Airport Demand Management Strategies

Discrete event simulation approach for evaluation of the effectiveness for airport demand management strategies

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Landing Aircraft on runway of Malaga Airport,
http://blog.altavistaproperty.com/malaga-airports-new-runway-to-open-in-2012/landing-plane/, 2011

Preface

This report is my Master Thesis at the Aerospace engineering faculty in the specialisation on Air Transport & Operations(ATO). The thesis is the result of a year long graduation research project carried out at Delft University of Technology. Conducting the research at the university itself made it possible to focus on solution which would be best from a theoretical point of view. It forced me to extend my knowledge on airport operations and model simulation, useful for purposes in further life.

The origin of the assignment came from a collaboration between Paul Roling and myself, therefore Paul assisted me throughout the whole process towards this result as the principal supervisor. I want to thank Paul for all his support and out of the box ideas on the subject. In a later stage Mihaela Mitici joined the team as a second supervisor on the project. I really want to thank you for your help on the quality of the research. The discussions on the calculations and notations of the method helped in forcing me to take the result to a higher and more detailed level.

Furthermore I want to thank Richard Curran, chairman of the Master track Air Transport & Operations, and Joost Ellerbroek for participation in the Graduation Committee. Thanks to my good friends Bas Ceulemans and Milan Baars for the support on structuring the research project, brainstorm sessions and feedback on the report. The last six months you helped me a lot in meeting the important deadlines and focus on the important parts of the research.

At last I want to thank my family; Marianne, Jan, Michael and Lucille for the endless love and support during my whole education and especially during this research project. Next to my family I also want to thank a number of important people in my life; Corinne, Akkerixt, Wytze and Koen thanks for the support and the distraction when I needed it.

Sidney de Roos
Amsterdam, January 2019

Executive Summary

In the last years the amount of passengers travelling by aircraft increased and the expectations are that the following 20 years the annual growth will be 3.9 % per year. Growth in amount of passengers also leads to growth in the amount of flight movements at airports leading to a growth in the demand for landing capacity. A growth in demand of landing capacity automatically leads to more pressure on this capacity, resulting in less room for error. In changing weather conditions, the air traffic control at airports needs to make adjustments due to a short term decrease in capacity. With the increase of flight movements, a small change of the capacity could have a large impact on the landing operation.

Therefore it would be beneficial for air traffic controllers to have support in decision making in case of capacity issues. Support for air traffic control could be given by the use of demand management strategies, which are given rules to make adjustment to the current planning and operations to guarantee a safe and smooth operation. Demand management strategies are given boundaries to control the aircraft landing operations. The interpretation of demand management strategies can have several approaches, which are described in this research, with the following objective:

The Evaluation of the effectiveness and development of new insights on the Airport Demand Management Strategies for arrival operations.

The goal of the research is to obtain a model to test the effectiveness of demand management strategies and develop it in such a way that more insights can be achieved on a number of different strategies. In this research the scope was limited to the airport arrival operations only. The model works by simulating the daily landing operation at an airport. It aims for an advise on the cancellations based on the expected delay of the arrival operation. The simulation model was based on a discrete event simulation method. Using this approach, it is possible to simulate queue forming in front of the runways. The arrival and service time for every flight are the inputs for the discrete event simulation.

The flight schedule consists of a random generated arrival and service time. A uniform probability distribution is used to generate arrival rates per hour, within each hour the arrivals are evenly distributed. To every flight in the arrival schedule a distance from origin to destination and weight class are assigned. Both the distance and weight class are based on a Schiphol schedule. The actual arrivals behave stochastic. This is incorporated by a normal probability distribution to vary the slot allocated arrival and service time of every flight. The service time is based on the wake turbulence separation. Regulations dictate a different separation time for different weight classes.

The Monte Carlo simulation method is combined with the discrete event simulation approach to minimise the uncertainty of the results. It gives an advise on the number of runs required to assure a certain accuracy. In this way 200 simulation runs would give an accuracy of above 90%. The discrete event simulation model is designed such that different strategies can be implemented in the model to test the effectiveness of each particular strategy. Two strategy approaches are chosen to test the model behaviour:

- Time-based delay strategy; This strategy gives a boundary to the delays generated by the arrivals based on the individual delay of an arrival. If the delay exceeds a certain time, the arrival is cancelled from the flight schedule.
- Consecutive delay strategy; This strategy gives a boundary to the delays generated based on the absolute number of delays. So it takes into account if an arrival has a delay, without using its magnitude, and then it counts as a consecutive delay. If the amount of consecutive delays exceeds an acceptable level, the next arrival will be cancelled if it also generates a delay.

Both strategies search for an optimal combination of delays and cancellations, given that the arrival can not exceed the strategy input.

The result of every simulation consist of an optimisation of the delays and cancellations and a number of monitoring results. An optimal Pareto front is used to present the optimisation of the strategies. The arrival operations monitoring results consist of:

- Waiting time distribution
- Individual delay per arrival
- Average & Maximum queue propagation
- Average delay per hour

For both strategies, optimisation and monitoring results were generated and discussed based on different inputs. The optimal Pareto front shows the relation between the delays and cancellations for a range of strategy inputs while the monitoring results focus on only one strategy input.

To verify the model "the forecast moment" is introduced. This means that the model takes into account the amount of hours there is between the take-off of the aircraft from origin and the moment the simulation is made. When the aircraft is already airborne it can not be cancelled. This limits the amount of possible cancellations, therefore it is expected that the number of cancellations and average delays increases. This was acknowledged by the models results.

A case study on real life Schiphol data are used to observe the behaviour of the model on actual arrival rates. The real schedule consists of more alternation between the arrivals per hour due to peak moments compared to the random arrival schedule. Results of the model give more cancellations during the peak hours in combination with pressure on the capacity. This is also confirmed by increased queue propagation and average delays. In the optimal Pareto fronts of both strategies it could be seen that the time-based delay strategy showed an expected smooth transition between the different strategy inputs. The consecutive delay strategy has difficulties in coping with low and peak hours.

Based on the results it can be concluded that the approaches used for modelling the demand management strategies and the possibility of measuring the effectiveness of the strategies are useful for decision making in the arrival operations. The air traffic controllers are able to monitor an expected delay and queue at particular hours of the operation, the bottlenecks during operation can be analysed and a suitable strategy can be chosen. The model shows that the main advantage can be achieved in the first cancellations where a small number of cancellations already results in a large decrease in average delay.

A major recommendation from the research is to link the optimised ratio of the cancellations and delays with a cost analysis. The cost for delaying and cancelling flights need to be determined and by adding the cost to the model an optimisation can be made with respect to the cost. The result will be an optimised ratio, focused on cost instead of amount of delay. An alternative optimisation possibility is to combine environmental aspects, optimisation on the noise and emissions on and around the airport. This might result in specific cancellations have more priority due to emissions or noise on the planned arrival track.

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List of Abbreviations

Acronym	**Description**
AAS	Amsterdam Airport Schiphol
AC	Aircraft
ATC	Air Traffic Controller
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATP	Air Traffic Planner
CMC	Conditional Monte Carlo method
DEM	Digital Elevation Model
DES	Discrete Event Simulation
EU	European Union
EWR	Newark Liberty Airport
FRA	Frankfurt Airport
FIFO	First In First Out
IMC	Instrumental Meteorological Conditions
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
KPI	Key Performance Indicator
LAX	Los Angeles International Airport
LCFS	Last Come First Serve
LLN	Law of Large Numbers
LVNL	Lucht Verkeerleiding Nederland
MC	Monte Carlo
MIT	Massachusetts Institute of Technology
MS	Management Science
MTOW	Maximum Take-off Weight
NIMA	National Imaginary and Mapping Agency
OR	Operations Research
PRSA	pre-scheduled random arrivals
SIRO	Service In Random Order
US	United States
VMC	Visual Meteorological Conditions

List of Symbols

Symbol	Description
C	Number of cancellations per hour
C_s	All cancellations summed over all runs per hour
$C_{s_{avg}}$	Average amount of cancellations per hour
C_{tot}	Total number of cancellations
d	Delay
d_{avg}	Average delay
$\overline{d}_{avg_n}$	Average delay over multiple runs
d_{cum}	Cumulative delay
$d_{c_{max}}$	Boundary input for the Consecutive delay strategy
d_{cancel}	Cancel or not of the arrivals
d_{cons}	Consecutive delay information
$d_{t_{max}}$	Boundary input for the Time-based delay strategy
d_p	Delay or not information of the arrivals
d_s	All average delays summed over all runs per hour
$d_{s_{avg}}$	Average delay per hour over all n
d_λ	Sum of the delays in one hour
f	Forecast number
h	Number of hours per simulation
n	Number of simulations
$\mathcal{N}$	Notation for the normal probability distribution
q	Queue length
s	Distance from origin to destination
t	Starting time
t_{arr}	Arrival time of an aircraft
$t_{arr_{slot}}$	Arrival daytime per slot
t_I	inter-arrival time
t_s	Separation time between arrivals according to stochastic planning
t_{sep}	Separation time between arrivals according to regulations
t_μ	Separation time
t_w	Waiting time
T_{slot}	Time per slot
$T_{f_{slot}}$	Time per slot for that forecast
$\mathcal{U}(a,b)$	Notation for uniform distribution between boundaries a and b
V_{app}	Approach velocity of an aircraft
WC	Weight class
x_{sep}	Separation distance

Symbol	**Description**
δx	Distance interval
$\Delta t_{arr_{slot}}$	Inter-arrival time
ε	Allowable percentage error
λ	Arrival rate
λ_C	Arrival rate including the cancellations
λ_f	Arrival rate for the forecast f
λ_{lower}	Lower boundary of the arrival rate
λ_{upper}	Upper boundary of the arrival rate
μ_{arr}	Mean of the normal probability distribution for the arrival time
μ_{ser}	Mean of the normal probability distribution for the service time
σ_{arr}	Standard deviation of the normal probability distribution for the arrival time
σ_{ser}	Standard deviation of the normal probability distribution for the service time

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Introduction

The amount of passengers is increasing over the last years and according to the International Air Transport Association(IATA) that number will grow in future years, generating a higher pressure on the capacity of airports not only on the terminal capacities but also on the landing capacities of airports[7]. Eurocontrol is already expecting a global growth on flight movements with a factor of 2,2 in 2030 compared to 2009 with an annual growth of 3,9% per year [50]. Due to the growth in demand of passengers the pressure on airport runways will increase and the limits of the airport capacity will be under pressure. With these increasing numbers, the focus on increasing the efficiency on the airports operations is getting more important.

1.1. Research Motivation

Airport operations are already under pressure, while economic growth causes another increase in demand of passengers [14]. Limitations on airport capacity increases the vulnerability for external changes. Investing in new facilities on airports can be difficult, due to lack of nearby space to build or financial situations.

Airports across the world are constructed based on a forecast of the amount of passengers and flight movements. Doubling the amount of passengers in future years will have impact on future plans for designing airports. Therefore the pressure on runway capacity also grows, increasing importance of an extensive design planning of the runway operations by Air Traffic Control(ATC).

Operating under maximum capacity conditions requires the ability to cope with sudden changes in the capacity at airports. A change in weather conditions is an example of a capacity decreasing event, while the demand is unchanged resulting in an increase in pressure on the capacity. The importance of support on runway operations is increasing with increasing pressure on arrival operations.

To deal with such capacity changes on short notice, a forecasting solution could be implemented to assist the operational decisions. A forecast supporting the ATC controllers by giving advice on steps to be undertaken to assure a safe and efficient operation despite the increase in pressure. An advice could consists of several short term cancellations or deviations of arrivals to other airports.

1.2. Problem Statement

Capacity usage at airports differs for different parts of the world, there are clear deviations comparing the United States(US) with the Europe Union(EU) capacity planning. In the US, planning of the runway schedule is based on their complete capacity usage, while in the EU the planning incorporates only around the 80% of the capacity of the airports[41]. The strategy of planning the capacity in the US, means when coping with unforeseen capacity issues the capacity of the airport exceeds, resulting in issues concerning continuous operation. In Europe airports can cope with small unforeseen issues because of a 20% buffer on the planned flights.

Currently landing slots are managed and planned 6 months in advance of operation, followed by adjustments based on the forecast made by ATC[8]. On the day of operation itself, more on airports capacity is known due to accurate weather forecasts. Under these circumstances, a new forecast should be made of the expected operations[33].

The definition of handling capacity and demand problems is demand management. Strategies on demand management can support runway operations to cancel and delay specific flights depending on the decisions at the particular airport[24]. These strategies will be an input as advise on which flights are best to cancel or delay in case of capacity issues. Problem with current operations is that there is no structure for limiting the damage in case of decreasing capacity, damage control on delays and cancellations is lacking.

1.3. Research Objective & Questions

The Research objective follows from the motivation and the problem statement issued in the previous sections. Combined with the knowledge gained by the literature review it leads to a research objective. The result should be of assistance for the ATC to make choices in the cancellations and delays on a day of operation, it focuses on the short term forecast which eventually assist in the decision making. The research objective for this research is as follows:

Research Objective:

Evaluation of the effectiveness or develop new insights on the Airport Demand Management Strategies

In order to obtain knowledge on the effectiveness of airport demand management strategies a system should be constructed to test strategies. By testing a number of demand management strategies under different circumstances, i.e. strategies with different inputs, it is possible to compare strategies and obtain whether the system is reliable or not. The goal is to test these strategies and the system and obtain whether it is possible that strategies assist in decision making for the ATC. A research question is obtained from the research objective and given goal, and is given below.

Main Research Question:

How can the effectiveness of Airport Demand Management strategies be evaluated?

This main research question is then split up in the sub-questions shown below. In appendix A a more detailed list of the sub-questions can be found.

Sub questions:

- What are demand management strategies and how is it used in the landing operations?
- What data can be used and how is it obtained?
- How can the data be used in a model?
- Do the modelling techniques give a good representation for the evaluation of the airport demand management strategies?
- What could be the advantage of using a model for the demand management issue on airports?

1.4. Research Scope

The research will focus on testing the demand management strategies at airports. Departures will not be taken into account for this model. A reason is that modelling the system only for arrivals will already give a clear overview on the performance of demand management strategies.

To test the effectiveness of demand management strategies, the results will focus on delays and cancellations instead of using metrics in cost, emissions or noise. This to focus on the actual operations and the impact of demand management strategies on the operations. In the discussion and recommendations these limits on the research will be treated once more to explain what the benefit would be on having an extra metric for the demand management strategies.

1.5. Methodologies

The research objective and question are the foundation for the choices made to get to the methodologies. To give a visual image of the methodologies and a brief overview of the topics, a work breakdown structure is illustrated in Figure 1.1. The first step in the research was to gather knowledge on the research objective by analysing previous research. Using this as a guideline through the research it gave a clear step-by-step plan on the important phases in this scientific research[55].

First the conceptual design of the research is made, which includes; the research objective and research questions. The literature study is framed by the scope and research objective. Topics as demand management in general and examples of strategies were examined. Also methodologies of the possible approaches were searched for such as a queuing model, Discrete Event Simulation(DES) and Monte Carlo(MC) simulations this is also shown in Figure 1.1.

Using knowledge obtained from literature, the next part is creating data generators for generating random data. Followed by a DES in combination with MC simulation. Important step in simulation is implementing the demand management strategies, it is chosen to use two different strategy approaches to test the model on:

- Time-based delay strategy: This strategy is based on the individual time delay of an arrival. The input variable of the time-based delay strategy is a limit of the time delay per arrival, if an arrival exceeds this limit it will be cancelled. It is a manual input in seconds of time delay and every time a different input is done, it can be seen as a new strategy because it results in a different combination of cancellations and delays.
- Consecutive delay strategy: This strategy is based on the absolute individual delay of an arrival. It is not important what the amount of delay is per strategy but just that it has a delay. The strategy input is the maximum acceptable amount of consecutive delays. So the number of arrivals with a delay is summed during the run and if it exceeds the manual limit than the next arrival will be cancelled.

The data analysis and simulation model is done in Python and based on examples of queuing systems from literature. The data generators and analytics are finally based on probability distributions established from real airport schedules. Results from simulation will be presented in the form of a Pareto front creating an optimal line between two different variables[53]. At last conclusions and recommendations will be given to present the answers on the research questions.

1.6. Outline of Master Thesis

The outline of the master thesis is to give an overview of all different chapters and built up of the research report. Every chapter gives the reader more knowledge of the subject and the research itself. It starts with the introduction followed by an explanation on current demand management strategies in Chapter 2. Next Chapter 3 will explain structure and method of the model, consisting of flow diagrams and equations used. In this chapter the probabilistic data analysis, DES, strategy tool and MC simulation will be presented. The model eventually obtains a result presented and discussed in Chapter 4, including a part on the verification of the model and a small case study on a real Schiphol schedule as the validation. The discussion of the recommendations will be presented in Chapter 5. The conclusions accompanied with recommendations on future ideas and improvements on the research, is shown in Chapter 6. At the end of the report the appendices are given to support several sections.

