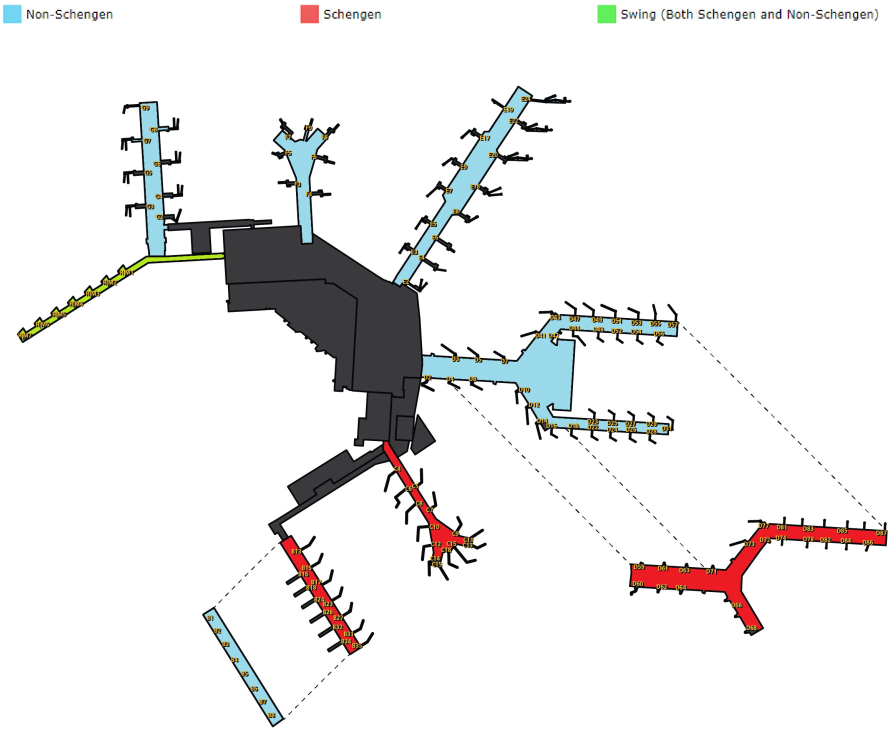


Figure 2.5: Sectorisation at Schiphol: Schengen, non-Schengen and swing piers[5]

2.2.2. Destination restrictions on stand utilisation

The effect of origin and destination on stand capacity is very large. During the design of a master plan it is very important to determine capacity needed for these groups due to the effects on terminal design. Typically a pier or a set of stands is dedicated for either Schengen or non-Schengen operations, because these passengers are not allowed to mix. As can be seen in the master plan flowchart in Figure 1.1 the facility sizing is the next step after capacity analysis, which makes it very useful for this model to determine dedicated stands to specific origin/destination groups.

Another option are swing stands. These stands are a good example of the shared use of a stand to increase flexibility. One stand is configured to allow use by Schengen or non-Schengen flight operations. Swinging a gate is performed by segregating passengers using partition walls inside the terminal building. Schengen and non-Schengen can still be separated to make sure the groups are not mixing for security reasons. This does adds complexity to the terminal design but it adds flexibility and increases gate capacity which can be necessary during peak hours.

There are two drivers to build a swing stand:

1. To increase stand utilisation when peaks of Schengen flights and non-Schengen flights are such that a common share using a swing pier is preferable (peaks are not occurring at the same time)

2. To prevent operational cost of bussing passengers or towing aircraft that have international origins and domestic destinations (or vice versa).

The second reason is not an obvious one, but appeared after Schiphol data analysis. These sector-switching aircraft are a result of routing where an aircraft does not necessarily returns to their originating airport, and might even switch from a Schengen country to a non-Schengen country. The amount of aircraft that switch on the day of analysis of 7th of August 2017 can be seen visually in Figure 6.4 which is made for this research and can be accessed using the Strand Stand Capacity Software tool made for this research. On a daily basis these sector-switching flights reach up to 21 percent of total demand.

Despite the fact that, using swing stands, operational cost due to bussing and towing for all these flights go down, the initial capital investment is higher for a swing stand due to the extra layer of the terminal. In Figure 2.5 this extra layer for Schiphol pier D can be seen visually. In the strategic stand capacity model it is therefore important to make a trade-off between capital investment and operational cost.

Figure 2.6: Aircraft flow from sector of origin to sector of destination

2.3. Airlines: the main players

Schiphol is the hub airport for KLM. Other prominent players is the regional airline KLM Cityhopper as well as Martinair, Transavia, TUIfly Netherlands and Corendon Dutch Airlines. It is also the European hub for Delta AirLines.

In 2017 over 163 unique airlines are identified that operated at Schiphol, of which 38 only visited Schiphol once or twice. About 28 airlines are solely transporting cargo. In Table 2.1 the top 10 airlines and their corresponding airlines can be seen. It is clear that KLM holds the strongest position with 48 percent of all flights.

Table 2.1: Top 10 airlines and their market share in 2017

Airline	Arrival & Departures	Market share
KLM	202141	48%
Easyjet	31202	7%
Transavia	29081	7%
Flybe	10512	2%
Delta Airlines	10142	2%
Air France	9695	2%
TUIfly	9189	2%
British Airways	9025	2%
Vueling	8614	2%
Lufthansa	6712	2%

Airlines that are considered to have codeshares with KLM are shown in Table 2.2 as of December 2017 [9].

Table 2.2: Codeshares

Adria Air	Alitalia	Croatia Airlines	Korean Air	Xiamen Airlines
Aer Lingus	Atlasglobal	Czech Airlines	Malta	Air Malta
Aeroflot	Belavia	Delta Airlines	MNG Airlines	Alaska Airlines
Aeromexico	Bulgaria Air	Etihad Airways	Pegasus	Bangkok Airways
Air Baltic	China Airlines	Garuda	SAS	Copa Airlines
Air Europa	China Eastern	Georgian Airlines	Tarom	HOP!
Air France	China Southern	Jet Airways	Transavia	Middle East Airlines
Air Serbia	Cityjet	Kenya Airways	Ukraine	Malaysia Airlines
Air Astana	Westjet	Vietnam Airlines	Sichuan Airlines	Saudia

2.3.1. Alliance market share division

The effect of a large alliance such as Skyteam is that they operate in a hub structure where each arrival wave is followed by a departure wave. At schiphol maximum runway capacity is nearly reached, and that is why low cost carriers and other airlines tend to operate in the off-peaks of the main alliance. Due to high traffic and high landing fees at Schiphol some LCC decided to operate at other airports in the Netherlands, such as Eindhoven, Rotterdam The Hague Airport and Lelystad Airport.

In Figure 2.7 it is clear that Skyteam holds the biggest market share. With over 17 Skyteam airlines, Schiphol is the worlds most diverse Skyteam partner [1]. KLM and it codeshare partners together hold a network of 193 destinations, together with all codeshare partners. The alliance division will form the basis of the scenarios analysed for the strategic stand capacity model.

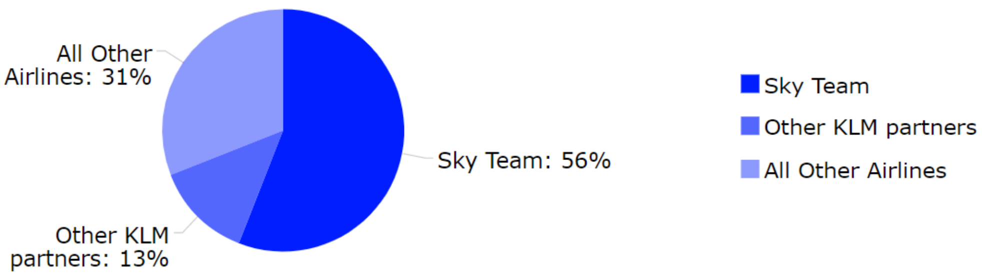


Figure 2.7: Alliances and their market share

2.3.2. Airline effects on stand utilisation

The effect of airlines on stand utilisation is twofold. Firstly airlines desire stands that minimise taxi-distances. Secondly, airlines may have the desire to operate at stands with favourable passenger walking distances to optimise their connectivity. However, this model is pre-facility design, which means that these stand capacity calculations occur before the location of the stands is known. Without a location it is not possible to determine passenger walking distances and there airline effects left out of scope for this model. It is therefore decided to leave pure airline dedicated stands out-of-scope.

Another important influence of airlines is the combination with ground handlers. According to Hoogeveen [10] it is convenient to allocate airline to specific ground handlers at Schiphol for daily planning, since it creates the convenient situation where both parties have the incentive to ensure that the first flight leaves within time. However, for this research it is assumed that the effects on total capacity are small and will be investigated during facility planning design phase.

2.4. Aircraft size and stand size

ICAO standardised five aircraft design groups by the ICAO which are used as a basis to define stand sizes [11]. An overview of these types can be seen in Table 2.3. At Schiphol these are translated into C, D, E and F stands, which can be seen in seen visually as the red, black and yellow aircraft in Figure 2.9. Size D is left out of scope since these aircraft sizes are currently being phased out according to NACO.

[1] From http://www.annualreportschiphol.com/results/our-results/top-connectivity

Table 2.3: Stand Size Codes defined by ICAO [11]

AC Design Group	Stand Code Letter	Length Wing Span	Outer main gear wheel span
I	A	< 15 m	< 4.5 m
II	B	15 m - 24 m	4.5 m - 6 m
III	C	24 m - 36 m	6 m - 9 m
IV	D	36 m - 52 m	9 m - 14 m
V	E	52 m - 65 m	9 m - 14 m
VI	F	65 m - 80 m	14m - 16m

It is an important constraint in stand allocation that a flight is assigned to a stand sized for the size aircraft. This is due to the fact that the capital investment of a larger stand is higher. Another important constraint states that it can occur that two adjacent stands can not be assigned large aircraft at the same time, due to the size of the aircraft. However, it is not possible to take adjacency into account in this research due to the fact that capacity calculations occur before the location of the stands is known.

2.4.1. Aircraft size effects on stand utilisation: cross-usage

Stand utilisation will vary per stand size because aircraft size is directly related with turn-around-time and therefore has influence on the amount of aircraft handled on a daily basis. Schiphol has specific wave behaviour where after 16:00 barely any widebody aircraft land, which implies that these stands are not used the rest of the day. However, narrowbody demand does have peaks in the end of the day, that is why these use the empty widebody stands in the rest of the day. This cross-usage is very important factor in achieving high stand utilisation.

2.4.2. Multi-Aircraft Ramp System

To increase stand utilisation a relative new concept of MARS has been introduced. To maximise stand capacity the Transportation Research Board developed recommendations on the application of a MARS of which an example can be graphically seen in Figure 2.8 [12]. A MARS stand allows for use by two smaller aircraft or one larger aircraft: two narrowbody aircraft operating independently within the same area, or one heavy widebody such as the A380 using the same two flexible PBB. According to IATA, if the flight schedule dictates the MARS stand, it is the preferred option due to increased stand utilisation while reducing infrastructure cost [13].

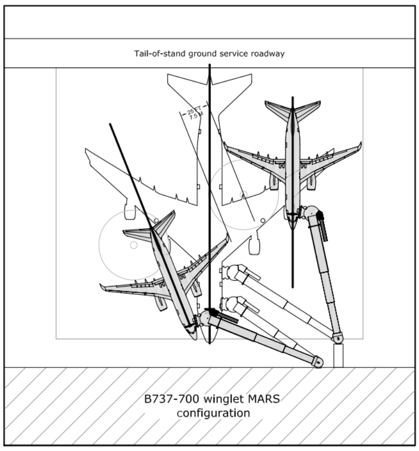


Figure 2.8: Example of a MARS configuration [12]

2.5. Stand capacity

Based on all the factors explained in previous sections a particular set of stands is provided at Schiphol. The ratio between passengers processed at an contact stand and a remote stand is used as an indicator of a certain level-of-service that an airport offers. In this section the capacity offered at Schiphol is provided for both contact and remote stands.

The nomenclature around stands tends to create confusion about the seemingly interchangeable terms ’gates’, ’stands’ and ’bays’. In this research a clear distinction is made based on master thesis research by Van Goethem [14] which is as follows. A *stand* is the passage for passengers to access the the terminal, where one gate can serve multiple stands. A *stand* is the physical parking space of the aircraft. The term bay is typically used for holding bays, which are parking places used for aircraft that are parked just before departure or after arrival. Bays are therefore typically located nearby the runway.

In Figure 2.9 an overview of stands can be seen, where aircraft stands are colour-coded for widebody and narrowbody stands. Four types of aircraft parking stands can be defined based on operational functionality: contact stands, remote, ground loaded and RON positions [15]. The decision for one of these stands does not only depend on geometry and physical constraints but also depends on level-of-service objectives and the expected aircraft fleet and operations. A requirement for the strategic stand capacity model is to support this trade-off.

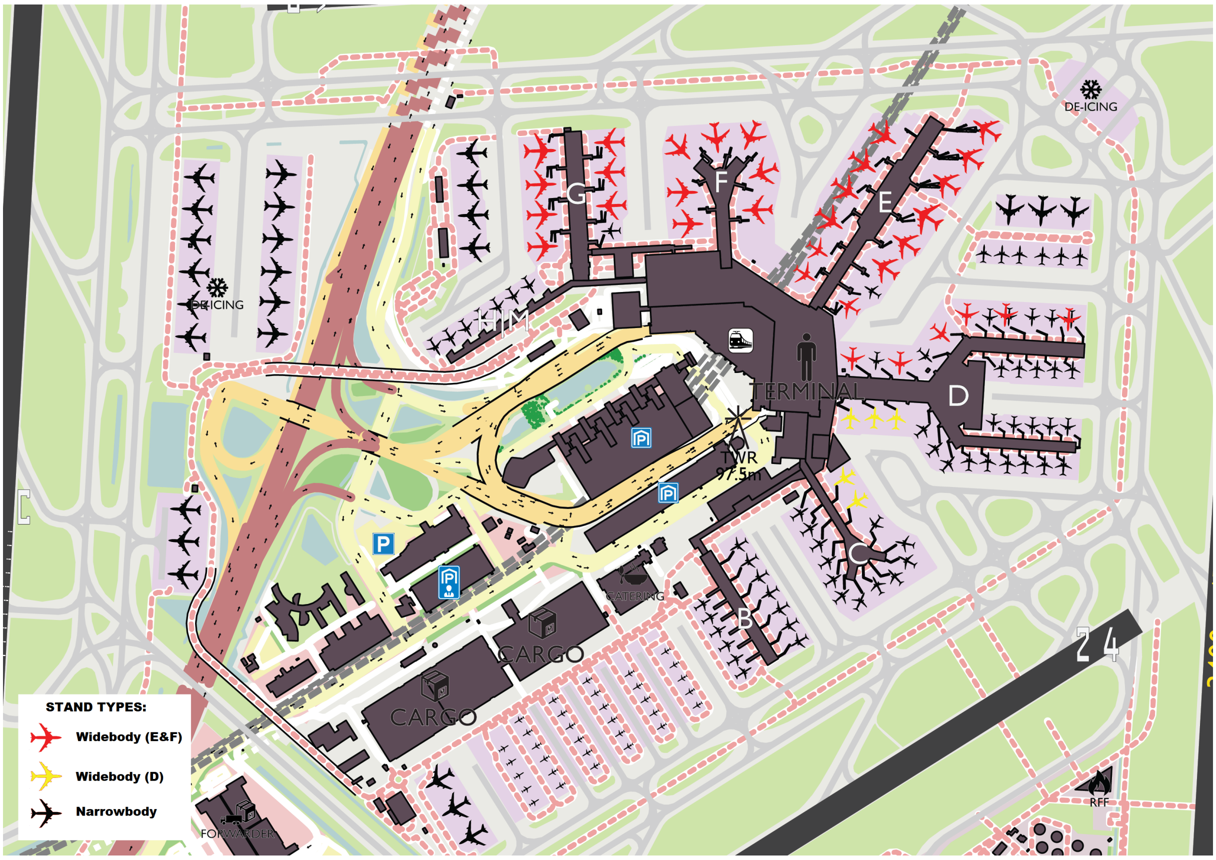


Figure 2.9: Layout of schiphol with aircraft stands [5]

2.5.1. Contact stands

An overview of current capacity of contact stands at Schiphol can be seen in Figure 2.10. At Schiphol the gate numbers and stand numbers align, with exception of the extra gate numbers for the Swing stands at pier D and the bus gates at pier B, which can be both be seen in the figure as the dotted line translation of these piers. In Table 2.4 the amount of contact stand capacity available at Schiphol, listed per IATA aircraft standsize and sector.

Table 2.4: Current contact stand capacity

IATA size	Sector	Number of stands
C	Schengen	25
C	Non-Schengen	13
C	Swing	20
Total Narrowbody		**58**
D	Schengen	2
D	Non-Schengen	0
D	Swing	3
E	Schengen	0
E	Non-Schengen	25
E	Swing	6
F	Non-Schengen	2
Total Widebody		**38**
Grand Total		**96**

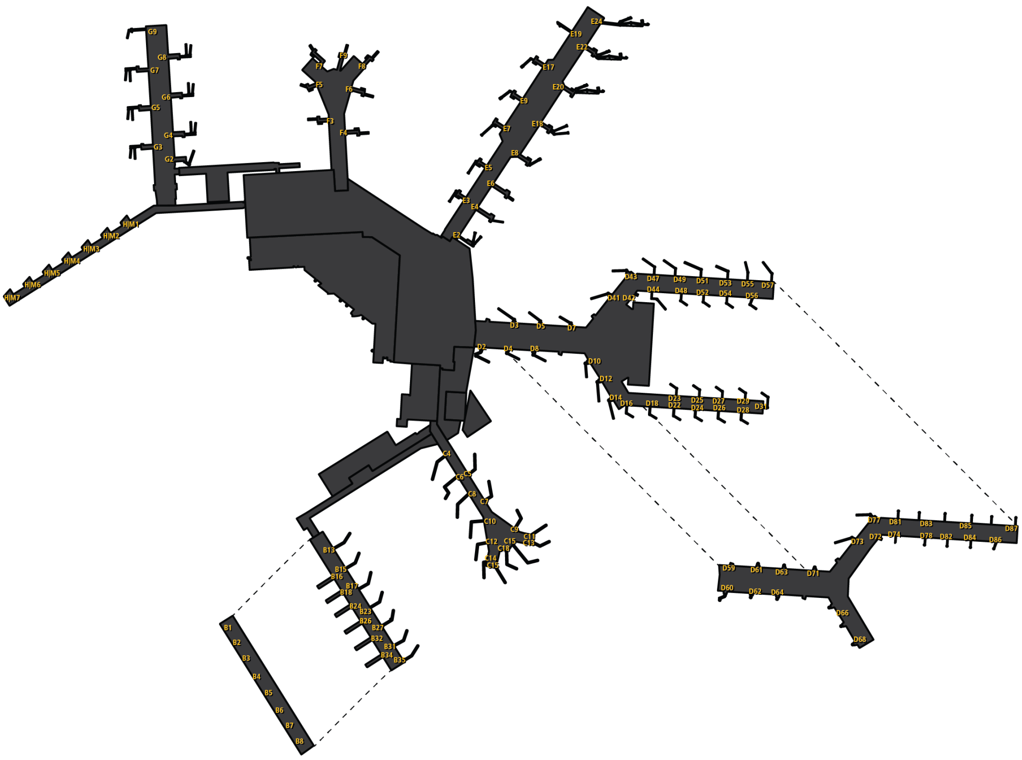


Figure 2.10: Contact stands with gate numbers[5]

2.5.2. Remote Stands

When these stands are used for operational parking, passengers are transported to the terminal using busses, in contrast to contact stands which are connected to the terminal using passenger boarding bridges. Remote stands can be used either for operational or non-operational flights. Non-operational parking is typically for longstay aircraft, which are towed away from a stand to free a valuable contact stand for other aircraft. However, towing increases operational cost. Therefore a trade-off is needed between the capital cost of a new contact stand versus the operational cost of bussing.

The remote stands at Schiphol are used both operational and non-operational. There are 9 located between the E and the D pier, and 4 next to the G pier, as can be seen in Figure 2.9. On the west side of the airport behind the highway another 20 aircraft stands are available for non operational parking.

Table 2.5: Current remote stand capacity

Size	Number of stands
Narrowbody stand	51
Widebody stand	21
Total	33

2.5.3. Stand capacity expansions

Due to political reasons at Schiphol currently maximum capacity is nearly reached which is set om 500.000 ATM till 2020. This has to be taken into account when the flight schedule of 2017 is used as in input for the strategic stand capacity model.

Schiphol has announced stand capacity expansion of a new pier and connected terminal south of Schiphol Plaza which will be ready in 2019 and the new terminal in 2025 [16]. In the first phase this will consists of 8 new gates - where 5 aircraft stands are available for narrowbody aircraft at the north side, and 3 aircraft stands are available for widebody aircraft at the south side. In a second phase two extra widebody stands are added at the south side. The expansion can be seen as the yellow structures in Figure 2.11.

Research by de Man [17, 18] on stand capacity planning at Schiphol concluded a lack of a stand capacity tool that takes stand allocations into account while analysing different scenarios. De Man showed that the current tool used at Schiphol is mainly based on expert judgement and a simplified demand-supply comparison build in Excel spreadsheet.

Figure 2.11: Capacity expansion: The new A-pier with connected terminal expansion in yellow [19]

3

Developing the Mixed Integer Linear Model

In the previous chapter the physical problem at Schiphol is explained. These can now be translated in a mathematical model.

An optimisation model consist of an objective function, which is the equation that drives the solution to a certain business goal. The constraints define the rules of the game - what is allowed, what is preferred and what is absolutely not allowed. The algorithm then searches the solution space for an optimal solution by varying the decision variables.

The model consists of two optimisation models, where the first optimises the stand capacity and the second allocates aircraft to individual stands to create a planning based on this capacity. In this chapter the structure of these models is explained and how a solution is obtained.

In this section the model is expressed mathematically accompanied with underlying reasoning, covering first the model 1 "Stand Capacity" in section 3.1 followed by model 2 "Stand Allocation" in section 3.2. After that the method of resolution is explained in section 3.3.

3.1. Formulation of Optimisation Model 1 "Stand Capacity"

The main goal of this model is obtain the capacity needed for a given flight schedule, minimising cost while making a trade-off between initial capital investment and operational cost during daily airport operations. The output of this optimisation model is the amount of stands needed per standtype, defined in stand size and stand sector. However, transforming the real life problem to a model requires a detailed analysis to include all the operational rules in a mathematical formulation.

In this section the decision for the Mixed Integer Linear Problem formulation is argued. Then, descriptions are provided of the variables, objective and finally the constraints of the model.

3.1.1. Decision for a Mixed Integer Linear Problem

Before explaining the details of mathematical model first the decision to use a Mixed Integer Linear Program to tackle this optimisation problem is justified.

Before a trade-off can be made, first the operational characteristics are analysed. Stand allocation can be defined as follows: Assign a given set of flights to a set of stands while making sure that certain criteria are met. In literature this problem is called the GAP or SAP. Over the last decades much research is done into the application of optimisation models to solve this problem.

In 2015 an extensive survey is published by Bouras which covers most GAP research of the last decades for all types of formulation styles. Examples of these different formulation styles are Integer Linear Programming, Binary Programming, Non Linear Programming, Dynamic programming or combinations of these programming formulations. Bouras crystallises the fact that in first instance the best method is to use a binary or integer model formulation using a standard linear programming tool applying the primal simplex algorithm [20].

To continue the survey done by Bouras a more complete overview of GAP research of the last decades is made which can be found in Appendix D. In Table D.3 and Table D.4 an overview is seen of formulation styles where an relationship can found between objectives and formulation type.

For the strategic stand capacity model various trade-offs are made to converge to a decision between these formulation types. As can be seen in this table the type of formulation is depending on the type of objectives. Since this problem has capacity as a variable instead of capacity as a given input, the model requires integer variables, which eliminates the pure binary models.

The strategic stand capacity model has both an allocation variable and capacity variable, which have a dependency on eachother. This can be described using various strategies, e.g. using a stepwise objective. For a multi-objective research by Bolat used nonlinear objectives with little success trying to solve the problem within reasonable computation times[21].

The two variables of stand capacity and stand allocation can be defined as integer and binary variable, where a constraint will ensure their dependency. In this light the MILP formulation shows to be most suitable for this problem. The MILP is a formulation used commonly for optimisation problems where some of the decision variables are constrained using integers. Various authors used MILP to formulate the problem within reasonable computation time [21–28].

Based on these sources the decision is made to formulate the problem as a MILP. This decision is based on the research done in the literature survey written for this research in a separate document. This decision is confirmed by research by Diepen and Hoogeveen [29] [30] [31] who also apply MILP, solve it with CPLEX within reasonable computation time and apply it at Schiphol Airport to tackle the daily gate assignment problem at this airport.

3.1.2. Decision variables

An optimisation problem is called solved when the best values of the decision variables are found which optimise the objective function. Before explaining the objective of this model, the ingredients of this problem are explained: the decision variables.

Only two decision variables are defined for this problem: one that defines capacity and the other one the allocation of an aircraft to a standtype. First the capacity variable is explained, followed by the allocation variable.

Capacity variable

The variable y_j is integer variable defining the amount of stands of standtype j. The different types of stands j are unique for the following elements:

1. ICAO size:
    - C (Narrowbody)
    - E (Widebody)
    - F (Heavy Widebody)
2. Sector:
    - Schengen
    - non-Schengen
    - multi-sector: Swing

For the case of Schiphol the sectors Schengen and non-Schengen are defined. For other airports these can be changed, e.g. into the sectors international and domestic.

Allocation variable

This variable models daily planning at an airport, where aircraft are given one stand or multiple stands during the time spent at the airport. The binary variable x_{ij} can be seen in Equation 3.18 which represents the assignment of an operation i to a standtype j.

$$x_{ij} = \begin{cases} 1, & \text{if operation } i \in O \text{ is assigned to compatible stand } j \in S_i \\ 0, & \text{otherwise} \end{cases} \tag{3.1}$$

Sets

The dimensions of the model are defined by the following sets O, T, S, S_i, B and W_i which together form the ingredients of the optimisation problem:

- $O = \{1,..,i\}$ equals the **set of operations**. Each operation i ∈ O is described by arrival time a_i and departure time d_i, where $a_i < d_i$. The variables a_i and d_i are integers. The code for an operation i is the unique combination of *tailnumber, day of year* and *arrival hour of day.*

- $T = \{1,..,t\}$ equals the **set of unique arrival times** rounded to a 5 minute interval of the set operations O

- $O_t = \{i \in O \mid a_i \leq t < d_i\}$ is the set of operations which overlap time line t. Set of operations that land before time t and still on the ground at time t, where one set exists for each t in T

- $S = \{1,..,j\}$ equals the **set of stands**. The different types of stands can be found in Table xxxx. They are unique for ICAO stand size, destination group(International, Domestic, Schengen or Swing), security group (clean or unclean), and alliance.

- $S_i \subset S$ is the **set of compatible stands for operation** $i \in O$. Each operation has a set of compatible stands, depending on ICAO stand size, airline restrictions and other operational restrictions.

- $B = \{1,..,k\}$ are the buffer times between operations, for a set of k different scenarios, depending on airport guidelines, the type of aircraft and on whether the next operation at that stand is a tow or arrival/departure operation.

- W is a set of tow times, where duration is depending on aircraft type, turn around time and whether the operation is split in 2 parts or 3 parts.

The set of operations O is given in the form of a flight schedule, which is a time table with arrival and departure times for aircraft operations with the following details:

- Flight number
- Arrival/Departure Times
- Origin
- Destination
- Aircraft Type
- Operator/Airline/Alliance information
- Passenger Number
- Sector of origin/destination

3.1.3. Scoping the objective

Before defining the objectives of this model an extensive literature study is done where stand allocation models and gate assignment models are compared on their definitions in objectives. The references found can be seen in Table D.3 and Table D.4.

The main objective of this problem is to minimise cost, defined in two ways:

- **MINIMISE Capital cost** of investing in the physical construction of stands
- **MINIMISE Operational cost** of allocating aircraft to stands, including towing and bussing

At first the problem was defined as a multi-objective problem, where capital cost was minimised and allocation preferences were maximised. After careful analysis of the problem of airport design the allocation preferences are substituted with operational cost, which much better reflects the trade-off at the heart of this problem. Between capital cost and operational cost lies a particular solution that an airport desires. Some airport decide to invest heavily in capacity, creating large capital cost. Capacity is abundantly available and this airport offers a very high level-of-service. This is very rare and only few airport in the world operate these type of airports. Other airports are close to their maximum capacity and want to invest every few years by adding a small amount of capacity. In this way they invest in capacity while watching their demand growth closely to make wise decisions in capital investments. This trade-off is very much related to level-of-service that an airport wishes to provide.

Even inside the operational cost different airports have different behaviour. According to research by Dorndorf into robust gate assignment different airports significantly differ in towing preferences, where at some airports an extra tow is accepted to increase gate preferences, and other airports avoid these procedures [32]. This boils down to the effect of a level-of-service that an airport offers.

This trade-off between operational cost and capital cost is taken into account by given a weights to both. Then, a range of solutions of calculated to provide a proper trade-off instead of one single solution.

Operational cost:

$$\text{MIN} \quad \alpha \sum_{i \in O} \sum_{j \in S_i} c2_{ij} x_{ij} \tag{3.2}$$

This equation minimises operational cost and tries to allocate flights to stands while avoiding operational cost such as towing or bussing or allocating narrowbody aircraft on a costly widebody stand. The variable $c2_{ij}$ represents the operational cost of assigning operation i to standtype j. The parameter α represents the weight given to operational cost in the objective function.

Capital cost:

$$\text{MIN} \quad (1-\alpha) \sum_{j \in S_i} c1_j y_j \tag{3.3}$$

The decision variable y_j is an integer which describes the amount of stands of a particular standtype j. The variable $c1_j$ defines the capital cost to build that particular standtype j.

The weight α of in the objective function will be determined using a Pareto Front analysis where the decision maker selects an α solution point.

In literature the maximisation of airline preferences is a typical objective, however this is not possible since the location of stands is not yet known in this design phase. The same holds for the minimisation of passenger walking distances. These influences will have to be analysed in a later stage in designing the airport.

3.1.4. Constraints

Under no circumstances the model's constraints can be violated. Together, they define the rules of stand allocation, airport regulations and capacity definitions.

According to Dorndorf, who wrote a complete state-of-the art on stand allocation and gate assignments, three typical constraints can be defined: firstly a stand can process only one aircraft at the time, secondly the space restrictions and service requirements with respect to adjacent stands must be fullled and thirdly minimum ground time and minimum time between sequenced aircraft must be assured [33].

Shadow restrictions that follow from adjacency constraints are left out of scope, since it is impossible to model without having stand location.

In this section the constraints are verbally explained after which in the section the constraints are mathematically described.

Flight Splitting

According research at Schiphol by Diepen and Hoogeveen the stand allocation at Schiphol is modelled by allowing long stay operations to split over multiple stands [31]. This is also described in the publicly available document 'Regulation Aircraft Stand Allocation Schiphol' (RASAS) [34]. Especially for longstay aircraft this yields many advantages in terms of capacity. Planners at schiphol have the possibility to split a flight into three different parts:

Version 1: Full

- The flight is fully handled at one stand only

Version 2: 2-split

- *Arrival part:* After the aircraft lands it will stay at a stand to disembark passengers and then towed to another remote or contact stand.
- *Departure part:* The aircraft is made ready for departure where passengers and cargo enter the aircraft.

Version 3: 3-split

- *Arrival part:* After the aircraft lands it will stay at a stand to disembark passengers.
- *Non-operational Parking:* After landing part the aircraft is towed to a remote stand for non-operational parking.
- *Departure part:* The towed aircraft is made ready for departure where passengers and cargo enter the aircraft.

Currently at Schiphol the option for splitting flights is only applied when no solution is found without splitting, due reasons of level-of-service and the minimisation of operational cost. This is done frequently since they are currently constraint on capacity. The disadvantage of towing is the increase in operational complexity and the operational cost that it creates. There are three main advantages for capacity by allowing splitting option. Firstly, by removing long stay operations from contact stands, these valuable stands are available capacity for allocation of other operations. Secondly, flights that operate particular combinations of origin and destinations that normally require either bussing or swing stands, can now be towed to the correct stand. The third reason for splitting flights it the fact that decoupling of parts yields extra flexibility in scheduling operations for certain available capacity.

Stand Size Compliance

Each aircraft that is allocated to a stand has to fit the physical parking space according to international regulations. It is allowed for narrowbody aircraft to utilise widebody stands, which at Schiphol is even preferable since the peak for widebody is in the morning and for narrowbody in the night. This means that the narrowbodies can use the empty widebody stands which increase stand utilisation and reduces the total amount of stands needed.