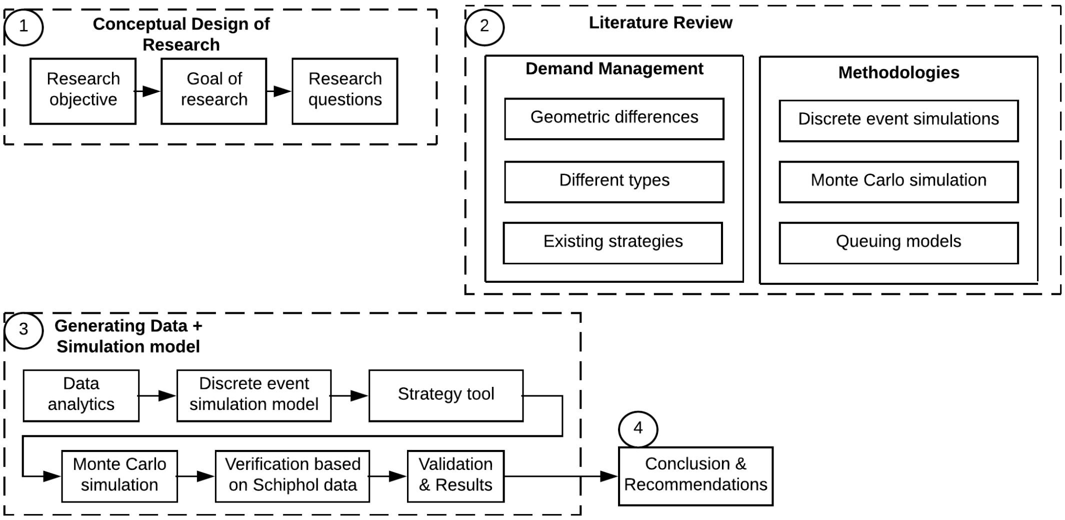

Figure 1.1: A visualisation of the research methodologies used in the research on the effectiveness of demand management strategies

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Demand Management

In this chapter the basic principles of demand management and corresponding strategies will be explained. First demand management in general will be treated in Section 2.1 followed by major differences between approaches on demand management strategies in the world; US & EU in Section 2.2. Next a number of examples on demand management strategies will be shown to get familiar with the idea of demand management strategies at airports, given in Section 2.3.

2.1. Basic Principles of Demand Management

Currently demand management on airports is defined as the planning of arrivals and departures within the boundaries of capacity of an airport, taken into account regulations of that particular region. Demand management is to improve and control operations, especially when it comes to management of operation during capacity limits. Runway operations and segmentation between arrivals and departures is said to be the most sensitive part of airport operations[46]. There are three main approaches of demand management; administrative, economic & a hybrid of both. Economic and hybrid approach also take into account the extra cost caused by delayed flights. Extra cost for the other airport users due to a delayed flight is called congestion cost which is explained in Section 2.1.1.

2.1.1. Demand Management Approaches

In the following paragraphs three different approaches of demand management will be explained:

- Administrative demand management
- Economic demand management
- Hybrid demand management

These approaches will be presented to show current demand management within airport operations. It will give knowledge on demand management and also shows the importance of implementation of such approaches.

Administrative demand management

Administrative demand management approaches are based on bureaucratic planning aspects. Capacity of airports are primarily determined in advance based on long term contracts between airports and airlines. A number of slots are free on market every year and will be allocated by an administrative controller. This is largely focused on predefined slots for different aircraft types, for every airline the slots will be allocated with their aircraft types. International Air Transport Association (IATA) organises a slot conference to divide slots between airlines every year. The slots are based on different separation distances based on wake turbulence regulations[1].

Allocation of slots is the main focus of all demand management approaches, administrative demand management approaches are based on predefined criteria. Examples of these criteria; the number of arrivals each week and contract-length an airline has with an airport. These are mainly criteria which focus on continuity of service and to maintain or develop partnership between airline and airport. For competitors it is difficult to start such partnership with new destinations and therefore with airports. Smaller airlines experience difficulties on slot auctions due to overruling larger airlines with larger financial power. Slot auctions are therefore equipped with certain regulations, such as keeping the slot allocations in the same ratio as the market shares. While these demand management approaches were used in the EU, it chose to change to a hybrid demand management structure, where the economic and the administrative approach are combined.

IATA worldwide scheduling shows scheduling coordination approaches which are acknowledged and presented by Massachusetts Institute of Technology(MIT) [5, 6, 23]. The IATA schedule coordination is divided into three categories, these levels are based on level of pressure on capacity at airports:

- Level 1: The non-coordinated airports; there is no pressure on capacity with current amount of demand at the airport.
- Level 2: The coordinated airports; there is some pressure from demand but it is at capacity limits, therefore there are no large issues concerning capacity of the runways and airport.
- Level 3: The fully coordinated airports; most of the Hub airports operate in this level. An airport of level 3 operates an unbalanced use of capacity during the day, so at one moment there are peak hours and capacity exceeds it maximum level and on the other hand, at less busy hours the airport uses a small percentage of capacity. In this situation a schedule coordinator is assigned whose task is to allocate free slots to aircraft which are planned on congested moments. These aircraft are fully coordinated by the schedule coordinator whose also responsible for the procedures according to the regulations by the European Council[45]. Some example researches on this topic of fully coordinated level give more insight on implementation of level 3[25, 56].

In 2004, IATA introduced these approaches and at that time there were 140 airports using a level 3 schedule coordination approach for their planning operation. The administrative approach of demand management is largely focused on planning by changing the schedule based on changing capacity.

Economic demand management

The economic approach of demand management is mainly about congestion pricing. Congestion pricing is based on charging a user for using the facilities of an airport, these charges can vary throughout the day. The prices go up when the congestion at an airport is at a higher level and go down when there is no congestion. The goal is to force airlines to operate on other possible hours at the airport, to have a more equalised capacity coverage during the day[46, 52].

The landing fees at airports are mainly based on the weight of the aircraft; the heavier the aircraft the higher the landing fees. Weight-based landing fees are a traditional way for charging airlines, but in new charging models the fees are conducted through a more elaborate way[48].

Landing fees consist of different aspects and also depend on demand at an airport. Possibilities for landing at an airport in the region has effect on the landing fees due to existence of competitors in the area[27]. Two different approaches of charging an airline are given below:

- Congestion price is a fixed number per landing during the peak hours or a vast increase in percentage of the basic landing fee[32].
- Charge the airline a total price for being at their airport, a goal for this strategy could be to mask the high landing fees during peak hours[13].

In early research it is shown that with an increase in number of flight movements the internal and external cost of delays increase exponentially[42, 46]. Including congestion pricing, the internal and external costs for airports will increase, therefore the cost for the airline will increase with increase in flight movements during peak hours. This illustrates the reason for congestion pricing as an economic demand management approach.

Hybrid demand management

Hybrid demand management is a combination of administrative and economic demand management. Schedule coordination is accompanied by pricing of congestion to cope with capacity issues at airports. There are different approaches in hybrid demand management such as slot coordination plus congestion pricing and slot auction. Research by Odoni shows the connection between the two demand management approaches. The focus in this research is on the combination of these two strategies towards a cost efficient and safe operation within limits of the capacity at the airport[24].

Figure 2.1 shows an example on a hybrid demand management system, here shown as the OR(Operations Research)/MS(Management Science) strategy. On administrative level the schedule coordinator, indicated as Air Traffic Management(ATM), plans the slots such the airport capacity is used optimal. In the planning the congestion pricing is also taken into account by charging the airline with the corresponding price with the slot the airline is using. In case the capacity is at its maximum the figure should have an extra loop from airport capacity back to schedule limits and congestion pricing. If airports operate at maximum capacity the congestion prices need to go up to counteract the demand at peak hours.

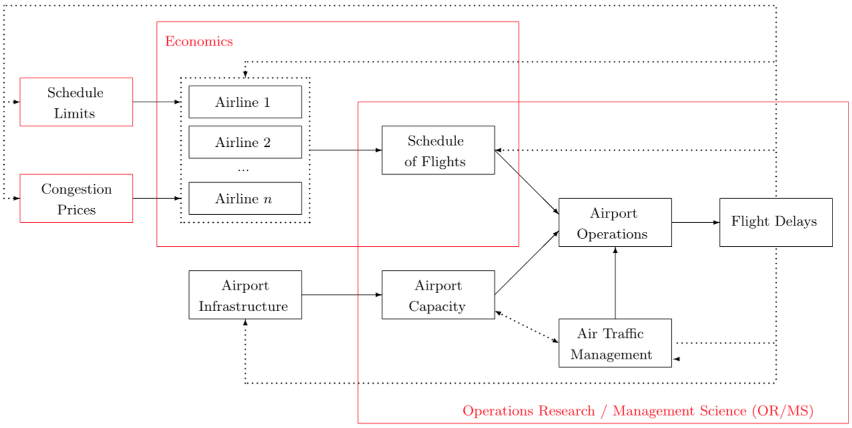


Figure 2.1: Schematic overview of the flow between the economic and the administrative (OR/MS) demand management [24]

A research on the airport operations using such a system shows that it is useful in irregular situation to clear the responsibilities of the operation to increase the efficiency on decision making.[10, 11].

The second example of a hybrid demand management approach are slot auctions. Slot auctions are based on free market approaches on selling the slots of an airport. The airlines can bid on landing and take-off slots. The price of a slot depends on the demand for a slot. Eventually the airport is focused on optimising the utilisation of the airports capacity, while controlling the prices for the landing slots. An important aspect of the slot auction is that it still focuses on minimisation of congestion & delay costs while safe operation is maintained and the amount of passengers travelling is maximised[35]. This operation is already complicated but because there are different stakeholders in this operation it creates a difficult political situation in the decision making process. In the end the slot allocation is executed by the airport, so it decides the airlines classification of the slots and as mentioned before the slots are mainly based on the historic distribution over the airlines. These deals between, for example Amsterdam Airport Schiphol, and the airlines have guidelines such as half a year before the day of operation the 80% check on the slots is performed to decide if the airline gets the same slots this year. The 80% rule is that the airport demands from an airline that it uses at least 80% of the planned flights[16, 47]. 5 Months prior to day of operation, the slot coordinator decides whether the slots go back into free market or go to the regular airlines[18].

2.1.2. Airport Capacity

The airport capacity is an important part of demand management. First airport capacity is explained, followed by the effect of weather conditions on airport capacity. The capacity of an airport has many diverse aspects such as runway capacity, terminal capacity, gate capacity and more different capacity forms. Airport capacity is in this research mainly focused on the runway operations of airports. So the definition on airport capacity in this research is; the amount of aircraft a runway is capable to handle within the time of operation. The runway capacity is a combination of the departures and the arrivals, when the amount of arrivals increases the amount of departures decreases because of the total amount of flight movements possible on a runway/runways. Figure 2.2 shows the capacity envelope, the visual meteorological conditions(VMC), corresponding with the visual flight rules(VFR), indicated with the red area and instrumental meteorological conditions(IMC), corresponding with the instrumental flight rules(IFR), with blue. Both have different runway capacities and proportions in the differentiation between departures and arrivals, with higher amount arrivals, less departures are possible and vice-versa.

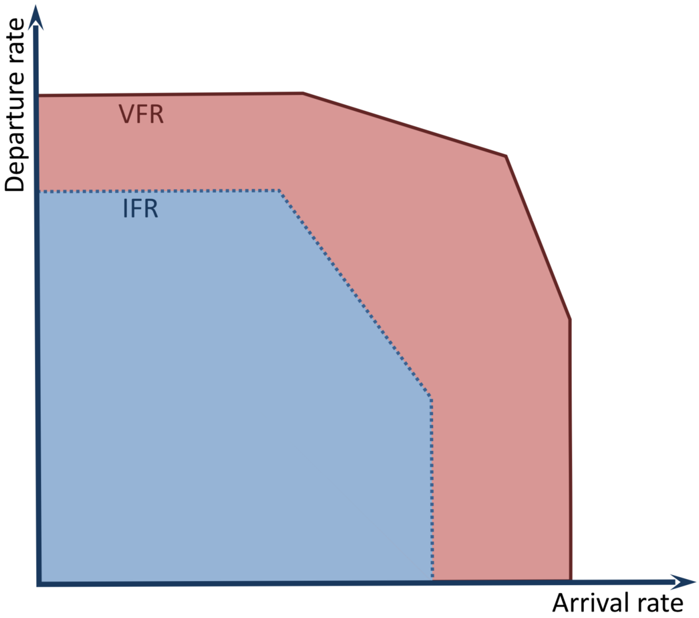


Figure 2.2: An example of a capacity envelope on the departing and arriving aircraft: in the figure a distinction is made between the VFR capacity (red) and the IFR capacity (blue)[44]

Changing weather conditions is the major reason for delays and cancellations at airports. Bad weather forces the airport to operate with larger service time per aircraft, to maintain safe operation the regulations forces a larger separation between aircraft[15, 22]. Increasing separation between two arriving aircraft results in a lower capacity per hour at the airports, leading to pressure on the runway operations due to the unchanged demand. The main difference in airport capacity is due to the weather conditions by two meteorological conditions; VMC and IMC, both explained below. Followed by the calculation of the difference between the VMC and the IMC in percentage of the capacity based on 5 different large Hub airports in Europe the capacity difference is also shown in Figure 2.2. Below an explanation on both conditions and their consequences.

- VMC - Conditions where the weather is that clear that the pilots vision is good enough see the aircraft's track. VMC is regulated by the VFR.
- IMC - These conditions requires the pilot to fly mainly by the use of instruments. It goes hand in hand by the IFR, which are needed in cause the visual outside of the aircraft is limited due to clouds and bad weather.

These different conditions and therefore flight rules have impact on the capacity of landing operations at an airport. Instrumental flight rules are operational during bad weather, resulting in higher separation time between arrivals, decreasing the arrival capacity of the airport. Figure 2.2 shows that the total capacity is lower with IMC than with VMC. And as already mentioned most delays and cancellations are due to bad weather conditions, which are difficult to forecast accurately.

Weather conditions can be used for research on demand management strategies, it is important to give the VMC and IMC a value to translate the regulations into values which can be used for the calculations. Several researches on VMC and IMC on different Hub-airports can be found, explaining the differences and obtaining values for the different weather conditions[28, 31, 34]. Also International Civil Aviation Organization(ICAO) published reports on manual to cope with all weather conditions and the regulations accompanying these manuals[19, 29]. Using both the knowledge from the ICAO manuals and the researches on the VMC and IMC differences it results in Table 2.1, showing the values for capacity on arrivals of 5 different airports.

Table 2.1: The different capacity rates of 5 airports for VMC and IMC[3, 9, 17, 26, 54]

Airport	VMC	IMC	IMC compared to VMC(in %)
1	39	33	84.6
2	39	33	84.6
3	36	30	83,3
4	48	39	81,3
5	33	28	84,8
Average	39	32.8	83,7

2.2. Differences in Demand Management

There are different interpretations on the most effective or efficient demand management strategies. To obtain more knowledge on these interpretations, this section will give the operation in both the US and Europe followed by the differences between the two geographic areas.

2.2.1. Demand Management in the United States

Slot coordination in the US is regulated to a certain extend, but the airport itself is largely responsible for the planning. This means that capacities can exceed the limits if approved by the airports planning. In a research from Odoni this is also shown with a comparison between two airports, resulting in differences in the planning between VMC and IMC [40]. Figure 2.3 shows the capacity of Newark Liberty Airport(EWR) with the airport's planning for a year and each month separately, also the two weather restrictions, IMC and VMC, are shown. The operation between 13:00 and 19:00 exceeds the limitations of the capacity. Both VMC and IMC capacity exceed the limits given. That the IMC-limit is exceeded for almost half a day on average, this means that in case of IMC the airport does have a capacity issue resulting in delays and/or cancellations.

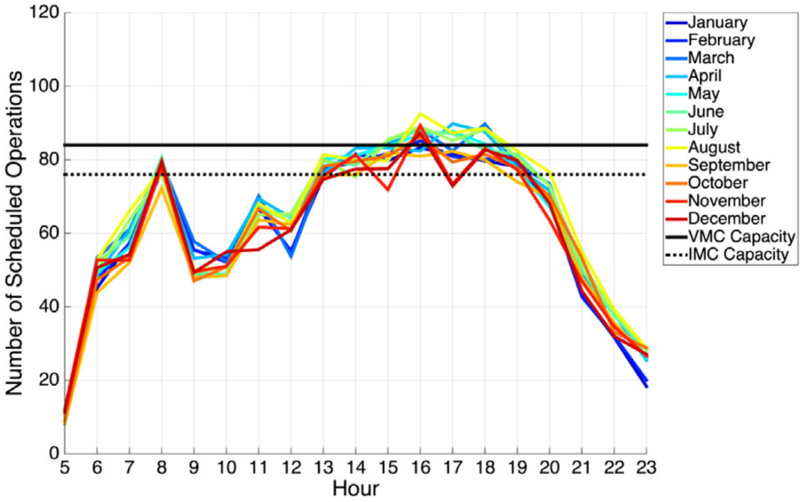


Figure 2.3: Capacity with planned flights per month of the year on EWR [40]

Planning strategies as shown could result in issues causing delays or cancellations. By operating on maximum capacity, profits are high with good weather conditions but with bad weather conditions the impact on delays is high. Such strategies can lead to vulnerability of the operations to sudden changes. In a research from 2002 it is stated that if the runway capacity is over-utilised, the delays increase exponentially[12]. Also a case study on Newark Liberty shows certain scheduling limits in the United States[43].