Stand Sector Compliance

Each stand is able to receive aircraft from all sectors, however not all passengers are allowed to enter the terminal. This occurs when there is no match between the terminal sector and the origin or destination of a stand, and therefore a penalty is applied in the objective function when this occurs. This penalty holds the cost of bussing the people to the correct stand. It therefore will only be allowed when it decreases total capacity needed. An exception for these bussing cost are swing stands, these match with all sectors due to terminal double layer construction. When flights are split in multiple parts, for the arriving part the origin sector and the stand sector are constraint to always have a match. This also holds for the departing part and the destination sector.

No Overlapping

At no point in time two aircraft can be parked at the same stand. To constrain overlapping, a sense of time has to be given to the model. Within stand allocation research two types of models can be distinguished; either single-time slot models or multiple-time slot models. The single-time slot model first defines conflicting sets of aircraft that are at the same time at the airport, and then constrains each stand to only pick a maximum of one of each set. The multiple time slot divides the flights in time blocks, e.g. 15 minute blocks, which has the advantage of less constraints but the drawback of more decision variables. It is also found that multi-time slots influence stand utilisation and is less exact that single time slot models [35]. Also, research for gate assignment at Kenya Airways showed that the running time increases by a factor two comparing the two models [36]. It is therefore decided to define the strategic stand capacity model in a single time slot. Overlapping is then constraint by defining conflict sets in the pre-processing module. In an iterative manner the amount of conflicting aircraft is determined for each unique arrival time.

Variable Capacity

Up to this moment in time no research has been done in stand allocation modelling having capacity as a variable. Normally, capacity is a hard input and solutions are compared with each-other in terms of operational cost or preferences. For this model, capacity is variable. Therefore capital cost and operational cost are weighed against each other while searching the solution space. The model is constrained to ensure that for each allocation to a standtype, sufficient capacity is added while taking the capital cost for that stand into account. This constraint is mathematically combined with the overlapping constraint in one equation.

3.1.5. Mathematically formulation of constraints

The constraints described can be combined and mathematically expressed in only two constraint sets. The first set of constraints makes sure that each operation is allocated to a maximum of 1 compatible stand, while choosing from three options. The second constraint makes sure that for each stand type the necessary amount of stands are build, while making sure flights are not overlapping at one stand.

Constraint 1: Stand Allocation

The first set of constraints ensure that each operation is allocated to a maximum of 1 compatible stand, choosing from three options. To model split flights the set of all flight operations O is changed as follows. If a flight is eligible for 2-split, the operation i is split into an arrival and departure part and two operations are added to the main set of operations O. For a 3-split the same holds, and 3 operations are added to the main set of operations O. This means that either the full, or the 2-split, or the 3-split version can be selected. This is modelled with the following constraints. They are defined as hard constraints, since every flight has to be assigned to only one stand and only one of the three split version can be selected.

$$C(1,i): \quad V_{1i} + V_{2i} + V_{3i} = 1 \quad \forall i \in O \tag{3.4}$$

Equation 3.4 guarantees that of the three versions only one is selected.

$$C(2,i): \quad V_{1i} = \sum_{j \in S_i} x_{ij} \quad \forall i \in O \tag{3.5}$$

The variables V_{1i}, V_{2i} and V_{3i} are binary variables which represent the selection of either the full, 2-split or 3-split version. For the full allocation version, Equation 3.5 describes that each flight i from entire flight set O can be assigned to exactly one stand, choosing from a set of compatible stands S_i.

$$C(3,i): \quad 2 \cdot V_{2i} = A_{2,i} + D_{2,i} \quad \forall i \in O_2 \tag{3.6}$$

$$C(4,i): \quad A_{2i} = \sum_{j \in S_i} x_{ij} \quad \forall i \in O_2 \tag{3.7}$$

$$C(5,i): \quad D_{2i} = \sum_{j \in S_i} x_{ij} \quad \forall i \in O_2 \tag{3.8}$$

The variable $A_{2,i}$ en $D_{2,i}$ are binary variables which represent the allocation of the arrival and departure part of a 2-split parking option. For the 2-split allocation version, Equation 3.6 describes that when this version is selected, both the arrival part and departure part of the flight are allocated to a compatible stand. This constraint is only active for flights in set O_2 which are eligible for splitting (minimum 120 min long stay). Equation 3.7 and Equation 3.8 describe the flight-stand options respectively for the arrival and departure part.

$$C(6,i): \quad 3 \cdot V_{3i} = A_{3,i} + P_{3,i} + D_{3,i} \quad \forall i \in O_3 \tag{3.9}$$

$$C(7,i): \quad A_{3i} = \sum_{j \in S_i} x_{ij} \quad \forall i \in O_3 \tag{3.10}$$

$$C(8,i): \quad P_{3i} = \sum_{j \in S_i} x_{ij} \quad \forall i \in O_3 \tag{3.11}$$

$$C(9,i): \quad D_{3i} = \sum_{j \in S_i} x_{ij} \quad \forall i \in O_3 \tag{3.12}$$

The variable $A_{3,i}$, $P_{3,i}$ en $D_{3,i}$ are binary variables which represent the allocation of the arrival, parking and departure part of a 3-split parking option. For the 3-split allocation version, Equation 3.9 guarantees that if the 3-split allocation is selected, all three parts are allocated to a stand that is compatible for that part. Equation 3.10 till Equation 3.12 describe the flight-stand options respectively for the arrival, non-operational parking and departure part.

Heuristics

This constraint was initially defined in 1 equation per flight. However, to improve heuristics this is replaced by a set of 9 constraints per flight. A small test is done to compare Type 1 with Type 9, the results can be seen in Table 3.1. As can be seen, the exact same solution in terms of capital and operational cost is achieved using the two different type of formulation styles for this constraint. For Type 9 the run time has improved from 32 seconds to 4 seconds, even though the amount of constraints and decision variables have increased. This is due to the lower complexity of the constraints for Type 9.

Table 3.1: Heuristic improvements of new formulation

Constraint	Running time [sec]	Capital cost[€]	Operational cost[€]	Nr of constraints	Nr of decision variables
Type 1	32	78900	669781	10534	16460
Type 9	4	78900	669781	18333	37977

Constraint 2: Variable Stand Capacity

The second constraint has two functions: firstly it forces the model to build as many stands as necessary to allocate demand, while secondly making sure that operations are not overlapping by allocating two operations to one stand at one point in time. This means that the concept of time needs to be described mathematically. A time dimension can have a very heavy impact on computational time since it has the power to create many more variables. For example, if for every second during a day a check is performed to make sure no aircraft are overlapping, 86400 checks should be performed, for every aircraft and every stand. In literature various options are mentioned in solutions found to tackle the Gate Assignment Problem (GAP). In terms of heuristic the overlap constraint is selected. First for each unique arrival time of operation set O a set of conflicting operations are selected. The conflict set of unique arrival time t consist of operations that land before time t and are still on the ground at time t. Combining the overlap constraint with the multi-objective nature of this model where capacity is a decision variable instead of an input, an extra variable is added to make sure that for every extra aircraft selected in one overlap set, an extra stand needs to be build. That means that the model will try to minimise the amount of aircraft selected in one overlap set, while taking the price for that aircraft-stand combination and the price for that stand into account, and weighing it against other solutions.

$$C(10, j, t): \quad \sum_{i \in O_t} x_{ij} \le y_j \quad \forall t \in T, j \in S_i \tag{3.13}$$

Equation 3.13 describes that for each standtype j and each conflict set O_t a constraint is made that guarantees that the amount of stands built of that standtype y_j is equal or more than the sum of flights allocated from that conflict set.

Constraint 3: Variable definition
The third group of constraints are variables definitions; all x variables are binary and y variables are integers, as expressed in Equation 3.14 and Equation 3.15

$$x_{ij} = \{0,1\} \tag{3.14}$$

$$y_j \ge 0 \quad \forall j \in S \tag{3.15}$$

3.1.6. Optional Constraints to Force Stand Capacity Solution

To force the a predetermined capacity solution in the stand capacity model the possibility arises to determine the performance of that solution. To always find a solution only the contact stands are forced into the solution and the amount of remote stands are kept variable. In Equation 3.16 the mathematical formulation of this constraint is provided.

$$C(11, j): \quad y_j = Cap_j \quad \forall j \in S \tag{3.16}$$

Where the set Cap_j is defined as:

- Cap_j is the predetermined number of stands of standtype j. This set can be the current stand capacity offered by an airport or a scenario of stand capacity.

3.1.7. Optional Constraints for a Split in Airline Scenario

The Strategic Stand Capacity Model can support research in airline divisions by letting the model choose a strategic airline split in demand. This application will allow for further research in how airlines should be placed together in order to most optimally utilise stand capacity available. In this section the variables and constraints are presented which support this extra feature.

Two new sets are defined:

- $M = \{1,..,m\}$ equals the **set of demand segments** which are groups of airlines which together form all demand
- $L = \{1,..,l\}$ equals the **set of airlines**

Decision variables

For this scenario an extra binary decision variable x_{ijm} is created which represents the allocation of flight i to stand j of demand segment m.

$$x_{ijm} = \begin{cases} 1, & \text{if operation } i \in O \text{ is assigned to compatible stand } j \in S_i \text{ of demand segment } m \in M \\ 0, & \text{otherwise} \end{cases} \tag{3.17}$$

Z_{lm} is an integer decision variable that represents the sum of all flights of airline l to demand segment m. To ensure that all flights are allocated to the same demand segment, a binary variable is created W_{lm}.

$$W_{lm} = \begin{cases} 1, & \text{if airline } l \in L \text{ is assigned to demand segment } m \in M \\ 0, & \text{otherwise} \end{cases} \tag{3.18}$$

Constraints:

Equation 3.19 defines that variable Z_{lm} is the sum of all flights defined per airline per demand segment.

$$C(12,l,m): \quad \sum_{j\in S_i}\sum_{i\in O} x_{ijm} = Z_{lm} \quad \forall l \in L, m \in M \tag{3.19}$$

To connect Z_{lm} to a binary option of allocating to only one demand segment, the binary variable W_{lm} is created. Following IBM CPLEX guidelines an indicator constraint is used to connect these variables [37]. The resulting equation can be seen in Equation 3.20

$$C(13,l,m): \quad W_{lm} = 0 \rightarrow Z_{lm} = 0 \quad \forall l \in L, m \in M \tag{3.20}$$

Equation 3.21 constrains the model that all demand from an airline is allocated to one demand segment.

$$C(14,l): \quad \sum_{j\in S_i}\sum_{i\in O} x_{ijm} = Z_{lm} \quad \forall l \in L, m \in M \tag{3.21}$$

Equation 3.22 is an optional constraint that can be used to constrain the model to force a particular airline l on one of the demand segments m. When this constraint is not used that airline is free to move between demand segments.

$$C(15,l,m): \quad W_{lm} = 1 \tag{3.22}$$

3.2. Optimisation model 2: Stand allocation

Because the first optimisation model only gives an integer value of the amounts of stands of a specific *stand-type*, it does not give any information on the specific allocation to an individual stand. Therefore a second optimisation model is built. This second model allocates flights to specific stands to obtain a stand planning, using the capacity determined in the first optimisation as input. There are various reasons to add this second model. Mainly because it is important during validation of this strategic stand capacity model to dive into solution characteristics, to track exactly how the trade-off between capital cost and operational cost is made, to analyse operational behaviour of the solution, and to validate the model with current capacity solutions at an airport. Especially the following two advantages are the drivers for this second optimisation model:

Firstly, it makes it possible to generate Gantt charts of all allocations. Secondly, it is possible to see how stand utilisation is different within one stand type instead of only averages within a standtype.

To provide these insights a second optimisation model is created. This model has a slightly different model structure as the first optimisation since it uses the stand capacity of the previous model as hard input. In this section firstly the formulation style of a Binary Linear Problem is argued, followed by a description of the mathematical model in terms of sets, decision variables, objective function and constraints.

3.2.1. Binary Linear Programming

Since this problem does not has capacity as a variable it is a simplified version of the previous optimisation. The problem can be defined without an integer variable, which makes it a binary problem. In literature many binary formulations are found which are used as a reference for the formulation of this problem [38–45].

3.2.2. Sets

Beside the flight schedule, the input of this problem is the results of the previous optimisation, specifically the amount of stands of each standtype and the flights that are assigned to that type. These are expressed in the following sets:

- $K_j = \{1,..,k\}$ equals the **set of stands build of standtype** $j \in S$. These are the results of the previous optimisation. One set exists for each $j \in S$. E.g. for standtype C-Schengen 30 stands are build: $K_{C-S} = \{1,..,30\}$

- $O_j = \{1,..,i\}$ equals the **set of operations assigned to stand** $j \in S$. These are the results of the previous optimisation. E.g. for standtype C-Schengen 90 flights are assigned all grouped in set $O_{C_S} = \{1,..,90\}$. Each operation i ∈ O is described by arrival time a_i and departure time d_i, where $a_i < d_i$. The code for an operation i is the unique combination of *aircraft tail-number*, *day of year* and *hour of day*.

- $T = \{1,..,t\}$ equals the **set of unique arrival times** rounded to a 5 minute interval of the set operations O
- $O_t = \{i \in O \mid a_i \leq t < d_i\}$ is the set of operations which overlap time line t. Set of operations that land before time t and still on the ground at time t, where one set exists for each t in T
- $S = \{1,..,j\}$ equals the **set of stands**. The different types of stands can be found in Table xxxx. They are unique for ICAO stand size, destination group(International, Domestic, Schengen or Swing), security group (clean or unclean), and alliance.

3.2.3. Decision variables

The model searches the solution space for an optimal value of the objective function by varying the decision variables. For this problem no integer variables but only binary variables are present.

$$x_{ik} = \begin{cases} 1, & \text{if operation } i \in O_j \text{ is assigned to stand } k \in K_j \\ 0, & \text{otherwise} \end{cases} \tag{3.23}$$

The binary variable x_{ijk} can be seen in Equation 3.23 which represents the assignment of an operation i to a standtype j, to specific stand number k. Here j is the standtype solution for that flight found in the previous optimisation.

$$q_{jk} = \begin{cases} 1, & \text{if stand } k \in K_j \text{ of standtype } j \in S \text{is used} \\ 0, & \text{otherwise} \end{cases} \tag{3.24}$$

The binary variable q_{jk} can be seen in Equation 3.24 which states whether a specific stand-number k of standtype j is used or not.

3.2.4. Objective

The objective function defines the goal of the optimisation. In the first optimisation model the minimisation of cost was the goal. In this second model the goal is to minimise the amount of stands used, expressed in the amount of stands instead of cost.

$$\text{MIN} \quad \sum_{j \in S} \sum_{k \in K_j} q_{jk} \tag{3.25}$$

This equations minimises the amount of allocations operational cost and tries to allocate flights to stands while avoiding operational cost such as towing or bussing or allocating narrowbody aircraft on a costly wide-body stand.

3.2.5. Constraints

To push the objective function into a field of feasible solutions, constraints are added which represent the rules of the game of flight allocation. Due to these constraints each flight is assigned to one specific stand of the standtype that it was allocated to in the previous optimisation.

$$C(1,i): \quad \sum_{k \in K_j} x_{ik} = 1 \quad \forall i \in O_j, \forall j \in S \tag{3.26}$$

Equation 3.26 is a hard constraint that guarantees that each flight is allocated to a stand. The constraint describes that for each standtype, all flights that are assigned to that standtype get the constraint that they need to be allocated to one specific stand of that standtype.

$$C(2,k,t): \quad \sum_{i \in O_t} x_{ik} \leq q_{jk} \quad \forall t \in T, \forall k \in K_j, \forall j \in S \tag{3.27}$$

Equation 3.27 prevents overlapping. The constraint describes that for each stand standtype, for each specific stand, of all conflict sets a maximum of one flight per conflict set can be allocated to this stand, if this stand is build.

3.3. Resolution Method

Due to the computation complexity of optimisation problems, it is sometimes impossible to use exact methods to converge to a solution within reasonable time. Therefore various heuristic and meta-heuristic methods have been applied to the GAP and SAP problem. To create a clear picture of the options for resolution methods an overview is made of GAP research of the last decades. In appendix B this table is presented of GAP research which shows GAP research with corresponding algorithms used. In this table four categories are defined in these optimisation based techniques: Exact methods, Heuristic Algorithms, Metaheuritic algorithms and Optimisation Programming Language methods.

As stated earlier, in the survey made by Bouras it becomes clear that the best strategy is to start with a binary or integer formulation using a standard linear programming tool applying the primal simplex algorithm [20]. When problems due to computation time arises heuristics can be developed to speed up the algorithm applied, or other algorithms can be used to increase performance.

Guepet in 2015 showed that solutions found for a MILP for GAP with CPLEX without heuristics show better results for SAP than four other heuristic algorithm(Greedy algorithm, Ejection Chain Algorithm and Stand Decomposition and Time decomposition methods) due to the fact that SAP can be defined as a simpler version of GAP [25].

Based on these sources the decision is made to solve this problem using the primal simplex algorithm. This decision is confirmed by research by Diepen and Hoogeveen [29][30][31] who also apply MILP, solve it with CPLEX and then apply the model at Schiphol Airport to tackle the daily stand allocation problem.

3.3.1. Dynamic Search Algorithm

Inside the CPLEX optimisation box the simplex algorithm is used, specifically the Dynamic Search Algorithm. This dynamic search offers: LP relaxation, branching, cuts, and heuristics. LP relaxation is when the original problem is replaced by a problem with the same objectives and constraints but with the requirement that integers are replaced by continuous constraints. The solution to this problem is the initial starting point. Branching is used to build a tree in which each subproblem is a node, where cplex solves a full series of continuous subproblems. If the solution to the relaxation has one or more fractional variables the next step is try to find cuts. Different types of cuts are made by the algorithm, which reduces the number of branches needed to solve an integer problem. Clique cuts, cover cuts, flow cuts, rounding cuts, zero-half cuts, gomory fractional cuts are applied to this particular MILP. For every step the algorithm takes the gap is computed, and optimisation is proven when upper and lower bound evaluate the same value and result is 0 percent.

3.3.2. Optimisation resources: CPLEX

Many tools are available to apply the simplex algorithm for optimisation problems such as this model. In Figure 3.1 a performance benchmark is shown of various commercially available 2017 simplex solvers for a problem size comparable to one day of flights, made by H. Mittelman [46]. Tools that are compared are the open-source tools Google-GLOP, GNU-GLPK, LPSolve, CLP, SOPLEX. Other tools that are compared are Matlab, Gurobi, Mosek and XPRESS. It is clear that open-source tools do not peform high. Of the commercially available tools Gurobi slightly outperforms CPLEX for the characteristics of this particular problem.

In Gate Assignment literature it is found that CPLEX successfully solves MILP problems within reasonable computation times [23, 25, 28, 42, 47–50]. Also CPLEX is known to have high performance and offers possibilities to change parameters and behaviour of the strategic search for the optimal solution. Lastly, the full CPLEX optimisation license is available for TUDelft students which concludes the decision to use CPLEX. The version of Cplex used is 12.7.1.0 which is only compatible with python version 3.5.

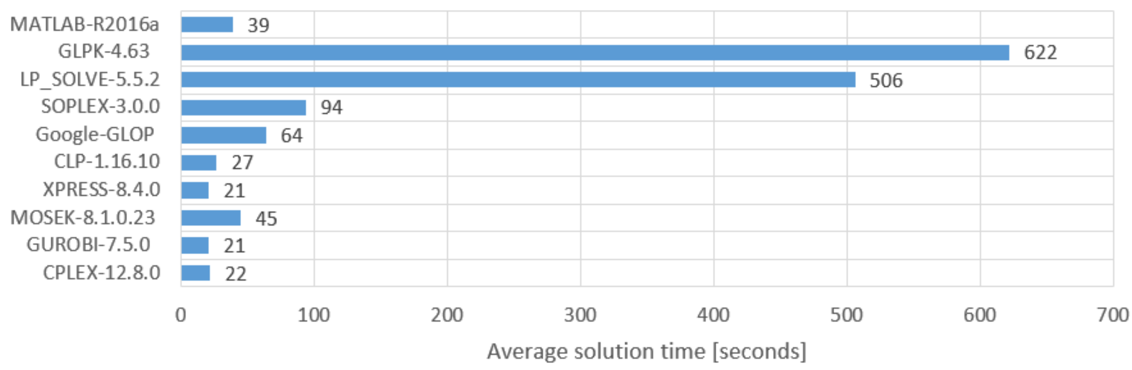


Figure 3.1: Performance benchmark of commercially available simplex LP solvers[46]

The Computer used to optimise the model has 4 cores, 8 logical processors, 1 socket. This is a constraining factor and if larger problem sizes needs to run more processing power should be added. The settings for the CPLEX model are set on 8 threads because according to IBM CPLEX guidelines setting the number of threads to a number greater than the number of cores on the machine will typically results in degradation of the performance of CPLEX optimiser.

3.4. Conclusion

The main goal of the model presented in this chapter is to minimise both capital and operational cost, expressed in separate parts of the objective function. They are both given a weight to allow for a trade-off between these two, which defines the type of airport that is designed. Based on this problem context and an extensive literature review the mathematical model is formulated a Mixed Integer Linear Problem.

For the first and main optimisation two important constraints are defined that model the behaviour at the airport. The stand allocation constraint ensures that only one version of flight splitting is selected, complying with stand size and sector. The second constraint of variable capacity makes sure enough stands are added while ensuring that no flights are overlapping.

The second optimisation model consists of two constraints, one that guarantees that each flight is allocated to a stand and one that prevents overlapping. The output of this model is a Gantt chart and stand utilization distribution per stand type.

A trade-off is made between available optimiser tools where IBM CPLEX is selected, which will be integrated in a python framework. Both optimisation models are solved using the Dynamic Search Algorithm in CPLEX. In the next chapter the framework around these two models is described.

4

Constructing the Software Architecture

The optimisation model is incorporated in a larger framework which holds all the software needed to support the main mathematical model. This framework consists of multiple building blocks, which have different purposes and are defined in different programming languages.

In this chapter the structure of the framework is given with details on each specific building block. Then the Pareto front model is explained, followed by a section on the agile strategy behind the software development of this tool.

4.1. Software Architecture as a Framework

A software architecture is the abstract design concept of an application. It is a structure of all parts and how they are connected. A framework is a pre-built special purpose architecture, with a design that is made with continuous extension in mind.

In Figure 4.1 a functional flow block diagram (FFBD) is shown which visualises the framework that is created around the two optimisation models. A FFBD is a time-sequenced, step-by-step flow diagram of all the functions that are sequenced in a system. This flowchart is used as a guide throughout this research. The lay-out consist of five building blocks.

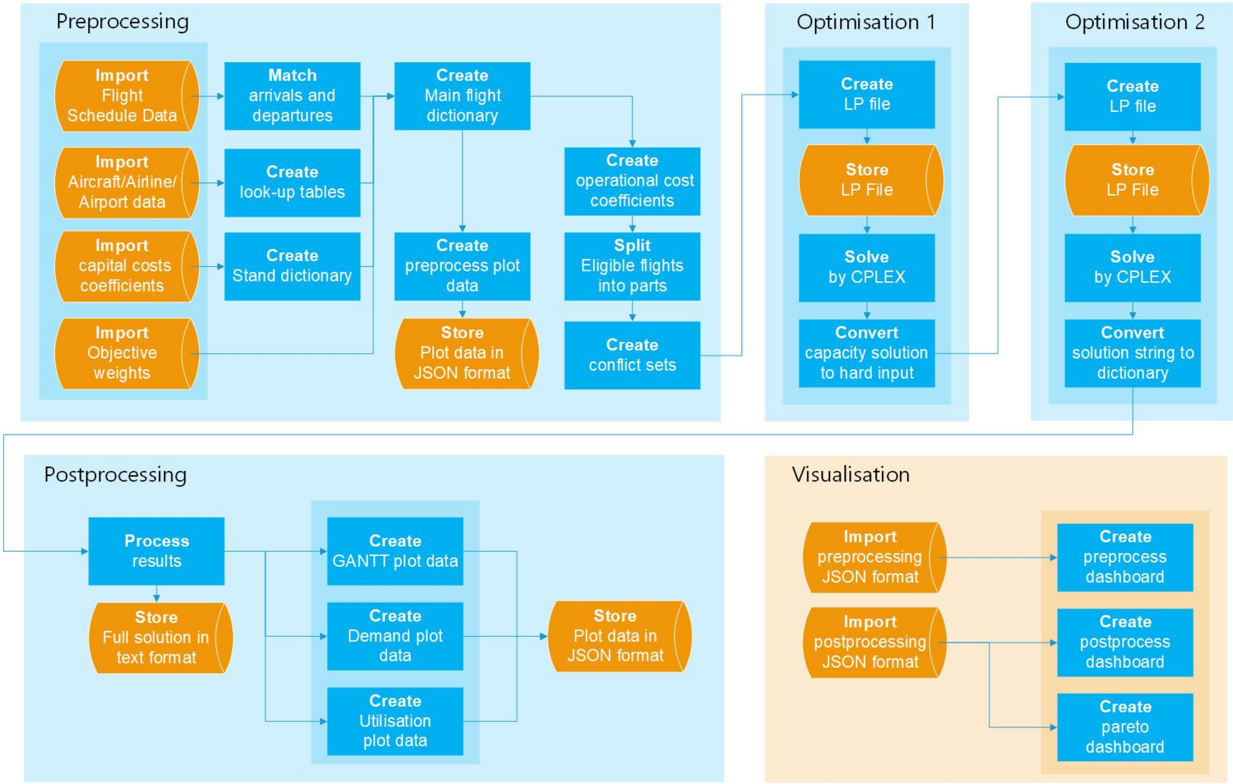


Figure 4.1: Model Framework around optimisation

This framework is developed with a focus on continuous development of a running model, instead of developing the blocks separately without testing the connections of the blocks.

4.1.1. Functional Programming in Python

The building blocks of the model that are seen in flowchart Figure 4.1 are build in python, with the exception of the visualisations. Python is chosen because it is open source and has high performance for larger datasets.

A dictionary based approach is chosen for python because the performance for dictionaries is optimised in the nature of this programming language. Using dictionaries matches in the data are made based on keys in stead of indices, which is beneficial for this combinatorial problem to ensure correct matches between flights, standtypes and other look-up tables. Also, python dictionaries are easily converted to JSON data format which is the data format that Javascript requires in the visualisation module.

The model is coded applying functional programming, which is a programming style where software is made composing pure functions. The difference with often used object orientated programming is that global defined variables are not used and variables are always passed through functions. Because it avoids shared states and mutable data it is very easy to test and debug.

4.1.2. Module: Pre-processing data

In this module data from different sources are combined to create a combined input for the optimisation modules. Firstly a main list of dictionaries is created, with a dictionary for each flight. Each flight is based on a match between an arrival and departure listed in the flight schedule data. This list of dictionaries is then improved using look-up tables for airport, aircraft and airline data. The resulting dataset is then intermediately saved in an adjusted JSON format dataset for pre-processing plot visualisations. Then, the list of dictionaries is adjusted for split parking operations. Flights that are eligible for splitting are divided into two or three separate operations and added to the list of dictionaries. This resulting dataset will be used to define the decision variable of flight allocation.

Secondly, a stand dictionary is created with specifications about size, sector, cost and contact/remote functionality. These define the decision variable of the variable stand capacity.

Thirdly, cost parameters are calculated for each combination of a parking operation to a particular type of stand. These are depending on bus cost and towing cost. Fourthly, to support the stand capacity constraint the conflict sets O_t need to are created. These sets will prohibit flights from overlapping. The resulting flight dictionaries, stand dictionaries, cost parameters and overlapping sets are send to the optimisation modules.

4.1.3. Module: Optimisation models

In these modules the optimisation model is integrated into the larger framework. The dictionaries defined in the pre-processing module are now used to define the LPfile, which is a text-file format that CPLEX is able read and optimise. The LPfile holds the objective function, constraints and decision variables of the problem. When CPLEX solves the problem the result stream is saved in a separate .SOL text-file which holds solution specifics.

The output of the first optimisation are the amount of stands of each standtype for a particular solution and sets of flights that are allocated to a particular standtype. The format of this solution are arrays of integers and binary values, which is converted to a second stand list of dictionaries holding one dictionary for each individual stand.

The second optimisation then uses the amount of stands as a hard input, where the sets of flights are allocated to the previously determined standtype. Similar as the first optimisation a LPfile is created and solved. The format of the solution is only a list of binary values and a list of decision variable names. To add information about airline, aircraft, passengers, etc. a look-up dictionary is made to reconnect the flight-number of the decision variable to the original flight dictionary.

4.1.4. Module: Post-processing the results

In this module the results are processed to plot data-sets. For the GANTT visualisation the results are restructured and combined with separate bus elements. For demand visualisations a function is written that checks how many aircraft are utilising a particular standtype throughout the day. Lastly, for each standtype the utilisation in hours and aircraft handled is calculated. For these three charts the data-sets are converted to JSON format, which can be easily read by the Javascript Visualisation module.

4.1.5. Module: Visualisation module

In between a mathematical model and users a Graphical User Interface (GUI) is needed, which presents the result of the model. An increasing trend in engineering tools is the development of web-based applications. A web-application is a software computer application which is hosted in a browser controlled environment. Web-based applications have many advantages, since the tool can be accessed from any computer instead of traditional applications which are installed on a local computer. Another advantage is that these tools can be developed using open-source codes which are subjected to high innovation because everyone can contribute. Another strong benefit is that an update is immediately available for everyone and everywhere from any device. Lastly, for this model the main advantage is that processing power is not needed locally on the device of a user but on the cloud or server, which can deliver high computational power. By building this tool as the visualisation module, this research can be applied in strategic airport planning as a decision support tool.

As the GUI of the Strategic Stand Capacity model a web-app is developed. It is programmed using various programming languages, tools and libraries. Together, these can be described as a solution stack seen in Figure 4.2. A solution stack is a group of services that work in tandem to produce a result. The top layer is the Front-End, also called the client-side, which is the part of the code that describes the user interface. To connect the user interface with the database, the back-end part of the code communicates with the database by making data requests.

As can been seen in Figure 4.2 for the front-end the charts are made with the help of a JavaScript visualisation library named Amcharts. The advantage of creating JavaScript charts is that every single component can be changed or added. Especially for Gantt chart development the functionality of JavaScript visualisations showed high performance. Other tools investigated for Gantt charts were plotly, tableau, matplotlib, qlikview and excel but were all outperformed by JavaScript AMcharts. All the components of the dashboard of this tool are programmed using a combination of HTML, CSS and JavaScript. To simplify the client-side scripting of HTML the jQuery library is used. For interactive elements the Bootstrap library is used.

Figure 4.2: Solution stack of the web-based Strategic Stand Capacity Model Application

Screenshots of the resulting dashboards can be seen in Appendix B. The following dashboards are made:

- Pre-optimisation dashboard - input visualisations of airport demand characteristics
- Post-optimisation dashboard - output visualisations of individual runs
- Pareto-results dashboard - solution results along Pareto curve

4.2. Running the framework along the Pareto front

Since the model is multi-objective problem a Pareto front can be developed by running the optimisation model for various values of objective weights.

Along a Pareto curve each point represents a Pareto optimal objective point, which shows how improving one objective weight is related to deteriorating the second one while moving along the trade-off curve. One of these points is then selected by the decision maker based on preferences. In this case the trade-off is between capital investment and operational cost.

In this iterative process the preprocessing, optimisation 1 and 2 and the postprocessing modules are run in an iteration for 20 points along the Pareto front. To improve heuristics functions that are repetitive for each run are redundant and therefore removed from the framework. A noteworthy improvement is the conflict sets function, which, for the Pareto runs is only ran once in the first run of the Pareto front. A separate visualisation dashboard is made for the results of this set of optimisation runs.

4.3. Agile Software Development

In order to continuously test, verify and validate the model this software is constructed applying an agile software development strategy.

Agile development focuses on continuous development where frequently working software is produced, with a strong preference for a two week timescale. Applying this planning strategy a Gantt chart and a set of sequenced features are defined before the start of the project. As a base model a Minimal Viable Product is made.

4.3.1. Minimal Viable Product as an initial model

As part of the agile development strategy initially a Minimal Viable Product (MVP) is made which has just enough features to produce results. This MVP is used as a base model and is continuously improved by adding small features. The definition for the software development of this model is adopted from Ries [51]:

> *The minimum viable product is that version of a new product a team uses to collect the maximum amount of validated learning about customers with the least effort.*

The advantages of starting with a MVP is that in the first two weeks of the project a working model is produced, which accelerates learning, allows for early validation and verification and therefore reduces wasted engineering hours.

As the initial MVP a static stand allocation model is build, where immediately connections between the building blocks of Figure 4.1 are established. This model is tested with a set of data which allocates 8 flights to 3 given stands. This test is important to verify that the model complies with the rules set on stand allocation and stand capacity. Multiple checks are performed to verify that the allocation rules are obeyed; no overlapping flights. Now that it is validated that the MVP simulates airport operations correctly, different features are added. Adopting the agile development strategy these features are added sequentially, instead of creating multiple changes at once.

4.3.2. Features

The features are defined at the start of this research to act as a guideline throughout the project.