2.2.2. Demand Management in the European Union

European demand management is also explained by the use of an image of the airport's capacity. Figure 2.4 gives the capacity usage of Frankfurt airport(FRA) for different months. It shows that the distribution of the capacity usage over the day is between the 75 and 80 aircraft an hour through the whole year while the maximum IMC capacity is around the 85 aircraft an hour. Even if the weather is sufficient to operate under the VMC capacity the planned number of flights is still below IMC capacity. The airport plans a buffer to cope with unforeseen circumstances leading to delays, so in case of decreasing capacity by 20% the European airport can still operate the planned flights[24].

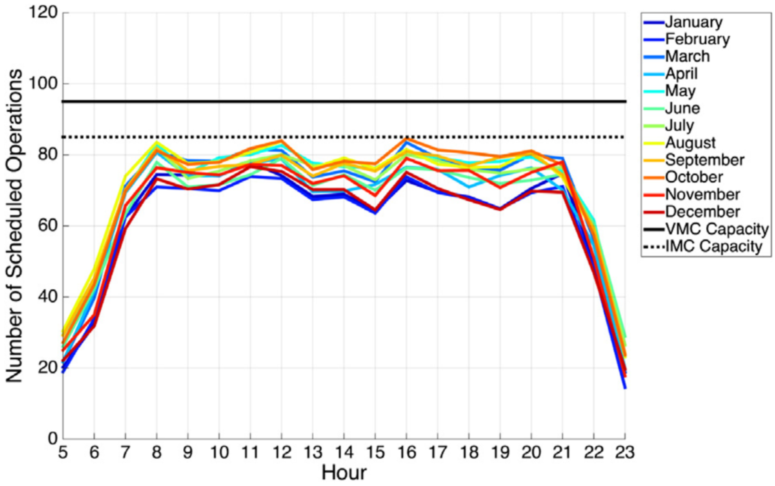


Figure 2.4: Capacity with planned flights per month of the year on FRA[40]

European Commission regulates the schedule coordination of the flight movements in Europe. The Commission gives certain guidelines and regulations to maintain fair market and operation as safe as possible. The administrative part given in Section 2.1.1 already gives information about the regulation of the European Aviation agencies to regulate the slot coordination. As stated in the book about Airport Systems, the EU regulations force schedule coordinators to operate by their guidelines[46]. This means that the EU can force airports to perform a certain planning even if, according to the airport, it is not the most feasible planning on delay or economic perspective. So the EU has, by its regulations, influence on the planning of the airport's schedule coordination which is also stated in a policy research on demand versus capacity[36].

2.2.3. Main Differences between US & EU

Important differences between the US and EU strategies will be given in this section which follow from the research in the previous two sections. Below the major differences will be listed.

Schedule Coordination

As also indicated by the Figures 2.3 and 2.4 the distribution at busy airports in the US and EU is different. On schedule coordination the airports in the US are not bounded by regulations which indicate that US airports can plan passed the capacity limits. Runway operations in the EU are coordinated by regulations from the European commission, forcing airports in Europe to stay within their 80% capacity limit [46]. Therefore it can be said that the capacity management in Europe is more regulated than in the US, as well as the demand management on the airports.

Delay Propagation

Planning in the US is to maximised capacity, this also has influence on delays at US airports. In a research done by Morisset in 2011 it is explained that the propagation of delays is different in the US compared to Europe[37]. Data of 25 large airports in the US and EU was used for this research, which eventually gives a good overview of the influence of such planning on larger airports in these areas. Figure 2.5 shows that during the day the average delays in the US are increasing with a larger number than in Europe. Therefore it can be said that the slot coordination does have an influence on the delay propagation during runway operations.

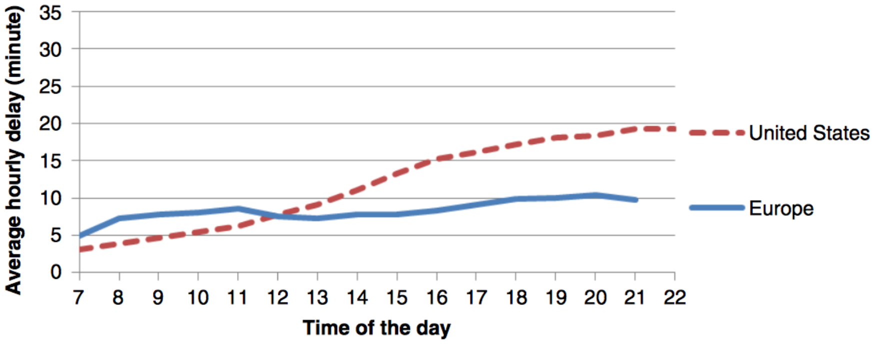


Figure 2.5: The delay propagation in the EU & US with data of the 25 largest airports in that area[37]

2.3. Demand Management Strategies

Strategies on demand management are rules and restrictions on how to operate during pressure on the capacity. The actual definition is that it is a strategic planning method used for forecast, plan and manage the demand. It can also be used for other processes but in the case of the airport operations it is about logistic strategies on demand management.

Demand at airports is increasing therefore more airports will operate at maximum capacity. This will lead to more probability of capacity problems due to issues as changing weather conditions resulting in stricter regulations on separation. Demand management strategies for the airport are designed to give support in the decision making during operation on these capacity limits. Below two examples on demand management strategies can be found:

- The amount of arrivals is to high compared to the capacity therefore queues develop in front of the runway, waiting for permission to land. A strategy would be that when an aircraft in the queue has an individual delay higher than a certain threshold the flight should be cancelled or rerouted towards a different airport. The leading factor in the strategy is the individual delay of the arrival.
- Also for the second example the queues are forming because of the capacity issues. At a certain moment when the capacity issues continue, the queue sizes are increasing. A demand management strategy could be to cancel or reroute an aircraft when it is for example fifth in the queue.

The importance of demand management strategies is to support during capacity issues with the goal to operate the runway as efficient as possible given that the capacity is under pressure. Most of current existing demand management strategies are mainly focused on the preliminary planning instead of real time changing and short term forecasts.

2.4. Conclusion

The previous sections show that common demand management strategies are mainly focused on long term effects. Section 2.1 gives the different approaches of demand management; administrative, economic and hybrid demand management are all based on prevention of capacity issues on day of operation. Most of these strategies obtain an evenly distributed usage of the capacity, by using schedule coordination, congestion pricing or slot auction.

Also regulations, mainly in Europe, the operations are planned such that the capacity is slightly lower than the capacity limits such that airports have the ability to cope with small issues. While all these strategies on demand management and planning are operational at this moment, there are still lots of moments that airports cope with capacity problems due to short term changes. So this means that still short term solution are required.

This research is focused on short term demand management strategies by forecasting the operations and advise on combinations between cancellations and delays.

3

Methodology

This chapter is about the structure and calculations used for the research on demand management strategies. To explain every part of the model in a clear and concise way this chapter is divided in several sections. Starting with listing the model assumptions in Section 3.1 to translate the research scope to boundaries for the model. The overall model structure in Section 3.2 followed by an explanation on the manual input of the model in Section 3.3. From then the structure and method of every separate part will be treated, first development of the arrival schedule will be explained in Section 3.4 followed by the arrival time and service time in Sections 3.5 and 3.6 respectively. The part on DES model is shown in Section 3.7 followed by the calculations of the delay in Section 3.8. The strategy tool is explained in Section 3.9 and the cancellation loop is given in Section 3.10. The last part shows the Monte Carlo simulation in Section 3.11.

3.1. Model Assumptions

The goal in the structure en methodology is to create a realistic simulation of the arrival operations but to stay within the scope of the research it is inevitable to make assumptions. Following assumptions have an influence on limitations of the model, which makes it possible to focus on specific parts of airport operations.

- Focus is on the arrival operation therefore it is chosen to model only an arrival schedule without including any departures. With that runways used for arrivals are not used for departures, so separate runways for departures and arrivals. At most larger airports these are also separate runways operations.
- It is assumed that the Schiphol schedule presented in Appendix B is leading in the travel distance and weight class probability distributions required for generating the arrival schedule.
- Simulation for different weather conditions, VMC and IMC inputs based on Table 2.1. The uniform probability distribution inputs for the arrival rate are also based on these values.
- Number of runways in the model is assumed to be one, operational for arrivals.
- It is assumed to model stochastic behaviour by using normal probability distribution for arrival and service time. This would not result in extreme delays but gives a realistic view of possible smaller delays in operation.

3.2. Model Structure

In this section an explanation will be given of the steps in the simulation model. In order to give a structured and clear overview of the sequence of the models steps, a master flow diagram is used for the explanation. Figure 3.1 shows the master flow diagram of the simulation model, in the following paragraphs every step will be shortly treated. In further sections a more detailed reasoning will be given on the different steps in the model.

In this simulation model, the manual inputs are all indicated with a manual input block. After the manual inputs are given, the simulation model is started and step 1 generates an arrival schedule including the amount of arrivals per hour randomly generated between the boundaries given by the boundaries for number of flights per hour and a total schedule of a length depending on the input for amount of hours. The arrival schedule consist of the total amount of aircraft within the simulation length and the properties per flight such as weight class of arriving aircraft, distance flown and travel time.

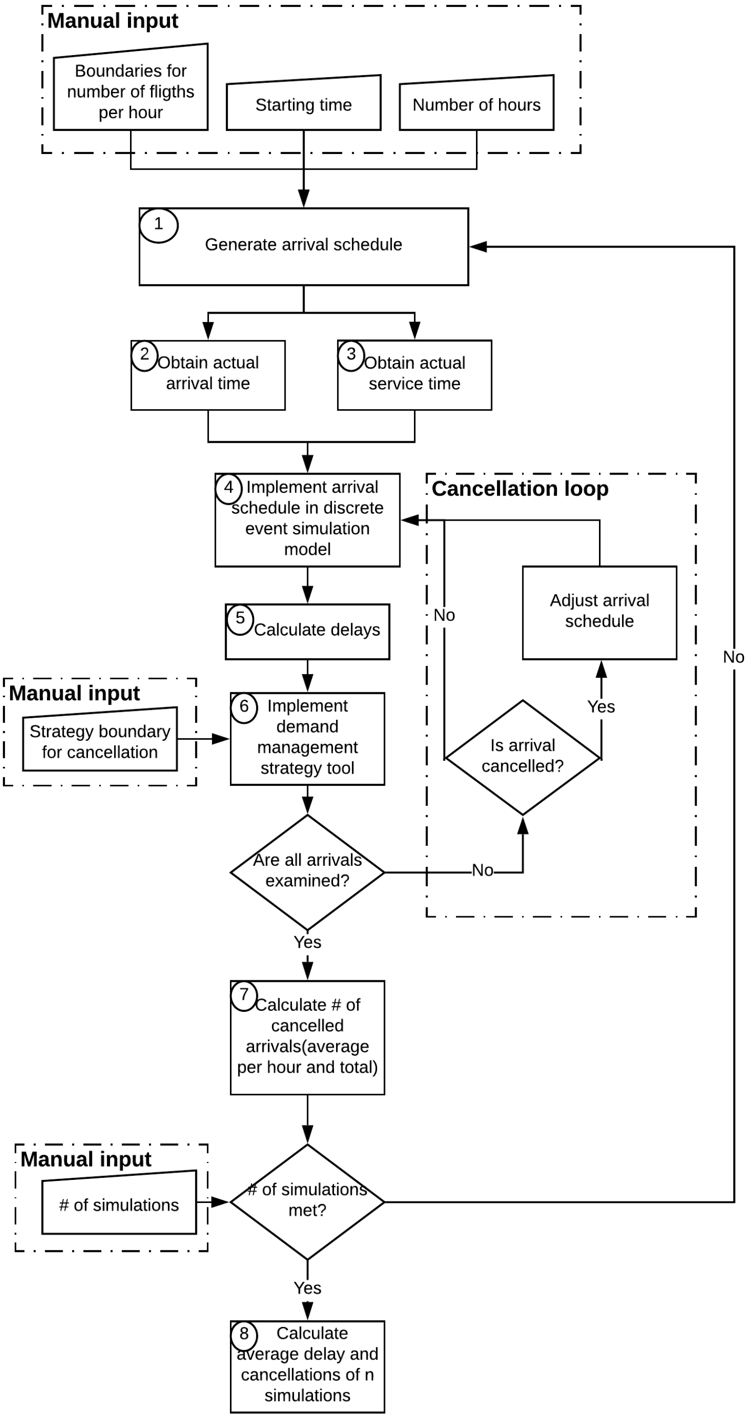


Figure 3.1: Master flow-diagram of the simulation model for testing the effectiveness of demand management strategies

With the arrival schedule and properties of every flight, as an input actual arrival time and service time are generated separately, indicated with step 2 and 3 respectively. In the arrival schedule a planned time is already obtained, but to include a stochastic behaviour of arrivals and therefore uncertainty of operation, every arrival is subjected to a probability distribution separately, leading to an individual arrival time. The actual service time, the time it takes to land an aircraft and leave the runway, is obtained. The weight classes in the arrival schedule and regulations on wake vortex separation are used to obtain the service time. A normal probability distribution is used to incorporate the stochastic behaviour of the arrival operations into the actual service time.

The actual arrival time and service time are inputs for the discrete event simulation model, indicated with step 4. From this simulation a waiting time for every individual arrival is obtained, followed by the calculations on individual delay in step 5. In part 6, the demand management strategy tool is implemented which indicates the boundary of a delay. Combining information of the delay of every individual arrival and boundary of the strategy it can be determined if an arrival should be cancelled.

For every arrival in the arrival schedule several steps will be executed, resulting in an extra loop, the cancellation loop, in the master flow diagram. A decision block is incorporated which checks whether all arrivals are analysed separately. If not, the model controls if the particular arrival should be cancelled; if the arrival should be cancelled the model erases this arrival from the arrival schedule and redetermines an arrival schedule. If the arrival is not cancelled the model continues with the same arrival schedule. It repeats these steps in the loop until every arrival in the arrival schedule is controlled by the model. From this loop the information about the number of cancellations is obtained, leading to the final result of one simulation. Step 7, the calculations of the number of cancelled flights and the average delays in this simulation are executed.

One of the final steps in the model as shown in the master flow diagram is the decision block containing the number of simulation runs. If the number of simulations completed in the model does not meet the input as indicated at the start of a run, the model starts over, generating a new arrival schedule and repeats every step as explained in the previous paragraphs. If the model reaches the set number of simulations, it determines the average delays and cancellations of all the simulation runs combined as indicated in step 8 of the flow diagram. Reason for multiple simulation runs is because of the probability of outliers and the use of a distribution for the random data generator which gives a variation around the mean. The final result of the model consists of information about the amount of delays and cancellations for different strategies, manual inputs of demand strategy tool.

3.3. Manual Input

In this section, the manual inputs of the model are explained briefly. Manual inputs are the values decided as input prior of running the model. Reasoning for these variables to be manual inputs is that these need to vary according to certain preferences of the simulation. The preferences of these inputs can differ because it could concern a different airport. A different airport has most likely a different arrival pattern and could operate during other hours on the day. The manual input for the strategies is a manual input to have the opportunity to obtain results of different strategies.

The manual inputs will be introduced below which are used in further calculations in the model. Each manual input creates limit or clarifies the result. Starting time, t, indicates the time the model starts and is used to define the time of arrival for the flights to create a realistic result. Amount of hours, h, limits the model to the amount of hours it is needed to run information about operation. Boundaries for the number of flights per hour, $[\lambda_{lower}, \lambda_{upper}]$, also called the arrival rate per hour is to select an amount of arrivals per hour for the arrival schedule. Amount of simulations is also a manual input because random generators are used for the arrival schedule and a minimum number of simulations is used to filter outliers from the random data generators. Input for the chosen strategy, is to limit the delay by a boundary as input that if arrivals delay exceeds the boundary the arrival is cancelled from the arrival schedule. Below the manual inputs are listed to give a small overview of five important manual inputs.

1. Starting time, t.
2. Number of hours per simulation, h.
3. Boundaries for the number of flights per hour, $[\lambda_{lower}, \lambda_{upper}]$.
4. Number of simulations, n.
5. Input for the chosen strategy, $d_{c_{max}}$ or $d_{t_{max}}$.