Each feature is divided into smaller features. The main features can be seen in Figure 4.3

- **Add a decision variable: stand capacity.** In the MVP the capacity is given as a hard input, similarly to a classic stand allocation problem. In this feature this hard input is changed into a stand capacity variable. Sub-features are, besides the definition of new variables, a required change in constraints and an initial estimation of cost per stand.
- **Add optimisation 2.** In this feature a simplified stand allocation optimisation is defined where the resulting capacity of the first model is used as a hard input. The main purpose of this feature is to allow for Gantt chart visualisations. A sub-feature here is to add airport, airline and aircraft data to replace IATA/ICAO codes with long names. Also, longitudes and latitudes airport data is connected to the model to create extra visualisations of the input data.
- **Improve decision variables: stand types.** Here different types of stands are defined in terms of IATA size and sector, which for the case study of Schiphol results in Schengen, non-Schengen. A sub-feature is the addition of swing stands.
- **Improve the objective function: towing and remote functionality**. This feature allows the model to create remote stands and tow between contact stands and between contact and remote stands.
- **Improve and fine-tune weights and cost parameters**. Now that most of the model behaviour is defined, the cost and weights can be refined for towing and bussing. Also a sensitivity analysis is performed on these variables.
- **Improve input by creating scenarios.** In this feature different scenarios are defined for case study Schiphol.

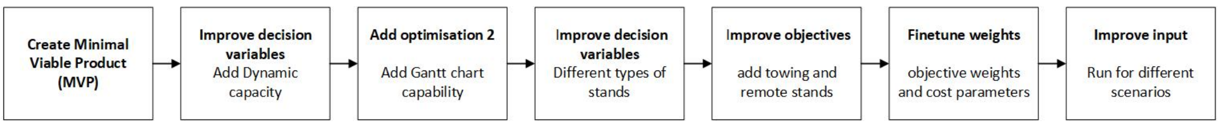


Figure 4.3: Features added in sequence

Along side these features, visualisations are continuously added to the three dashboards of the web-based tool.

4.3.3. Continuous verification

Applying the agile development strategy is industry standard and has various testing benefits. It is the fastest way to get initial results with minimal resources, but also has advantages during development. Because features are added in sequence it is easy to apply version control and go back to earlier versions of the model.

This also allows for continuous verification and debugging in smaller steps, which reduces the risk of large software problems when entire sections of code are not working and results can only be achieved when all bugs removed. Performance testing is repeated after each added feature by tracking running time. When performance of a decision variable or constraint is low, other formulations are tested.

Using this strategy it also allows for continuous validation, because results are always produced after each smaller step. These results can then be held against the requirements of the tool which reduces the risk of spending weeks on a feature that you do not need after all.

The testing procedures have a continuous nature which increases efficiency and transparency of the model. This allows for continuous steering of the requirements, where at each iteration the main goal of the research can be confirmed or adjusted.

5

Schiphol Data

In this chapter the data sources and handling are described that are supporting this model. This data handling occurs in the preprocessing model seen in the flowchart in Figure 4.1.

Different data sources are combined: the flight schedule arrivals and departures are matched using tail-numbers. This data holds a lot of codes (IATA and ICAO codes) which makes the data hard to analyse and understand. Therefore separate databases are used for aircraft, airline and airport information.

5.1. Day of analysis

The time horizon of the input can be anything ranging from an hour till a year, however, computation time will increase significantly.

According to strategic stand planning the main driver for aircraft stand capacity is the peak day. Two different peaks are defined - for landside planning the passenger peak, and for airside planning the air traffic movement peak. Peaks are analysed because throughout the year demand is not constant and is subjected to seasonality. In Figure 5.1 of Schiphol can seen, which besides seasonality also shows growth of air traffic movements per week.

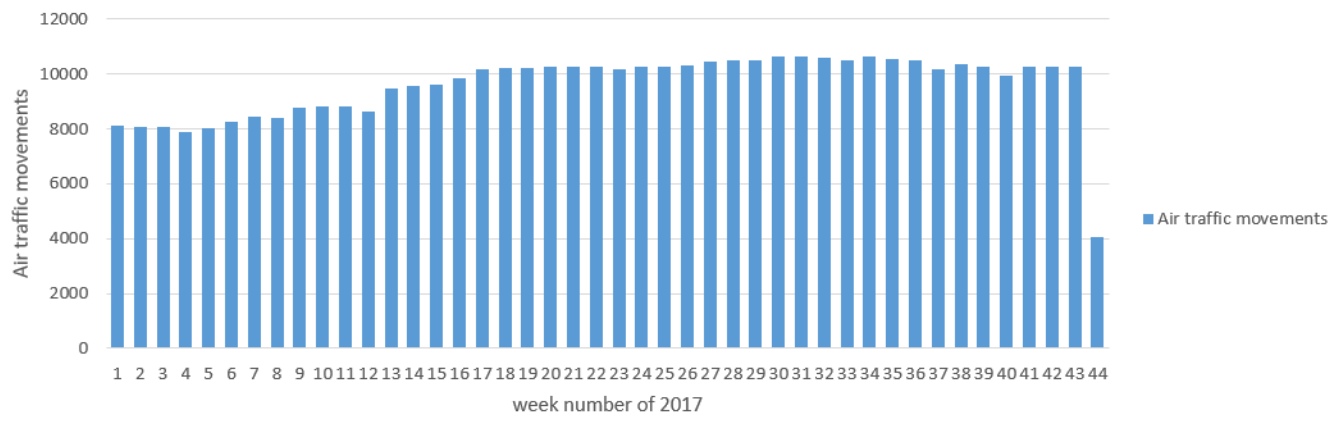


Figure 5.1: Seasonality in air traffic movements aggregated per week for 2017

In airside planning it is the design methodology to design stands on absolute peak of the year, since it is important to always have enough stands for all aircraft. In 2017 the absolute peak of air traffic movements per day is on August 7th. This day is selected as day of analysis. Over 1583 separate arrivals and departures are handled in one single day.

The main driver to apply a full day analyses is to capture all demand characteristics. One of these characteristics are influences of runway capacity. It is concluded by Mirkovic and Tosic that it is important to include all demand and flight schedule characteristics, to capture all effects of runway capacity on stand capacity [52, 53].

For traditional stand capacity analysis, the peak hour is selected and analysed. However, for this model a complete day is analysed. For the amount of stands needed a peak hour analysis is a good representation of the total number of stands required, but for the stand mix a complete day, or even a week or year is better, because a decision on stand capacity depends on utilisation through the year. This will be researched in the sensitivity analysis in chapter 6.

Some types of stands are needed in the peak hour but underutilised in the rest of the time. The algorithm will try to decide on a an amount of capacity while keeping stand utilisation high. It is important to keep stand utilisation high because the capital investment of a stand is very high. The decision on the amount of stands depends on utilisation through the year.

5.2. Datasets

To support the model a few extra sources are needed to complete all information regarding airports and aircraft.

5.2.1. Airport data

To create geographical visualisations another set of airport data is combined with this data set. This is taken from online open-source database Skybrary where all codes, city, country, longitudes and latitudes of airports are available[54].

5.2.2. Aircraft data

To get compatibility of aircraft with stand sizes all aircraft need to be sorted into aircraft design groups. To find information on aircraft size and aircraft codes an online open-source database by AVCodes is used [55]. Tables of this compatibility can be seen in Appendix C.

5.2.3. Flight Schedule

A flight schedule is delivered as separate arrivals and departures entries. To determine exactly how long each aircraft is present at the airport these have to be matched. However, in order to match these, tailnumbers of the aircraft are needed, which are unique registration numbers for each aircraft. To capture overnights from the night of 6th to 7th as well as the night from the 7th to the 8th the data of three consecutive days are matched.

Tailnumber data is sensitive due to safety reasons and not publicly available. This data was therefore was requested in cooperation with NACO from Schiphol, where a snapshot was taken from the Airport Operational Database. The data consists of the following elements:

- Passenger/freight
- Date actual
- Date block
- Date scheduled
- Time actual
- Time block
- Time scheduled
- Arrival or Departure
- Aircraft registration
- Airline
- Airline full name

- Alliance
- Codesharing with KLM
- Aircraft type IATA
- Aircraft type ICAO
- Seats
- total passengers
- Transfer passengers
- Airport IATA
- Airport ICAO
- Schengen indicator
- Continent
- Country
- City
- Contact stand [Y/N]
- Ramp to gate [Y/N]
- Ramp group
- Ramp group full
- Stand position (VOP)
- Ramp type

It is decided to run the model on scheduled arrival times, where in the sensitivity analysis it will be investigated how the model responds to actual times.

After the data is matched, the overlapping set is selected of aircraft that depart after 2017-08-6 23:59:00 and at the same time arrive before 2017-08-8 00:01:00, to ensure that all overnight flights of both nights are taken into account.

5.3. Data Handling

In the preprocessing module several steps are taken to prepare data for the strategic stand capacity model. A set of filters are applied to filter out groups of flights, and data is cleaned by removing specific individual arrival and departure entries.

5.3.1. Filtering Groups of Flights

A few filters are applied on the data to sort out flights that do not govern stand capacity at Schiphol Centrum. These are general aviation and aircraft that fall into aircraft design groups B. Also pure freight flights are removed because they are handled at a completely separate part of the airport.

5.3.2. Data Cleaning of Individual Flights

The data does show some faulty entries due to errors in data collection at Schiphol airport. Flights that miss aircraft registration, aircraft type, origin or destination are removed. These are manually removed from the data.

A set of 14 flights with very large turn around times are filtered from the data varying from 41 hours and 192 hours. These can be seen in Table 5.1. These were all flights operated by KLM with the exception of one flight operated by Air Canada. Reasons for these long turn around times can vary, or in the case of KLM can be related to scheduled or unscheduled maintenance. According to gate assignment research by Dorndorf [32] input data uncertainty for flight schedules typically have one of the following reasons:

- Flight on time performance
- Emergency flight
- Severe weather condition
- Flight cancellation or gate closure
- Errors made by airport staff/others [32]

One of these reasons may influence the results which do not represent daily airport operations. The data contained information regarding the actual time of arrival and actual time of departure. In the sensitivity analysis of this research the influence of the on time performance investigated. A total of 12 erroneous entries have been found, such as double entries or spelling mistakes, which have been corrected before the data was run through the model. The departure times are defined in DOY and HOD.

Table 5.1: Filtered flights

Airline	Tailnumber	Departure[HOD]	Departure[DOY]	Origin	Destination	TAT [hour]
KLM	PHBQE	222	13	UIO	JFK	48
KLM	PHAKE	220	5	LOS	MCT	54
KLM	PHBVN	220	6	CGK	GRU	52
KLM	PHBGB	220	19	LHR	BCN	49
KLM	PHEZP	222	19	STR	HAM	49
KLM	PHBHC	222	18	HGH	KIX	44
KLM	PHKZB	224	19	LUX	DRS	41
KLM	PHEZE	222	13	DUS	DUB	80
KLM	PHBFU	218	9	LAX	HKG	80
KLM	EIRJO	218	13	BHX	LCY	90
KLM	PHBGX	218	16	GLA	GLA	192
KLM	PHBFU	218	9	LAX	HKG	80
AIR CANADA	CGHLM	217	10	YYZ	YUL	50
KLM	PHEZH	217	21	VIE	TLS	62

Other longstay aircraft are kept in the dataset and are all verified with a second database supplied by Schiphol API environment, which gives the same results.

5.4. Cost and time parameters

Beside a flight schedule the model also uses a few parameters and variables as input.

Flights eligible for splitting

According to RASAS, for the split into three operations is only possible flights with a turn around time longer than 170 minutes [34]. After arrival the first tow is performed 60 minutes after arrival and is towed to a departure stand 60 minutes before operations. The parking part receives only a remote stand as compatible stand. RASAS states that for planning purposes the average time that towing an aircraft from one stand to another takes 10 minutes. This time is subtracted from the non-operational parking time.

Following RASAS guidelines, the split version into two operations is only possible for flights with a turn around time longer than 120 minutes. The tow between the two stands is scheduled 35 minutes after arrival. For the 2-split version the 10 minutes is subtracted from the time scheduled for the second part.

Separation time

In reality the duration of separation between flights will vary depending on problems or opportunities that arise during daily operations. When the stand allocation plan is developed, one of the objectives is to minimise the variance in separation times, to create a robust plan. Research by Hoogeveen at Schiphol showed improvements in planning by applying this strategy [31]. Because the research for this strategic stand capacity is variable, it is more logically to optimise for robustness for daily operations instead of long term strategic planning. Therefore the duration for separation times are taken from RASAS and can be seen in Table 5.2. The minimum separation time between two flights is 20 minutes for widebodies, 10 minutes for narrowbodies and 25 minutes for very heavy aircraft such as the Airbus A380 at Schiphol. The minimum separation time between a tow to or from a stand and a scheduled arrival or departure is 10 minutes. This is taken into account during calculation of the conflicting sets of flights. In a sensitivity analysis the influence of changing separation times will be investigated.

Table 5.2: Separation times for different aircraft sizes

	Separation time [min]	**Separation after tow [min]**
Aircraft size C	10	10
Aircraft size E	20	10
Aircraft size F	25	20

Capital cost of stands

The capital cost $C2_j$ associated with building a stand of a particular stand $j \in S$ can be seen as the bottom two rows in Table 5.4. The metric of these cost are cost per day. The cost per day for a stand initial investment is based on expert knowledge of NACO specialist in combination with reference airport financial analyses. As can be seen in the table, larger stand are more expensive due to larger area required. The swing stands are more expensive since they need an extra layer on the terminal to separate passengers. Assumption for this calculation is depreciation over 20 years.

Table 5.3: Calculation for depreciation of contact stands

Stand	**F**	**E**	**C**
Nr PBB	3	2	1
PBB Cost [€]	500000	500000	500000
Total PBB cost	1500000	1000000	500000
Area cost			
Cost stand area[€/m^2]	350	350	225
Area [m^2]	20000	13750	6050
Total Area cost [€]	7000000	4812500	1361250
Building Cost			
Layers building	2	2	2
Swing layers building	3	3	3
Width [m]	90	70	50
depth [m]	20	20	10
Building area cost [€/m^2]	4000	4000	4000
Cost building single sector [€]	14400000	11200000	4000000
Cost building swing [€]	21600000	16800000	6000000
TOTAL single sector cost[€]	22900000	17012500	5861250
TOTAL Swing cost[€]	30100000	22612500	7861250
Depreciation per day [€]	3137	2330	803
Depreciation per day for swing[€]	4123	3098	1077

Table 5.4: Calculation for depreciation of remote stands

	Remote Widebody	**Remote Narrowbody**
Cost stand area[€/m^2]	350	225
Area [m^2]	13750	6050
Total Area cost [€]	4812500	1361250
Depreciation per day	820	263

Operational cost for bussing
According to Schiphol stand allocation guidelines only 55 passengers per bus can be transported on the air-side [34]. Using this in combination with the amount of seats on board of an aircraft the movements needed to bus one flight can be calculated. To determine the cost of bussing all passengers of a flight, the cost per movement is calculated, which can be seen in Table 5.5. Then the operational cost to handle an entire aircraft using busses is determined.

Bussing is allowed for both arriving passengers and departing passengers. However, the operational complexity of bussing departing passengers is higher, because typically passengers are not all waiting at the gate. The chances for delay are higher when bussing passengers at departure. A penalty of 50% is given to the cost of bussing at departure. This ensures that the algorithm only selects this option if it benefits the total cost of objective function, which implies that a reduction of total capacity is possible.

Operational cost for towing
According to expert knowledge at NACO a preference Using a trade-off analysis the influence on operational complexity by choosing one is a situational decision that involves diminishing or losing one quality, quantity or property of a set or design in return for gains in other aspect Factors that play a role in this decision are the increase of operational complexity using towing compared to a bus solution. Based on expert knowledge at NACO weights are given.

Table 5.5: Calculation for cost per bus movement

Initial investment of bus [€]	115000
Initial investment of boarding stairs [€]	32000
Total initial cost [€]	147000
Depreciation per day over 10 years [€]	58
Electricity and other cost[€/day]	150
Total cost per day [€]	208
Average movements per day per bus	10
Cost per movement	21

For a narrowbody the 2-split is more costly than average narrowbody-bussing cost. This is due to preferences at Schiphol airport, where the swing solution is preferred over a tow-solution for narrowbody aircraft that switch sector. For a widebody the 2-split is less costly than average cost of widebody-bussing.

A 3-split tow is less costly, since they are long-stay and high preference weight is given to this solution where contact stands are not blocked by long-stay flights. For both widebody and narrowbody this results in cost lower than average bus cost. An overview of the resulting cost can be seen in Table 5.6.
This is in accordance with towing behaviour between widebodies piers at Schiphol, where more tows are occurring for widebodies than narrowbodies, which will be explained in chapter 6 using historic stand allocation data.

Table 5.6: Cost of towing as result of trade-off between preferences

	Average bus cost [€]	**Tow cost 2-split** [€]	**Tow cost 3-split** [€]
Narrowbody	60	70	50
Widebody	120	100	60

Overview cost coefficients
Concluding, the coefficients used to steer the solution towards making a trade-off based on cost are defined as follows:

- $(C2_{ij})_{O\times S}$ is a matrix of operational cost for all combinations of operation i ∈ O with particular stand j ∈ S. This also includes bus cost $cbus_i$ or tow cost $ctow_i$ or c_{sym} if it applies for a particular combination i and j. It also holds preferences to assign a particular operation to best match stand size.
- $C1_j$ are the capital cost associated with building a stand of a particular stand j ∈ S.

To force the solution to place flights to the smallest size stand available without influencing capacity, a symbolic cost of 1 euro is given to allocation of a narrowbody to a narrowbody stand and widebody to widebody stand. A cost of 1.000001 euro is given for a combination where the stand is larger than necessary, which implies a narrowbody allocation to a widebody stand. This small difference is created to give a preference for stand allocation of the second optimisation model to a matching stand if one is available. The symbolic cost is a strategy presented in stand allocation research by Prem Kumar to introduce perceived importance of certain allocations in a multi-objective airport gate assignment problem [42]. To analyse the influence of this cost a sensitivity analysis is performed and described in subsection 6.6.1

6 Results of Strategic Stand Capacity Model

In this section the results of the Strategic Stand Capacity Model are presented. Schiphol Airport is used as a case study for the peak day in 2017 occurring on the 7th of August.

The structure of this chapter is as follows. Firstly visualisations of the input are provided to give insight on Schiphol stand allocation and the specifics of the flight schedule of the day of analysis. Secondly, a Pareto optimal front is created where the a set of individual solutions along the Pareto optimal front is investigated. Thirdly, the solution offered by Schiphol is forced into the model to investigate how the model performs. The historic allocation data of Schiphol is then used to validate the model. Then a conclusion about the performance of the model is made.

6.1. Input: Data Analytics

An intensive input analysis on the flight schedule is performed. This is done to allow for verification whether the demand characteristics found in the input have influences on the resulting stand capacity. The input of the model is a flight schedule consisting of 803 flights that are present on Schiphol airport between 00:00 and 24:00 on the 7th of August 2017. In this section an overview of this flight demand is presented, using the Airport Demand Analytics dashboard created for this research as a basis. This will be used as the basis of validation and verification of the result of the model.

6.1.1. Wave Characteristics of Arrival and Departures

The arrival and departure wave patterns are specific characteristics for an airport. In Figure 6.1 these are seen, summed per 15 minutes for the day of analysis 7th of August 2017. At night there are few arrivals and even less departures, which is related to noise regulations at night. The day starts with the largest departure wave, followed by the largest arrival wave. It is also seen that the maximum of arrivals and departures combined stays semi-stable.

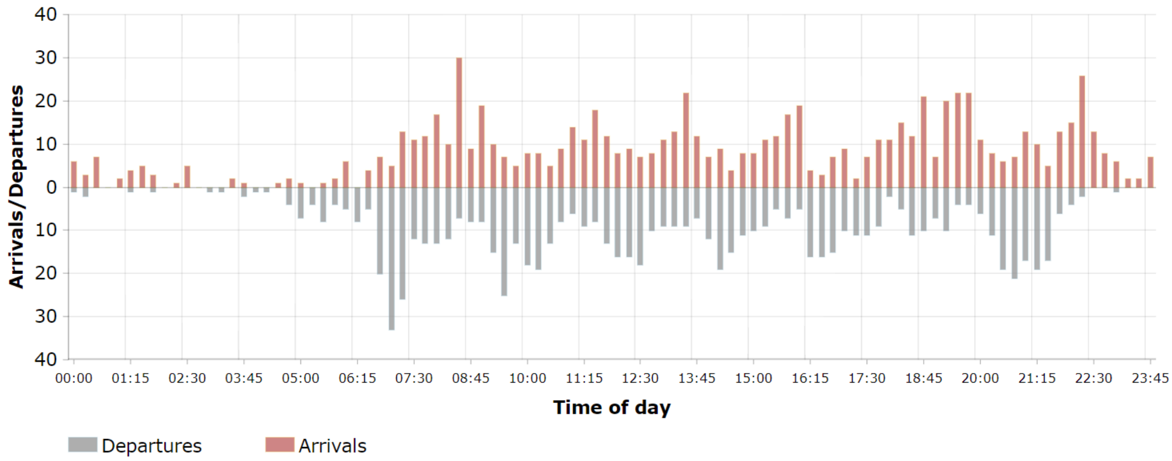


Figure 6.1: Arrival and Departure waves at Schiphol for 7th of august 2017

6.1.2. Aircraft Demand Throughout the day

When the separate arrivals and departures entries of the data are matched, an overview is made aircraft present at the airport during the day, split into three aircraft design groups C, E and F. The results are illustrated in Figure 6.2 which will will be shortly discussed in this next section.

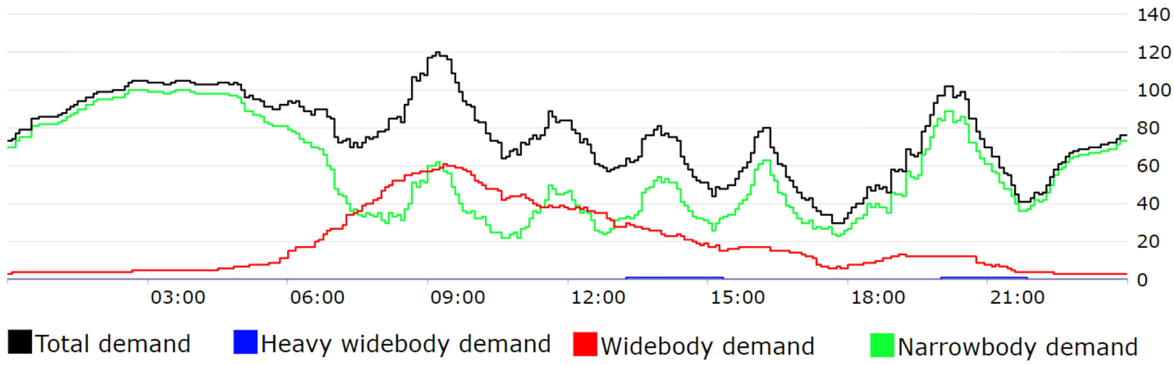
Figure 7.2a shows the total demand, split in light-blue line of narrowbody aircraft and bright-blue line of widebody aircraft. Widebodies are peaking in the morning, in between the largest departure and the largest arrival wave of the day. The narrowbody peak occurs just before the widebody peak, which consists of typically smaller regional aircraft that feed demand to the larger widebody flights.

Figure 6.2b shows the presence of aircraft that originate from a Schengen country and also return to a Schengen country. This set of flights is subject to a steady wave pattern with a larger peak in the evening. The pure Schengen demand consist of mainly narrowbody aircraft and a few widebody aircraft operated by TUIFly.

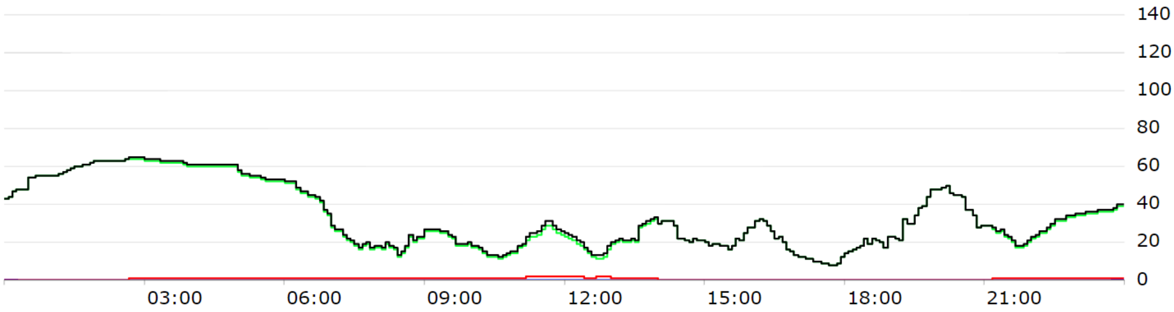
Figure 6.2c shows the demand of aircraft that originate from a non-Schengen country and also return to a non-Schengen country. The peaking behaviour is clear with a large peak in the morning.

Figure 6.2d shows aircraft that that switch from a Schengen country to a non-Schengen country or vice versa. These are difficult flights in terms of allocation, since they require either a tow, a bus or a swing stand. This demand is therefore the main driver for an increase in capital cost for swing stands, or an increase in operational cost for bussing or towing. The graph also shows that these aircraft are mainly narrowbody with the exception of a few widebody operations.

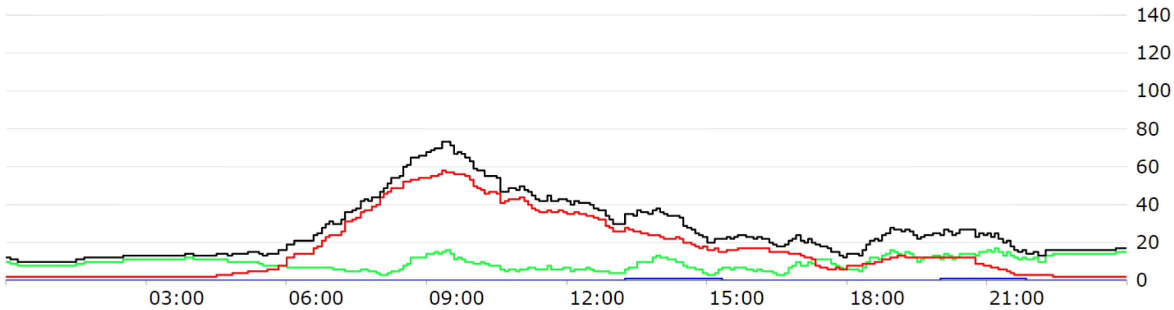
When these results are combined with Figure 6.1 it can be concluded that Schiphol airport has a high demand for remain overnight positions.



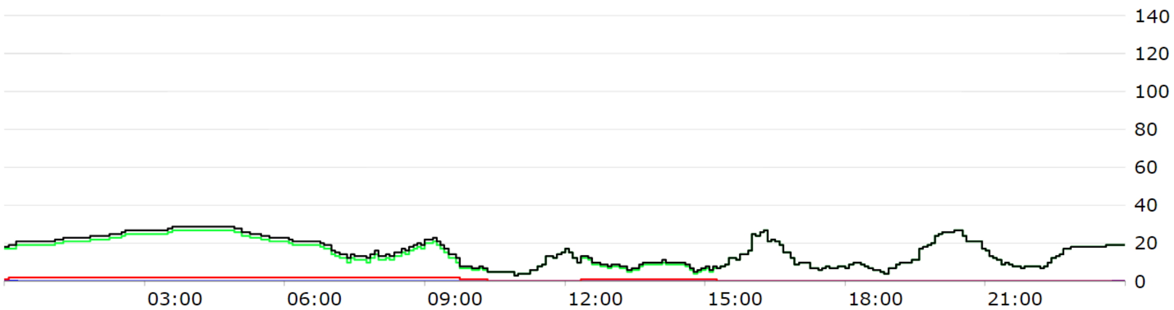
(a) Total demand of aircraft



(b) Aircraft with Schengen origin and Schengen destination

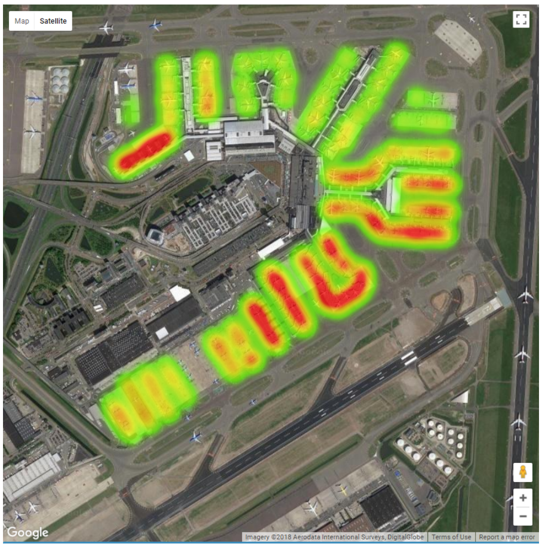


(c) Aircraft with non-Schengen origin and non-Schengen destination

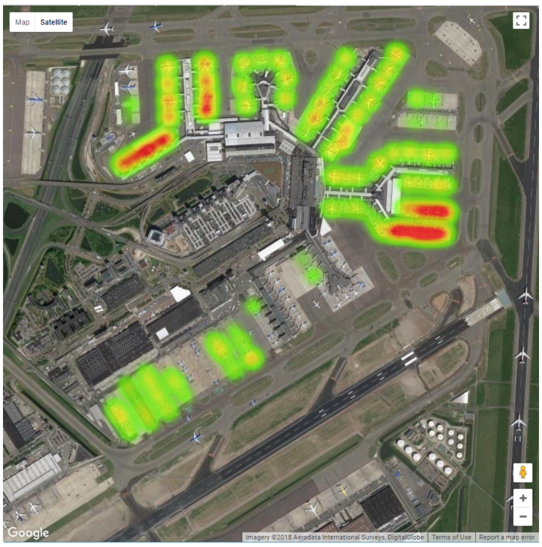


(d) Aircraft that switch from a Schengen country to a non-Schengen country or vice versa

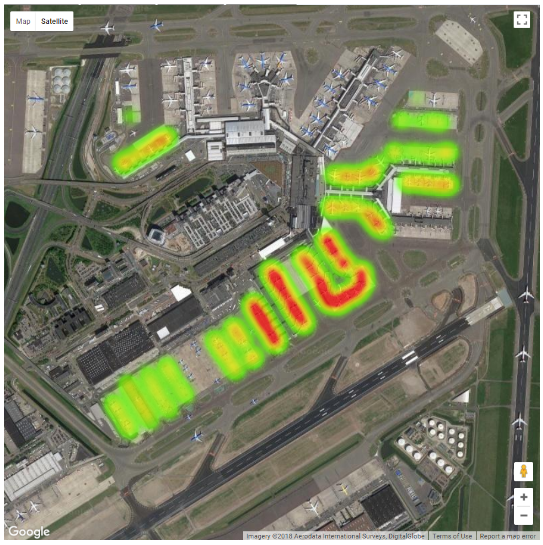
Figure 6.2: Air traffic movements on 7th of August 2017



(a) Total aircraft allocations on 7th of August 2017

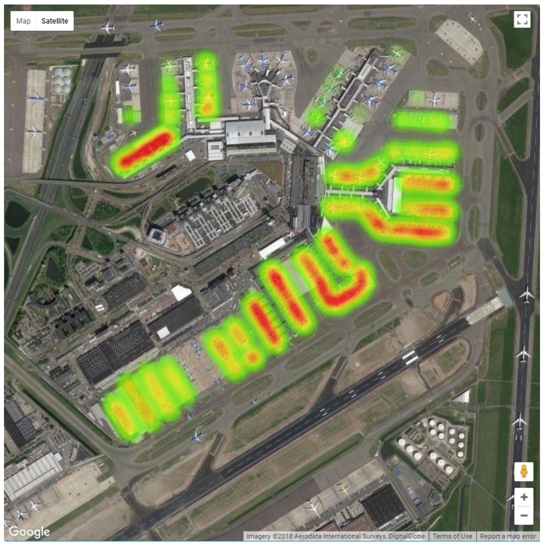


(b) Non-Schengen arrivals and departures



(c) Schengen arrivals and departures aircraft

(d) Widebody aircraft



(e) Narrowbody aircraft

Figure 6.3: Air traffic movements on 7th of August 2017

6.1.3. Utilisation Analysis of Historic Stand Allocation

To make sure the model simulates stand allocation correctly an analysis is made of the current use of stands in the form of heatmaps. These charts show the number of separate arrivals and departures handled by a stand. Stands that have a relatively high number of allocated aircraft are given a red colour and stands that have a relatively low number of allocations have a green colour.

The heatmap in Figure 6.3a shows the demand of aircraft of one day. Very high utilisation is reached at the H&M pier used by low cost carriers (LCC). The widebody stands in the north side of the terminal have less allocations due to the fact that widebody aircraft have a longer average turn around time. To investigate whether narrowbody aircraft are positioned on widebody stands, demand is shown separately in Figure 6.3e.

Narrowbody utilisation of widebody stands: In Figure 6.3e an heatmap is presented which shows demand of narrowbodies, when comparing this map with Figure 2.9 it shows that narrowbodies are utilising the widebody stands. Especially the six widebody stands at G-pier (top left) are showing high narrowbody activity, the north side of the D-pier, the 3 widebody stands at both C-pier and D-pier.

A focus on the sector of stands is seen in heatmaps in Figure 6.3. From the graph it is apparent that there is overlap of Schengen and non-Schengen flights, which occur on swing stands of pier H and D where aircraft can disembark passengers of both sectors. Also remote stands act as operational swing stands. Interesting are non-Schengen movements at A and B pier

6.1.4. Sector-Switching Aircraft

One of drivers of swing stands are sector-switching aircraft. These sector-switching aircraft are a result of routing where an aircraft does not necessarily returns to their originating airport, and might even switch from a Schengen country to a non-Schengen country. The amount of aircraft that switch on the 7th of August 2017 can be seen visually in Figure 6.4. On the day of analysis this reaches up to 21 percent.

Figure 6.4: Aircraft flow from sector of origin to sector of destination

6.1.5. Towing Aircraft from Pier to Pier

After matching arrivals and departures the data is filtered to find aircraft where the arriving part is allocated to a different pier than the corresponding departure part. In Figure 6.5 a Sankey visualisation is shown which demonstrates the amount of aircraft that are changing piers by using flow-nodes.

In Figure 6.5 the tows of the peak day of 2017 are seen between piers and remote stands. It is clear that little to no towing occurs at pure narrowbody piers/platforms A B and C. A large driver for towing are sector-switching flights. Data shows that of the aircraft that are towed in Figure 6.5 49% of flights switch from sector, of which 19% switch from Schengen to non-Schengen and 30% from non-Schengen to Schengen. Towing does provide a solution for these switching flights, however, it increases operational cost. Another solution for these flights are swing stands which require a larger capital investment. This trade-off between operational and capital cost will be possible by varying the weights of both these objectives in the objective function by creating a Pareto front.

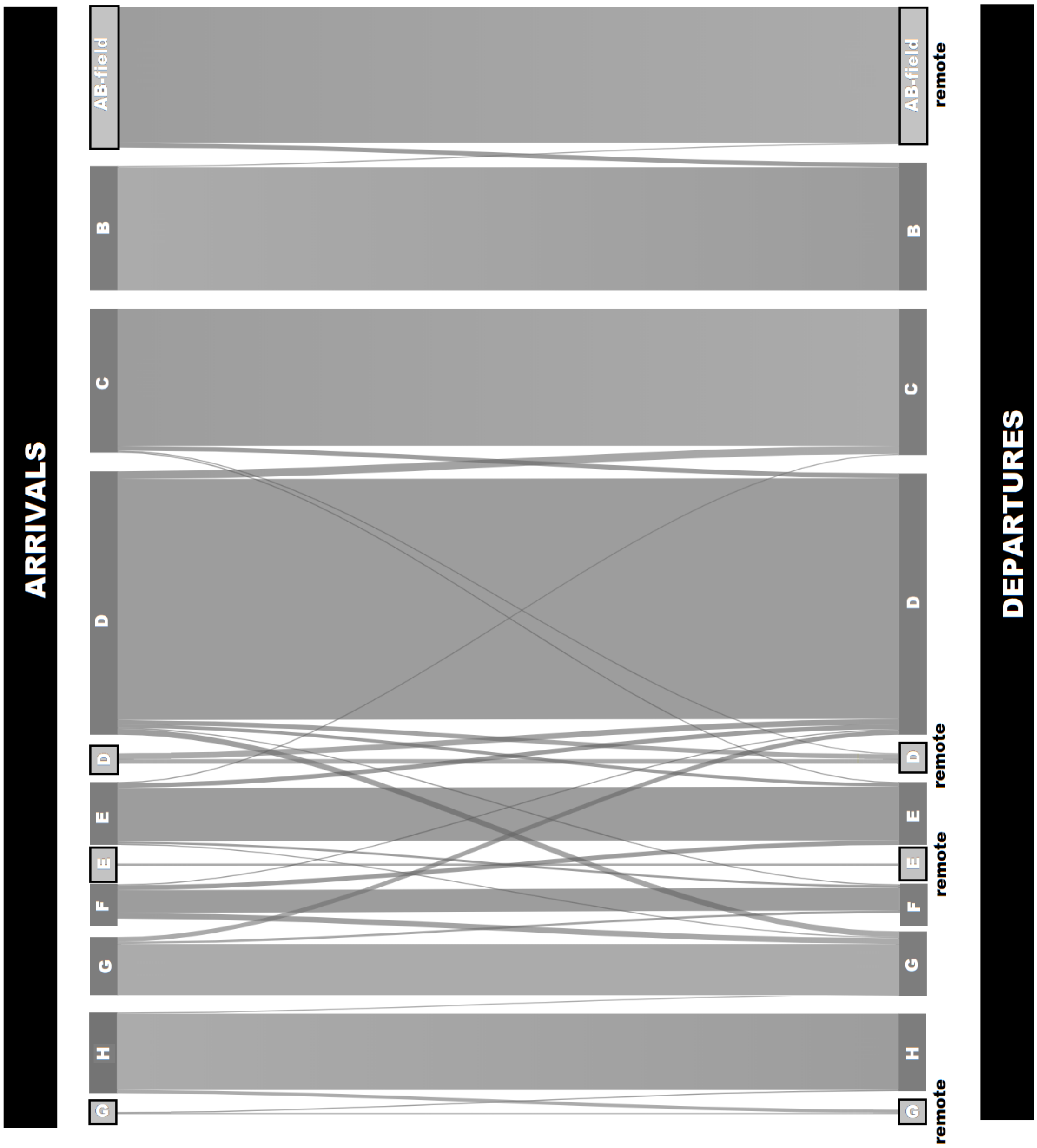


Figure 6.5: Sankey flow diagram of allocation data

6.2. Results of Optimisation Model 1: Stand Capacity

The results of the model are computed along a Pareto optimal front and are presented in this section for a flight schedule of 7th of August 2017. A total of 20 optimal solutions are computed and visualised. In this solution space the possibility of a trade-off arises between operational cost and capital cost. This defines the type of airport that is designed, having the wishes of a customer in mind.

The full flight demand schedule of 803 separate air traffic movements is used as input to formulate the lp-problem. This lp-file is then solved by IBM CPLEX. CPLEX reduces the initial stated mixed integer problem to a smaller problem of 10958 binary variables and 11 integer variables. As a starting point the algorithm creates a presolve solution, after which the dynamic search is applied to converge to an optimal solution.

6.2.1. Pareto Front Results: Trade-off Curve between capital cost and operational cost

A Pareto front is an standardised way to analyse the trade-off between two different objectives. It is a curve that defines a line of optimal solutions within the solution space, where each step in the curve is related to deteriorating one objective while improving one objective. Since all points are equally optimal, it is up to the decision maker to select a point on this curve. In this problem the objective is split into capital cost and operational cost. To create this curve the model is run 19 times for different values of α ranging from 0.05 to 0.99. The resulting Pareto curve can be seen in Figure 6.6. This chart shows that an increase in capital cost allows for a decrease in operational cost.

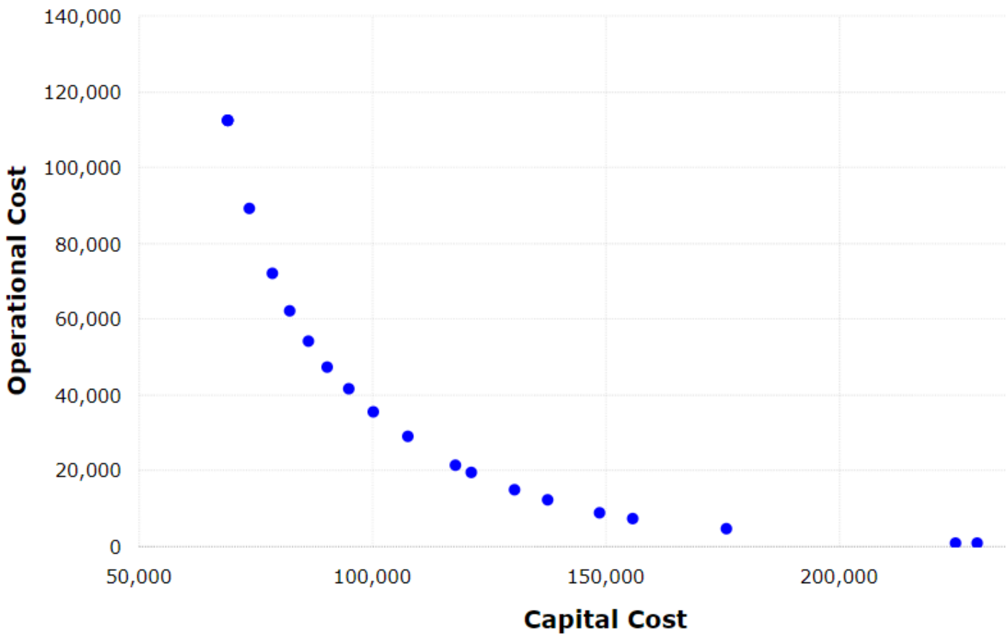


Figure 6.6: Pareto front for full flight schedule of 7th August 2017

6.2.2. Pareto Front Results: Stand Mix

When diving into the solution characteristics it becomes clear that a combination of different types of stands is made for each of the solutions along the Pareto curve. Table 6.1 shows the resulting stand capacity solutions found by optimisation 1. In Figure 6.19a a bar chart of these results can be seen as supporting visualisation. Here it can be clearly seen that for α is 0.05 only remote stands are build against low capital cost and high operational cost. This solution boils down to an airport solution where no stands are connected to the terminal and all passengers are bussed to the terminal. When α increases the weight on operational cost becomes larger and optimal solutions are found with more contact stands, against a higher capital cost. Finally, the solution for α is 0.99 requires a high capital investment and refers to an airport where every flight is handled fully at contact stands for a very high capital cost.

The grand total amount of stands stays stable around 131 stands, while the stand mix varies. The exception is the solution of α equals 0.9 where an extra 2 stands are built. During the sensitivity analysis of this model it is found that the optimisation repeats this behaviour. This is due to a tipping points in solution characteristics where along the optimal front in the solution space a solution is found that requires more stands. The model optimises for cost and therefore not necessarily finds the least amount of stands as an optimal solution.

Table 6.1: Stand mix solution along the Pareto curve

α	C S	C NS	C SW	E S	E NS	E SW	F S	F NS	F SW	R n	R w	Contact Total	Remote Total	Grand Total
0.05		-	-	-	-	-	-	-	-	69	62	0	131	131
0.1	-	-	-	-	-	-	-	-	-	69	62	0	131	131
0.15	-	-	-	-	-	-	-	-	-	69	62	0	131	131
0.2	6	3	-	-	-	-	-	-	-	60	62	9	122	131
0.25	13	5	-	-	-	-	-	-	-	51	62	18	113	131
0.3	17	8	-	-	-	-	-	-	-	44	62	25	106	131
0.35	20	9	2	-	-	-	-	-	-	38	62	31	100	131
0.4	22	9	4	-	1	-	-	-	-	34	61	36	95	131
0.45	23	9	7	-	2	-	-	-	-	30	60	41	90	131
0.5	25	10	8	-	4	-	-	-	-	26	58	47	84	131
0.55	28	9	10	-	7	-	-	-	-	22	55	54	77	131
0.6	30	9	11	1	10	-	-	1	-	19	50	62	69	131
0.65	32	9	12	1	11	-	-	1	-	16	49	66	65	131
0.7	33	8	14	1	16	-	-	1	-	14	44	73	58	131
0.75	35	8	14	1	20	-	-	1	-	12	40	79	52	131
0.8	40	5	17	2	24	-	-	1	-	7	35	89	42	131
0.85	38	3	23	2	24	2	-	1	-	5	33	93	38	131
0.9	41	2	28	1	33	3	-	1	-	-	24	109	24	133
0.95	29	2	38	1	42	18	-	1	-	-	-	131	0	131
0.99	29	2	38	1	36	24	-	1	-	-	-	131	0	131
Current capacity	**25**	**13**	**20**	**2**	**25**	**9**	**0**	**2**	**0**	**51**	**21**	**96**	**72**	**168**

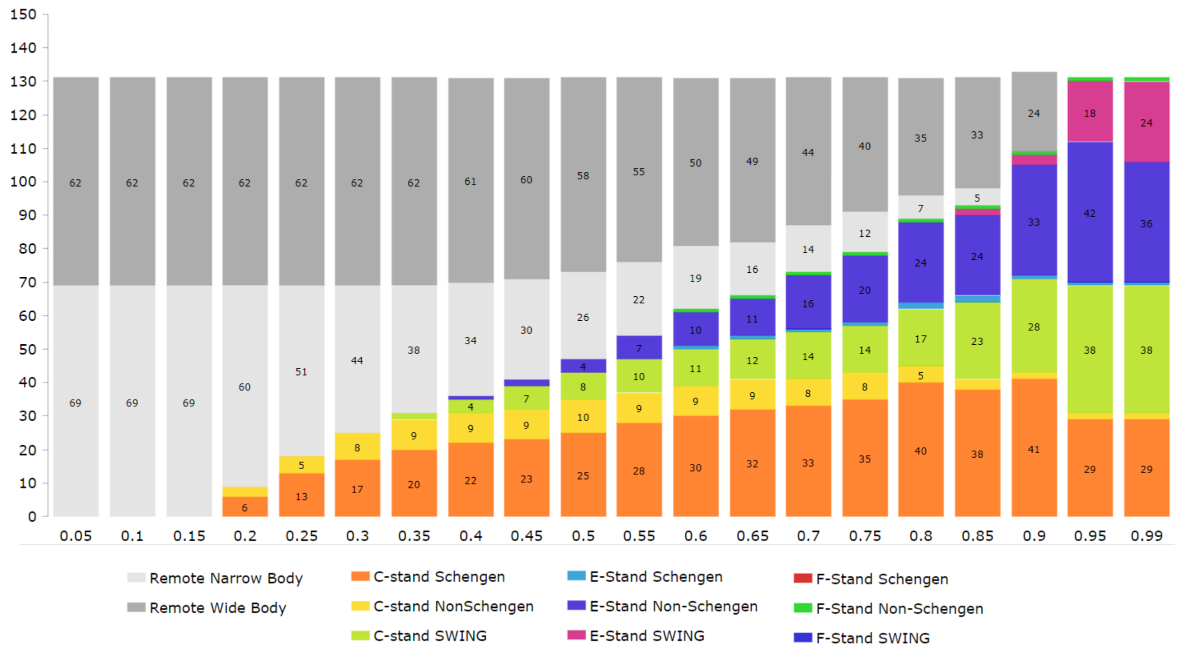


Figure 6.7: Pareto front of solutions found for Schiphol

6.2.3. Pareto Front Results: Tow movements

Directly related to operational cost are the tow movements. Along the Pareto curve the number of tow movements behaviour is measured and can be seen in Figure 6.8 and Table 6.2. Initially for $\alpha = 0.05$ till $\alpha = 0.15$ no tows are observed, because all aircraft are handled remotely which elimates the need for towing. Then, the amount of tows increases till a peak of 93 tows is observed at $\alpha = 0.5$ followed by a reduction to zero tows at

$\alpha = 0.95$.

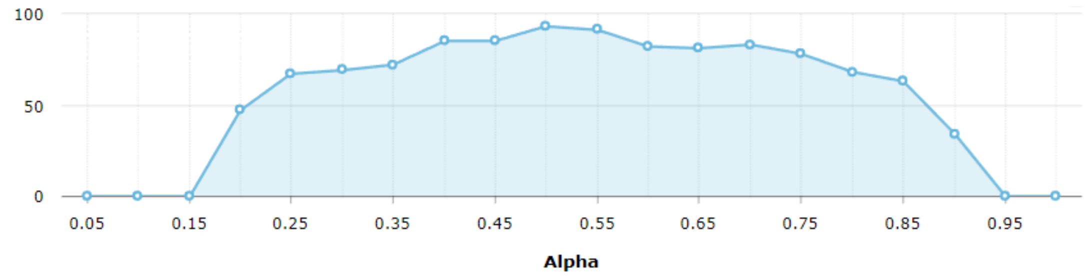


Figure 6.8: Number of tow movements along the Pareto front

Table 6.2: The number of bus and tow movements along the Pareto Front

α	**0.05**	**0.1**	**0.15**	**0.2**	**0.25**	**0.3**	**0.35**	**0.4**	**0.45**	**0.5**
Bus	4250	4250	4250	3265	2592	2214	1905	1621	1387	1143
Tow	0	0	0	47	67	69	72	85	85	93

α	**0.55**	**0.6**	**0.65**	**0.7**	**0.75**	**0.8**	**0.85**	**0.9**	**0.95**	**1**
Bus	900	629	554	370	250	151	88	38	6	0
Tow	91	82	81	83	78	68	63	34	0	0

6.2.4. Pareto Front Results: Bus movements

The amount of bus movements needed influence operational cost and change along the Pareto optimal front. Per aircraft that requires bussing, the amount of bus movements is depending on aircraft size, where each bus carriers 55 passengers, according to Schiphol RASAS regulations [34].

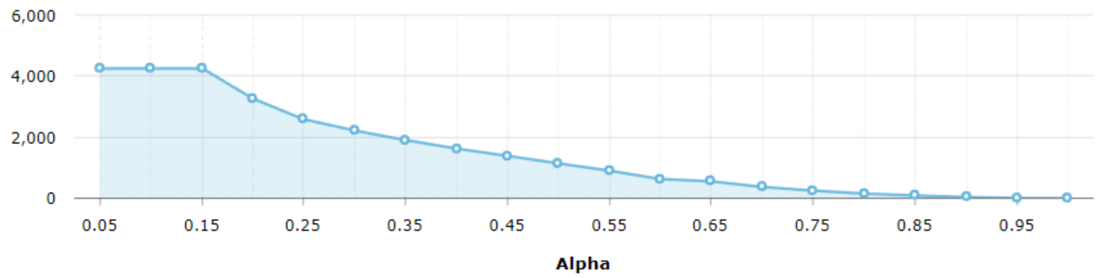


Figure 6.9: Number of bus movements along the Pareto front

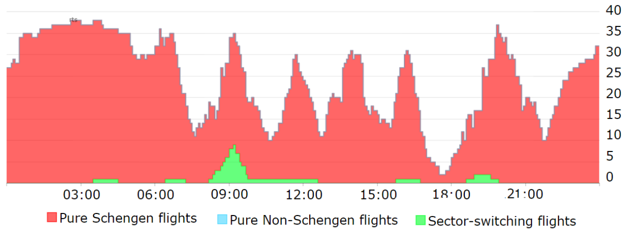
The number of bus movements decreases when α increases as can be seen in Table 6.2 and Figure 6.9. Along the Pareto Front the amount of bus movements for $\alpha = 0.05$ starts with 4250 movements, where all aircraft are allocated to remote stands and therefore all require bussing. The curve asymptotically drops, where at $\alpha = 0.5$ 1143 a total bus movements are required and the need for busses is completely eliminated at $\alpha = 0.99$.

6.2.5. Cross-Utilisation of Sectors per Stand-Type for $\alpha = 0.85$

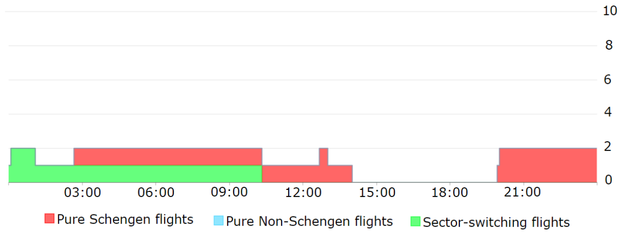
Diving into the solution characteristics of individual solutions along the Pareto optimal front the utilisation per standtype can be analysed. The solution of $\alpha = 0.85$ is selected because it is the first solution that handles all passengers at contact stand, with the exception of two arrivals of longstay aircraft.

To create transparency around the cross-utilisation between stand-sectors and aircraft-sector a set of charts is created, seen in Figure 6.10. These are a combination of bar charts and line charts, named stacked charts.

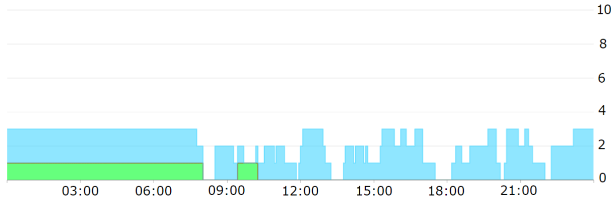
Cross-utilisation is made visual by dividing the demand in coloured demand segments. This creates insight in what the origin or departure sector is of the flights using a particular standtype, which is especially interesting to analyse usage of swing stands. The red area represents aircraft that are flying Schengen to Schengen, the blue area represents aircraft that are flying non-Schengen to non-Schengen, the green area represents aircraft that are switching between sectors. The left-hand column of charts are narrowbody stands, the right-hand column of charts are widebody stands. The top row two charts are Schengen stands, which are vertically followed by a row of two non-Schengen stand charts, a row of two swing-stands charts and a row of two remote stand charts.



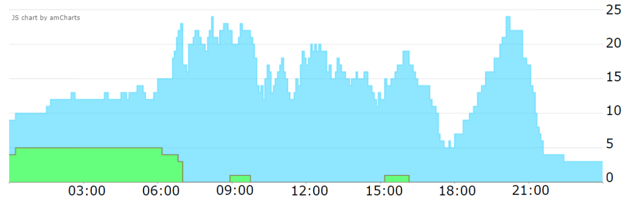
(a) Sectorised demand on narrowbody C-Schengen-stands



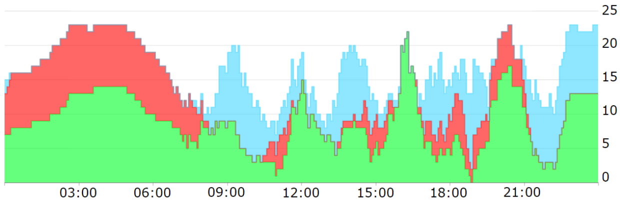
(b) Sectorised demand on widebody E-Schengen-stands



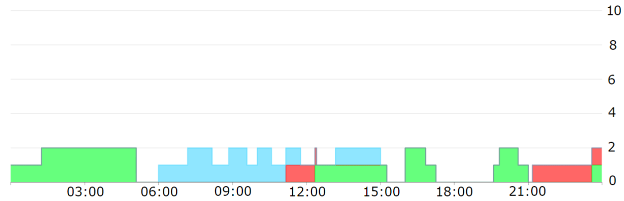
(c) Sectorised demand narrowbody C-non-Schengen-stands



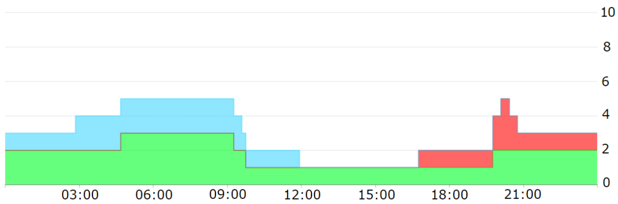
(d) Sectorised demand widebody E-non-Schengen-stands



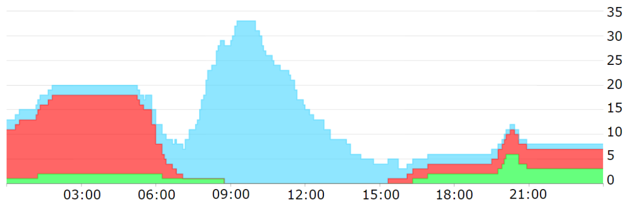
(e) Sectorised demand on narrowbody C-swing-stands



(f) Sectorised demand on widebody E-swing-stands



(g) Sectorised demand on narrowbody remote stands



(h) Sectorised demand on widebody remote stands

Figure 6.10: Sectorised aircraft utilisation per standtype of the current capacity scenario $\alpha = 0.85$

For Schengen dedicated narrowbody stands in Figure 6.10a and Figure 6.10b the utilisation is driven by pure-Schengen demand in red, which is slightly complimented by allowing sector-switching flights overnight and in the morning. This result aligns with input data peaks seen in Figure 6.2b. For widebody stands only two stands are needed, which also aligns with input data showing very low demand in Figure 6.2b. The effects observed in these charts will be shortly stated in this section.

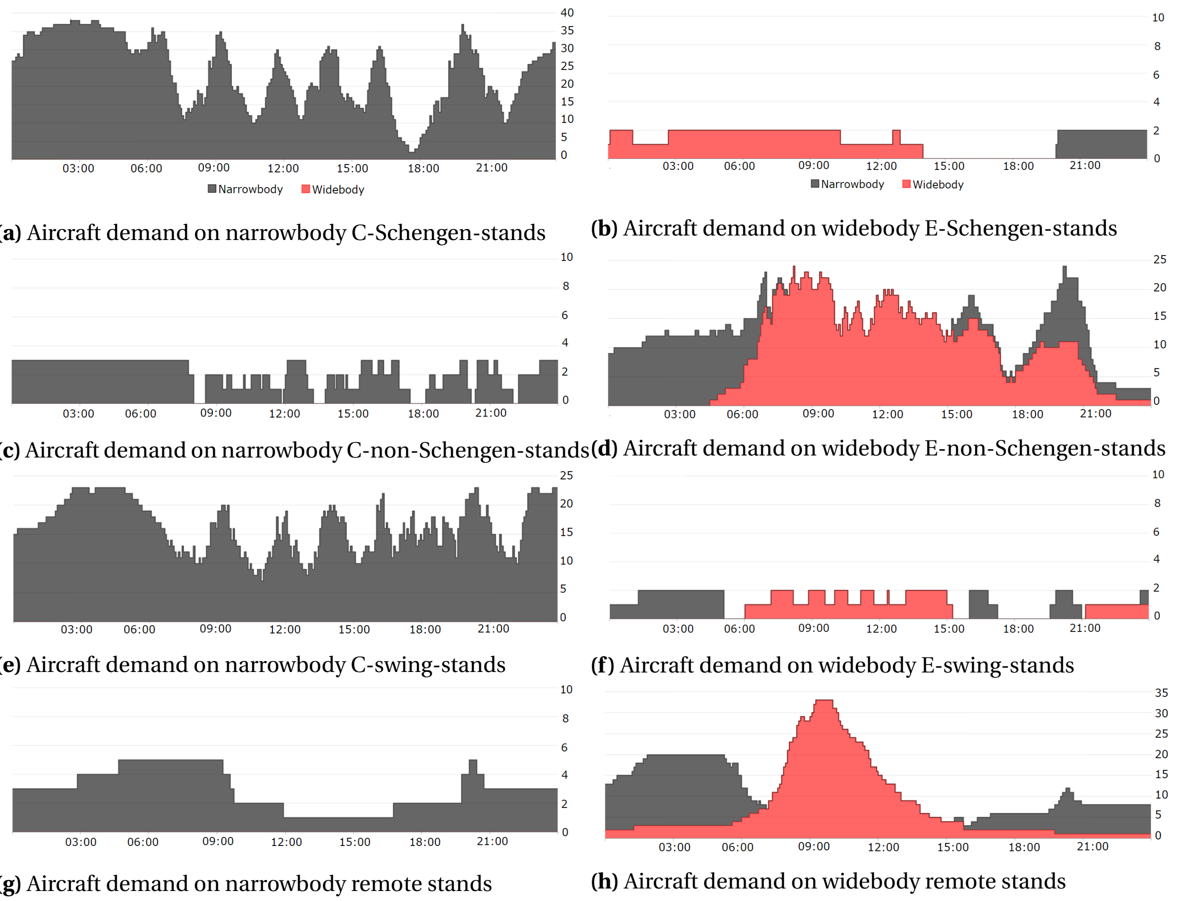
For non-Schengen stands in Figure 6.10c and Figure 6.10d the model optimises stand utilisation by allocating other sector flights to these stands at night, when demand for pure non-Schengen flights is low. This holds for both narrowbody in Figure 6.10c and widebody non-Schengen stands in Figure 6.10d, where the bright green demand complements the pure blue non-Schengen demand during the night.

For swing stands two drivers are found by analysing Figure 6.10e and Figure 6.10f. For narrowbody stands two clear observations can be made. Firstly, sector-switching aircraft define the largest peak of the three sector groups which occurs in the afternoon. Secondly, multiple peaks from pure-Schengen and pure-non-Schengen are observed at night and during the day. At night pure-Schengen demand for narrowbody aircraft can be seen as the red area in fig:5. This demand aligns with flight schedule input analysis in Figure 6.2b where the demand for narrowbody, overnight, pure-Schengen demand is very high. Since swing stands offer allocation for all sectors, in between the green peaks the utilisation is kept high by allowing pure Schengen-Schengen in red and non-Schengen-non-Schengen in blue. For widebody stands the same behaviour occurs in Figure 6.10f it is clear that the demand for this standtype is driven by sector-switching aircraft and a combination of peaks by pure-Schengen and pure-non-Schengen.

For remote narrowbody stands in Figure 6.10g the demand is driven by two separate peaks of Schengen and non-Schengen and a steady utilisation by sector-switching aircraft. For remote widebody stands in Figure 6.10h the capacity needed is mainly driven by the morning peak of longstay widebody aircraft.

6.2.6. Cross-Utilisation per Size of Stand-Type for $\alpha = 0.85$

The utilisation per stand-type can also be viewed from an aircraft size perspective, where the effects of cross-utilisation are also observed. Cross-utilisation in stand-types is the result of the usage of widebody stands by narrowbody aircraft. In Figure 6.11 these results are presented in stacked charts for $\alpha = 0.85$, with on the left-hand side the narrowbody stands and the right-hand size the widebody stands. The dark grey areas are narrowbody aircraft and the red areas are widebody aircraft.



(a) Aircraft demand on narrowbody C-Schengen-stands
(b) Aircraft demand on widebody E-Schengen-stands
(c) Aircraft demand on narrowbody C-non-Schengen-stands
(d) Aircraft demand on widebody E-non-Schengen-stands
(e) Aircraft demand on narrowbody C-swing-stands
(f) Aircraft demand on widebody E-swing-stands
(g) Aircraft demand on narrowbody remote stands
(h) Aircraft demand on widebody remote stands

Figure 6.11: Aircraft utilisation per aircraft-size per standtype of the current capacity scenario $\alpha = 0.85$

In Figure 6.11b, Figure 6.11d, Figure 6.11f and Figure 6.11h it can immediately be seen that the model optimises the utilisation of widebody stands by allowing narrowbody aircraft in off-peak periods. This can be seen visually as the dark grey areas for narrowbody aircraft that fill up the off-peaks of the red area of widebody demand. This is as expected following the input demand curves in Figure 7.2a which show high narrowbody demand when widebody demand is in its off-peak.

Due to the very small symbolic cost of allowing narrowbody aircraft on widebody stands the model favours to put an aircraft on the correct sized stand. This can be seen clearly in these resulting graphs, where utilisation of narrowbody stands is optimised to be high, even when widebody stands are available.

The effects of the strong peak in longstay widebody demand observed in the input data in Figure 7.2a can be seen as the high morning peak for remote widebody stand demand in Figure 6.11h. For widebody non-Schengen stands this peak is less visible, because the model tries to keep utilisation of these costly contact stands high.

These utilisation charts create insight on the usage of narrowbodies on different stand-sizes and also insight on the usage of aircraft-sector on sectors of stands. Based on these charts the conclusion can be drawn that the model strongly captures cross-utilisation. By capturing these effects, the stand-mix can be determined most optimally while taking stand allocation rules into account.

6.3. Results of optimisation model 2: Stand Allocation

The second optimisation produces flight-stand allocation for specific stands. This allows for visual insight on the solution where individual flights and stand combinations can be analysed.

Since the second optimisation has been run for 20 points along the Pareto optimal front, one of these points is selected to present in this section. The solution of $\alpha = 0.85$ is selected because it is the first solution that handles all passengers at contact stand, with the exception of two arrivals of longstay aircraft.

6.3.1. Results of GANTT Visualisation for Scenario of $\alpha = 0.85$

In the software tool made during this research the Gantt charts for each of the 20 solutions is accessible. They can be found in the Pareto Dashboard by clicking on one of the solutions along the Pareto Curve. An example can be seen in Figure 6.12. Each row represents an individual stand which is code named by a combination stand-size, stand-sector and a stand-number, e.g. C NS-1, which represents a stand of ICAO size C of sector non-Schengen. The black bars are widebody aircraft of design group F, which for this dataset are only two flights a day operated by Emirates. The light green bars are widebody aircraft of design group E and the dark green bars are narrowbody aircraft of design group C. The red diamond shapes are bus movements, either at the arrival part, the departing or both. A triangle shape down is an arrival and a triangle shape up represents a departure. When a bar is closed without a triangle or diamond shape, a tow occurs. In the software tool these can be clicked, which lights up all the parts that belong to that tail-number. When the mouse is hovered over a bar, a balloon appears that shows all information concerning that flight, turn-around-time, arrival and departure time, tailnumber, operator, origin, destination and sectors.