3.4. Structure and Method of Arrival Schedule

In this section the structure and the method on the arrival schedule is explained. Here, the arrival schedule generating flow diagram is used to explain the individual steps and the corresponding method. Figure 3.2 shows the sub-flow diagram of generating the arrival schedule, which is the first step in the model. As presented in the figure there are three important aspects in generating the arrival schedule; generate arrival rate, assign distance and weight class to each arrival in the arrival schedule.

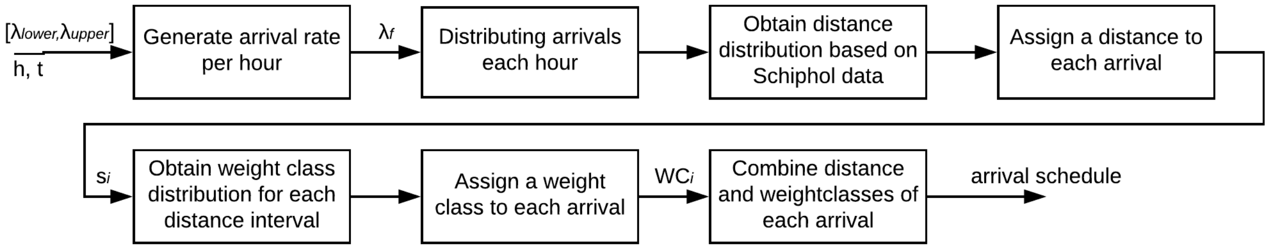


Figure 3.2: Sub flow diagram of generating the arrival schedule

The inputs which are used to generate the arrival schedule are the boundaries; $[\lambda_{lower}, \lambda_{upper}]$, the amount of hours and the starting time. These are used in the first step for generating the arrival schedule. Equation 3.1 shows that each arrival rate is generated by the use of a uniform probability distribution framed by the lower and upper boundary for the arrival rate. Boundaries for each arrival rate are based on the Schiphol schedule, shown in Appendix B, and information on other reference airports given in Section 2.1.2. Equation 3.1 generates an arrival rate for every hour, depending on the amount of hours h it gives the length of the matrix from this equation the length of $(t+(h-1)$ as also indicated in the last value of the matrix given in Equation 3.1. Figure 3.3 shows how the arrival rates are given in time until $(t+h)$, the model starts at t and as given finishes at $t=(t+h)$, therefore the last arrival rate is at $t=(t+(h-1))$.

$$\lambda_f = \mathcal{U}(\lambda_{lower}, \lambda_{upper}) = [\lambda(t), \lambda(t+1), \ldots, \lambda(t+(h-1))] \tag{3.1}$$

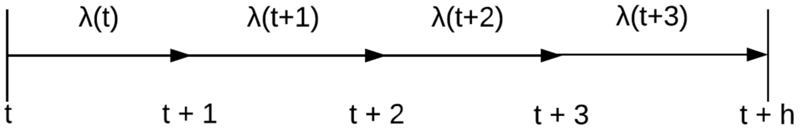


Figure 3.3: Time line of the selection of the arrival rate

At this point in the model, an arrival rate is shown for each hour. The next step is to distribute each of the arrivals over the simulated hours as Figure 3.4 illustrates. This is an example of the method on distributing the arrivals over the hours. It shows that T_{slot} is used to indicate the time between every arrival, which is the same between every arrival within one hour. In Equation 3.2 the calculation shows how to obtain T_{slot} for every hour, by dividing the amount of seconds of a particular hour by the corresponding arrival rate, $\lambda(t)$. This results in an arrival schedule with all arrivals planned at a fixed time as determined in Equation 3.3 for every hour. Here $t_{arr_{slot_j}}(t)$, is the arrival time for j^{th} aircraft determined for every hour separately. Eventually all hours are combined to obtain an arrival schedule containing the planned arrivals in specific slots per hour for the complete amount of hours of the simulation.

$$T_{f_{slot}} = \begin{bmatrix} \frac{3600}{\lambda(t)} \\ \frac{3600}{\lambda(t+1)} \\ \vdots \\ \frac{3600}{\lambda(t+(h-1))} \end{bmatrix} = \begin{bmatrix} T_{slot}(t) \\ T_{slot}(t+1) \\ \vdots \\ T_{slot}(t+(h-1) \end{bmatrix} \tag{3.2}$$

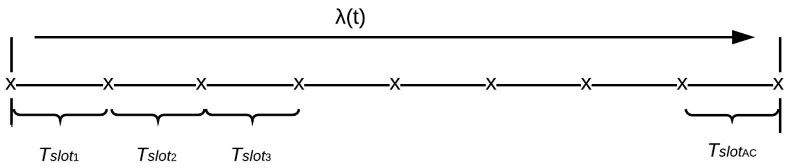


Figure 3.4: Time line example of the fixed slot allocation schedule

$$t_{arr_{slot_j}}(t) = t + T_{slot}(t) \cdot j \qquad for \quad j \in \{1, \cdots, \lambda(t)\} \tag{3.3}$$

To complete the arrival schedule, the properties distance from origin to destination and the weight class of each arrival are obtained. Both properties are based on the Schiphol schedule shown in Appendix B. As Figure 3.2 indicates, first the probability distribution of the distance is determined. From the Schiphol schedule, the origins are known but the exact distance is not. In order to calculate the distance from an origin to Schiphol the latitude and longitude are used as input to the great circle distance, as shown in Appendix C[21]. After these distances are calculated, the flights are summed over intervals of 500km. Figure 3.5 shows that, the distribution of the distance is the sum of the medium and heavy weight class flights, most arrivals are between the $500km$ and $1000km$. This distance distribution is used to assign a distance to every arrival. As shown the probability of an arrival from a distance less than $1500km$ is greater than the probability of assigning a distance of above the $1500km$. So for every arrival, a distance is added; $s_i \quad for \quad i \in \{1, \cdots, AC\}$ where s_i is the distance for i^{th} aircraft.

Assigning a weight class to every arrival is the last step in completing the arrival schedule. This is based on a weight class probability distribution obtained by the use of the Schiphol schedule, in this schedule the aircraft type is included in the schedule and can be transformed from aircraft type to a weight class, based on Table 3.1, resulting in only medium and heavy weight classes. Figure 3.5 shows for every distance interval of $500km$ a weight class probability distribution between the medium and heavy weight class. Based on these weight class probability distributions a weight class is assigned to every arrival separately. So for every arrival a weight class is assigned; $WC_i \quad for \quad i \in \{1, \cdots, AC\}$ where WC_i is the weight class for i^{th} aircraft.

Table 3.1: The ICAO Weight classes given in MTOW from the arrivals in Schiphol schedule in Appendix B [20]

Weight class	Maximum Take-off Weight (MTOW)	Aircraft types
Light	$MTOW < 7000kg$	—
Medium	$7000kg < MTOW < 136000kg$	B733, B734, B735, B738, B752, A319 A320, A321, E190, AT43, AT72, DH8D
Heavy	$136000kg < MTOW$	B744, B763, A332
Super Heavy	Airbus A380, $MTOW \approx 56000kg$	—

The output of this step in the model, described in this section, is an arrival schedule consisting of the arrival time, the distance travelled from origin to destination and weight class of the arrival. This arrival schedule is this the input for further calculations in the model.

3.5. Structure and Method of Arrival Time

The arrival time is the time on the day that the aircraft is expected to arrive. In the following paragraphs the structure and the method of the calculations of the arrival time for every arrival in the arrival schedule. The input for this part of the model is arrival time of every flight in the arrival schedule, $t_{arr_{slot_j}}$. Figure 3.6 presents the three steps for calculating the actual arrival time in a small flow diagram to clarify the order of these steps.

The first step is to determine the inter-arrival time between the aircraft in the slot allocated schedule, as Section 3.4. It is the time between every arrival as described in the arrival schedule. Calculating these inter-

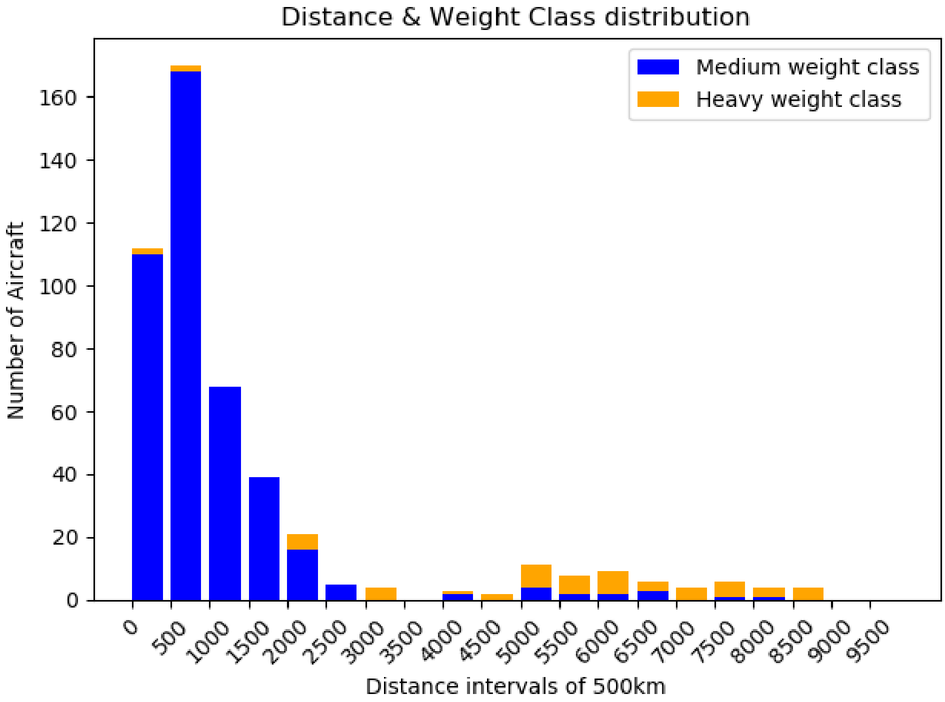


Figure 3.5: Distance and Weight class distribution based on Schiphol schedule

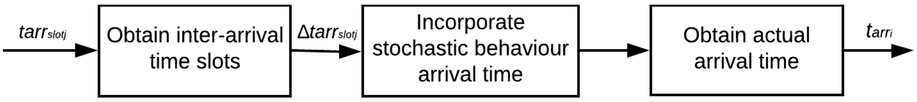


Figure 3.6: The flow diagram for obtaining the actual arrival time of each aircraft

arrival times is given in Equation 3.4 where the difference of the arrival time of the planned slots is the arrival time of the i^{th} aircraft minus the arrival prior to the i^{th} aircraft, which is the $(i-1)$ aircraft.

$$\Delta t_{arr_{slot_i}} = t_{arr_{slot_i}} - t_{arr_{slot_{(i-1)}}} \qquad for \quad i \in \{1,\cdots,AC\} \tag{3.4}$$

The second step is focusing on incorporating the stochastic behaviour of the arrival of aircraft. In the current arrival schedule the arrivals within one hour are accompanied by the exact same inter-arrival time in that hour. This will not represent a realistic arrival schedule therefore the stochastic behaviour of arrivals is included. To accomplish this, a normal probability distribution is introduced for every individual arrival with a mean equal to its current arrival time and the standard deviation is equal to the inter-arrival time obtained in Equation 3.4. In Equation 3.5, the calculation is shown of the actual arrival time by including the normal probability distribution for every arrival separately. Here t_{arr_i} is the actual arrival time with a mean $t_{arr_{slot_i}}$, which is the arrival time of the exact slot schedule, and a standard deviation $\Delta t_{arr_{slot_i}}$, which is the inter-arrival time between the arrival time of the exact slot schedule.

$$t_{arr_i} = \mathcal{N}(\mu_{arr_i}, \sigma^2_{arr_i}) = \mathcal{N}(t_{arr_{slot_i}}, \Delta t_{arr_{slot_i}}) \qquad for \quad i \in \{1,\cdots,AC\} \tag{3.5}$$

To conclude this step, obtain the actual arrival time of every individual arrival, the calculated values for the arrival time in Equation 3.5 will be added to the arrival schedule as t_{arr}. So at this point the arrival schedule consists of the actual arrival time, slot arrival time, travel distance and weight class of every arrival.

3.6. Structure and Method of Service Time

The service time of an arrival can be described as the minimum time for arriving aircraft to land and clear the runway. In order to determine this service times, the wake turbulence separation guidelines are used, where the separation intervals are defined for different weight class combinations. In these guidelines, the different weight classes are used to define the separation interval between the landing aircraft. Table shows 3.2 the minimum separation for four different aircraft types, however, as only medium and heavy weight classes are used in the schedule only the following four combinations are applicable:

- Medium weight class aircraft followed by a Medium weight class aircraft
- Medium weight class aircraft followed by a Large weight class aircraft
- Large weight class aircraft followed by a Medium weight class aircraft
- Large weight class aircraft followed by a Large weight class aircraft

Figure 3.7 presents the structure of obtaining the service time for every arrival separately.

Table 3.2: The ICAO wake turbulence separation between two consecutive aircraft in nautical miles, it is the minimum amount of separation between two consecutive arrivals for different following weight classes [20]

		Leading Aircraft			
		Light	Medium	Heavy	Super
Following Aircraft	Light	3	5	6	8
	Medium	3	3	5	7
	Heavy	3	3	4	6
	Super	3	3	3	3

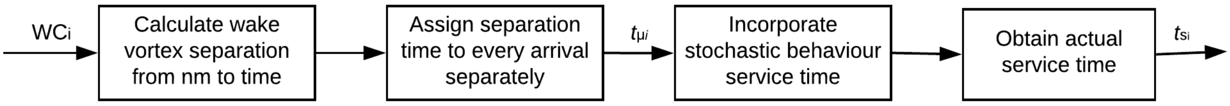


Figure 3.7: The flow diagram of obtaining the minimum separation time of the arrivals

As Figure 3.7 indicates, the wake vortex separation guidelines define the separation in nautical miles, the first step is to convert the distance into time. Equation 3.6 shows the calculation to minimum time separation, where the separation distance, x_{sep}, is divided by the approach velocity, V_{app}, to obtain the separation time t_{sep}. For the approach velocity, reference aircraft are used[2, 49]. Table 3.3 shows that, separation times differ between medium and heavy weight class aircraft, due to the combination of heavy aircraft displacing more air and medium aircraft being more heavily affected[20, 29].

$$t_{sep} = \frac{x_{sep}}{V_{app}} \tag{3.6}$$

Table 3.3: The ICAO wake turbulence separation transformed from distance to time separation, in seconds [20]

		Leading Aircraft	
		Medium	Heavy
Following Aircraft	Medium	79.7	126.1
	Heavy	78.7	101.7

In Equation 3.7, the results from Table 3.3 are assigned to the different combination of weight classes in the model. The separation time is indicated with t_{μ_i} and the weight classes are indicated with WC_i, M is medium and H is heavy weight class, for every i^{th} arrival. Here WC_i is the following aircraft and WC_{i-1} is the leading aircraft.

$$t_{\mu_i} = \begin{cases} 79.7s & \text{if} \quad WC_i = M \quad and \quad WC_{i-1} = M \\ 126.1s & \text{if} \quad WC_i = M \quad and \quad WC_{i-1} = H \\ 78.7s & \text{if} \quad WC_i = H \quad and \quad WC_{i-1} = M \\ 101.7s & \text{if} \quad WC_i = H \quad and \quad WC_{i-1} = H \end{cases} \qquad for \quad i \in \{1, \cdots, AC\} \tag{3.7}$$

Similar to the arrival time calculations, the service time needs to incorporate the stochastic behaviour of an arrival process. Therefore, step three in determining the minimum separation method is to use the normal probability distribution in Equation 3.8 to incorporate the stochastic behaviour. For the distribution a mean equal to the minimum separation time t_{μ_i} and a standard deviation for the service time of $\sigma_{ser} = 5$ sec is used to determine, t_{s_i}, the service time for the i^{th} aircraft.

$$t_{s_i} = \mathcal{N}(\mu_{ser}, \sigma_{ser}^2) = \mathcal{N}(t_{\mu_i}, 5) \qquad for \quad i \in \{1, \cdots, AC\} \tag{3.8}$$

To conclude the section on the structure and method of the service time, eventually the service time is determined by the use of the weight classes of the arrivals and the wake turbulence regulations. This results in the service time for every arrival separately and is also included in the arrival schedule. While the calculations of the arrival time and the service time still both are added to the arrival schedule and used as input for the discrete event simulation model.

3.7. Structure and Method of Discrete-Event Simulation Model

In the following paragraphs, the discrete-event simulation model will be explained. A further explanation on the basic principles of DES can be found in Appendix D.

A DES model is based on the time of certain events and with knowledge of the duration of every event it simulates the operation. In this case there are two types of events, where the number of events per type depends on the number of arriving aircraft simulated. Two types of events are the arrival and the service and both have the same amount of arrivals therefore same amount of events. As a DES model simulates the behaviour of the times of the events it also simulates the queue forming of the arrivals in front of the runway. Figure 3.8 shows the structure of the DES model as it applies to demand management strategies.