Figure 6.12: GANTT chart example of second optimisation model results

In Figure 6.13 the GANTT visualisation for widebody stands for the solution of $alpha = 0.85$ can be seen. During the morning these stands are mainly used by widebody stands. As seen in input data in Figure 7.2a there is very little overnight demand for widebody aircraft, this results in the allocation of narrowbody aircraft on these widebody stands during the night. Therefore it can be concluded that the solution found shows optimisation of utilisation of contact stands, which is a result of the minimisation of cost.

For heavy widebody aircraft capacity one F sized stand is built, driven by the two A380's movements operated by Emirates and visualised as black bars. It can be seen that the model optimises utilisation of this stand by allocating two extra aircraft: a narrowbody during the narrowbody peak at night and a widebody aircraft during the widebody peak in the morning. This effect continues at the other 26 widebody stands numbered E-NS-0 to E-NS-23.

Two Schengen dedicated widebody stand is built, number E-S-0 and E-S-1, which supplies capacity for widebody demand by TUIfly and IcelandAir which are the only flights operating widebodies on Schengen routes.
Two swing widebody stands are build, to supply capacity for a combination of pure Schengen, pure non-Schengen en sector switching demand. These three stands are not enough to supply demand for all sector-switching aircraft, the other sector-switching demand is resolved by either bus or tow movements. For the solution of $\alpha = 0.85$ a total of 88 bus movements are used at either arrival or departure.

Figure 6.13: GANTT chart for widebody stands for $\alpha = 0.85$

In Figure 6.14 the GANTT visualisation for narrowbody stands can be seen. Of these stands 38 are Schengen dedicated stands, 23 swing stands and 3 dedicated non-Schengen stands. It is immediately clear that narrowbody aircraft have a shorter turn-around-time compared to widebody aircraft. Another observation are the high amount of overnight positions.

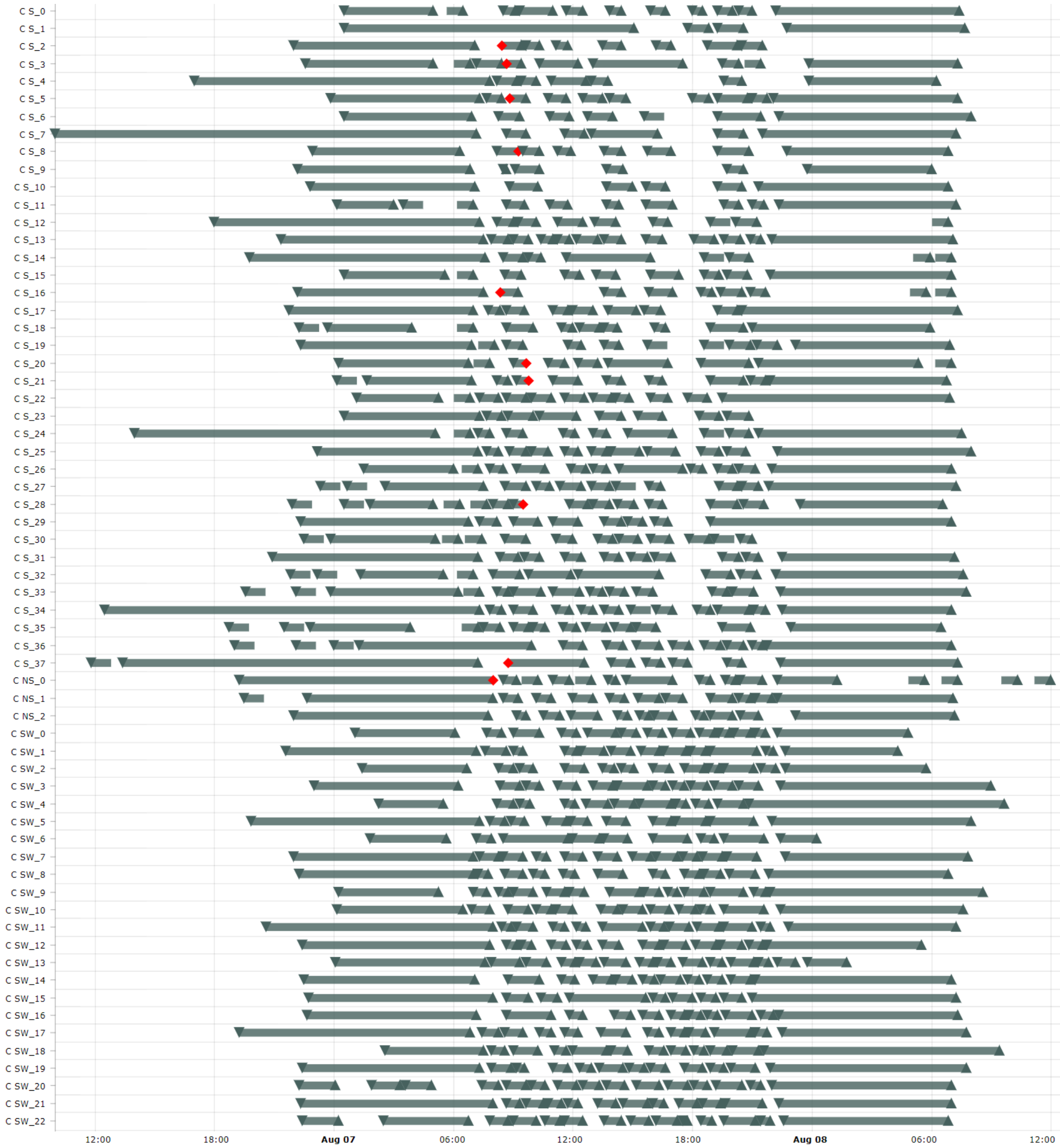


Figure 6.14: GANTT chart for narrowbody stands for $\alpha = 0.85$

The remote stands supplied capacity for longstay widebody demand occurs mainly during the morning peak. Remote stands also supply capacity for the overnight demand of narrowbody. Three extremely longstay aircraft are found, seen at remote widebody stand 14,15 and 19 and are all operated by KLM.

Most of the remote stand allocations are non-operational, or partly operational, with the exception of 8 flights. One widebody aircraft in the morning peak, two narrowbody overnight and five narrowbody aircraft in the evening peak are fully handled remote operational. The other aircraft that are operational at remote stands only use the remote stand for arrival and are towed to a contact stand for departure.

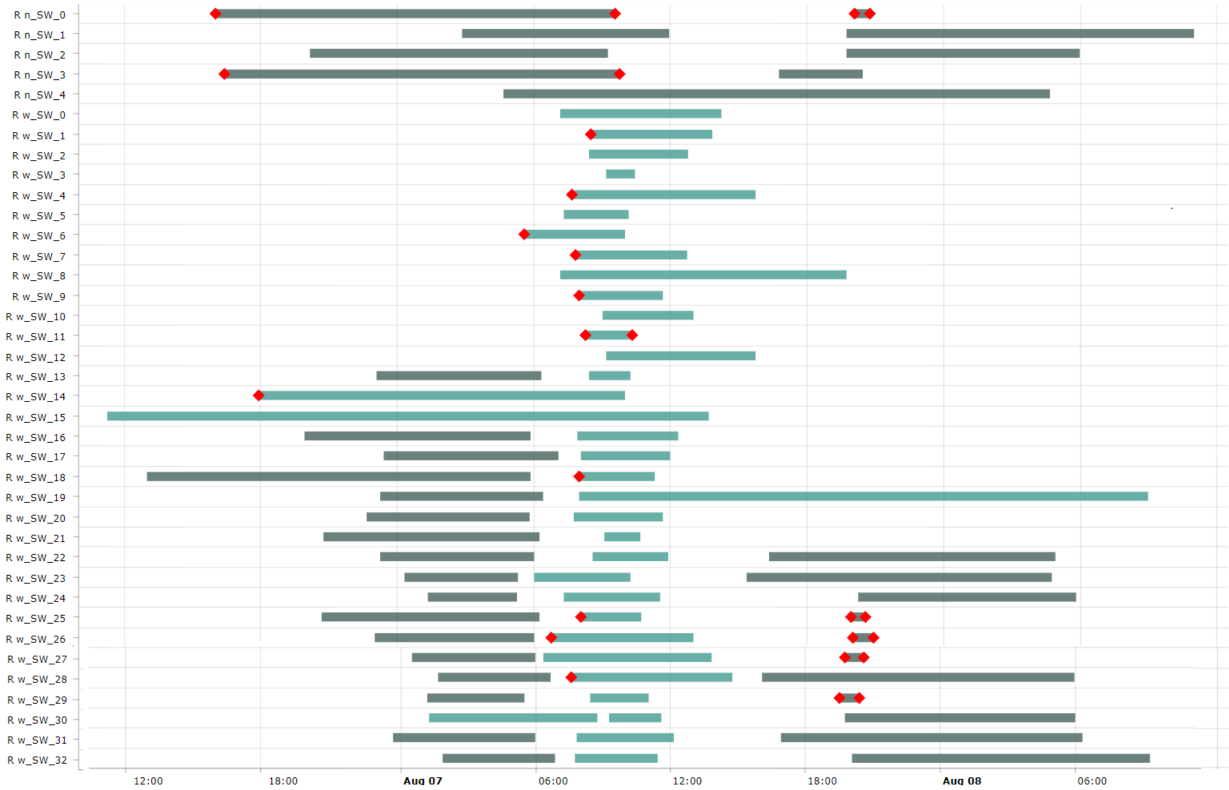


Figure 6.15: GANTT chart for remote stands for $\alpha = 0.85$

The GANTT chart results visualises that the utilisation per stand varies strongly. This is validated on historic stand utilisation data, visualised in Figure 6.3a which also shows a great variance in air traffic movements handled per stand.

6.4. Computation Time

Both optimisation models are tracked in terms of computation time. For both models the resulting run times of computation of 20 solutions along the Pareto optimal front are presented. Firstly model 1 in subsection 6.4.1 and secondly model 2 in subsection 6.4.2.

6.4.1. Computation time of optimisation model 1

The computation time of the stand capacity optimisation model for a full flight schedule of 803 flights can be seen in Figure 6.16 and Table 6.3, where all observations fall between 2.5 and 4.92 seconds. In order to reach these computation times constraints have been iterative changed to improve heuristics, as explained in chapter 3.

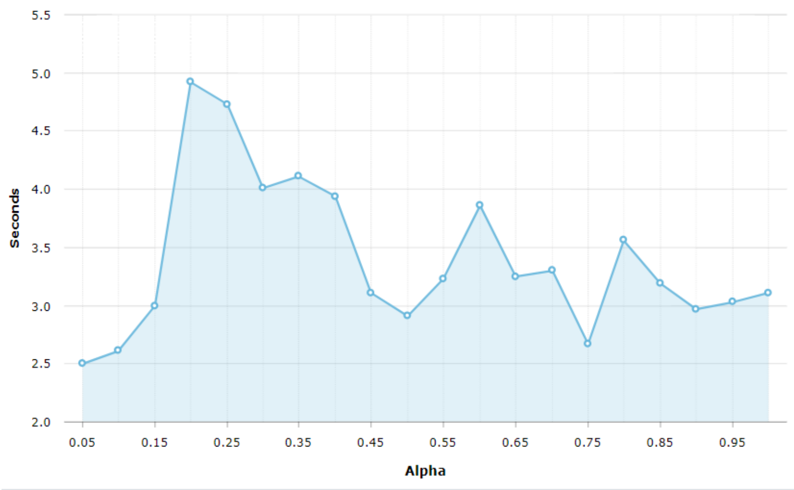


Figure 6.16: Computation time of first optimisation model along Pareto front for full schedule

Table 6.3: Results computation time

Alpha	Computation time [seconds] First optimisation model	Computation time [seconds] Second optimisation model
0.05	2.5	17.23
0.1	2.61	8.80
0.15	0.1	15.77
0.2	4.92	31.25
0.25	4.73	12.28
0.3	4.01	12.05
0.35	4.11	8.22
0.4	3.94	8.03
0.45	3.11	8.39
0.5	2.91	7.92
0.55	3.23	10.30
0.6	3.86	7.97
0.65	3.25	9.23
0.7	3.3	10.02
0.75	3.67	11.05
0.8	3.56	11.30
0.85	3.19	12.45
0.9	2.97	12.19
0.95	3.03	12.13
0.99	3.11	19.45

6.4.2. Computation time of optimisation model 2

For the second optimisation model the observations can be seen in Figure 6.17 and Table 6.3 varying from 7.92 seconds to 32 seconds.

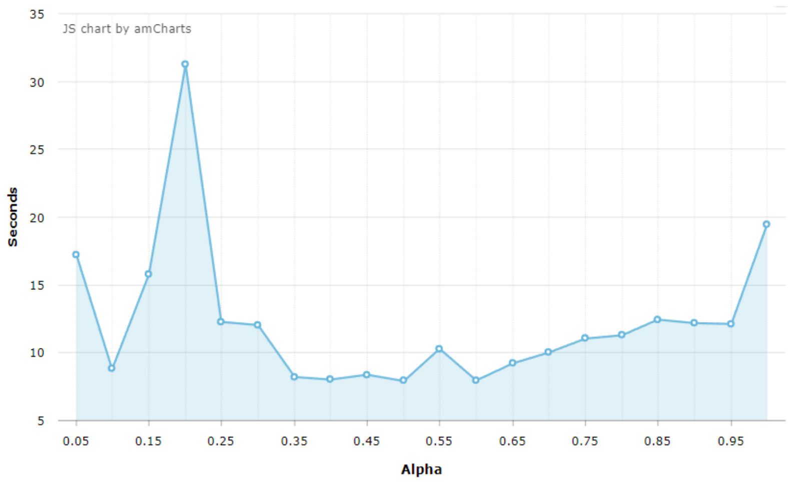


Figure 6.17: Computation time of second optimisation model along Pareto front for full schedule

6.5. Validating the Model on Schiphol Current Capacity

To validate the results of the model against the status quo at Schiphol, a set of runs is performed. Firstly, to validate the model on current capacity the amount of stands is added to the model in form of a hard constraint, as described in Equation 3.16 in chapter 3. This means, that the model is forced to only build the stands that are given to the model. The current capacity that is given to the model can be seen in Table 6.4. A second run is added for the capacity that will be added by Schiphol in the near future. The H-pier will switch from 7 C-stands to 4 widebody E-stands and, as explained in chapter 2 Schiphol, the new A-pier will offer new capacity while also reduce the amount of available stands of the B-pier and the A-field. The new capacity is shown as the bottom row in Table 6.4. To make sure the model can always converge to a solution, the amount of remote stands is unbounded.

Table 6.4: Current and future capacity of Schiphol Airport

	C S	C NS	C SW	E S	E NS	E SW	F S	F NS	F SW	R n	R w	Contact Total	Remote Total	Grand Total
Current capacity	25	13	20	2	25	9	0	2	0	51	21	96	72	168
Future capacity	25	14	16	2	29	15	0	2	0	34	21	103	55	158

6.5.1. Validation of Optimisation Model 1: Stand Capacity

The results of the validation runs are seen in Table 7.2. Both performed within expected computation time. When the resulting operational cost and capital cost are compared to the solutions found along the Pareto Front, the optimality of both solutions can be determined. In Figure 6.18 the Pareto curve is seen in blue and the resulting operational cost and capital cost are visualised as the red dots named A and B. Both run A for the current capacity and run B for future capacity show to be close to the Pareto optimal curve. This proves that a higher capital investment is put in this solution than the solutions on the optimal solution curve, but also more operational cost are made than necessary for that capital investment.

Optimality of current and future capacity: When the Pareto curve is interpolated the results of run A and B can be compared to optimal curve. Especially the influence on operational cost is analysed because the capital cost is a static variable fixed on current and future Schiphol capacity. This results in the following conclusions. If the capital cost used in solution A would be spend on a more optimal standmix, the operational cost can go down, for example, by 23% to the nearest point on the Pareto curve going down vertically from point A. If the capital cost used in solution B would be spend on a more optimal standmix, the operational cost have the potential to go down by 36% to the nearest point on the Pareto curve going down vertically from point B. This will result in less bus and tow movements needed to converge to a solution. The total amount of stands required for both solutions is 131, which is a 100% match with the total amount of stands along the

Pareto optimal front as shown in Table 6.1. It is therefore concluded that for both the current stand capacity and future stand capacity the stand-mix offered at Schiphol is currently sub-optimal.

Table 6.5: Results of validation runs

	Runtime model 1 [sec]	Runtime model 2 [sec]	Capital cost	Oper. cost	Obj. value	Aircraft Bussed	Tows	Remote total stands	Contact total stands	Grand total stands
Run A: Current capacity	2.88	7.55	171693	6464	178157	46	60	35	96	131
Run B: Future capacity	3.44	6.14	188685	5306	193991	44	49	28	103	131

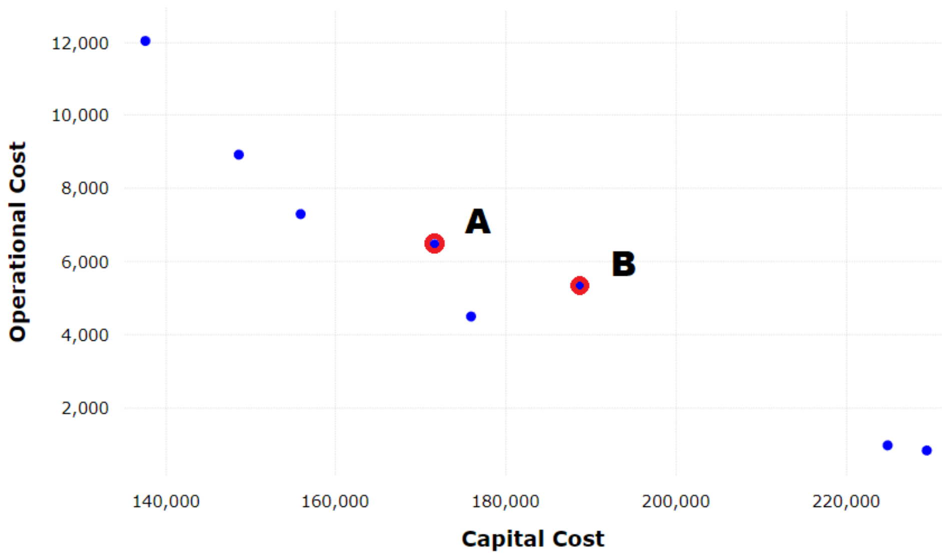


Figure 6.18: Results of Schiphol validation run compared to Pareto Front

Tow movement validation: To validate the number of tows of the model a comparison is made with Schiphol historic allocation data. For the day of analysis 65 aircraft are found that are towed from pier to pier, or pier to remote or vice versa. These are visualised in the Sankey diagram in Figure 6.5. The amount of tows found in the solution of run A are 64 tows, which is a very good result having a 97% match. When the expansion is modelled in run B a total of 49 tows are needed to converge to a solution, which is a reduction of operational cost as expected in a post-expansion scenario.

Performance of the new expansion: The solution performance of the capacity after the future expansion in Run B notes an increase of 10 percent in capital cost compared to original capacity in run A. This is as expected, because when the future capacity expansion is given as input the amount of contact stands increases by 7 and capital cost will increase. This increase has the result that the operational cost go down by 18 percent. This is due to two reasons. Firstly, a reduction in bus movement is noted, which for aircraft that require bussing goes down from 46 to 44. Secondly, the operational cost go down because required tow movements go down from 60 to 49 movements. It is concluded that for this expansion at Schiphol the capital investment in stands reduces operational cost by decreasing both bus and tow movements.

6.5.2. Visualisation by Optimisation Model 2: Stand Allocation

The results of the second optimisation are the Gantt charts, which are shown in Appendix A. A short discussion is presented here on these charts.

In Appendix A the Gantt chart of validation run A can be seen in Figure A.1, Figure A.3 and Figure A.5.

For narrowbody stands in Figure A.1 the shortage of swing stands can be clearly seen at the red dots for sector-switching overnight flights on stands C-NS on 2, 3, 5, 6, 8, 10 and 11. Similar problems occur in the evening peak on these stands.

For widebody stands in Figure A.3 also a shortage for sectorswitching aircraft is observed in the evening peak and overnight flights. These are 8 narrowbody and 1 widebody aircraft.

For remote stands in Figure A.5 the operational and nonoperational allocations can be seen. Not all flights can be handled at contact stands and therefore 11 narrowbody aircraft are fully handled at remote stands for both arrival and departure. For two widebody aircraft the arrivals are handled remotely during the morning-peak.

The resulting Gantt chart for validation run B can be seen in Appendix A in Figure A.2, Figure A.4 and Figure A.6. Since the stand capacity for this run is post-expansion, a few changes can be seen.

For narrowbody stands in Figure A.2 the amount of bus movements increased compared to run A due to the reduction of swing C stands after the expansion.

For widebody stands in Figure A.4 still 7 narrowbody aircraft require bussing due to the fact that they switch sector, and therefore require bussing at either arrival or departure.

The amount of remote stands required to converge to a solution are 14 narrowbody stands and 14 widebody stands as seen in Figure A.6. Compared to run A this is a reduction of 7 remote stands. This is due to the 7 extra contact stands in the post-expansion situation. However, it is still not possible to converge to a solution where all flights are handled at contact stands. For narrowbody aircraft still 11 aircraft are fully handled at remote stands at both arrival and departure. However, no widebody aircraft require operational remote handling.

It can be concluded that the new expansion shows improvements stand allocation, but is still unable to handle all demand at contact stands. Even though 7 extra contact stands are added for run B, in the morning peak a lack of narrowbody stands is observed where 10 aircraft require fully remote handling. An improvement for widebody aircraft is observed since no widebody aircraft requires remote operational handling.

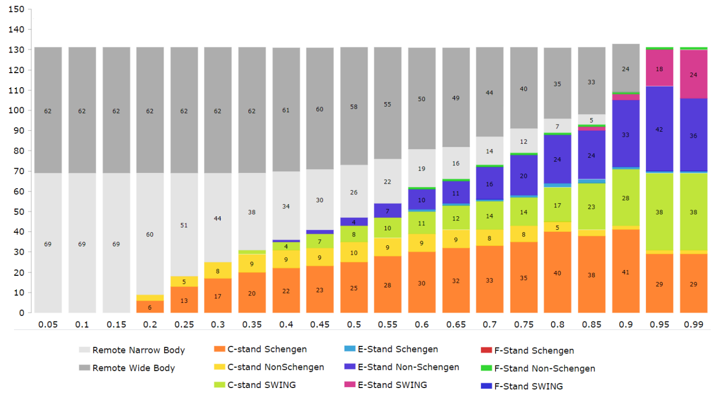
6.6. Results sensitivity analysis

To analyse the behaviour of the model a sensitivity analysis is performed. This is done by repeating the optimisation models for different values of a parameter, while holding all other parameters fixed at the same values. The parameters analysed are time variables and cost parameters. For each of these a sensitivity analysis as well as the impact on runtime is analysed. It has to be noted that in chapter 6 the Pareto Front between operational and capital cost is investigated, as well as the influence on computation time, bus movements and tow movements.

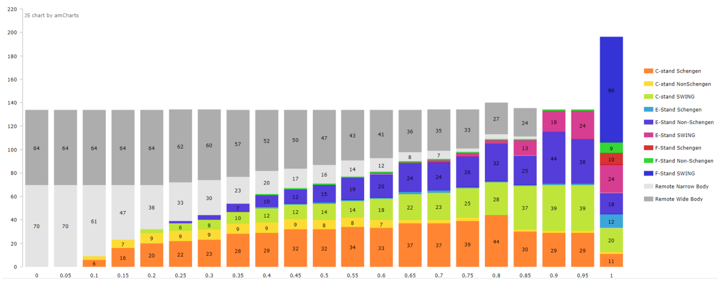
6.6.1. Model sensitivity of parameter of symbolic allocation cost

To force the solution to place flights to the smallest size stand available without influencing capacity, a symbolic cost is given to allocation of a narrowbody to a narrowbody stand and widebody to widebody stand. To investigate the influence on the entire Pareto Front by the symbolic cost parameter a set of three variations are investigated: $c_{sym} = 0$, $c_{sym} = 1$, $c_{sym} = 0.000001$.

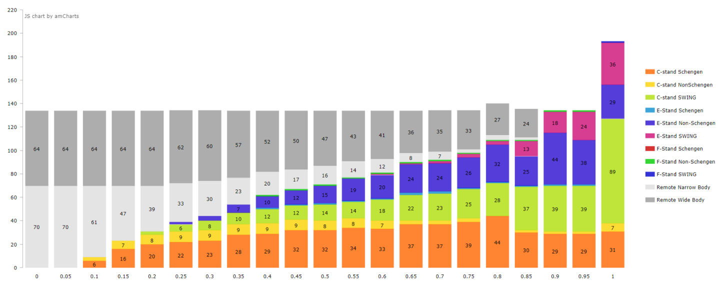
The Pareto Front solutions of the first variations of $c_{sym} = 1$ in Figure 6.19b shows an increase in the total amount of stands, which is not in line with expectations where stands that require a higher capital investment should not increase the total amount of stands needed. The Pareto Front solutions of the second variations of $c_{sym} = 0$ in Figure 6.19b shows the desired constant amount of stands until $\alpha = 1$. However, the second optimisation Gantt chart results show that narrowbody flights are allocated to widebody stands, even though narrowbody stands are available. This is not in line with airport operations. The Pareto Front solutions of the third variation $c_{sym} = 0.000001$ is seen in Figure 6.19c. This cost parameter is chosen since it shows the desired allocation to correct stands in the second optimisation, while not having an influence on standmix or total amount of stands needed.



(a) Pareto Front results with cost $c_{sym} = 1$



(b) Pareto Front results with cost $c_{sym} = 0$



(c) Pareto Front results with cost $c_{sym} = 0.000001$

Figure 6.19: Sensitivity analysis on cost parameter

During this sensitivity analysis also the small increase in total amount of stands observed at $\alpha = 0.8$ is found to be constant for all three runs. It is therefore assumed not to be a random event but part of the dynamics of the flight demand schedule.

6.6.2. Model sensitivity of Separation Time Parameter

In between aircraft allocations a separation time is given to flights, as stated in Table 5.2. To determine the sensitivity of this parameter a set of four different variations are tested. The separation times are multiplied with 1/2, 1, 2 and 4. The demand for a full flight schedule is used and all other variables are held still.

The results can be seen in Table 6.6. When separation times are doubled a separation time of 20 minutes for narrowbody and 40 minutes for a widebody will be planned for. This results in an increase of 3% in stand capacity needed for this flight schedule. As can be seen the amount of contact stands remains the same, but the amount of remote stands increases significantly. The operational cost also increases because remote stands are used for operational purposes.

Table 6.6: Separation time sensitivity analysis results

	Time model 1	Time model 2	Max conflict	Capital cost	Oper. cost	ObjF Value	Total Remote	Total Contact	Grand total	Variance
Buffer *1/2	3.08	7.39	321	48710	14193	62903	61	70	131	-2%
Buffer *1	4.31	9.95	325	48649	15964	64613	63	71	134	0
Buffer *2	5.28	11.20	329	51691	16419	68110	60	78	138	+3%
Buffer *4	3.53	31.58	361	54414	20119	74533	65	85	150	+12%

6.6.3. Model sensitivity of Towing Time Parameter

The three and two split option for flights is defined by specified tow times. For the Strategic Stand Capacity Model these are defined as 60 minutes after departure and 60 minutes before departure as described in section 5.4, following RASAS guidelines [34]. Two variations are tested of 40 minutes and 80 minutes. The results can be seen in Table 6.7 and show that the model is insensitive for changes in this parameter. For the two split option the tow times are defined as 35 minutes after arrival. The model is tested for a 20 minutes and 60 minutes variation, of which the results can be seen in Table 6.8. The model is insensitive for changes in this parameter.

Table 6.7: The sensitivity of tow time parameter for 3 split option

	Runtime model 1	Capital cost	Operational cost	Objective function	Total stands	Variance
40 min	3.52 sec.	48583	16527	65110	134	0
60 min	4.88 sec.	48649	15963	64612	134	0
80 min	3.75 sec	48583	16527	65110	134	0

Table 6.8: The sensitivity of tow time parameter for 3 split option

	Runtime model 1	Capital cost	Operational cost	Objective function	Total stands	Variance
20	3.05 sec.	16690	4835	64003	134	0
35	3.55 sec.	15963	4879	64612	134	0
60	3.73 sec.	15857	4879	65174	134	0

6.6.4. Model sensitivity of Time Variable

In the data provided three different time variables are defined for arrival and departure time:

- Block time
- Scheduled time
- Actual time

The sensitivity of the model is analysed by running the model separately for these three variations. The results can be seen in Table 6.9. The variance is calculated compared to the results of scheduled time variable. Using block time as the time variable results in 3% less stands compared to scheduled time, where actual time results in 4% more stands compared to scheduled time. For the strategic stand capacity model the scheduled time is taken since Schiphol states in RASAS that the scheduled time is used for planning purposes[34].

Both block time and actual time take longer to compute a solution compared to scheduled time. This is due to the fact that the scheduled variable is developed in 5 minute blocks, where block and actual time are not. This increases the amount of unique arrival times, which is directly related to the total amount and complexity of constraints.

Table 6.9: Sensitivity results of different time variables

	Runtime model 1	Capital cost	Operational cost	Objective function	Total stands	Variance
Block	6.86 sec	49470	15017	64487	130	-3%
Scheduled	3.17 sec	48649	15963	64612	134	0
Actual	13.17 sec	53282	15985	69267	139	+4%

6.6.5. Model Sensitivity of Input Time Interval

In terms of stand-mix the largest potential lies in the expansion of the time interval of the flight schedule. Since stand mix is driven on flight-schedule effects, it means that the more flight schedule demand characteristics are fed to the model, the better the model is able provide a balanced capacity trade-off. This is due to the effect that the day of peak of total demand does not necessarily coincide with the peaks of segments such as narrowbody peak or widebody peak.

In a sensitivity analysis the effects of increasing the interval of the input are investigated. To investigate how the stand capacity solution responds to time interval changes a full week schedule from 6th of August till 12th of August 2017. To allow for the model to run on other time intervals the capital cost are corrected, since these are defined per day.

The results are run along a full Pareto optimal front and can be seen in Figure 6.20. The main difference with the results for peak day in subsection 6.2.2 is that the demand for swing stand capacity for both narrowbody C and widebody stands E is higher. This results in a more flexible solution that can handle a wider variety of flight schedules. In order to increase the flexibility of a stand capacity solution it is recommended to increase the time interval as long as possible to allow for a more accurate trade-off.

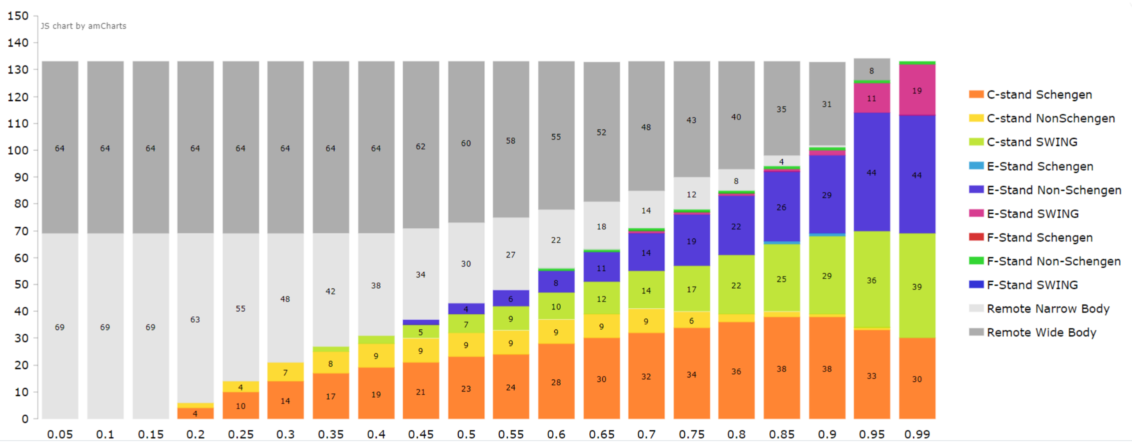


Figure 6.20: Results of Schiphol validation run compared to Pareto Front

6.7. Conclusion

The goal of this chapter is to validate the results Strategic Stand Capacity Model using a comparison with the current capacity of Schiphol. As a basis for validation and verification an extensive input data analytics section is provided.

The flight schedule input shows wave characteristics of arriving and departing aircraft at Schiphol, where a strong peaking behaviour is observed. Then, by matching arrivals and departures an overview is presented of aircraft present at Schiphol Airport during the day and two nights. These are split into three aircraft design groups which shows that narrowbody demand has strong peaking behaviour compared to widebody demand. The demand of Schengen and non-Schengen shows that there is a strong demand for sector-switching aircraft.

The main result of optimisation model 1 is the stand capacity required for the flight schedule of peakday 7th of August of 2017. By developing a Pareto optimal range of solution the model provides strong trade-off possibilities between capital and operational cost. These show for Schiphol that a minimum of 131 stands are required, with standmix depending on the solution selected by the decision maker.

The results of the second optimisation model are provided. The GANTT chart results visualises that the utilisation per stand varies strongly. This is validated on historic stand utilisation data, visualised in Figure 6.3a which also shows a great variance in air traffic movements handled per stand. In strategic airport planning it should therefore be taken into account that it is typically not possible to achieve the maximum stand utilisation on all stands.

As part of validation the model is checked on operational effects such as cross-utilisation in stand-flight combinations. This is investigated for aircraft size and for aircraft sector. By applying cross-utilisation the capacity can be used more optimally because peaks between different sizes or sectors are absorbed. These effects are visualised using coloured stack-line charts. Based on these charts the conclusion can be drawn that the model strongly captures cross-utilisation. By capturing these effects, the stand-mix can be determined most optimally.

Observations in these utilisation charts confirm the two drivers for swing stands stated in subsection 2.2.2:

1. To increase stand utilisation when peaks of Schengen flights and non-Schengen flights are such that a common share using a swing stand is preferable (peaks are not occurring at the same time)
2. To prevent operational cost of bussing passengers or towing aircraft that have international origins and domestic destinations (or vice versa).

The current capacity offered by Schiphol is forced into the model to investigate it's optimality. The results are close the optimal solution curve, but there is room for improvement. The amount of stands needed with the current stand capacity is a 100% match with the total stands needed on the entire Pareto optimal curve. No conclusion can be made about the amount of contact stands versus remote stands, because it is a ratio depending on the trade-off that a decision maker desires. However, the current solution offered by Schiphol is proven to be sub-optimal in terms of standmix where for the capital cost spend a reduction of 18% in operational cost is possible.

A validation on airport tow operations is performed. The rules on stand allocations are confirmed to be captured by the model. The Strategic Stand Capacity Model models operational rules closely, with a 98% match on tow movement observed in historic stand allocation data.

The future expansion at the H-pier and A-pier has proven to induce a reduction in operational cost by 24% by adding a new set of contact stands. It can be concluded that the new expansion shows improvements in stand allocation, but is still unable to handle all demand at contact stands. Even though 7 extra contact stands are added for the capacity, there is still room for capacity improvement in the morning peak.

Finally, it is important to note that there is no single solution for stand capacity, but a range of solutions. The model has proven to mimic Schiphol airport operations. In the next chapter the model is applied to analyse strategic division in airline demand.

7

Results for Strategic Airline Division Scenarios

As part of this research the model is subjected to various strategic division in airline demand. In this section the results of the Strategic Stand Capacity Model for strategic airline division scenarios are presented. This application will allow for further research in how airlines should be placed together in order to most optimally utilise stand capacity available. This can support strategic airline planning for expansions or other forms of segregating demand. Therefore different scenarios of clustering demand are investigated for a split into two segments. The results of this analysis can provide early insight for strategic capacity planning. Schiphol Airport is used as a case study for the peak day in 2017 occurring on the 7th of August.

It is most efficient to cluster activities of hub-alliances, and therefore a particular separation of activities is investigated. A split can made in flight demand; Skyteam alliance, Star Alliance and Oneworld Alliance, but also KLM codeshare partners, LCC and charter airlines can be segregated. For simplicity the term AOL will be used in the remaining part of this chapter when separating a group of airlines from the rest of demand.

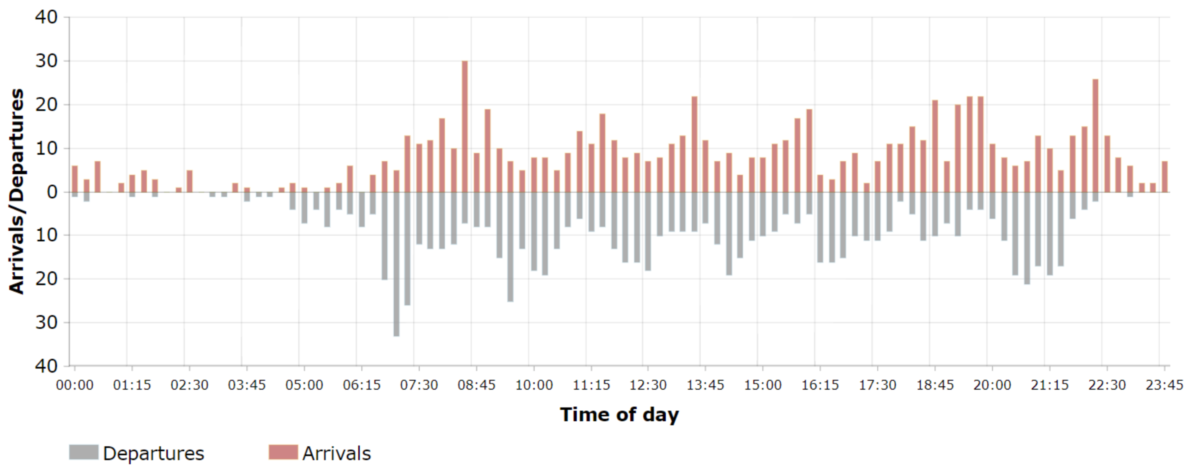
The structure of this chapter is as follows. Firstly, the wave characteristics of arrivals and departures is analysed, followed by a demand analysis. Then, the results of the model are presented for a hard split in demand. Then the results are presented for scenarios where where the split in demand is kept as a variable.

7.1. Input Data Analytics for a Hard Split in Demand

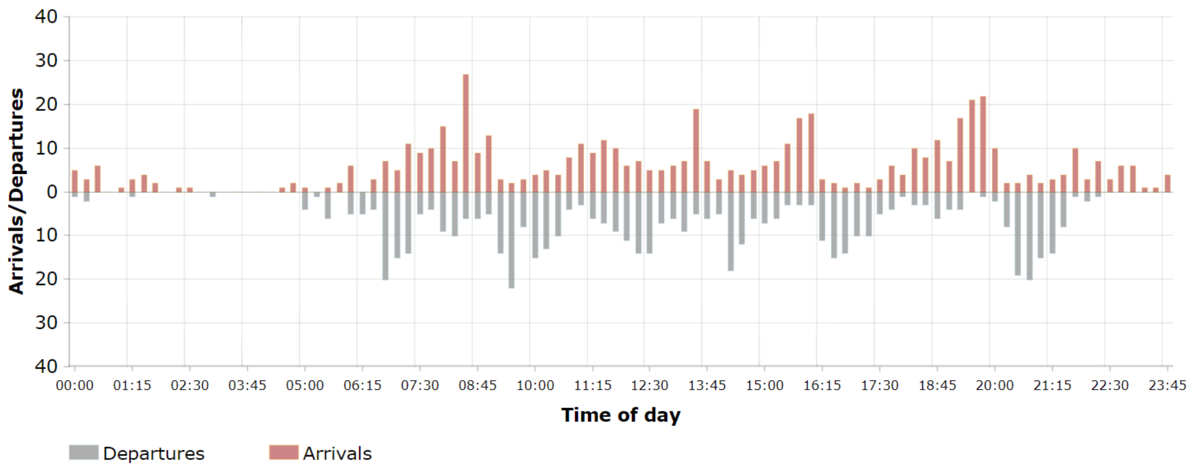
Before the stand capacity is optimised for the demand an input analysis is performed on the two important demand segments of the flight schedule. Skyteam holds 69% of all demand versus AOL with 31%. This is done to allow for verification whether the demand characteristics found in the input have influences on the resulting stand capacity. The input of the model is a flight schedule consisting of 806 flights that are present on Schiphol airport between 00:00 and 24:00 on the 7th of August 2017. In this section the demand for both Skyteam and AOL is presented.

7.1.1. Skyteam Wave Characteristics of Arrival and Departures

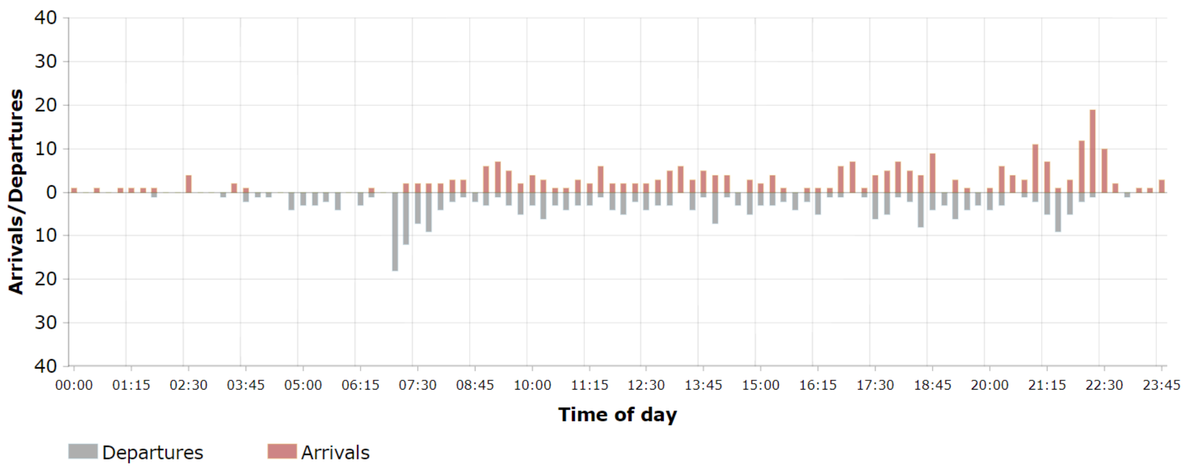
Firstly the demand is split into separate graphs to analyse specific wave characteristics and peaking behaviour. In Figure 7.1 the arrivals and departures summed up per 15 minutes during the day can be seen. Comparing these graphs to the total demand of Schiphol in Figure 7.1a it is clear that Skyteam drives most of the peaking behaviour. This is common for a hubbing alliance which connects its flights using wave patterns of arrivals and departures. AOL has a more stable peak pattern with an exception of a large departure peak in the beginning of the day, and a large arrival peak at the end of the day. Another effect observed is that AOL peaks are occurring in the off-peaks of Skyteam.



(a) Total Demand



(b) Demand by Skyteam and KLM codeshare partners



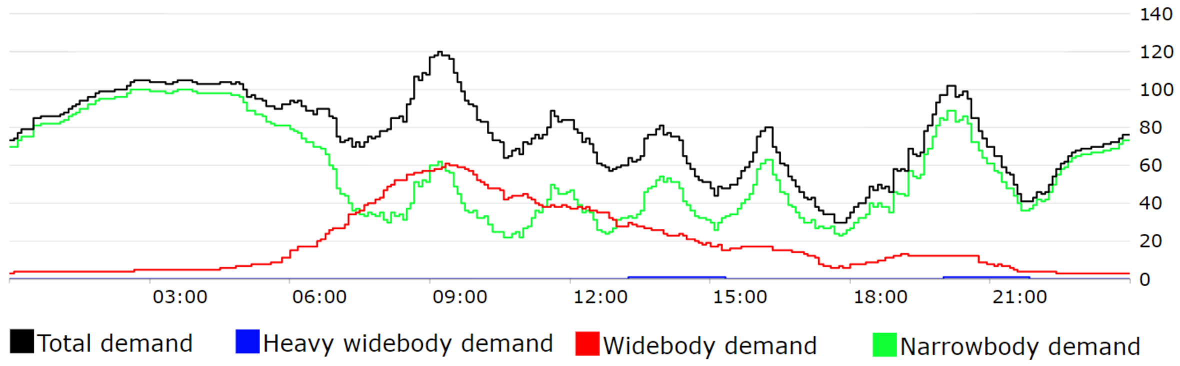
(c) Demand by AOL

Figure 7.1: Arrival and Departure waves at Schiphol for 7th of august 2017

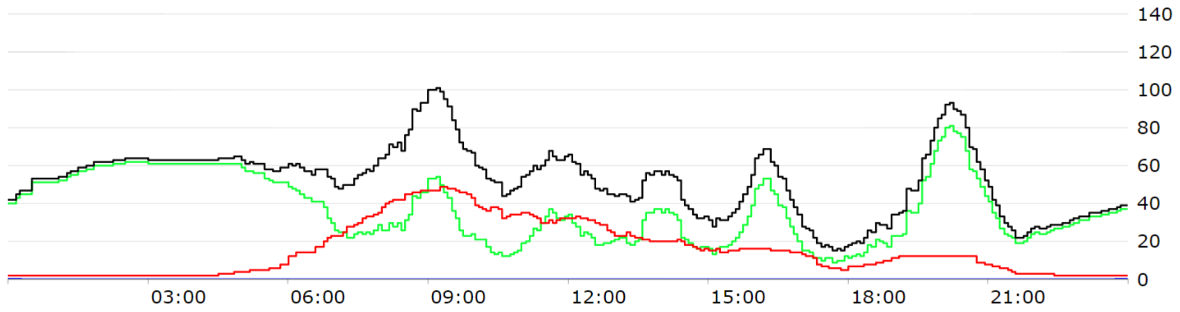
7.1.2. Skyteam Aircraft Demand Throughout the day

The aircraft demand during the day is visualised in Figure 7.2, where the total demand is shown in black, split in a green line for narrowbody aircraft, a red line for widebody aircraft and a blue line for heavy widebody demand.

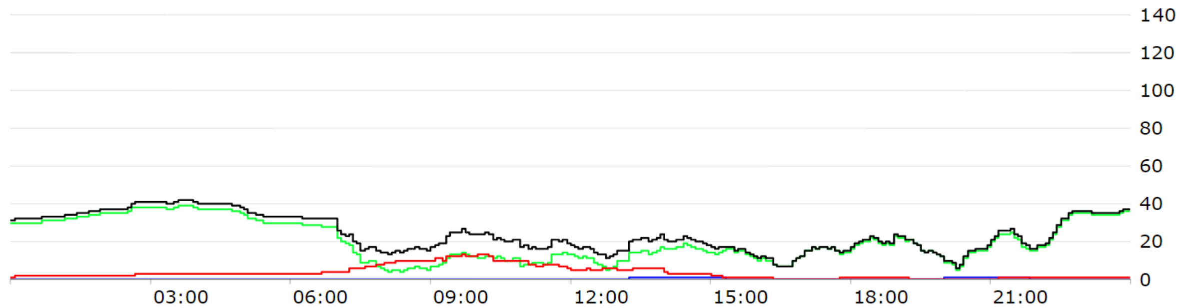
For AOL demand in Figure 7.2c the high amount of remain overnight aircraft is confirmed with over 42 aircraft at it’s peak, which are mainly narrowbody aircraft. The narrowbody aircraft present on the airport then decreases during the morning. The relatively weak peak in the morning and evening which both reach 27 aircraft. During the day a weak peak pattern for narrowbody is observed. The widebody aircraft demand does not show wave patterns but a single weak peak of 13 aircraft in the morning, which gradually reduce till no demand is observed around 15:00. Between in the afternoon two heavy widebody movements are noted, which are A380 movements by Emirates.



(a) Total demand of aircraft



(b) Demand by Skyteam and KLM codeshares



(c) Demand by AOL

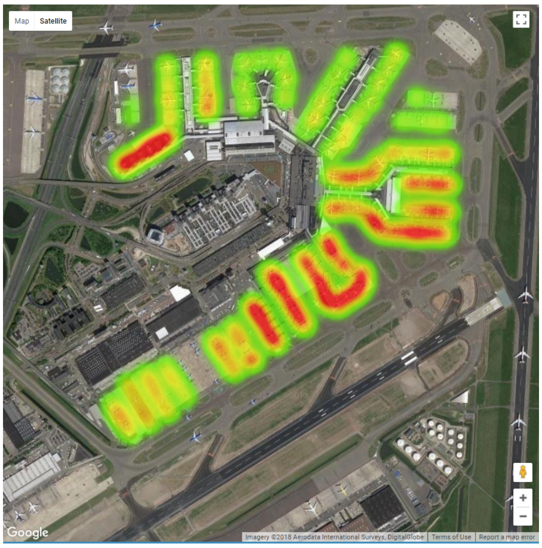
Figure 7.2: Air traffic movements on 7th of August 2017

Skyteam demand can be seen in Figure 7.2b has an overnight peak of 65 aircraft, where at 9:15 the morning peak overshoots this peak with a total of 101 aircraft that are present at the airport at the same time. The only widebody peak occurs at this time with 49 aircraft, which slowly reduces during the day. The narrowbody aircraft demand has many peaks, and is the cause of peaking behaviour in Skyteam demand. The largest narrowbody peak occurs in the beginning of the evening at 20:10 with 81 aircraft.

It can be concluded that Skyteam shows most of the peaking behaviour, where AOL show a more continuous demand. Also it can be concluded that AOL has relatively a higher overnight demand. These characteristics will have effect on stand capacity.

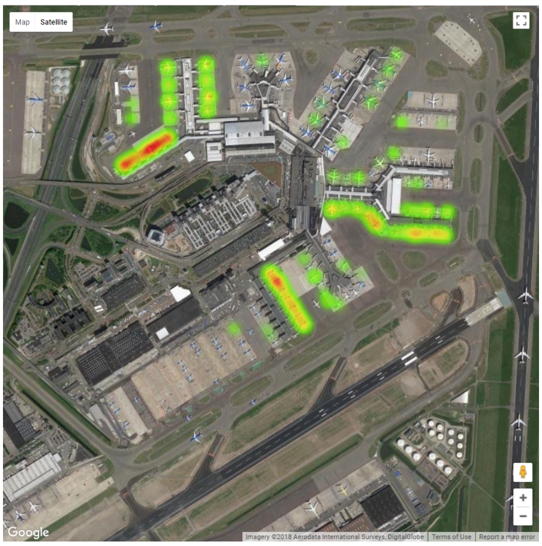
7.1.3. Stand Allocation per Airline or Alliance using Historic Data

Historic stand allocation data is used to analyse current stand utilisation at Schiphol. In Figure 7.3 a heatmap analysis is shown of stand allocation per airline group. For the AOL heatmap in Figure 7.3c it can be seen that the low-cost-carrier H pier is heavily used by AOL. This will change in the near future when the H pier is changed from 7 narrowbody stands to 4 widebody stands. The south side of the D-pier and the east side of the B-pier are used heavily by AOL. For the Skyteam heatmap in Figure 7.3b complements the AOL with zero utilisation at the H-pier. High utilisation occurs at the west side of the B-pier. For the codeshare partners of Skyteam in Figure 7.3d a distributed low demand is observed with no critical peak utilisation in this group.



(a) All airlines

(b) Skyteam



(c) AOL: Airlines not in Skyteam or codesharing with KLM

(d) KLM-codesharing

Figure 7.3: Air traffic movements on 7th of August 2017

7.2. Results for a Hard Split Scenario

The Strategic Stand Capacity Model is run separately for AOL and for Skyteam to analyse the impact on the required stand capacity. Firstly, the stand capacity is determined for AOL. Pareto front results are presented, which will provide multiple capacity solutions for the AOL flight schedule. Then, the stand-mix of these solutions are visualised. Secondly, the model is run for Skyteam demand, first with capacity variable and secondly with the current stand capacity at Schiphol forced into the model.

7.2.1. AOL Pareto Front Results: Trade-off curve

This trade-off curve supports strategic airport planning by allowing a decision maker to select on of the solutions on the trade-off curve. As explained in the previous chapter, the curve defines a line of optimal solutions within the solution space, where each step in the curve is related to deteriorating one objective while improving one objective. In this problem the two objectives are capital cost and operational cost. To create this curve the model is run 20 times for different values of α. The resulting curve can be seen in Figure 6.6. Compared to the Pareto curve of the full demand schedule the capital cost and operational cost of this solution are significant lower, which is to be expected.

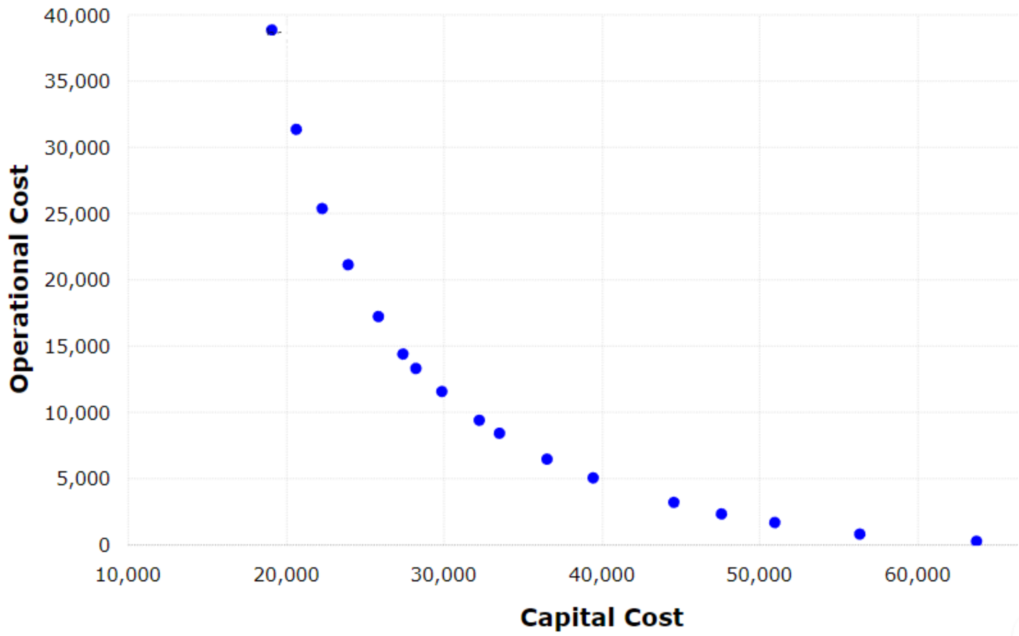


Figure 7.4: Operational and capital cost along the Pareto front

7.2.2. AOL Pareto Front Results: Stand Mix

In Figure 7.5 the different combinations of stand mix are shown that the model found along the Pareto Front. In Table 7.1 these results are show in a table format, which shows that the grand total amount of stands stays stable around 43 stands. The most left-hand solution in Figure 7.5 shows an airport where all aircraft are handled remote using busses to get passengers to the terminal. Here it can be seen immediately that 14 widebody and 29 narrowbody stands are needed to converge to a solution, which aligns with demand described in Figure 7.1c where the peak of widebody was found to be 13 aircraft and narrowbody to be 42 during the night. This shows that cross-utilisation occurs where narrowbody aircraft are placed on widebody positions during the night.

In terms of strategic airport planning the solution of $\alpha = 0.9$ seems most appropriate due to special characteristics. This is the solution with the lowest capital investment while handling all passengers at contact stands.

This solution requires 39 contact stands of which 28 narrowbody stands and 11 widebody stands. A combination of 1 remote narrowbody and 3 remote widebody stands is neede for non-operational parking. Due to the fact that 100% of passengers are handled at contact stands the level-of-service is high. Therefore this solution is highlighted, however, the selection of a solution on the trade-off curve is up to the individual decision maker. Solutions more on the left side in Figure 7.5 require less capital investment but do need remote operational handling to converge to a solution.

Table 7.1: Stand mix solution along the pareto curve for AOL

α	C S	C NS	C SW	E S	E NS	E SW	F S	F NS	F SW	R n	R w	Contact Total	Remote Total	Grand Total
0.1	-	-	-	-	-	-	-	-	-	29	14	0	43	43
0.15	-	-	-	-	-	-	-	-	-	29	14	0	43	43
0.2	2	1	-	-	-	-	-	-	-	26	14	3	40	43
0.25	4	2	-	-	-	-	-	-	-	23	14	6	37	43
0.3	5	4	-	-	-	-	-	-	-	20	14	9	34	43
0.35	6	5	1	-	-	-	-	-	-	17	14	12	31	43
0.4	8	6	1	-	-	-	-	-	-	14	14	15	28	43
0.45	8	6	2	-	-	-	-	-	-	13	14	16	27	43
0.5	10	7	2	-	-	-	-	-	-	10	14	19	24	43
0.55	10	7	3	-	1	-	-	-	-	9	13	21	22	43
0.6	10	8	3	-	-	-	-	1	-	8	13	22	21	43
0.65	10	8	3	1	1	-	-	1	-	8	11	24	19	43
0.7	11	5	6	1	2	-	-	1	-	7	10	26	17	43
0.75	13	4	7	1	3	1	-	1	-	5	8	30	13	43
0.8	15	2	7	1	5	1	-	1	-	5	6	32	11	43
0.85	17	2	8	2	5	1	-	1	-	2	5	36	7	43
0.9	18	1	9	1	6	3	-	1	-	1	3	39	4	43
0.95	19	1	9	1	6	6	-	1	-	-	-	43	0	43
0.99	19	1	9	1	6	6	-	1	-	-	-	43	0	43

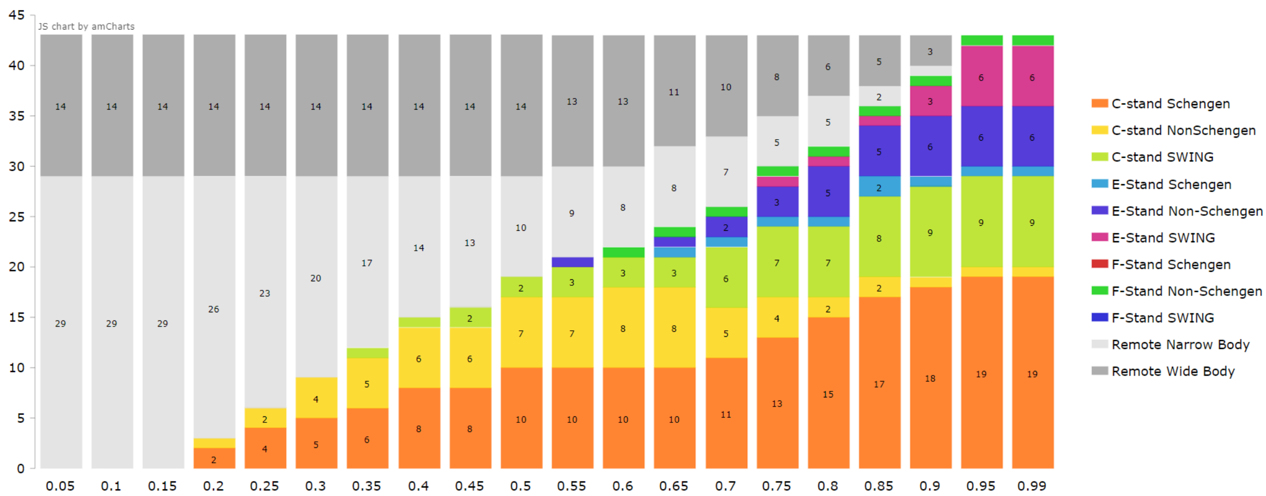


Figure 7.5: Pareto front of solutions found for AOL

7.2.3. AOL Pareto Front Results: Tow Movements

Directly related to operational cost are the tow movements. Along the Pareto curve the number of tow movements behaviour is measured and can be seen in Figure 7.6. Firstly the amount of tows increase fast to a peak at $\alpha = 0.4$ at 35 tows. This is slightly higher than expected looking at the results of Schiphol total demand runs in chapter 6 which achieves a peak of 94, were AOL requires 34 tows for only 31% of total demand. This is due to the high amount of overnights, which are split into separate parking activities where the smaller arriving and departing part are towed to contact stands. The first reduction of tows occurs at $\alpha = 0.4$ when the model chooses to build widebody stands. However, the amount of tows then increase when tows are needed to keep the utilisation of these stands high enough for the particular trade-off between capital cost and operational cost. Then, the model slowly removes all tows needed when the weight for capital cost is decreased and more contact stands are build.

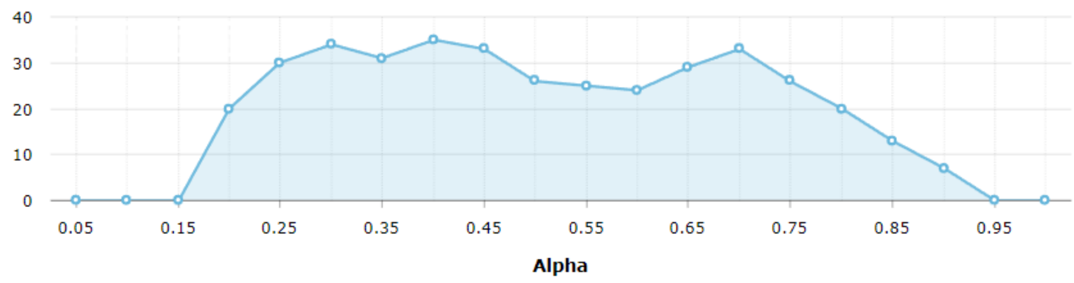


Figure 7.6: Number of tow movements along the Pareto front

7.2.4. AOL Pareto Front Results: Bus Movements

Besides tow movements, also related to operational cost are the bus movements. Along the Pareto curve the number of bus movements behaviour is measured and can be seen in Figure 7.7. The number of bus movements decreases when α increases as can be seen in the visualisation. The movements peak immediately at $\alpha = 0.05$ at 1472 bus movements. This high amount is reached because for this solution all aircraft require bussing because there are no contact stands available. Per aircraft that requires bussing, the amount of bus movements is depending on aircraft size, where each bus carries 55 passengers.

The curve exponentially drops to 379 bus movements for $\alpha = 0.5$. In solutions for high α busses are still needed when the situation occurs that the investment in an extra stand is not worth the reduction in operational cost. The amount of contact stands to eliminate all need for busses is reached at $\alpha = 0.9$.

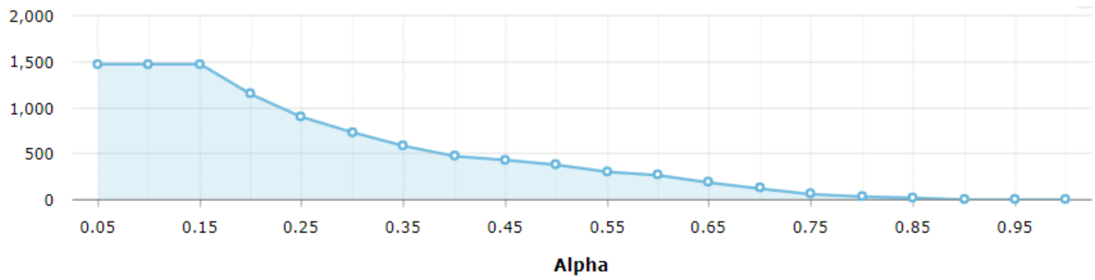


Figure 7.7: Number of bus movements along the Pareto front

7.2.5. AOL Results of GANTT Visualisation

The result of optimisation 2 are processed for the highlighted solution of $\alpha = 0.9$ due to the fact that this is the first solution where all passengers are handled at contact stands. The charts for widebody stands can be seen in Figure 7.8. One F-sized stand is build for the heavy widebody aircraft both operated by Emirates. During the morning and evening peak this stand is used for other narrowbody (dark green) and widebody demand (light green), which proves the effects of cross-utilisation. One Schengen widebody stand is built for TUIFly flights that operate widebody aircraft on Schengen countries. Six dedicated non-Schengen stands are build, and two swing widebody stands. These swing stands are used mainly sector switching flights of both widebody and narrowbody aircraft.

The narrowbody stands are divided in 18 dedicated Schengen, 1 non-Schengen and 9 swing stands. The most interesting schedule behaviour observed is the large gap in the GANTT chart for Schengen stands during the day. This does not only occur for this solution and this gap is also found for solutions when moving either left or right on the trade-off curve. This gap is driven by a high peak in overnight narrowbody demand and the evening narrowbody peak. When AOL demand was combined with Skyteam together on the current Schiphol-centrum these peaks could be combined with other demand to keep utilisation high. This is however not possible for AOL demand. A solution to this gap could be to add more remote stands and remove these contact stands. This is the equivalent of moving to the left on the trade-off range of solutions and will result in remote operational handling of the evening peak flights. It has to be noted that in real life operations stand allocation schedules are created more evenly distributed since the objective for short-term stand allocation is also to create robust plannings, where the variance of time buffers between flights is minimised.

In Figure 7.10 it is clear that the demand on remote stands is all non-operational parking. This visualisation also shows the sensitivity of stand capacity of longstay aircraft. On stand R-n-SW-0 an aircraft operated by Easyjet stays 1130 minutes on this stand, and R-n-SW-1 an aircraft 905 minutes, which is operated by TU-Ifly. To make sure that these flights are not erroneous these flights are verified by using flight schedule data for 7th of August from a second database, using the API of Schiphol.nl. This resulted in the same duration for these specific tailnumbers. It is therefore decided to keep these aircraft in the dataset. It is concluded that the model is sensitive for these type of flights.