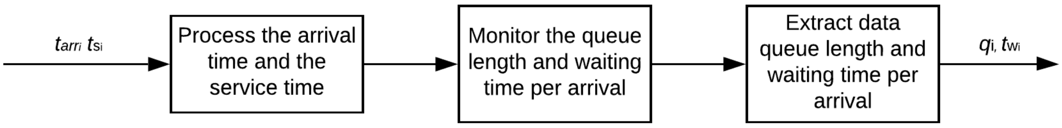


Figure 3.8: The flow diagram of the discrete event simulation model

The first step of the DES model is processing the data of the arrival time and service time. As can be seen from the flow diagram in Figure 3.8 the inputs are the arrival time, t_{arr}, and service time, t_s. By processing this data in the DES model, knowledge on the propagation of the queue and the waiting time can be monitored during the simulation. In the second part of the flow diagram it is stated that it does monitor these two variables but without the help of a simple calculation it is not possible to extract the waiting time in the end. Equation 3.9 shows the simple calculation of the waiting time of every arrival. In this calculation it shows that the waiting time depends on the service time, the inter-arrival time and the waiting time of the previous arrived aircraft. By including the previous arrived aircraft and the waiting time of this previous aircraft the build-up waiting time is included in the model. The waiting time of the current arrival is indicated with t_{w_i} and the waiting time of the current aircraft is indicated by $t_{w_{i-1}}$. Also the service time of the previous arrival is included and indicated by, $t_{s_{i-1}}$, and for both the previous and current arrival the arrival time is indicated with, t_{arr_i} and $t_{arr_{i-1}}$ respectively. By subtracting the previous arrival time and the current arrival time it actually uses the inter-arrival time for the calculations of the waiting time. The function $max()$ in Equation 3.9 max, indicates that it determines if this function is positive and if not then the value for the waiting time is zero. In some cases the value of the inter-arrival time is larger than the previous waiting time and service time together resulting in no queue and sufficient time to land.

$$t_{w_i} = max(t_{w_{i-1}} + t_{s_{i-1}} - (t_{arr_i} - t_{arr_{i-1}}), 0) \qquad for \quad i \in \{1, \cdots, AC\} \tag{3.9}$$

In Equation 3.10 the calculation of the queue length is given, a max function is used because a queue size can never be below zero, therefore if the calculation shows a negative number the max function gives a zero for the queue length. It shows that the queue length at a current arrival, q_i, is the queue length at the previous arrival, q_{i-1}, subtract by the amount of serviced aircraft which is determined by the inter-arrival time divided by the service time.

$$q_i = max(q_{i-1} - \frac{t_{arr_i} - t_{arr_{i-1}}}{t_{s_{i-1}}}, 0) \qquad for \quad i \in \{1, \cdots, AC\} \tag{3.10}$$

In this section the DES model to simulate the arrival process at an airport was shown which resulted in an output of the waiting time per individual arrival and the corresponding queue length. Both will be used in further calculations.

3.8. Structure and Method of Delay Calculations

In the following paragraphs the delay calculations will be explained by using the structure and the corresponding method for each step in this part of the model. Figure 3.9 gives the steps for the delay calculations. As can be seen the input for calculating the delay is the waiting time, t_{w_i}, and the service time, t_{s_i}, of the arrivals.

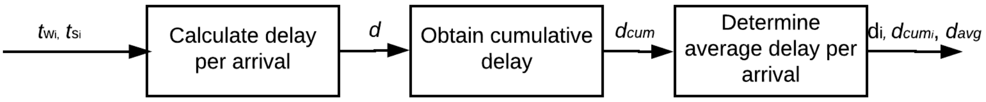


Figure 3.9: The sub-flow diagram of the delay calculations

In the first part, the delay per individual arrival is determined. In Section 3.7 the calculation is given of the waiting time shows the basis for the delay per arrival. Equation 3.11 shows the calculations of the delay, d_i for i^{th} aircraft, by subtracting the service time, t_{s_i}, from the waiting time, t_{w_i}.

$$d_i = t_{w_i} - t_{s_i} \qquad for \quad i \in \{1, \cdots, AC\} \tag{3.11}$$

The reason that the delay is calculated in the first step is because it is required for obtaining the cumulative and average delay. Cumulative delay is determined for every arrival by adding its delay to the previous delay, it is a continuous calculation. Equation 3.12 shows the calculation of the cumulative delay, d_{cum_i}.

$$d_{cum_i} = \sum_{k=1}^{i} d_{cum_k} \qquad for \quad i \in \{1, \cdots, AC\} \tag{3.12}$$

As final step, the average delay per hour is determined. Average delay per hour is obtained by adding the delay of every arrival within one hour and then divide it by the corresponding arrival rate. Equation 3.13 shows this calculation.

$$d_{avg}(t) = \frac{\sum_{k=\lambda(t-1)}^{\lambda(t)} d_k}{\lambda(t)} \tag{3.13}$$

The output of the delay calculations part are the following output values; delay per individual arrival, the cumulative delay and the average delay per hour, will be used in the further part of the model.

3.9. Structure and Method of Strategy Tool

The strategy tool is the part on the simulation model where a chosen strategy can be implemented as a constraint for the delays. In the following paragraphs the structure of the strategy tool will be explained accompanied by the method of each separate step as the flow diagram in Figure 3.10 shows.

There are two inputs for the strategy tool; calculated individual delay of an arrival and a manual input for the strategy boundary for cancellation. In the first step of the calculation of this part of the simulation model it is determined whether an arrival should be cancelled i.e. if it exceeds the boundary given as manual input. As indicated the method for both strategies is different so these will also be explained separately below. First

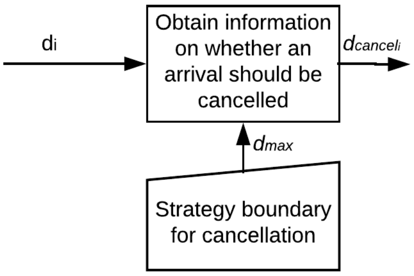


Figure 3.10: Flow diagram of the strategy tool

the time-based delay strategy will be treated followed by the consecutive delay strategy.

Time-based delay strategy

In the time-based delay strategy arrivals will be cancelled if an arrival exceeds the time boundary, in number of seconds, as indicated by the strategy boundary for this strategy. As given in the first step of strategy tool it is focused on obtaining information on whether the arrival should be cancelled. Equation 3.14 shows that if an arrival exceeds the time delay boundary, $d_{t_{max}}$, it should be cancelled and is given a one to indicate a cancellation, if not the model assigns a zero. So the cancellation information for i^{th} aircraft, d_{cancel_i}, consists of zeros and ones.

$$d_{cancel_i} = \begin{cases} 1 & \text{if } d > d_{t_{max}} \\ 0 & \text{if } d \leq d_{t_{max}} \end{cases} \qquad for \quad i \in \{1, \cdots, AC\} \tag{3.14}$$

Consecutive delay strategy

Consecutive delay strategy is based on the absolute number of delays, so if the number of consecutive delays exceeds the boundary the next arrival will be cancelled. The step in the strategy tool on obtaining information about cancellation of an arrival is similar to the time-based strategy only the calculation method is slightly different. The consecutive delay strategy requires an extra step on calculating the cumulative sum of consecutive delays. Equation 3.15 shows that first, information about the delay of an arrival is required, indicated with a one or zero respectively,d_{p_i} for i^{th} aircraft. Equation 3.16 follows in obtaining the number of consecutive delays at every arrival indicated with d_{cons_i} for i^{th} aircraft. Using this knowledge, the cancellation information can be obtained, Equation 3.17 shows the calculations. d_{cancel_i} for i^{th} aircraft contains the similar information as given in time-based strategy, the information on whether an arrival should be cancelled or not, indicated with a one or zero respectively.

$$d_{p_i} = \begin{cases} 1 & \text{if } d_i > 0 \\ 0 & \text{if } d_i = 0 \end{cases} \qquad for \quad i \in \{1, \cdots, AC\} \tag{3.15}$$

$$d_{cons_i} = \begin{cases} \sum d_{p_i} & \text{if } d_i > 0 \\ \sum d_{p_i} = 0 & \text{if } d_i = 0 \end{cases} \qquad for \quad i \in \{1, \cdots, AC\} \tag{3.16}$$

$$d_{cancel_i} = \begin{cases} 1 & \text{if } d_{cons_i} > d_{c_{max}} \\ 0 & \text{if } d_{cons_i} \leq d_{c_{max}} \end{cases} \qquad for \quad i \in \{1, \cdots, AC\} \tag{3.17}$$

The output of the strategy tool is the information of which arrivals exceed the boundary given by the strategy boundary. It is indicated by d_{cancel_i} for i^{th} and will be used for further calculations.

3.10. Structure and Method of Cancellation Loop

In this section the cancellation loop will be explained. The cancellation loop checks if all arrival in the arrival schedule are controlled. If the the arrival should be cancelled the decisions block in the cancellation loop conforms and executes a cancellation followed by adjustments on the arrival schedule. Figure 3.11 zooms in on the cancellation loop. The loop itself is to repeat the parts on implementing the DES model, delay calculation and strategy tool explained in Sections 3.7, 3.8 and 3.9 respectively. After the strategy tool the

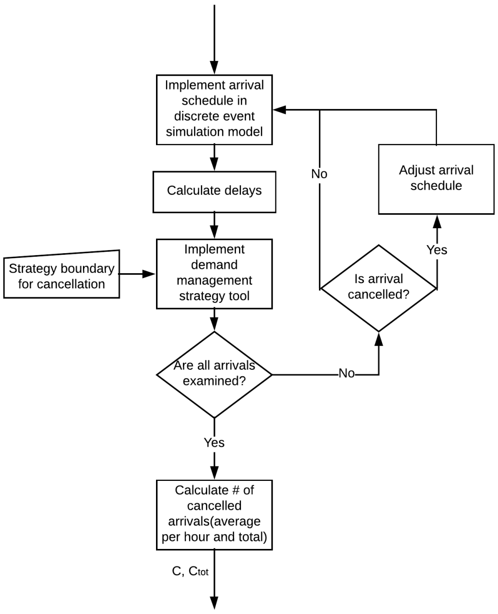


Figure 3.11: Flow diagram of cancellation loop

decision is made whether all arrivals in the arrival schedule are examined. If the process is not completed the cancellation loop shows a new decision based on the information of cancellation of an arrival. In case of the arrival is not cancelled then the same arrival schedule as previous loop is used for the next arrival. If the arrival should be cancelled the arrival schedule is adjusted as indicated in the flow diagram. The cancelled arrival is erased from the arrival schedule and this arrival schedule is then used for a recalculation in the DES model. A repetition of the calculation is required to control whether the adjusted arrival schedule including the new cancellation determines different waiting times, therefore different delays which leads to different cancellation information.

In the last part of the given flow diagram the total cancellations per run, average cancellations per hour and the cancellations per hour are determined. This can only be performed after all arrivals are examined. The input for calculating the total number of cancellations is the information of all arrivals on, if arrival is cancelled or not, d_{cancel}. Equation 3.18 shows the sum of all cancellations in d_{cancel}, resulting in the total number of cancellations, C_{tot}. Equation 3.19 determines the number of cancellations per hour, $C(t)$. It shows that the sum of the cancellations calculated for the arrivals between that particular hour is taken into account. Using the information of the total number of cancellations and total number of modelled hours it is possible to determine the average number of cancellations per hour,C. Equation 3.20 shows the calculation of the average number of cancellations per hour. The cancellations per hour and the average number of cancellations per hour will be used in further calculations.

$$C_{tot} = \sum_{k=1}^{AC} d_{cancel_k} \tag{3.18}$$

$$C(t) = \begin{cases} \sum d_{cancel_i} & \text{if } t < t_{arr_i} < (t+1) \\ 0 & \text{if } t > t_{arr_i} \text{ or } t_{arr_i} < (t+1) \end{cases} \qquad for \quad i \in \{1, \cdots, AC\} \tag{3.19}$$

$$C = \frac{C_{tot}}{h} \tag{3.20}$$

3.11. Structure and Method of Monte Carlo Simulation

The Monte Carlo simulation part of the model is about the amount of runs the simulation needs to execute. To obtain a certain level of accuracy of the result a number of simulations are required. Calculation on the accuracy and corresponding number of runs is given in the following paragraph, next the average delay and

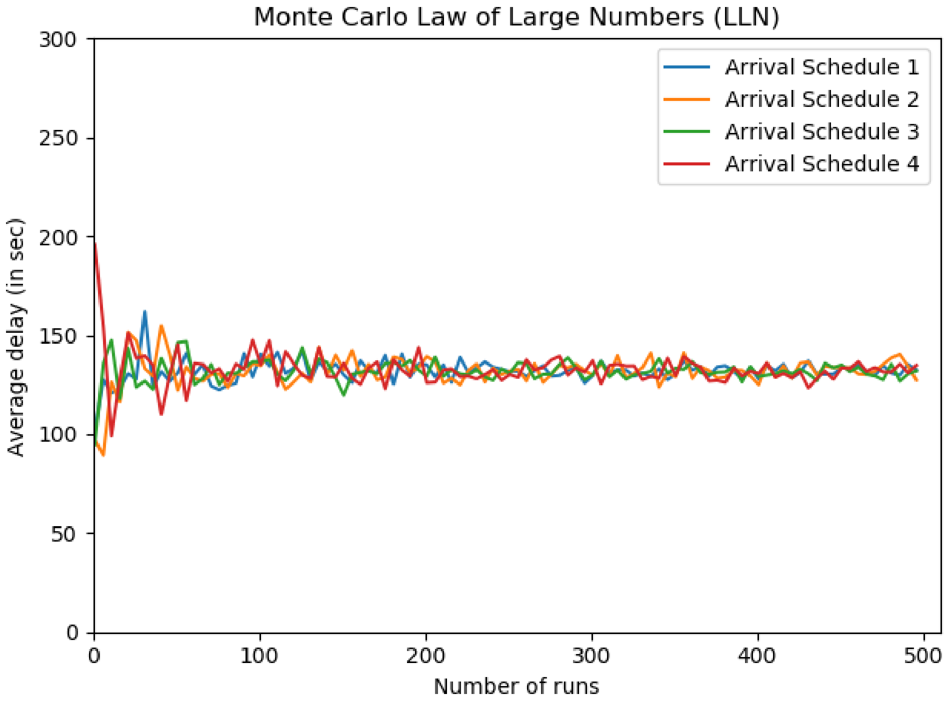


Figure 3.12: LLN test to obtain the number of runs required

cancellations of the simulations will be shown. More on the basic principle of Monte Carlo simulation in Appendix E.

Monte Carlo simulation is to cope with the probabilities of uncertainty in the model. Uncertainty of the model is mainly because of the use of random data generators and a number of probability distributions. To deal with the uncertainties a solution is to run the model for a number of times, by averaging the values from all runs together the outliers in the result are filtered. There are several techniques to obtain the minimum number of runs required for a certain accuracy. For this research the Law of Large Numbers(LLN) is used to obtain the minimum number of runs required and show the behaviour of the uncertainty. Equation 3.21 shows the basic calculation of LLN and shows what inputs are used to obtain the right number of simulations for this model. Number of simulations, n, is determined by the use of the average delay per arrival, d_{avg}, for each run and then divided by the number of runs. This is executed for every situation from $n = 1$ till $n = 500$ and then four times to assure an accuracy based on more than only one arrival schedule, this is given in Figure 3.12. Four different arrival schedules were used to obtain the amount of runs required to reach a certain accuracy. The four schedules were obtained the as described in Section 3.4. It is shown that in the beginning of the graph, at $n < 20$, the average delay per arrival varies largely but while increasing the number of runs the variation decreases. The reason for decreasing variety in average delays is because dividing by the number of runs while increasing, also shown in Equation 3.21. From Figure 3.12 it can be seen that that at $n = 200$ the accuracy is already above the 90% therefore it is chosen to use $n = 200$ for the simulation runs of the results.

$$\overline{X}_n = \frac{X_1 + \cdots + X_n}{n} = \frac{d_{avg_1} + \cdots + d_{avg_n}}{n} = \overline{d}_{avg_n} \tag{3.21}$$

With the information of 200 runs it is required to process this data to usable figures. An average delay per arrival and the average number of cancellations per hour will be obtained both will be shown below. In Equation 3.22 sum of all average delays of simulation runs divided by the number of runs. This the same calculation as did for the LLN calculations resulting in average delay over all simulation, $d_{s_{avg}}$. In Equation 3.23 average number of cancellations per hour is given divided by the number of simulations, n, resulting in the average number of cancellations over the total number simulations, $C_{s_{avg}}$.

$$d_{s_{avg}} = \frac{\sum_{k=1}^{n} d_{avg}}{n} \tag{3.22}$$

$$C_{s_{avg}} = \frac{\sum_{k=1}^{n} C}{n} \tag{3.23}$$

This finally results in an average number of cancellations, $C_{s_{avg}}$, and an average delay per arrival, $d_{s_{avg}}$, obtained from the 200 simulation runs. Obtained values for these variables will be used in the optimisation results of the different strategies.

4

Results, Verification & Validation

In this chapter the results of the model will be presented and explained. Starting with presenting the model assumptions in Section 4.1 followed by the model input in Section 4.2. Next the main result of the research will be presented in Section 4.3, the optimisation of strategies. Followed by the results on the arrival operations in Section 4.4. In the sensitivity analysis a number of important variables will be tested presented in Section 4.5. The influence of changing the forecast moment on the operational cancellations and delays is examined in Section 4.6 and is used as verification of the model. In the last section of this chapter a validation of the model is done based on the data of an actual Schiphol schedule shown in Section 4.7.

4.1. Assumptions of Model Inputs

The assumptions on model input in this chapter will focus on the distinguishing values of the manual inputs. In the model there are inputs with different purposes, most of the inputs are used to give boundaries to the model and the strategy inputs give limits to the actual delays. Below the assumptions of the input values are listed, including an explanation on the particular model input. The corresponding values of the input are presented in Section 4.2.

- Number of arrivals per hour is constant for every simulation run - To compare different strategies the generated arrival rates need to be constant. The uniform probability distribution generates an arrival rate for every hour based on a random seed, this will not change for each of the simulation runs in this research, except for the case study.
- Strategy input for both strategy approaches - The strategy inputs are selected at the start of the simulations. Starting with a strategy with no cancellations, low impact, and the last tested strategy input has low average delay and large amount of cancellations, high impact. Between low and high impact a number of strategy input is chosen to obtain the differences between the different strategies.
- Number of runways - Arrival operations are assumed to be on one runway. So the demand management strategies are only measured for the operations on one runway, solely used for arrivals.
- Standard deviation of the arrival time - To incorporate stochastic behaviour a normal probability distribution is used for the arrival time. For this normal probability distribution the mean is the generated arrival time, the standard deviation is an input. The standard deviation is determined based on the inter-arrival time as Section 3.5 explains.
- Standard deviation of the service time - To incorporate stochastic behaviour a normal probability distribution is used for the service time. For this normal distribution the mean is based on wake turbulence regulations and the standard deviation is chosen to have a fixed value.

4.2. Model Input

In this section every model input is given a value such that it meets the requirements as described in the assumptions. All seven inputs will be treated separately. Table 4.2 gives a summary of the manual input values is.

Starting time
The starting time, t, is the time the model starts. An input of 08:00 am is used, so the input is $t = 8$. It is not necessarily the most impacting input because the data generated in the model is random and therefore not fixed to a time, however, when using real data this input gives the actual time of the arrivals.

Number of hours per simulation
The number of hours per simulation, h, is leading when it comes to duration of every simulation run. The user of the model can decide whether it requires a long term or short term simulation of the expected operation. In testing the model and obtaining the results an input of $h = 10hrs$ is used.

Boundaries for the actual amount of arrivals per hour
The boundaries for the amount of arrivals, $[\lambda_{lower}, \lambda_{upper}]$, are the lower and upper boundary of the uniform probability distributed random arrival rates. It is difficult to give a certain number to the arrival rate because it varies greatly in real operation, comparing peak and low demand hours. Data of five different airports is used to obtain the boundaries for the number of arrivals per hour, see Table 2.1. This results in the following values for the arrival rate: $[\lambda_{lower}, \lambda_{upper}] = [35, 45]$. In order to be able to compare the different strategies, a constant seed is used to create identical arrivals per hour. Table 4.1 shows the constant number of arrivals per hour.

Table 4.1: Arrival rate per hour

Hour	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Number of arrivals	37	42	42	37	41	40	41	43	36	43

Number of simulations
In Section 3.11 an explanation is given on obtaining the number of simulations, which resulted in $n = 200$ securing an accuracy of above the 90%.

Strategy input
The strategy input is the limiting factor for operations in deciding whether an aircraft is cancelled or not. The inputs for both the time-based delay strategy and consecutive delay strategy are explained separately. For both the strategies it holds that between low and high impact there are also a number of inputs tested. Low impact indicates low amount of cancellations and high impact, high number of cancellations. So the values of the strategy input are focused on covering from zero cancellations till zero seconds or consecutive delays as strategy input.

- Time-based delay strategy input, $d_{t_{max}}$. The inputs given for this strategy vary from low impact, $d_{t_{max}} = 600s$, to high impact, $d_{t_{max}} = 0s$.
- Consecutive delay strategy input, $d_{c_{max}}$. The inputs given for this strategy also vary from low impact, $d_{c_{max}} = 200$, to high impact, $d_{c_{max}} = 0$.

Standard deviation of the normal probability distribution for the arrival time
To incorporate stochastic behaviour of arrivals, the values obtained for the arrival time are subjected to a normal probability distribution. The standard deviation for the arrival time, σ_{arr} is chosen to have a value which is dependent on the inter-arrival time, $\sigma_{arr} = 1 \cdot t_I$. In this case the actual input is the multiplying factor of the inter-arrival time.

Standard deviation of the normal probability distribution for the service time
Also for the service time the standard deviation is a manual input. The standard deviation for the normal probability distribution of the service time, σ_{ser}, is 5 seconds, which is based on expert opinions.

Table 4.2: Manual inputs and their values

Manual input	Value	Unit
t	$08:00$	-
h	10	hrs
$[\lambda_{lower}, \lambda_{upper}]$	$[35, 45]$	$\frac{AC}{hr}$
n	200	runs
$d_{t_{max}}$	$[0, 600]$	sec
$d_{c_{max}}$	$[0, 200]$	consecutive aircraft
σ_{arr}	$1 \cdot t_I$	sec
σ_{ser}	5	sec

4.3. Optimisation of Strategies

This section focuses on evaluation of the optimal combination of cancellations and delays. Sections 4.3.1 and 4.3.2 consist of the results and explanation of respectively the optimal ratios of the time-based delay strategy and consecutive delay strategy.

4.3.1. Time-Based Delay Strategy

In the Time-based delay strategy it is chosen to focus the strategy input on time delays. This is also the limiting factor whether an arrival is cancelled or not, the number of aircraft exceeding the limit is depending on the arrival schedule and strategy input, $d_{t_{max}}$. In Figure 4.1 the optimal Pareto front for the minimum, maximum and average delay are given based on the inputs as given in section 4.2. All different strategy inputs are indicated with a number which corresponds with the strategy in Table 4.3.

Figure 4.1 shows 11 different strategies, strategy 1 has no impact with no cancellations executed and strategy 11 has high impact corresponding with high number of cancellations. At strategy number 3, a low impact can be seen of 2.8% cancellations, due to these cancellations the maximum and average delay per flight are both decreasing. Increasing the impact of the strategy results in more cancellations and at zero seconds acceptable delay, strategy 11, the number of cancellations has increased to 31.3% of the number of arrivals. At high impact the amount of cancellations is large but the average delay per flight is therefore low.

The increase of cancellations between strategy 1 and 3 causes a decrease in average delay from 135 seconds to 65 seconds, which is 51.8% decrease in average delay per flight. For strategies 5 till 11 only the percentage of cancellations is increasing while the average delay is just slightly decreasing. The maximum delay is decreasing with an increase in strictness of the strategy limit. This shows that when comparing the cancellations with the delays, the relative effectiveness decreases with a decrease in $d_{t_{max}}$. Table 4.3 shows that at an acceptable delay of zero seconds the average delay is also zero because the simulation with this strategy input cancels every arrival with a delay.

Table 4.3: Strategies of time-based delay strategy including the results in Pareto front

Strategy #	Strategy input [s]	Cancellations [% of arrivals]	Average delay [s]
1	600	0	104
2	300	0.6	89
3	200	2.8	65
4	150	6.3	47
5	100	12.2	27
6	80	15.6	21
7	60	20.9	11
8	40	25.3	5
9	20	28.3	3
10	10	29.7	2
11	0	31.3	0

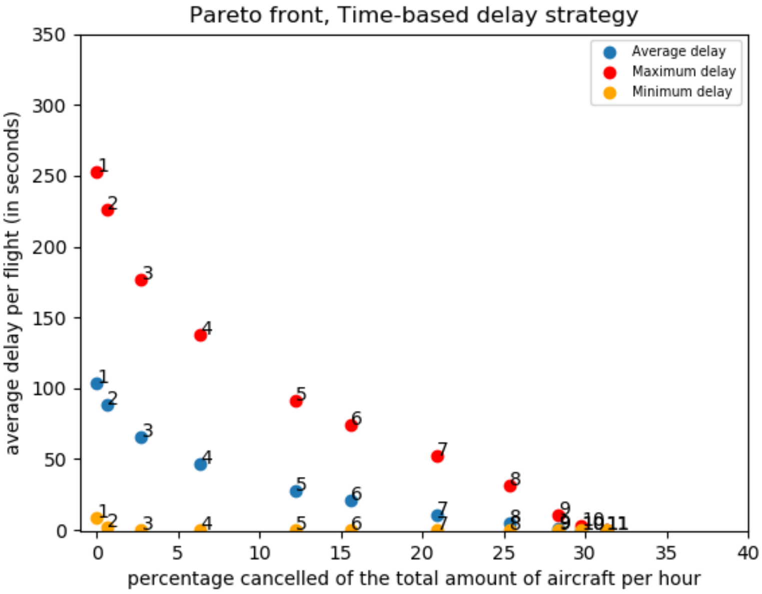


Figure 4.1: Average,minimum and maximum delay optimal Pareto front of time-based delay strategy

4.3.2. Consecutive Delay Strategy

The limit of consecutive delay strategies consist of the number of consecutive arrivals with a delay, if this sum of consecutive delays exceeds the strategy input, $d_{c_{max}}$, this arrival will be cancelled. In Section 4.2 the inputs for multiple consecutive strategies are given, which are between $d_{c_{max}} = 0$ and $d_{c_{max}} = 200$ consecutive delays, high impact and low impact respectively. In Figure 4.1 the optimal Pareto front for the minimum, maximum and the average delay is given. All different strategy inputs are indicated with a number which corresponds with the strategy in Table 4.4.

Figure 4.2 shows 12 different strategies, strategy number 1 is the strategy corresponding with zero cancellations and strategy 12 corresponds with a high impact of 28.8% of the arrivals. Strategies with strict limits have large impact on the number of cancellations and on average delay per flight, it also shows that the impact on both cancellations and average delay starts at strategy 5, $d_{c_{max}} = 60$ arrivals. Table 4.4 shows the values of the percentage of cancellations of the arrivals corresponding with the strategy number. From strategy 9 till 12 it looks as if this part has a linear behaviour for both the maximum delay as the average delay. At the most strict strategy, #12, the average delay is still 20 seconds because the consecutive delay strategy only cancels if a consecutive arrival is also delayed, therefore it is possible that an arrival has a delay while the consecutive arrival has no delay and is not cancelled.

Table 4.4: Strategies of consecutive delay strategy including the results in Pareto front

Strategy #	Strategy input [consecutive delays]	Cancellations [% of arrivals]	Average delay [s]
1	200	0	102
2	150	0	102
3	100	0.3	101
4	80	0.4	100
5	60	0.6	97
6	40	1.4	95
7	20	3.2	82
8	10	7.1	69
9	7	10.2	63
10	4	15.8	50
11	2	22.1	32
12	0	28.8	20

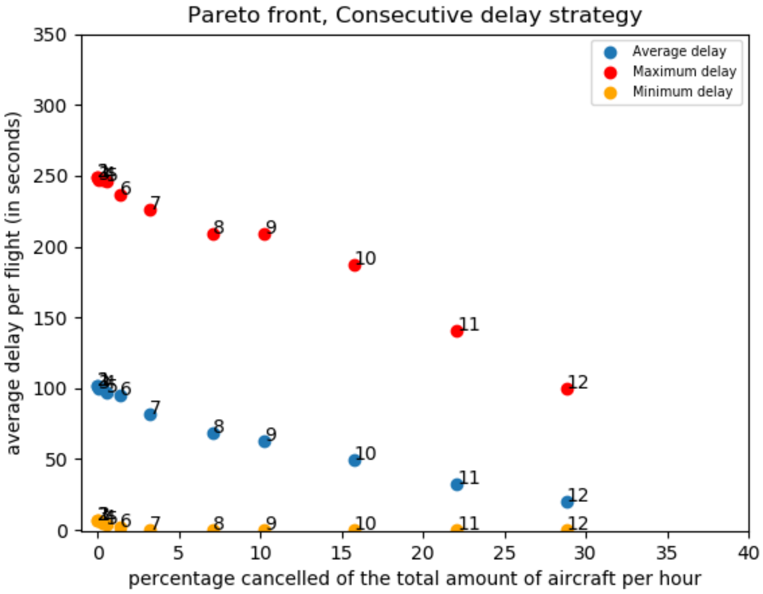


Figure 4.2: Average,minimum and maximum delay optimal Pareto front of consecutive delay strategy

4.3.3. Comparison Time-Based and Consecutive Delay Strategy on Optimisation

In comparison between the time-based delay strategy and the consecutive delay strategy both optimisation will be given in one figure. Figure 4.3 shows the comparison between the two strategic approaches, here a line is used to indicate the propagation of the strategies. The same strategy inputs, indicated in previous sections on the optimisation are used.

Both strategies start at the same average delay for zero percent of cancellations. The blue line indicates the time-based delay strategy and the red line the consecutive delay strategy. When comparing the two strategies it can be seen that the time-based delay strategy achieves a more rapid decrease in average delay with less cancellations. For all tested strategies, the time-based delay strategy performs more efficiently, the decrease in average delay per cancellation is higher. The last tested strategy indicates a zero average delay for the time-based delay strategy while for the consecutive delay strategy it shows around 20 seconds of average delay, both for around the same percentage of cancelled flights. The time-based delay strategy has a more effective manner of cancelling flights from the flight schedule compared to the consecutive delay strategy.

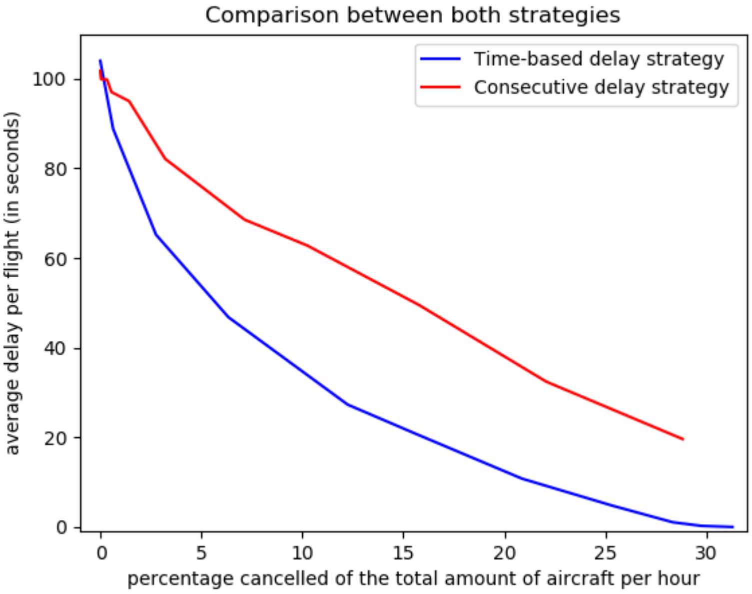


Figure 4.3: Comparison between the average delay of time-based and consecutive delay strategy

4.4. Arrival Operations for Different Strategies

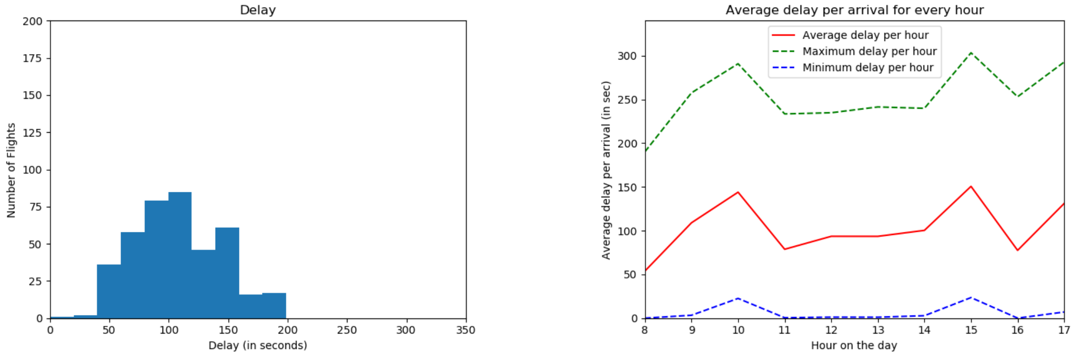
This section is about monitoring the process of aircraft arriving at an airport. So the focus of this part is on the behaviour of the arrival schedule through the DES. The arrival schedule for the results is shown in Section 4.2. The arrival schedule behaves different for every type of strategy therefore three separate sections will be given: No strategy in Section 4.4.1, time-based delay strategy in Section 4.4.2 and consecutive delay strategy in Section 4.4.3. The following results will be presented for all three sections:

- Waiting time distribution
- Average delay, average minimum delay and average maximum delay per hour through the modelled hours
- Queue propagation
- Queue propagation including maximum queue propagation

4.4.1. Operations without Strategy Input

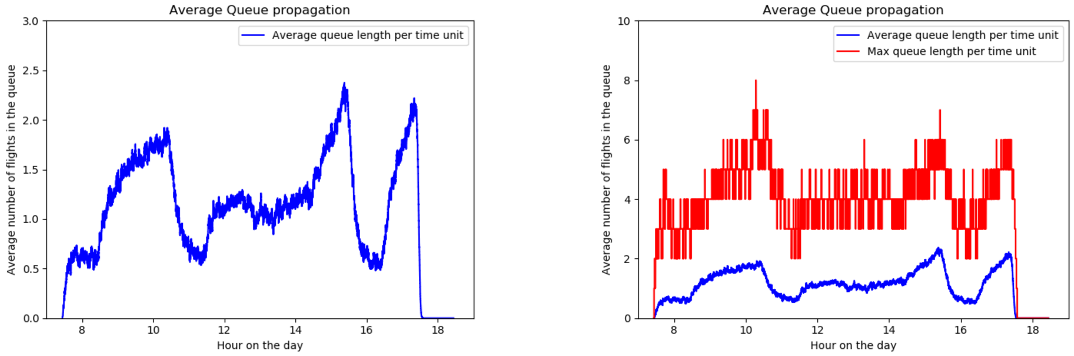
Model simulation without the use of a strategy input this means that the model will not perform any cancellations during the simulation. All arrivals will eventually land on the airport but the delays will be relatively high, resulting in large queues and large average delays. Figure 4.4 gives the results of the simulation without strategy input, based on the arrival and service data processed in the discrete event simulation model.