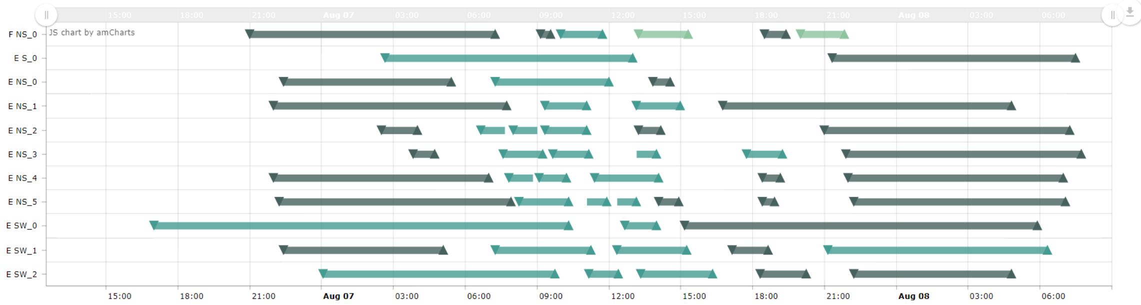


Figure 7.8: GANTT chart results for AOL demand of widebody stands of $\alpha = 0.9$

Figure 7.9: GANTT chart results for AOL demand of narrowbody stands of $\alpha = 0.9$

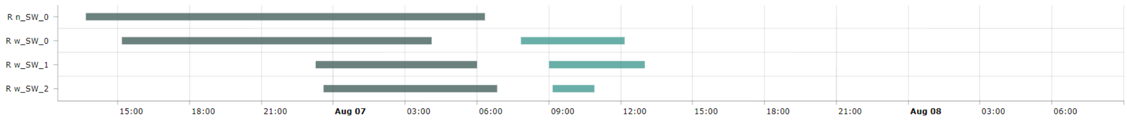


Figure 7.10: GANTT chart results for AOL demand of remote stands of $\alpha = 0.9$

7.2.6. Skyteam Results

The model is rerun for the demand of Skyteam separately for the entire Pareto Front. Interestingly enough, Skyteam separately converged to a solution of 108 stands. Since AOL converged to 43 stands, the two add up together to 151 stands. However, when this demand set is optimised together at one terminal, a smaller stand capacity of only 131 stands is found. This again shows how cross-utilisation influences stand utilisation. During strategic planning it should be carefully taken into account that individual stand utilisation can not reach the same levels as reached at Schiphol-centrum for a full demand schedule, as proven with this schedule where 14% extra stand capacity is needed when demand is split.

As a solution to this problem an extra constraint is developed which allows to model to optimise airline division strategically, the results of this adjusted model are presented in section 7.3.

7.2.7. Skyteam Results with Forced Capacity Solution

Similar to the validation chapter the future capacity as of 2019 on Schiphol is given to the model as static capacity where the amount of stands is added to the model in form of a hard constraint. This is the future capacity as defined in Table 6.4.

The results show that only 1 narrowbody and 5 widebody remote stands are needed to converge to a solution beside the given contact stands. In this solution no remote operational activities take place and all passengers are handled at a contact stand. Only 7 tows are used to place longstay aircraft at remote stands. However, 14 busses are needed to support this solution, of which all 14 are sector-switching flights. All of these are narrowbody aircraft, where 11 flights occur during the morning peak and 3 flights occur in the evening peak. This again proves the importance of having a correct standmix. It has to be noted that 2019 stand capacity is compared to Skyteam demand of a flight schedule of 2017, which enhances the importance of extra capacity during these problems in evening and morning peak.

Table 7.2: Results of Schiphol-centrum with pure Skyteam and KLM codeshares demand

	Runtime model 1 [sec]	**Runtime model 2 [sec]**	**Capital cost**	**Operational cost**	**Objective function**	**Aircraft Bussed**	**Tows**
Future capacity Skyteam at Schiphol-Centrum	1.42	1.27	176246	1441	177687	14	7

7.3. Results for a Variable Split Scenario

Due to the loss of efficiency of 14% for a hard split in demand, an extra dimension is given to the model to enable it to split up demand in groups of airlines. The model can choose which airline to allocate to which segment. The model will divide demand such that capital cost and operational cost for stands are minimised. First the division of airlines and the degree of freedom of the model is explained, after which the results are presented.

7.3.1. Division of Airlines and Alliances

The variable split is defined as follows. Skyteam, The main alliance of Schiphol, is allocated to segment A together with airlines that codeshare with KLM. The other alliances Star Alliance and Oneworld Alliance are allocated to segment B. The remaining 26 airlines are free to move between the two segments. The 26 airlines that are not part of the three main alliances and are free to move can be seen in Table 7.3 and together hold 19.44 percent of total demand in 2017. Of this group the airlines with the highest demand share at Schiphol are Easyjet, Flybe and TUIFly. By allowing these airlines to be allocated to segment A or segment B a most optimal division can be chosen.

In order to analyse when the model chooses a particular combination of airlines, the model is run for 26 different scenarios. For each scenario a number of airlines is forced to be allocated to segment A or B, where the model is allowed to pick a strategic combination of airlines. It will choose a combination of airline demand that together minimise cost.

Table 7.3: Demand of airlines in 2017

Airline	ATM	Demand
Air Arabia Maroc	810	0.20%
Air Transat	290	0.07%
Arkia	160	0.04%
BH Air	58	0.01%
Corendon	1285	0.32%
Corendon Dutch Air	3292	0.81%
Easyjet	31202	7.66%
EL AL	966	0.24%
Emirates	1216	0.30%
Eurowings	1151	0.28%
Flybe	10512	2.58%
Free Bird	90	0.02%
Icelandair	940	0.23%
Israir	22	0.01%
Jet 2	584	0.14%
Norwegian Air	1461	0.36%
Norwegian Air Int.	518	0.13%
Onur Airlines	316	0.08%
Royal Air Maroc	1112	0.27%
Ryan Air	2720	0.67%
Small Planet Airl.	726	0.18%
SmartWings	36	0.01%
Sun Express	790	0.19%
TUIfly	9189	2.26%
Vueling	8614	2.12%
WOW Air	1032	0.25%
Grand Total	**79153**	**19.44%**

7.3.2. Results for Stand Capacity

The results can be seen in Table 7.4 where each row represents results of the optimisation model in terms of stand capacity needed for segment A and segment B. Each new run an extra airline is shifted from segment B to A, until all 26 variable airlines are allocated to A.

The runs are calculated for $\alpha = 0.75$ and not along the whole Pareto optimal curve since results in chapter 6 showed stable consistency in terms of the total amount of stands needed.

For each new run one more airline has to be chosen to shift from segment B to A. In most cases the model chooses to shift only one new airline from B to A on top of the results of the previous run, with exceptions of runs for 7, 13, 16, 18, 19 and 20 airline allocation where two airlines are added and one removed. The most right-hand column represents airlines that are removed from the airline set compared to the previous run.

To visualise the effect on stand capacity an extra visualisation is made in Figure 7.11. The most left hand solution is the solution for a hard split as presented in the previous selection. A total of 151 stands is needed. When the model can chose an airline division the total amount of stands needed can be reduced to 136, which is a reduction of 10 % in stand capacity needed. The model already reaches the most optimal amount of stands of 136 by shifting 9 airlines to segment A.It can be concluded that a hard split in airlines results in an inefficient combination of airlines.

It should be noted that for the flight schedule used for this model the results in chapter 6 showed that a total amount of stands of 131 can be achieved, which implies that the division chosen will never reach the same efficiency as a combined usage in stands.

Table 7.4: Results for strategic division of airlines

Airlines segment A	Airlines segment B	Stands segment A	Stands segment B	Total stands	Airline Addition to segment A	Airline Removed from segment A
0	26	108	43	151		
1	25	113	29	142	TUIfly	
2	24	118	23	141	Easyjet	
3	23	118	22	140	EL AL	
4	22	118	20	138	Vueling	
5	21	118	20	138	WOW air	
6	20	118	19	137	Flybe	
7	19	118	19	137	Ryan Air and BH Air	Flybe
8	18	119	18	137	Corendon Dutch Air	
9	17	119	17	136	Flybe	
10	16	119	17	136	Icelandair	
11	15	119	17	136	Royal Air Maroc	
12	14	119	17	136	Corendon	
13	13	119	17	136	Air transat and Smartwings	Corendon
14	12	119	17	136	Corendon	
15	11	119	17	136	Onur Airlines	
16	10	119	17	136	Arkia, Small Planet Airl	Onur Airlines
17	9	119	17	136	Onur Airlines	
18	8	119	17	136	Norwegian Air Int.,Free Bird	Arkia
19	7	119	17	136	Air Arabia Maroc, Arkia	Onur Airlines
20	6	119	17	136	Norwegian Air, Onur Airlines	Free Bird
21	5	119	17	136	Free Bird	
22	4	119	17	136	Emirates	
23	3	119	17	136	Israir	
24	2	119	17	136	Sun Express	
25	1	119	17	136	Eurowings	
26	0	120	17	137	Jet 2	

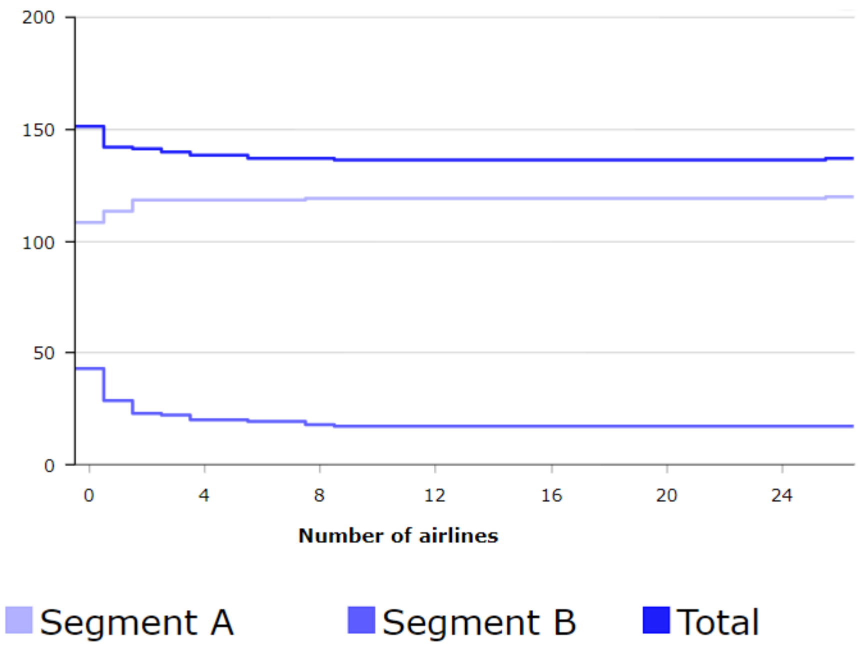


Figure 7.11: Different scenarios of airline distribution

The computation time for all 26 runs can be seen in Figure 7.12 which vary between 1.59 seconds and 104.48 seconds. This is due the increased amount of decision variables for the strategic stand capacity model by adding the dimension of variable airline division.

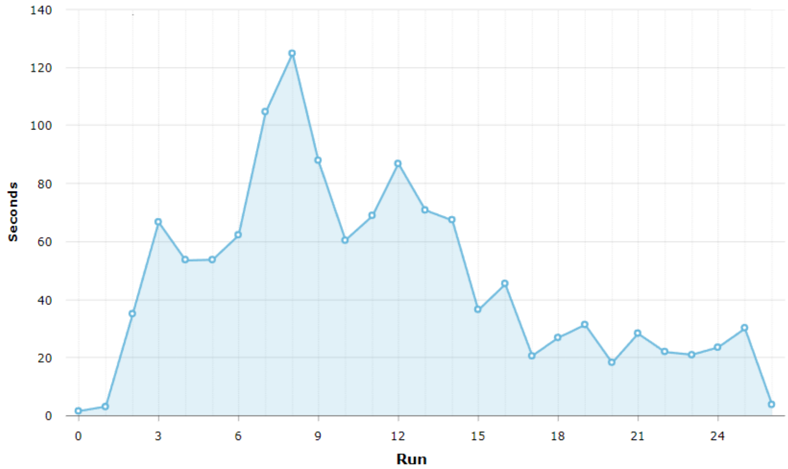


Figure 7.12: Computation time for 26 scenario's of airline distribution

7.4. Conclusion

The Strategic Stand Capacity model provided a range of solutions for AOL demand segment. The minimum amount of stands needed to converge to a solution are 43 stands. The stand-mix can be chosen along a range of optimal solutions. Special attention is paid to the solution of $\alpha = 0.9$ which requires the lowest capital investment while handling all passengers at contact stands. This solution requires 38 contact stands of which 27 narrowbody stands and 11 widebody stands. A combination of 3 remote narrowbody and 3 remote widebody stands is needed. Due to the fact that 100% of passengers are handled at contact stands the level-of-service is high. However, the selection of a solution on the trade-off curve is up to the individual decision maker.

When separating the AOL demand from Skyteam demand a problem is observed concerning overnight flights. Demand for Schengen stands is driven on overnight demand, however, there is not enough demand during the day to utilise these stands. In the traditional current combination with Skyteam and AOL a higher utilisation can be achieved, because demand peaks of these groups are at different times of day such that a common share of stands enhances efficient utilisation for the flight demand characteristics at Schiphol Airport. It can be concluded that a separation of demand will therefore result in a decrease of overall utilisation. This is proven by applying the Strategic Stand Capacity Model on both demand segments, which shows that a separation of demand increases the minimum amount of stands required by 14%. It is therefore decided to add an extra feature to the strategic stand capacity model where the model can optimise the strategic division in airlines.

The split in demand is defined as follows. Skyteam, The main alliance of Schiphol, is allocated to segment A together with airlines that codeshare with KLM. The other alliances Star Alliance and Oneworld Alliance are allocated to segment B. The remaining 26 airlines are free to move between the two segments.

A total of 151 stands is needed when all these airlines are allocated to segment B. When the model can chose an airline division the total amount of stands needed can be reduced to 136, which is a reduction of 10 % in stand capacity needed. The model already reaches the most optimal amount of stands of 136 by shifting 9 airlines to segment A. It can be concluded that a hard split in airlines results in an inefficient combination of airlines. It should be noted that for the flight schedule used for this model the results in chapter 6 showed that a total amount of stands of 131 can be achieved, which implies that the division chosen will never reach the same efficiency as a combined usage in stands.

While applying this model to strategic airport planning one important limitations of the model needs to carefully considered. It has to be noted that these results are the minimum amount of stands that would need to build, based on current demand, for a particular trade-off between capital cost and operational cost. It is recommended to use this model mainly for guidance for contact stand calculations. This is concluded, because the amount of remote stands is not only based on a flight schedule but also on robustness and the capability of an airport to harbour emergency flights, or other non-planned aircraft activities. It is concluded that these buffer remote stands are crucial and remote stand demand is not purely driven by flight schedule analysis.

8

Conclusions and Recommendations

This thesis is an outcome of a collaboration between TUDelft and NACO to obtain the degree of Master of Science at the faculty of Aerospace engineering TU Delft. The research commissioned by NACO is boiled down to the following research objective:

"*To contribute to the development of Strategic Stand Planning for airports, by finding an optimal required Stand Capacity using mathematical optimisation techniques.*"

In this chapter conclusions are drawn on how the Strategic Stand Capacity Model reaches meets objective. The structure of this chapter is as follows. First the main conclusions that can be drawn from this research are presented. Then, to maximise the future potential of the model, a list of recommendations is stated, which can be used for follow-up research.

8.1. Conclusion

This research shows that there is not a single solution for stand capacity, but many. As main result the model provides a range of Pareto optimal solutions as a trade-off between operational cost and capital cost to support decision making in strategic airport planning.

An intensive input analysis on the flight schedule is performed. This is done to allow verification and validation on how the demand characteristics found in the input have influences on the resulting stand capacity. The flight schedule input shows wave characteristics of arriving and departing aircraft at Schiphol, where a strong peaking behaviour is observed. Analysis on sectorised demand shows that there is a strong demand for sector-switching aircraft holding 21% of all flights, these will be one of the main drivers of swing stands in the standmix solution.

The main result of optimisation model 1 is the stand capacity required for the flight schedule of peakday 7th of August of 2017. By developing a Pareto optimal range of solution the model provides strong trade-off possibilities between capital and operational cost. These show for Schiphol that a minimum of 134 stands are required, with standmix depending on the solution selected by the decision maker. Stand-mix is strongly dependent on the trade-off of operational cost and capital cost.

The results of the second optimisation model are provided. The GANTT chart results visualises that the utilisation per stand varies strongly. This is validated on historic stand utilisation data, which also shows a great variance in air traffic movements handled per stand. In strategic airport planning it should therefore be taken into account that it is typically not possible to achieve the maximum stand utilisation on all stands.

As part of model validation a check is performed on the operational effects of cross-utilisation in stand-flight combinations. This is investigated for aircraft size and for aircraft sector. By applying cross-utilisation the capacity can be used more optimally because peaks between different sizes or sectors are absorbed. These effects are visualised using coloured stack-line charts. Based on these charts the conclusion can be drawn that the model strongly captures cross-utilisation. By capturing these effects, the stand-mix can be determined most optimally.

The model is validated on the status quo of Schiphol Airport capacity by forcing the current stand capacity into the model. The results show a match with the optimal Pareto curve having 134 stands required. However, the solution found requires a slightly higher capital investment than an optimal solution, with at the same time creating more operational cost. The capital cost and operational cost of this solution are together proven to be sub-optimal by comparing the result with the Pareto optimal curve. If the capital cost used for this stand capacity solution would be spend on a more optimal standmix, the operational cost can go down by 18%. It is therefore concluded that the current stand capacity offered by Schiphol is sub-optimal. The operational rules are validated by comparing tow movements with historic stand allocation data, with a 98% match in tow movements for the flight schedule of 7th of August 2017.

When the model is applied to the future capacity after the planned expansions of the A-pier and H-pier, the results for operational and capital cost are close to the Pareto optimal curve but still create more operational cost than necessary for the capital investment. This proves that the stand-mix is still sub-optimal. The expansion creates in increase of 10.7% in capital cost and shows its benefits with a reduction in operational cost of 27.4%. The expansion shows great promise for stand capacity, but is not yet capturing all demand in the morning peak, still requiring remote operational handling for 10 aircraft. Since the demand input is the flight schedule of 2017, and this expansion will be delivered in 2019 the demand is expected to grow even more.

The Strategic Stand Capacity model is then applied to a hypothetical future expansion for a new second terminal. Various scenarios of demand segmentation are investigated which splits demands in two segments: one group of Skyteam and KLM-codeshare partners and a second group of all other airlines (OAL). As a solution the Strategic Stand Capacity model provides a range of solutions for AOL demand segment. The minimum amount of stands needed to converge to a solution are 43 stands. The stand-mix can be chosen along a range of optimal solutions. Special attention is paid to the solution of $\alpha = 0.9$ which requires the lowest capital investment while handling all passengers at contact stands. However, the selection of a solution on the trade-off curve is up to the individual decision maker.

When separating the AOL demand from Skyteam demand a problem is observed concerning overnight flights. Demand for Schengen stands is driven on overnight demand, however, there is not enough demand during the day to utilise these stands. In the traditional current combination with Skyteam and AOL a higher utilisation can be achieved, because demand peaks of these groups are at different times of day such that a common share of stands enhances efficient utilisation for the flight demand characteristics at Schiphol Airport. It can be concluded that a separation of demand will therefore result in a decrease of overall utilisation. This is proven by applying the Strategic Stand Capacity Model on both demand segments, which shows that a separation of demand increases the minimum amount of stands required by 14%. To further analyse what would be a better division in airlines the model is altered to choose a division in airlines.

For a strategic airline division the strategic stand capacity model is changed slightly. The split in demand is defined as follows. Skyteam, The main alliance of Schiphol, is allocated to segment A together with airlines that codeshare with KLM. The other alliances Star Alliance and Oneworld Alliance are allocated to segment B. The remaining 26 airlines are free to move between the two segments. A hard split in demand resulted in a total of 151 stands needed when all these airlines are allocated to segment B. When these 26 airlines are variable and the model can chose an airline division, the total amount of stands needed can be reduced to 136, which is a reduction of 10 % in stand capacity needed. The model already reaches the most optimal amount of stands of 136 by shifting 9 airlines to segment A. It can be concluded that a hard split in airlines results in an inefficient combination of airlines. It should be noted that for the flight schedule used for this model the results in chapter 6 showed that a total amount of stands of 131 can be achieved, which implies that the division chosen will never reach the same efficiency as a combined usage in stands.

8.2. Contribution to strategic airport planning

The model created adds knowledge to the body of scientific research on stand allocation while being practically applicable for strategic airport planning. Scientific literature does not show any evidence of a stand allocation model that can determine optimal capacity, but only works on hard input of capacity. This model is therefore is a significant improvement, because there are no stand allocation models that can be applied for strategic airport stand planning. On the other hand no stand capacity tools are found that take stand allocation rules into account. Research by de Man on stand capacity planning at Schiphol concluded a lack of a stand capacity tool that takes stand allocations into account while analysing different scenarios [17, 18]. De Man showed that the current tool used at Schiphol is mainly based on expert judgement and a simplified demand-supply comparison build in Excel spreadsheet.

An improvement on current stand capacity calculations at NACO is provided by the Strategic Stand Capacity model. Firstly a new trade-off is possible between operational and capital cost to support decision making, where traditionally a single solution was found. Another benefit is that the model develops results within 3 seconds computation time using a flight schedule in excel as an input. The software made to support the two optimisation models also creates insight on demand and airport characteristics. The cross-utilisation effects in stand capacity add a new insight on stand operations.

8.3. Recommendations

The main recommendation of this research is to develop flight schedules as input for the strategic stand capacity model instead of using a historic peak day. This can be done in a separate flight schedule module which develops different scenarios of current capacity. Another part of this module should be the development of different scenarios for future flight schedules, which is closely related to forecasting. Here scenarios can be developed by changing the fleet characteristics, adding distributions on arrival and departure times and changing peak structures. Using this module it is also possible to optimise stand capacity over time. This will add value especially for research into expansions. Using this module a more robust stand capacity can be determined. This way the certainty of a particular solution can be determined.

While applying this model to strategic airport planning one important limitations of the model needs to carefully considered. It has to be noted that these results are the minimum amount of stands that would need to build, based on current demand, for a particular trade-off between capital cost and operational cost. It is recommended to use this model mainly for guidance for contact stand calculations. This is concluded, because the amount of remote stands is not only based on a flight schedule but also on robustness and the capability of an airport to harbour emergency flights, or other non-planned aircraft activities. It is concluded that these buffer remote stands are crucial and remote stand demand is not purely driven by flight schedule analysis.

One important factor in stand capacity is stand location, which is left out-of-scope for this research. The location of individual stands influences stand utilisation due to passenger walking distances. Airlines have strong preferences for stands that are located centrally in the terminal, which makes other stands underutilised. For Schiphol this is important due to the hubbing characteristics of this airport. For the strategic stand capacity model this effect can not be taken into account because this model is at a strategic level in the design phase of an airport, before facility sizing, and therefore it is not yet known where each stand will be located. For follow-up research it will be interesting to apply a similar model which can be used during facility sizing, for a more detailed result of stand capacity.

The types of stands considered in this research are defined per sector and size, but also contact, swing and remote stands are taken into account. However, more types of stands can be added, such as MARS stands. Another type of stands are walk-in walk-out stands. These are considered contact stands but with a slightly lower level of service of passengers. For the Strategic Stand Capacity Model it is left out of scope because typically these type of stands follows in more detailed design phase where low-cost-carrier airline effects are taken into account.

In terms of data there are limitations found on specifics of tow and bus data. Also the park duration on different stands is not provided. It is therefore not possible to determine stand utilisation based on historic data. It is recommended in future research to compare this stand utilisation to the results of the Strategic Stand Capacity Model.

Currently the tool supports airport strategic planning by having two objectives of minimising operational cost and capital cost. However, it is recommended to identify different objectives for airport operators but also airport stakeholders, such as airlines and ground handlers. For this reason it might be interesting to add the option airline-dedicated stands. Another recommendation is to incorporate this model in a decision support tool where certain cost are allocated to different stakeholders. This will steer the solution to other potential solutions which will be beneficial to particular stakeholders

A

Gantt Charts

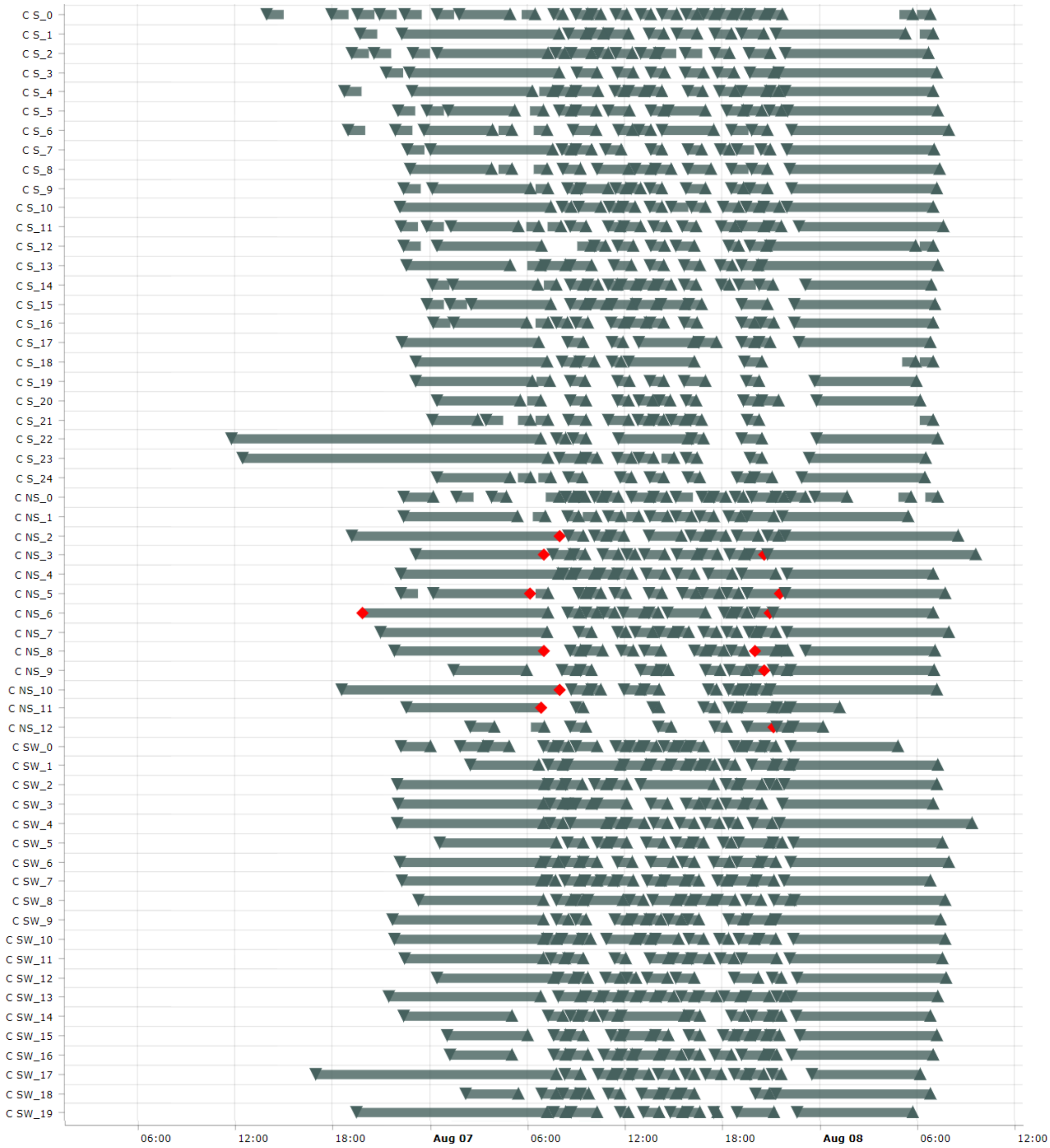


Figure A.1: GANTT results for narrowbody stands of validation run A

Figure A.2: GANTT results for narrowbody stands of validation run B

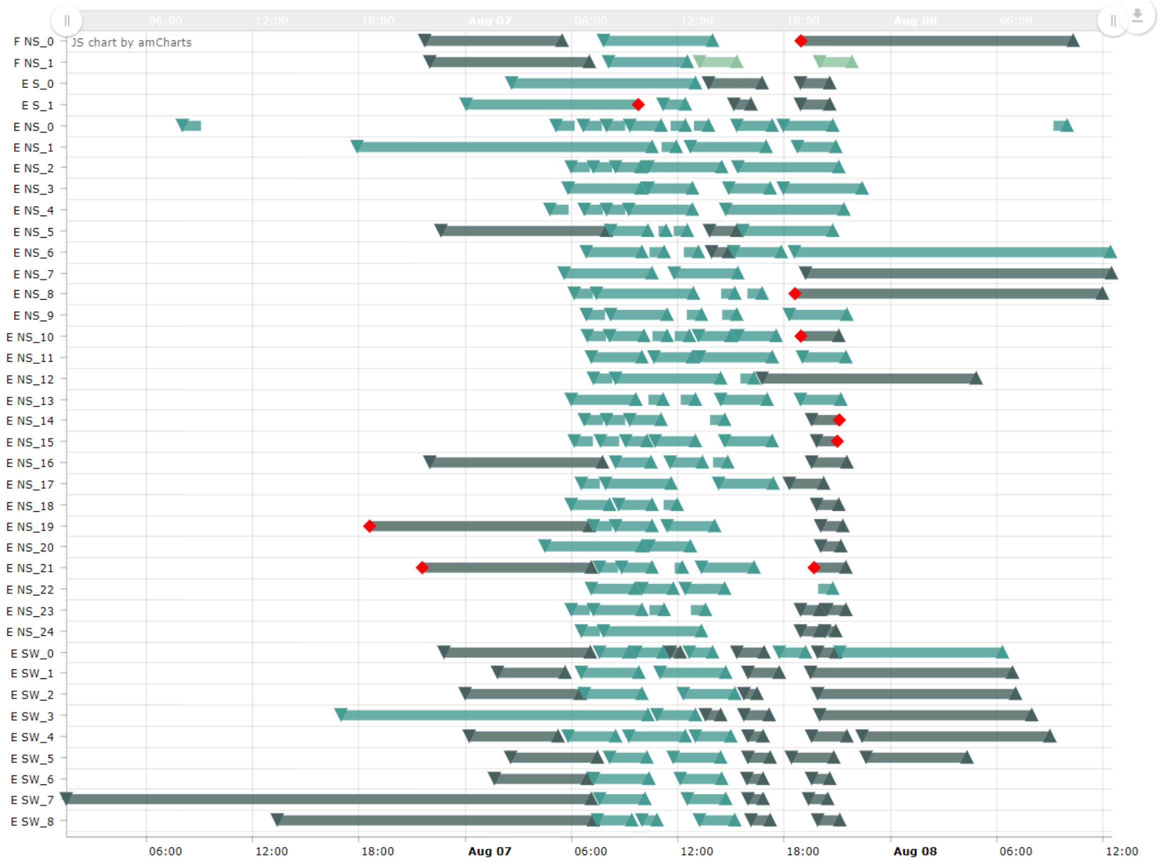


Figure A.3: GANTT results for widebody stands of validation run A

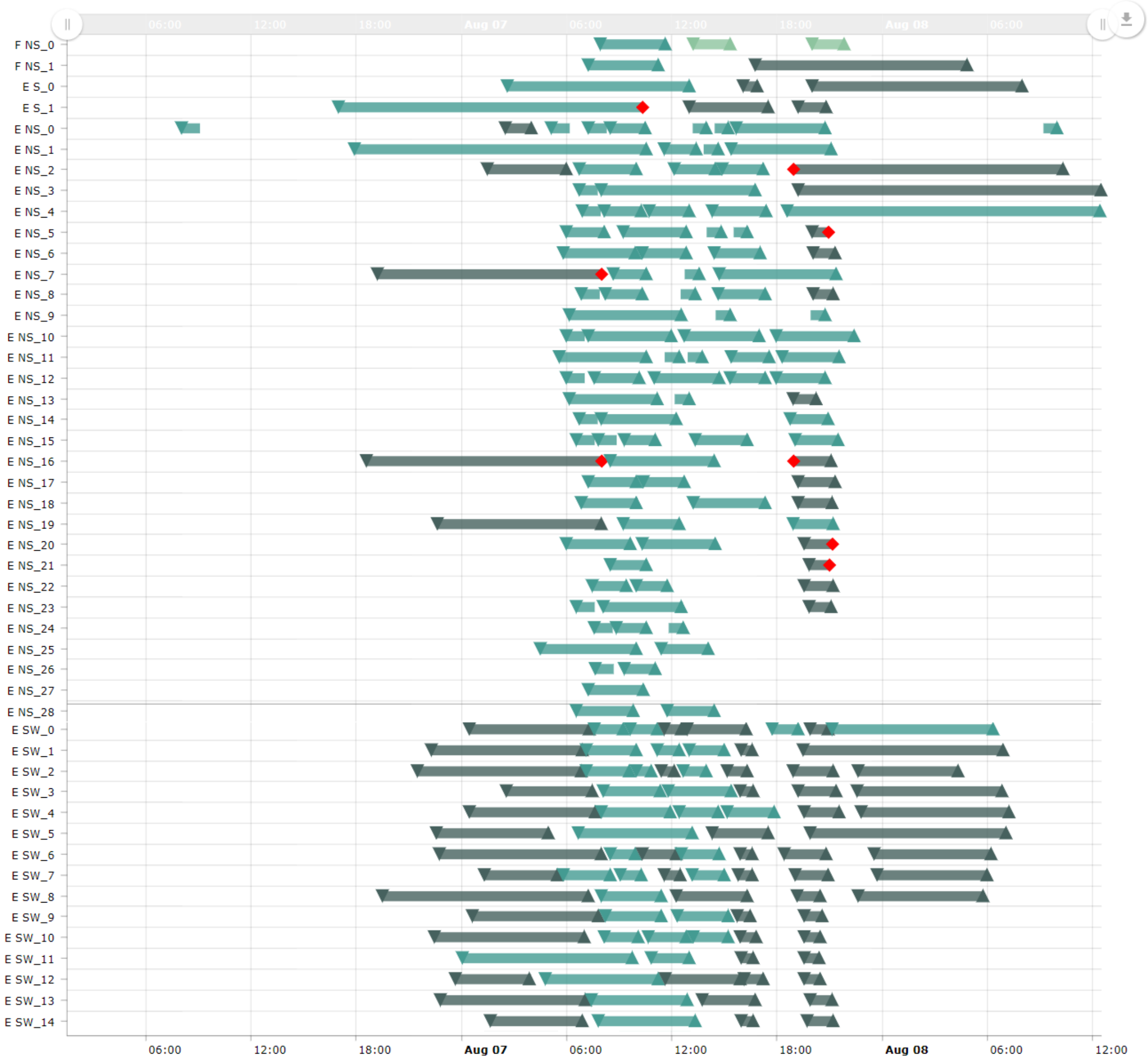


Figure A.4: GANTT results for widebody stands of validation run B

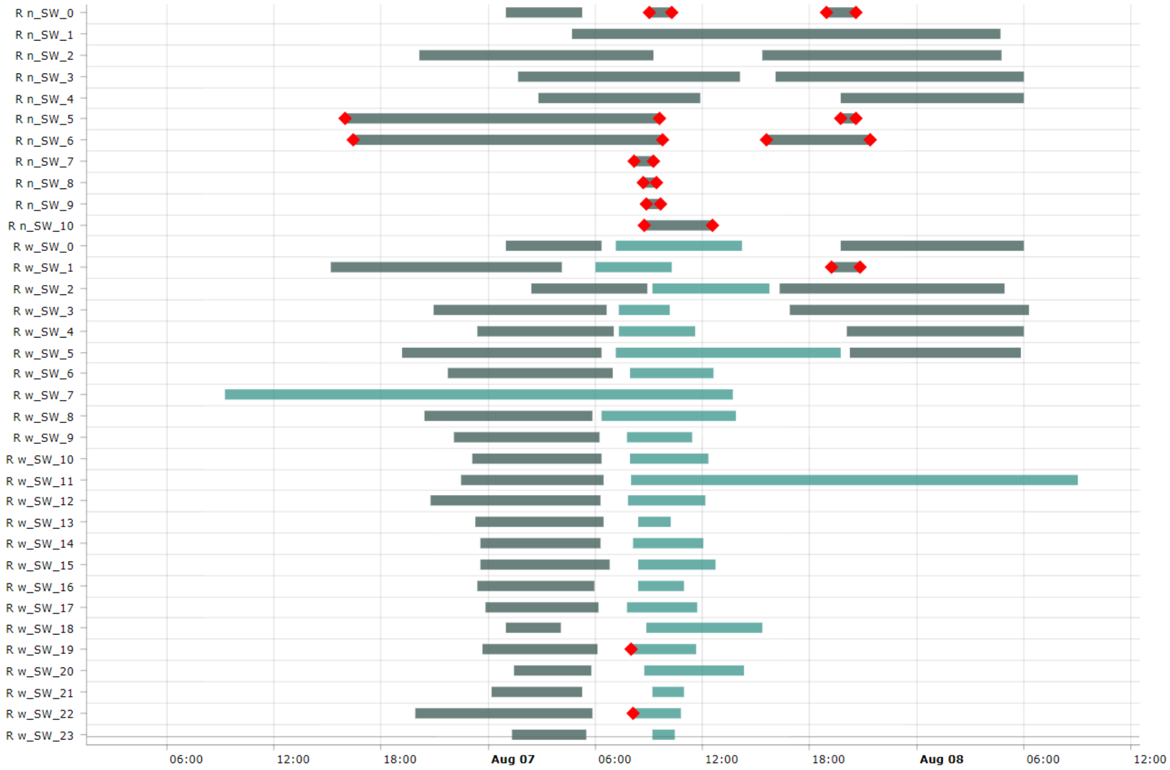


Figure A.5: GANTT results for remote stands of validation run A

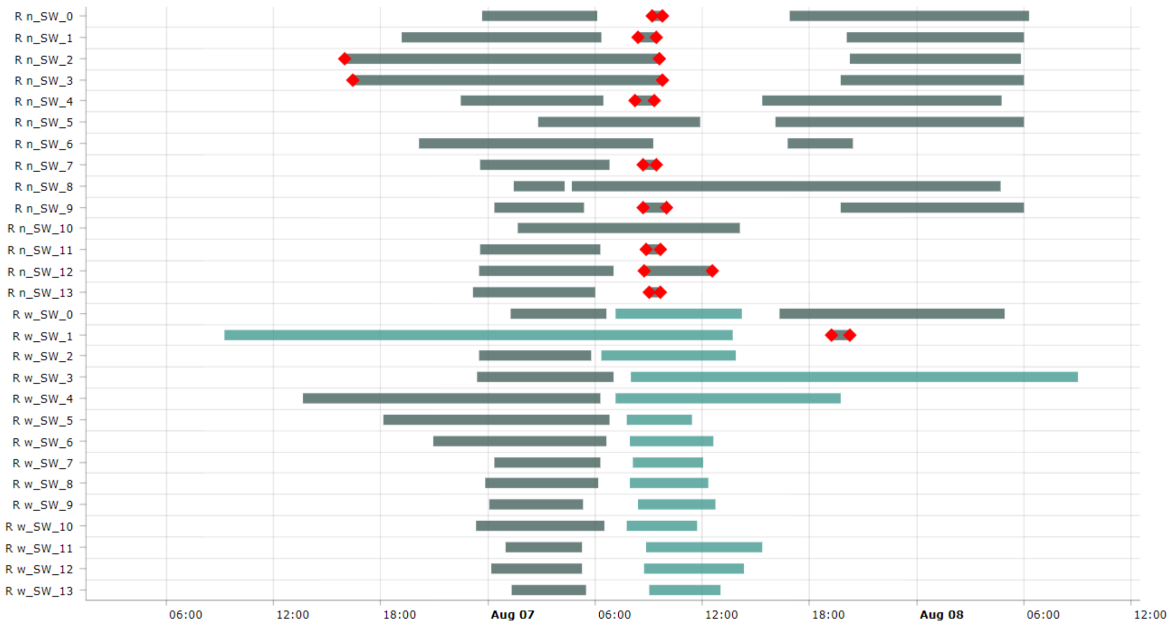


Figure A.6: GANTT results for remote stands of validation run B

B

Dashboards

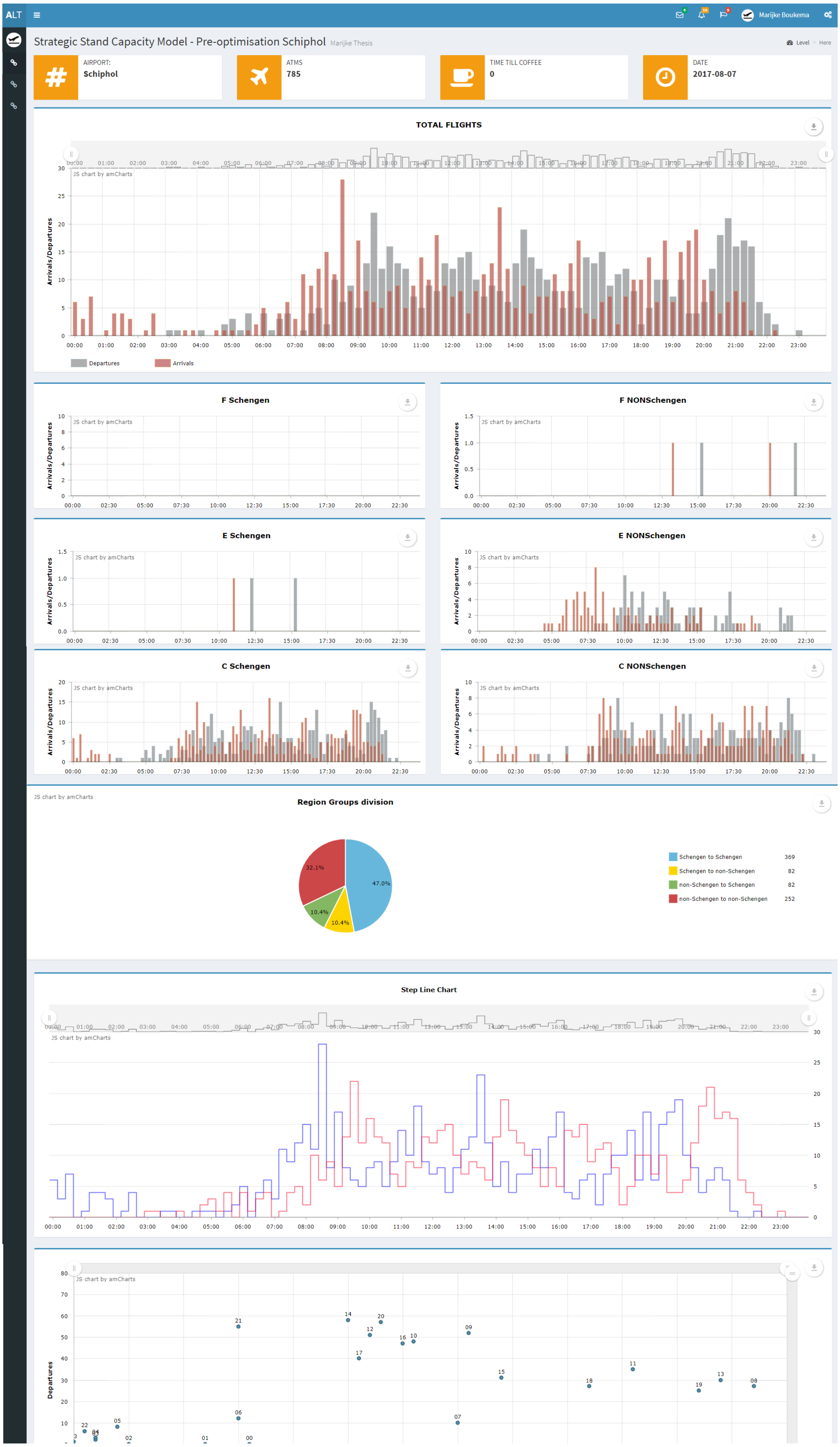
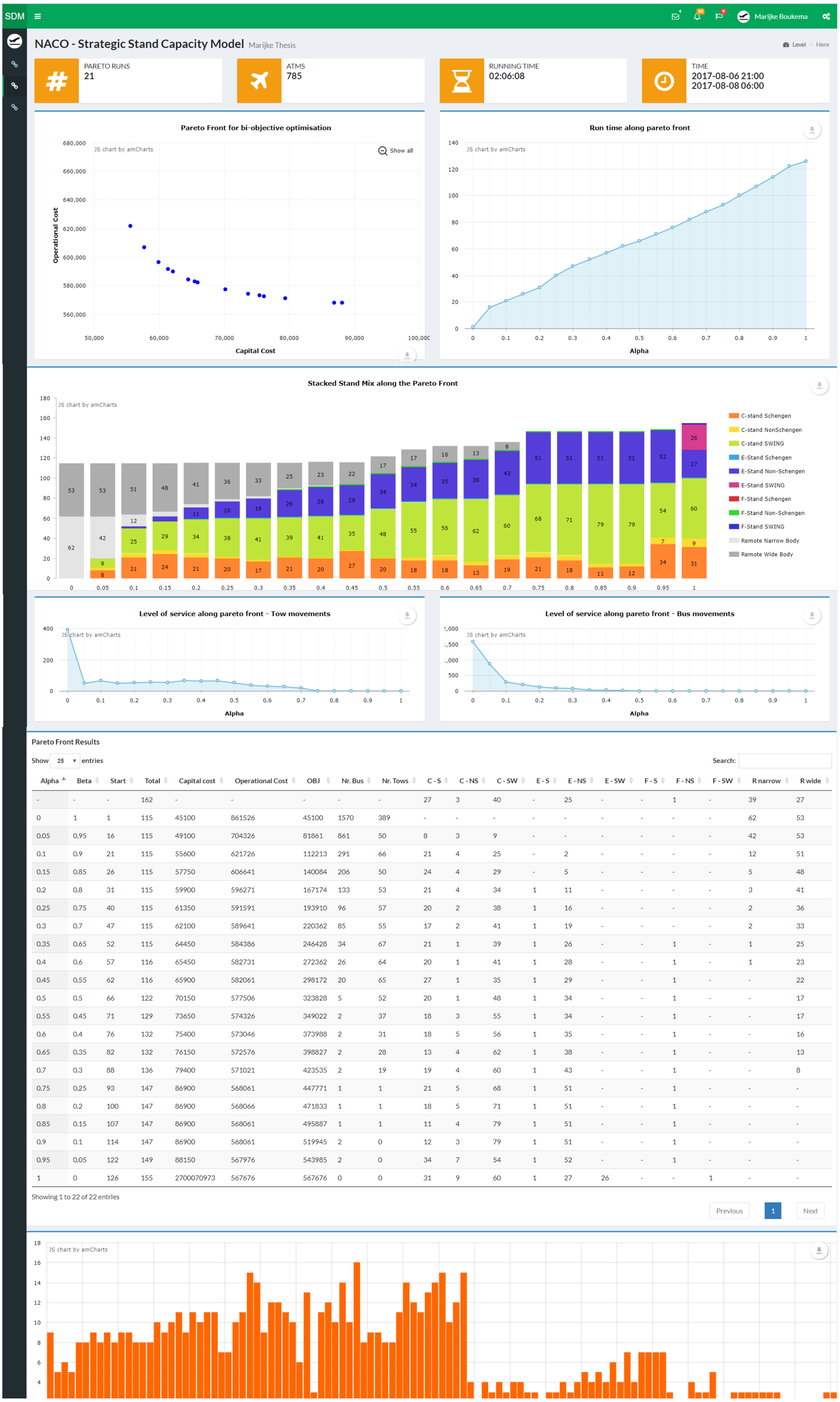


Figure B.1: Example Screenshot of Airport Demand Dashboard of the input of the strategic stand capacity model

Figure B.2: Example Screenshot of Airport Dashboard of the input of the strategic stand capacity model



Alpha	Beta	Start	Total	Capital cost	Operational Cost	OBJ	Nr. Bus	Nr. Tows	C - S	C - NS	C - SW	E - S	E - NS	E - SW	F - S	F - NS	F - SW	R narrow	R wide
-	-	-	162	-	-	-	-	-	27	3	40	-	25	-	-	1	-	39	27
0	1	1	115	45100	861526	45100	1570	389	-	-	-	-	-	-	-	-	-	62	53
0.05	0.95	16	115	49100	704326	81861	861	50	8	3	9	-	-	-	-	-	-	42	53
0.1	0.9	21	115	55600	621726	112213	291	66	21	4	25	-	2	-	-	-	-	12	51
0.15	0.85	26	115	57750	606641	140084	206	50	24	4	29	-	5	-	-	-	-	5	48
0.2	0.8	31	115	59900	596271	167174	133	53	21	4	34	1	11	-	-	-	-	3	41
0.25	0.75	40	115	61350	591591	193910	96	57	20	2	38	1	16	-	-	-	-	2	36
0.3	0.7	47	115	62100	589641	220362	85	55	17	2	41	1	19	-	-	-	-	2	33
0.35	0.65	52	115	64450	584386	246428	34	67	21	1	39	1	26	-	-	1	-	1	25
0.4	0.6	57	116	65450	582731	272362	26	64	20	1	41	1	28	-	-	1	-	1	23
0.45	0.55	62	116	65900	582061	298172	20	65	27	1	35	1	29	-	-	1	-	-	22
0.5	0.5	66	122	70150	577506	323828	5	52	20	1	48	1	34	-	-	1	-	-	17
0.55	0.45	71	129	73650	574326	349022	2	37	18	3	55	1	34	-	-	1	-	-	17
0.6	0.4	76	132	75400	573046	373988	2	31	18	5	56	1	35	-	-	1	-	-	16
0.65	0.35	82	132	76150	572576	398827	2	28	13	4	62	1	38	-	-	1	-	-	13
0.7	0.3	88	136	79400	571021	423535	2	19	19	4	60	1	43	-	-	1	-	-	8
0.75	0.25	93	147	86900	568061	447771	1	1	21	5	68	1	51	-	-	1	-	-	-
0.8	0.2	100	147	86900	568066	471833	1	1	18	5	71	1	51	-	-	1	-	-	-
0.85	0.15	107	147	86900	568061	495887	1	1	11	4	79	1	51	-	-	1	-	-	-
0.9	0.1	114	147	86900	568061	519945	2	0	12	3	79	1	51	-	-	1	-	-	-
0.95	0.05	122	149	88150	567976	543985	2	0	34	7	54	1	52	-	-	1	-	-	-
1	0	126	155	2700070973	567676	567676	0	0	31	9	60	1	27	26	-	-	1	-	-

Figure B.3: Example Screenshot of Pareto Front Dashboard of the results of the strategic stand capacity model

C

Aircraft stand compatibility

Table C.1: Aircraft stand compatibility

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
321	Airbus	A321-100/200	C
32S	Airbus	A318	C
318	Airbus	A318	C
32S	Airbus	A318/319/320/321	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	737-900 With Winglets	C
73N	Boeing	737-300 Mixed Config	C
73Q	Boeing	737-400 Mixed Config	C
73S	Boeing	737 Advanced	C

Table C.2: Aircraft stand compatibility

Code	Manufacturer	Type	Compatible Stand
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	737-800 With Winglets	C
73M	Boeing	737-200 Combi	C
73P	Boeing	737-400 Freighter	C
73W	Boeing	737-700 With Winglets	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
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

Table C.3: Aircraft stand compatibility

Code	Manufacturer	Type	Compatible Stand
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 pax models	D
76X	Boeing	767-200 Freighter	D
76Y	Boeing	767-300 Freighter	D

Table C.4: Aircraft stand compatibility

Code	Manufacturer	Type	Compatible Stand
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	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
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
77F	Boeing	777 Freighter	E
77L	Boeing	777-200LR	E
77W	Boeing	777-300ER	E

Table C.5: Aircraft stand compatibility

Code	Manufacturer	Type	Compatible Stand
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	X
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	F28Fellowship	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	X
SF3	Saab	SF-340	X
SFB	Saab	SF-340B	X
TB7	Socata	TBM-900	X
SWM	Swearingen	Merlin twin prop	X

D

Resolution methods

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Table D.1: Part 1 Overview of GAP resolution methods [20]

Method	References	Approach / Algorithm	Problem type
Exact algorithms	Mangoubi and Mathaisel 1985 [56]	Linear programming relaxation	Real case (Toronto InternationalAirport)
	Bihr 1990 [57]	Primal-dual simplex	Theoretical
	Bolat 2000 [22, 58]; Xu and Bailey 2001 [59]	Branch and bound	Real case (King Khaled InternationalAirport, KSA); Theoretical
	Yan and Huo 2001 [60]	Simplex. Branch and bound	Real case (Chiang Kai-Shek Airport)
Heuristic algorithms	Mangoubi and Mathaisel 1985 [56]	Heuristic approach	Real case(Toronto Airport)
	Vanderstraeten and Bergeron 1988 [39]	ADAP	Theoretical
	Bolat 1998 [22]	Heuristic branch and bound, SPH heuristic	Real case(Riyadh Airport RUH)
	Haghani and Chen 1998 [61]	Heuristic approach	Theoretical
	Bolat 1999 [22]	Heuristic branch and trim	Real case(Riyadh Airport RUH)
	Yan et al. 2002 [38]	Greedy heuristics	Real case (Chiang Kai-Shek Airport)
	Thengvall et al. 2003 [62]	Bundle algorithm approach	Theoretical
	Ding et al. 2004 [43, 44]	Greedy algorithm	Theoretical
	Lim et al. 2005 [63]	The Insert Move Algorithm, the Interval Exchange Move Algorithm, and a Greedy Algorithm	Theoretical
	Yan and Tang 2007 [64]	Heuristic approach	Real case (Taiwan InternationalAirport)
	Diepen et al. 2007 [30]	Column generation	Real case (Schiphol AAS)
	B.A.C.o.E.B. Team and A.I.C.o.E. Team 2009 [**Team2009**]	A hybrid heuristics algorithm guided by simulated annealing and greedy heuristic	Theoretical
	Genc 2012 [65]	Ground time maximization heuristic, and idle time minimization heuristic	Theoretical and real case (Ataturk Airport of Istanbul)
	Dorndorf et al. 2012 2017[32, 66]	Heuristic based on the ejection chain algorithm	Theoretical
	Guepet 2015 [25]	**SAP** Exact MIP using CPLEX compared with: Spatial (or stand) decomposition Time decomposition Greedy Algorithm Ejection Chain Algorithm Result show that CPLEX performs better for SAP	Real case(two major European Airports)

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Table D.2: Part 2 Overview of GAP resolution methods [20]

Method	References	Approach / Algorithm	Problem type
Metaheuristic algorithms	Gu and Chung 1999 [67]	Genetic algorithms approach	Theoretical
	Bolat 2001 [21]	Genetic algorithm	Real case (King Khaled InternationalAirport, KSA)
	Ding et al. 2004 [**Ding2004nogeen**, 43]	Tabu search	Theoretical
	Xu and Bailey 2001 [59]	Tabu search	Theoretical
	Ding et al. 2005 [45]	Simulated annealing, hybrid of simulated annealing and tabu search	Theoretical
	Lim et al. 2005 [63]	TS algorithm and a memetic algorithm	Theoretical
	Hu and Di Paolo 2007 [**paolo2007**]	New genetic algorithm with uniformcrossover	Theoretical
	Drexl and Nikulin 2008 [35]	Pareto simulated annealing	Theoretical
	Zheng et al. 2010 [68]	A tabu search algorithm and metaheuristic method	Real case (Beijing International Airport, China)
	Seker and Noyan 2012 [69]	Tabu search algorithms	Theoretical
	Cheng et al. 2012 [70]	Genetic algorithm (GA), tabu search(TS), simulated annealing (SA), and a hybrid approach based on SA and TS	Real case (Incheon International Airport, South Korea)
	Wei and Liu 2013 [71]	A hybrid genetic algorithm	Theoretical
	Zhao 2014 [24]	Ant colony Algorithm (ACO)	Theoretical
	Bouras et al. 2014 [20]	Genetic algorithm (GA), tabu search(TS), simulated annealing (SA)	Theoretical
	Marinelli 2015 [72]	Bee Colony Optimization (BCO)	Real case (Milano Malpensa airport)
	Marinelli 2015 [73]	Biogeography-based Bee Colony Optimization	Real case (Milano Malpensa airport)
	Yu et al. 2016 [26]	diving heuristic, relaxation induced neighborhoods (RINS), local branching (LB), Variable reduce neighborhood search (VRNS)	Theoretical
	Liu et al. 2016 [27]	Genetic algorithm	Real case (Beijing Capital International Airport (PEK))
	Benlic 2017 [74]	breakout local search (BLS) and a greedy constructive heuristic	Real Case (Manchester Airport)
	Zhang et al. 2017 [75]	Biogeography-based optimization algorithm (BBO)	Theoretical
	Zhang et al. 2017 [75]	Guided diving heuristic algorithm based on general upper bound branching (GDGUB) Variable rolling horizon algorithm (VRH)	Real case (large US airport)
	Kaliszewski and Miroforidis 2017 [28]	Evolutionary Multi-objective Optimisation algorithm (EMO) Compared to CPLEX OPL (latter is preferred)	Theoretical
Optimisation programming language (OPL)	Li 2008 2009 [47, 48]	OPL - CPLEX	Real case(Houston Airport (IAH))
	Yan and Tang et al. 2011 [49]	CPLEX 10.0 solver concert with C language	Real case (Taiwan Airport
	Neuman 2013 [23]	CPLEX 12.2	Real case(Manchester Airport
	Prem Kumar and Bierlaire 2014 [42]	OPL	Theoretical
	Maharjan and Matis 2012 [50]	AMPL/CPLEX 11.2	Real case(Houston Airport (IAH))
	Guepet 2015 [25]	SAP: Stand Allocation Problem CPLEX 12.4	Real case(two major European Airports)

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Table D.3: Part 1 Overview of GAP formulation styles and objectives [20]

Formulation	References	Objectives	Problem Type
Integer linear programming (IP)	Lim et al. 2005 [76]	(i) Minimising the sum of the delay penalties (ii) Minimising the total walking distance	Theoretical
	Diepen et al. 2007 [30]	(i) Minimising the deviation of arrival and departure time (ii) Minimising replanning the schedule	Real case (Amsterdam Schiphol Airport)
	Diepen et al. 2009 [29]	Minimising deviations from the expected arrival and departure times	Real case (Amsterdam Schiphol Airport)
	Hoogeveen 2015 [10]	Maximize the idle time between flights	Real case (Schiphol AAS)
Binary integer programming (BIP)	Mangoubi and Mathaisel 1985 [56]	Minimising passenger walking distances	Real case (Toronto International Airport)
	Yan et al. 2002 [38]	Minimising passenger walking distances	Real case (Chiang Kai-Shek Airport)
	Vanderstraeten and Bergeron 1988 [39]	Minimising the number off-gate event	Theoretical
	Bihr 1990 [40]	Minimising of the total passenger distance	Theoretical
	Tang et al. 2010 [41]	Developing a gate reassignment framework and asystematic computerized tool	Real case (Taiwan International Airport)
	Prem Kumar and Bierlaire 2014 [42]	(i) Maximising the gate rest time between two turns (ii) Minimising the cost of towing an aircraft with along turn (iii) Minimising overall costs that include penalization for not assigning preferred gates to certain turns	Theoretical
Mixed integer linear programming (MILP)	Bolat 1998 [22]	Minimising the range of slack times	Real case(Riyadh Airport RUH)
	Bolat 2001 [21]	Minimising the variance or the range of gate idle time	Real case(Riyadh Airport RUH)
	Neuman 2013 [23]	Maximising the time gaps	Real case(Manchester Airport)
	Zhao 2014 [24]	(i) Minimise the weighted sum of departure delay (ii) Minimise buffer time (iii) Maximise matching degree of aircraft with gate	Theoretical
	Guepet 2015 [25]	**SAP: Stand Allocation Problem** (i) maximising the number of passengers/aircraft at contact stands (ii) minimising the number of towing movements	Real case (two European Airports)
	Yu et al. 2016 [26]	(i) Minimise conflict cost (robustness of the schedule) (ii) minimise tow cost (iii) minimise passenger transfer cost (satisfaction level)	Theoretical
	Liu et al. 2016 [27]	Minimise the dispersion of idle time periods	Real case (Beijing Airport (PEK))
	Kaliszewski and Miroforidis 2017 [28]	(i)Minimise sum of all waiting times for flights (ii)Minimise unassigned flights	Theoretical
Mixed integer non linear programming (MINP)	Li 2009 [48] [47]	Minimising the number of gate conflicts of any two adjacent aircraft assigned to the same gate	Real case(Houston Airport (IAH))
	Bolat 2001 [21]	Minimising the variance or the range of gate idle time	Real case (King Khaled International Airport)
Clique partitioning problem (CPP)	Dorndorf et al. 2008, 2012 [66, 77]	**SAP: Stand Allocation Problem** (i) Maximising the total assignment preference score (ii) Minimising the number of unassigned flights (iii) Minimising the number of tows (iv) Maximising the robustness of the resulting schedule (v) Minimise deviation from a given reference schedule	Theoretical
	Dorndorf et al. 2017 [32]	**SAP** (i) Maximisation of flight/gate preference scores (ii) Minimisation of the number of tows (iii) Minimisation of the expected number of overlaps (iv) Minimisation of the expected number of gate closure violations (v) Minimisation of the expected number of shadow restriction violations (vi) Minimisation of the expected number of tow time restriction violations	Real case (Various International Airports)

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Table D.4: Part 2 Overview of GAP formulation styles and objectives [20]

Formulation	References	Objectives	Problem Type
Multiple objective GAP formulations	Hu and Di Paolo 2007 [**paolo2007**]	Minimise passenger walking distance, baggage transport distance, and aircraft waiting time on the apron	Theoretical
	Wei and Liu []	(i)Minimising the total walking distance for passengers (ii) Minimising the variance of gates idle times	Theoretical
	B.A.C.o.E.B. Team andA.I.C.o.E. Team	(i) Minimising walking distance (ii) Maximising the number of gated flights (iii) Minimising flight delays	Theoretical
	Yan and Huo 2001 [60]	(i) Minimising passenger walking distances (ii) Minimising the passenger waiting time	Real case (Chiang Kai-Shek Airport)
	Marinelli 2015 [72, 73]	(i) Minimisation of total walking distance (ii) Minimisation of flights assigned to remote gates	Real case (Milano Malpensa airport)
	Benlic 2017 [74]	Group 1: Maximise idle times between conflicting aircraft: (i) at the same gate (ii) at gates where shadowing constraints applies (iii) at gates within same gate group Group 2: Preferences (iv) Maximise usage of gate space (v) Maximise airline preferences for particular gate (vi) Maximise number of tows to terminal gates (vii) Minimise number of passengers using remote gates Group 3: Tows (viii) Minimisation of tows(park) activities and gate changes Group 4: (ix) minimise transfer passenger walking	Real case (Manchester Airport)
Dynamic Programming	Jaehn 2010 [78]	**SAP: Stand Allocation Problem** maximise flight/gate preference scores	Real case (European Airport)
Stochastic model	Yan and Tang 2007 [64]	Minimising the total passenger waiting time	Real case (Taiwan Airport)
	Yan et al. 2008 [79]	Minimisation of the passenger flows	Real case (Taiwan Airport)
	Yan and Tang 2011 [**Yan2011**]	Minimise delay time	Real case (Taiwan Airport)
	Genc et al. 2012 [65]	Maximising gate duration, which is total time of the gates allocated	Theoretical and real case(Ataturk Airport of Istanbul, Turkey)
	Seker and Noyan 2012 [69]	Minimising the expected variance of the idle time	Theoretical
Markov decision process (MDP)	Aoun 2014 [80]	Maximise robustness	Real case (Hong Kong International Airport)
Quadratic assignment problem (QAP)	Drexl and Nikulin 2008 [35]	(i) Minimising the number of ungated flights (ii) Minimising the total passenger walking distances or connection times (iii) Maximising the total gate assignment preferences	Theoretical
	Haghani and Chen 1998 [61]	Minimising the total passenger walking distances	Theoretical
Scheduling problems	Li 2010 [81]	(i) Maximise the sum of products of the flight eigenvalue (ii) Maximise the gate eigenvalue of assigned flight	Theoretical
Quadratic mixed binary programming	Bolat 2000 [58]	Minimizing the variance of idle times	Real case(Riyadh Airport RUH)
	Zheng et al. 2010 [68]	Minimizing the overall variance of slack time	Real case (Beijing Airport)
	Xu and Bailey 2001 [59]	Minimizing the passenger connection time	Theoretical
Binary Quadratic Programming	Ding et al. 2004, 2005, 2004 [43–45]	Minimize the number of ungated flights and the total walking distances or connection times	Theoretical
Network representation	Maharjan and Matis 2012 [50]	Minimizing both fuel burn of aircraft and the comfort of connecting passengers	Real case(Houston Airport (IAH))
	Zhang et al. 2017 [75]	(i)minimise the weighted sum of total flight delays (ii)minimise gate re-assignment operations (iii) minimise missed passenger connections	Real case (large US airport)
Robust optimization	Diepen, Hoogeveen et al. 2012 [31]	Maximizing the robustness of a solution to the gate assignment problem	Real case (Amsterdam Airport Schiphol)

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