Figure 4.4 shows four separate figures of the simulation for the arrival schedule without strategy input. Between 09:00 - 11:00, 15:00 and 17:00 there are more arrivals compared to the other simulated hours. Given these peak hours, both the average queue propagation as the maximum queue propagation experience a large increase in queue length during these peak hours, which can be seen in Figures 4.4c and 4.4d. Also the average delay increases during these peak hours given by Figure 4.4b. The results in the figure indicate that higher arrival rates correspond with the larger queues and higher average delays i.e. peak hours. Figure 4.4a shows the average waiting times, most arrivals have delay between the 80 seconds and 150 seconds which means that almost all arrivals have a delay. This indicates that the demand is during the whole day higher than the service rate over the day, also confirmed by the average queue propagation which is never zero during operational hours.



(a) Average waiting time distribution

(b) Average delay per arrival through the operation



(c) Average queue propagation

(d) Average and maximum queue propagation

Figure 4.4: Operational monitoring results of simulation without strategy input, no cancellations

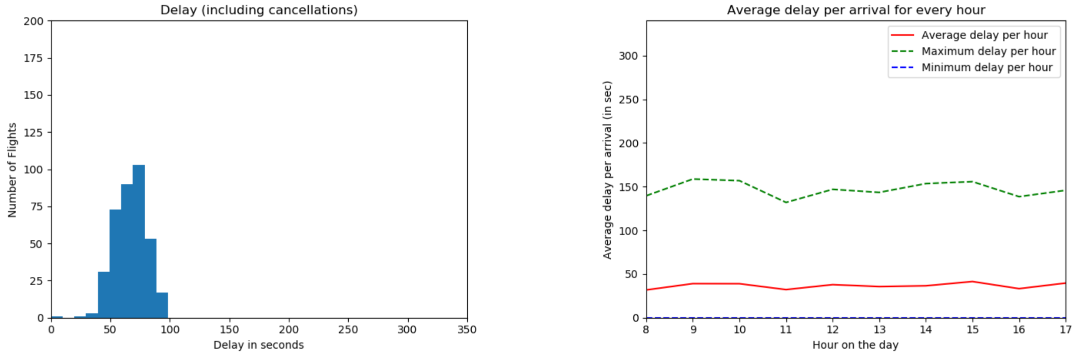
4.4.2. Time-Based Delay Strategy

In the time-based delay strategy it is chosen to obtain the results for one of the strategy inputs. More results of the time-based delay strategy can be found in Appendix F. The strategy input used for this section is the limit $d_{t_{max}} = 100s$ and it corresponds with strategy 5 in Section 4.3.1.

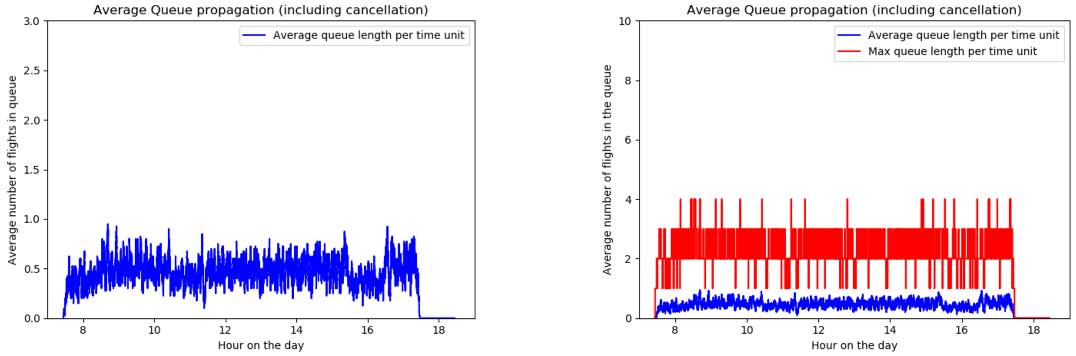
Table 4.5 gives the number of cancellations per hour for this strategy, it shows that during the peak hours the amount of cancellations is higher. Figure 4.5 shows the four operational monitoring figures and the result of cancellations on the operation. The used strategy input for these figures is a medium impact strategy with around 12% cancellations. It can be seen from the figures for the average and maximum queue propagation that there are no peak moments after this amount of cancellations. Only at 16:00 the queue is slightly shorter because the pressure on the capacity in this hour is low. Figure 4.5b gives the average delay and maximum delay of this strategy, the maximum delay is just below the 100 seconds, which is the limit of this strategy. During the day of operation the average delay tends to be constant, caused by the number of cancellations during peak hours. Compared with no strategy, the cancellations cause a decrease in pressure on the capacity. Resulting in evenly distributed average delays, queue propagation and waiting time. The waiting time distribution in Figure 4.5a shows that all arrivals have a delay below the 100 seconds, which corresponds with the maximum delay plot.

Table 4.5: Number of cancellations for the consecutive delay strategy with strategy input, $d_{t_{max}} = 100s$

Hour of operation	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	**Total**
Cancellations	3.8	5.9	5.8	4.1	5.2	5.0	5.2	6.2	3.5	5.8	50



(a) Average waiting time distribution (b) Average delay per arrival through the operation



(c) Average queue propagation (d) Average and maximum queue propagation

Figure 4.5: Operational monitoring results of simulation for $d_{t_{max}} = 100s$

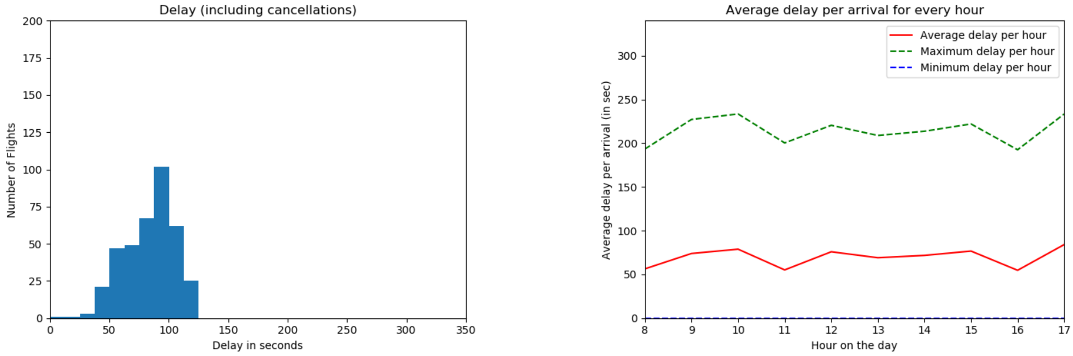
4.4.3. Consecutive Delay Strategy

In this section the results on a strategy input of the consecutive delay strategy will be presented, only one input will be treated and in Appendix F more results on different strategy inputs can be found. The strategy input presented in this section is the limit $d_{c_{max}} = 10$ consecutive delayed arrivals. This strategy corresponds with strategy number 7 in the Pareto front shown in Section 4.3.2.

Table 4.6 shows the number of cancellations per hour on the day of operation. It gives that for the hours with a larger demand the model shows more cancellations. The reason for the higher amount of cancellations is that the average delay is already increasing between 09:00 and 10:00 leading to an exceeding of $d_{c_{max}}$ in the hour 10:00-11:00. Figure 4.6 shows the results of monitoring the operations throughout the simulation. The simulation model first strives to find a point where the result is an evenly distributed average delay and queue propagation, then it lowers the average delay over the whole operation. As can be seen in maximum and average queue propagation, the peak moments are filtered compared to the no strategy situation of the arrival schedule. The queue is slightly larger at a higher arrival rate but the extreme peaks are filtered. In Figure 4.6b showing the average delay it can be seen that it is more evenly distributed but due to the medium impact of this strategy input the average delay still has differences between the separate hours. From these figures in the peak hours it shows that with a number of cancellations in this strategy it reduces largely on the pressure on the capacity. The waiting time distribution shows that the arrivals have a smaller and stacked waiting time, due to the cancellations.

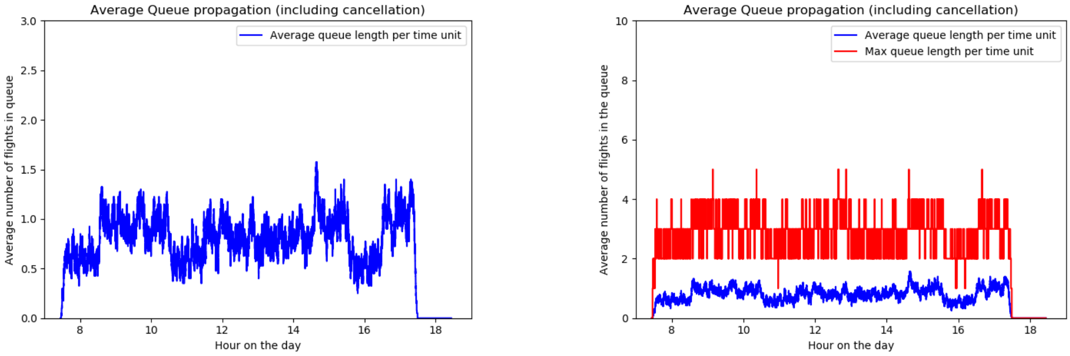
Table 4.6: Number of cancellations for the consecutive delay strategy with strategy input, $d_{c_{max}} = 10$

Hour of operation	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	**Total**
Cancellations	0.7	4.0	4.8	1.2	3.0	2.8	3.0	5.4	0.9	4.9	30.7



(a) Average waiting time distribution

(b) Average delay per arrival through the operation



(c) Average queue propagation

(d) Average and maximum queue propagation

Figure 4.6: Operational monitoring results of simulation for $d_{c_{max}} = 10$

4.5. Sensitivity Analysis

The sensitivity of the standard deviations of the arrival time and service time will be discussed by the use of several results of an optimisation of strategies in this section. A sensitivity analysis on these variables helps in understanding the influence of the assumptions made. The strategies used for the sensitivity analysis will be identical to the optimisation analysis. The following sections give insight on the effect of changing the standard deviations, on the strategies and their average delays and cancellations. The effect will be examined on the time-based delay strategy, the effect on the consecutive delay strategy is expected to be the same. In Section 4.5.1 the standard deviation of the arrival time will be treated and in Section 4.5.2 the standard deviation service time is analysed.

4.5.1. Standard Deviation of the Arrival Time

The standard deviation of the arrival time in the results of the model is equal to the inter-arrival time. In the following research on its sensitivity, the standard deviation will be tested on three different values, $\sigma_{arr} = [0.1 \cdot \Delta t_{arr_{slot}}, 1.0 \cdot \Delta t_{arr_{slot}}, 10.0 \cdot \Delta t_{arr_{slot}}]$. In Figure 4.7a three optimal Pareto fronts for these three standard deviations of the arrival time will be given.

Figure 4.7a shows that for lower impact strategies, strategy 1 till 6, an increase in standard deviation increases the average delay and cancellations. An increase of the value for the standard deviation causes a higher probability of arrivals with an overlap in their arrival time. This leads to a higher probability of large delays, causing more cancellations. For strategies 2 till 4, it is clearly visible that for a standard deviation of $1.0 \cdot \Delta t_{arr_{slot}}$ less cancellations are required compared to $10 \cdot \Delta t_{arr_{slot}}$ to achieve an average delay of the same magnitude. So increasing the standard deviation results in higher delays and cancellations for strategies 1 - 4.

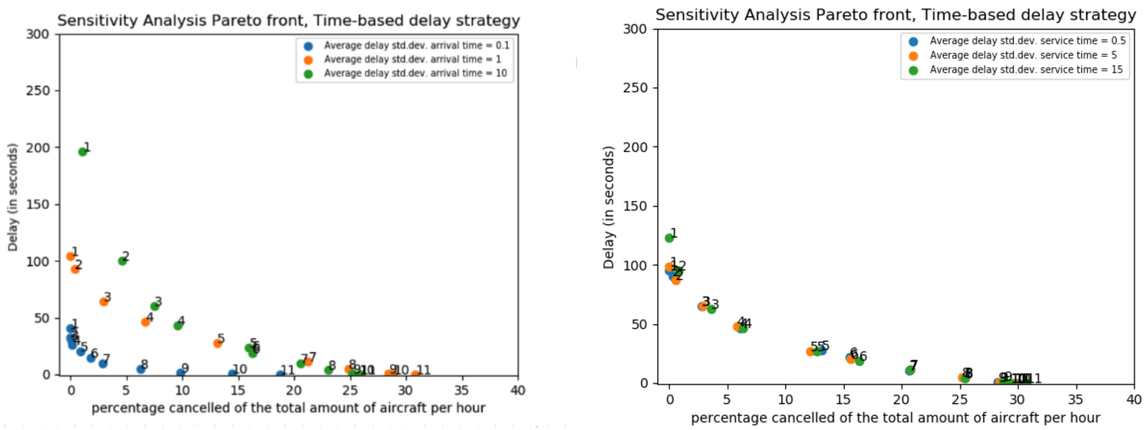
For input value $0.1 \cdot \Delta t_{arr_{slot}}$ it shows that for a low standard deviation the probability of overlap in arrival time is small. From strategy 8, the average delay is already zero with 6% of cancellations. Comparing the

$1.0 \cdot \Delta t_{arr_{slot}}$ and $10 \cdot \Delta t_{arr_{slot}}$, from strategy 7 till 11 the differences become smaller. The main difference is that for the same average delay more cancellations are required when the standard deviation of the arrival time increases.

4.5.2. Standard Deviation of the Service Time

In this part the sensitivity of the standard deviation of the normal probability distribution of the service time will be examined. The section on the assumptions states that $\sigma_{ser} = 5s$, the reason for this value is the expert opinion of professors and a small research on the buffer airport's use for servicing aircraft on the runway. To test the effect of changing the service time three different inputs were used, $\sigma_{ser} = [0.5s, 5s, 15s]$.

Figure 4.7b shows the results of the different standard deviations of the service rate. The effect on most of tested strategies results in equal values of average delay and percentage of cancelled flights. In some of the strategies, $\sigma_{ser} = 0.5s$ shows a slightly larger percentage of cancelled flights and therefore also lower average delay. Reason for an overall same result is the mean in the normal probability distribution which is based on the wake turbulence regulations and has a value which is around 100 seconds. The relatively low standard deviations have almost no effect on the average delay and cancellations of different strategies.



(a) Sensitivity analysis of the standard deviation for arrival time

(b) Sensitivity analysis of the standard deviation for service time

Figure 4.7: Optimisation Pareto front for the sensitivity analysis

4.6. Influence of Forecast Moment on Operation

In this section the influence of the forecast moment on the operational delays and cancellations will be examined and presented. The results will be used as a verification of the model and presented whether the expected results are obtained. First a number of basic verification steps executed during the research will be explained.

Verification of the research is control of the design requirements set at the preliminary model design and check whether the model behaves as expected for the given inputs. Before the model was completed by adding all simulation runs, the whole system was calculated step-by-step to verify every part of the model separately. To assure that every intermediate step gives a reliable result and is applied for several different inputs to control the behaviour of every step in the model for different situations.

The Discrete event simulation model is used to test the arrival pattern of aircraft at airports. A simulation of the real operation at an airport including a number of assumptions mentioned in the chapters before is simulated to obtain the behaviour of the strategies. So the models results is first tested on the results from several inputs with predictable results to test whether the model gives the expected end-result for these inputs. After these results where verified the inputs used for the runs as the Pareto fronts could be used. This is executed for both the, Time-based delay and Consecutive delay strategy.

To make sure that a number of assumptions would not influence the result with an exponential factor, a sensitivity analysis is performed. The assumptions mentioned in Section 4.1 have an influence on the final result, and to assure the final results it is required to test the assumptions which have a probability to have sensitive abilities these are researched in the sensitivity analysis in Section 4.5.

A forecast moment is included as an input which is used as a constraint whether an arrival can be cancelled or not. The forecast moment is the moment when the simulation model is used for the operation. For example the controller uses this model to forecast the behaviour of operation 5 hours before operation on the airport, this means that arrivals start landing in 5 hours. If an arrival lands in the first hour of operation and it has a travel time larger than 5 hours it means that the flight is already departed from its origin airport, therefore impossible to cancel. This constraint is included in the model and by analysing the optimisation figures (Pareto fronts) for four different inputs of this forecast moment the model can be verified. The following inputs are used:

- forecast moment = 7 hours prior to operation
- forecast moment = 4 hours prior to operation
- forecast moment = 2 hours prior to operation
- forecast moment = 0 hours prior to operation

A buffer of two hours is added to the travel time of the arrivals to include the time required to board at the origin airport. For the results in Figure 4.8 the optimisation of the time-based delay strategy with the same strategy inputs as given in Section 4.3 are used. Expected outcome of these inputs is that the number of possible cancellations decreases with decreasing forecast moment. Figure 4.8 confirms the expected result. At forecast moment 7 hours prior to operation the average and maximum delays are smallest and moving the forecast moment towards the time of operation results in larger average delay and less cancellations. Figure 4.8d shows that the difference is larger comparing for each strategy. The strategies in Figure 4.8a are more wide spread compared to Figure 4.8d the strategies are more compact, the impact of the strategies is less when the forecast moment gets closer to moment of operation. It can be said that including a forecast moment in the simulation model as verification proves that the model behaves as expected, which verifies the model.

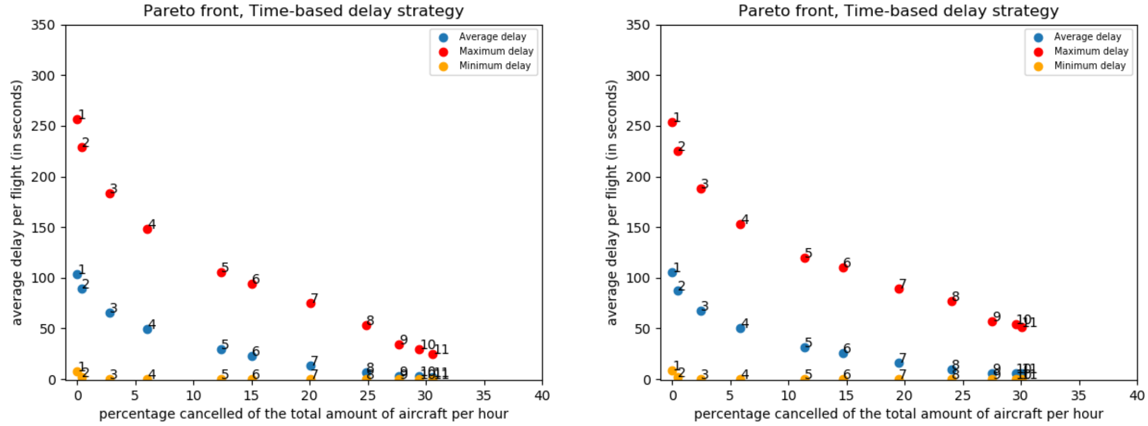
A better view will be given by focus on one of the strategies en presenting all strategies for the four different forecast moments. The strategy with the most clear impact of the different forecast moment will be emphasised, which is strategy number 6 in Figure 4.8. Table 4.7 shows the average delay for four different forecast moments for strategy number 6, $d_{t_{max}} = 100s$. Getting closer to moment of operation, the expected cancellations and average delay will change as can be seen in the table below. The possibility of performing cancellations gets smaller when getting closer, therefore the average delays will increase.

Table 4.7: results of strategy number 6 for the four forecast moments

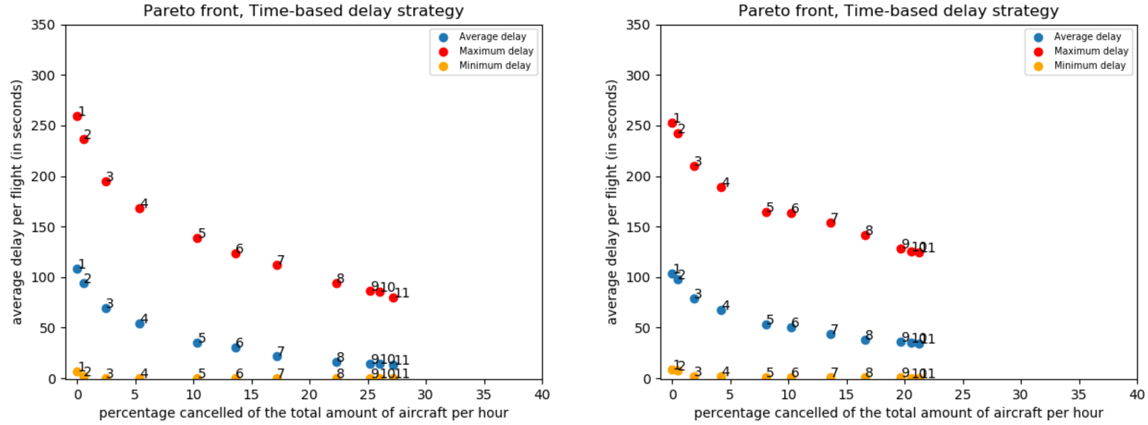
Forecast moment [hrs]	Average delay [s]	Cancellations [%]
7	22.7	15.0
4	25.8	14.7
2	30.2	13.6
0	50.9	10.2

4.7. Case study: Amsterdam Airport Schiphol

Amsterdam Airport schiphol is one of the busiest airports in the world and is used as an example case for the simulation model. The example case is to validate the model on its behaviour on real data. If the capacity of the airport changes it can happen that the pressure on the capacity increases. The simulation model will be used with the arrival rate of a Schiphol schedule, this section starts by an explanation of the arrival rate in Section 4.7.1, followed by the implementation and results of the schedule in the simulation model in Section 4.7.2.



(a) Forecast moment 7 hours prior to operation (b) Forecast moment 4 hours prior to operation



(c) Forecast moment 2 hours prior to operation (d) Forecast moment 0 hours prior to operation

Figure 4.8: Pareto fronts and the effect of changing forecast moment of operations

4.7.1. Input Values of AAS

In the example case of Schiphol the schedule in Appendix B is used to obtain the amount of arrivals per hour. Table 4.8 gives the hours from 08:00 till 18:00 of the Schiphol schedule which is the input for the case study of Schiphol. In the research the arrival rate generated was based on a 1 runway modelled airport, but for these arrival rates on Schiphol normally the airport operates with two runways during peak hours. As Table 4.8 shows, the morning peak at Schiphol is between 10:00 and 12:00 with a total of 122 aircraft. It can be said that based on the information from LVNL(Lucht Verkeersleiding Nederland), ATC in the Netherlands, that these peak hours also operate with two arrival runways[39]. These two hours will be implemented as there are two runways used so the arrival rate will be divided by two. Also a change in service rate will be implemented in the example case, in Section 2.1.2 the differences between VMC and IMC are explained and in this case the operation will be performed under VMC conditions, lowering airport runway capacity.

Table 4.8: Arrival rates of the 10 hours form 08:00 till 18:00 of the Schiphol Schedule

Daytime	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Arrival rate	22	25	72	50	19	29	48	34	20	41
Active arrival runways	1	1	2	2	1	1	1	1	1	1

4.7.2. Strategies with Input Data of AAS

The case study on Schiphol airport gives an example on the behaviour of the different strategies on real arrival rates instead of random generated arrival rates. For both the time-based delay strategy and the consecutive delay strategy the Pareto front will be given and the operational monitoring results will be given in Appendix G. A number of different strategies were tested because a different service rate is applied.

The Pareto front of the Time-based delay strategy showed in Figure 4.9a. A comparison with the results of Section 4.3 shows a larger average delay for the strategy without cancellation, strategy number 1, with Schiphol data. This is either because of a decrease in service rate or due to a heavy peak hour at 14:00. Most probable is the decrease in service rate because all other hours have a lower arrival rate than the random arrival rate. Similar is the decrease in average delay corresponding with a small increase in cancellations in the first three strategies. Table 4.9a shows an increase of 1.1% cancellations of the arrivals corresponds with 65.1% decrease in average delay per arrival. This confirms the statement made that the average delay decreases largely with a small increase in cancellations. The cancelled arrivals in the first strategies are only the arrivals with a large delay, therefore the impact on the average delay is large.

Figure 4.9b, shows the consecutive delay strategy for the Schiphol schedule. A lower service rate results in a scattered ratio between the average delay and the cancellations. Between the strategies, 60 and 7 consecutive delays it shows that the number of cancellations is increasing by only 2.4% and the average delays decreases with 37%. After the strategy of 4 consecutive delays the cancellations increase rapidly while the average delays decrease with a small amount. At around the 6% of cancellations there is a nod for the maximum and the average delay, the reason for the nod is the pressure on the capacity due to the peak in arrivals between 14:00 and 15:00. The peak pressure forces the amount of consecutive delays to increase during this hour while the model does not cancel these flights due to the high acceptable boundary as input for these strategies.

Comparison between the two types of strategies show that it the figures show a difference in maximum and average delay at the start while both arrival schedules are similar. The reason is that in the first strategy at the time-based delay there are already a number of cancellations which are the most delaying flights, therefore also the flights with the highest impact on the average delay. The time-based delay shows a more reliable forecast than the consecutive delay, in the first 5% of the cancellations the time-based delay decreases more than 80% of the average delay were it takes the consecutive delay strategy almost 12% of the cancellations. Therefore the time-based delay is more specific in the cancellations resulting in a more effective strategy.

Table 4.9: Results of strategies with Schiphol arrivals as input

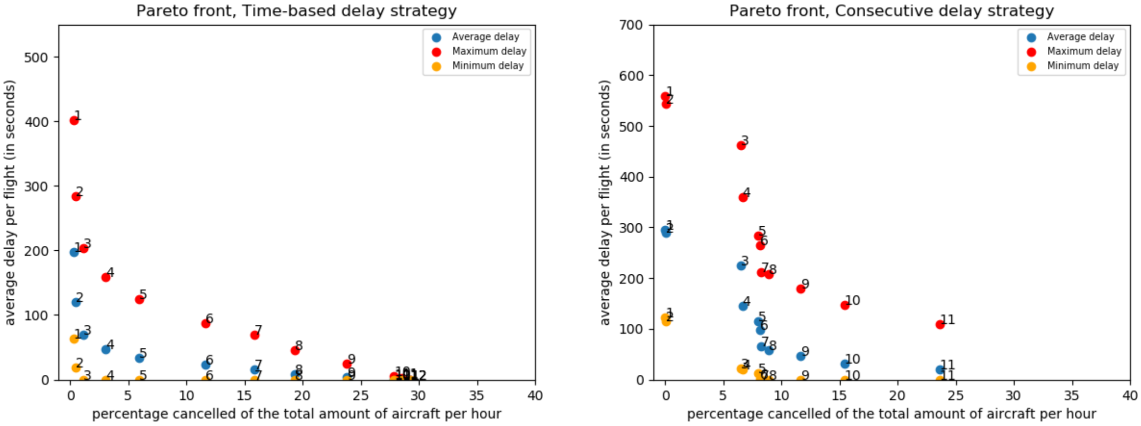
(a) Time-based delay strategy

Strategy #	Strategy input [s]	Cancellations [% of arrivals]	Average delay [s]
1	1000	0.3	198
2	600	0.5	119
3	300	1.1	69
4	200	3.1	47
5	150	6.0	34
6	100	11.6	23
7	80	15.9	16
8	60	19.3	9
9	40	23.8	3
10	20	27.9	1
11	10	28.5	0
12	0	29.3	0

(b) Consecutive delay strategy

Strategy #	Strategy input [consecutive delays]	Cancellations [% of arrivals]	Average delay [s]
1	150	0	102
2	80	0.1	101
3	60	6.5	100
4	40	6.7	97
5	30	8.0	95
6	20	8.2	82
7	10	8.3	69
8	7	8.9	63
9	4	11.6	50
10	2	15.4	32
11	0	23.6	20

Validation of the model using the actual AAS input data resulted in the expected results for majority of the figures. The operational figures indicate at which hours during the day the operation struggles with increasing queue length so at what hours a bottleneck can be found in the arrival operation. The optimisation of the strategies in the Pareto fronts shows the model also gives a great decrease in average delay with a small



(a) Time-based delay strategy

(b) Consecutive delay strategy

Figure 4.9: Pareto fronts of the strategies for Schiphol arrival input

amount of cancellations for the time-based delay strategy. The consecutive delay strategy shows a different propagation than expected; this strategy has difficulties with simulation of the cancellations because of changing number of arrivals per hour. Therefore it results in abrupt changes in the Pareto front of the consecutive delay strategy.

5

Discussion

In the discussion, the limitations of the model will be indicated for different topics presented in two sections. First a discussion on the optimisation of the model is given in 5.1 followed by a part on the implementation in operation in Section 5.2.

5.1. Optimisation on the Model

Optimisation of the model is about the criteria selected for optimising the model, in the scope of this research it is about the optimisation of the ratio between the cancellations and the delays. It is also possible to extend the models optimisation results to a economic or environmental goal. In the following sections a short discussion will be given on an economic optimisation in Section 5.1.1, followed by the environmental optimisation where both the emissions and the noise will be discussed in Section 5.1.2. Both the economic and the environmental optimisation approach are extensions on the model on the ratio between the delays and cancellations, both expected by combining the optimisation for usability in the arrival operations.

5.1.1. Economic

Economic optimisation of demand management strategies is about optimising cost of delays and cancellations. The model of the demand management strategies has as a result the ratio between the cancellations and delays for the different strategy inputs. On the economic best solution in case of capacity issues, an optimisation should be made on these outcomes of the cancellations and delays in combination with the cost of these delays and cancellation. In Appendix H some data on the delay cost en-route and at-gate is given and it can be seen that the relations between the time of delay and cost vary over the duration of time delay. Hence the model needs to incorporate the individual delay instead of the determined average delay. The cancellation cost depend on a lot of different aspects therefore difficult to define a certain amount of money to this. For the delay cost the aspects are more straight forward; maintenance, fuel, fleet, crew and passengers, while for the cancellation cost it is difficult to know what topics are required to include. Research on the cost of delay and cancellations could be a topic for a separate research. Combining such a cost analysis of the cancellations and the delays with the ratio of the strategies will result in a corresponding cost per strategy. Then the ATC could decide on the economic most viable strategy.

5.1.2. Environmental

In the environmental topic of the optimisation, both noise and the emissions will be discussed but for these subjects it is important to take into account that when optimising for an environmental issue it is obviously always best to just do not travel by aircraft.

Noise

If noise would be taken into account of the cancellations and the delays then in some cases it would be more beneficial to cancel a flight producing more noise than other flights. Also if optimising on the noise the regulations should be taken into account, then certain flights on the edge of regulations or on certain routes were the regulations on noise are more strict could be cancelled first in case of capacity issues. This would be an extension optimisation on the ratio between the delay and cancellation.

Emissions

Emissions of the aviation industry is all about the emission of the flights made. If this would be taken into account in the optimisation of the cancellations and delays. Most probably the delays will be minimised as much as possible, due to the minimisation of the emissions equalise minimising the amount of flight hours. More delays on the arrivals means more time in flight resulting in more emissions. But to couple these thoughts on the emissions of aircraft to the optimisation of the delays and cancellations could result in an advise on the best ratio for minimising the emissions.

5.2. Implementation in Operation

The implementation in the operation is about what the model could support in real operation and what the models limitations are at this moment. Limitations lead to the adjustments or addition the model requires to be a possible tool to be used as support for the ATC during operation. It is split-up into two different topics relevant for the credibility of the application of the model: The adjustments on the case-study and the runway variation.

5.2.1. Adjustments on Case-study

In current research, the results are mainly based on the arrival slot allocation with an extra added uncertainty of arriving in time by the normal probability distribution. According to the case study the generated data for the arrivals gives the same kind of results, however, this is not compared to a real data set where the arrivals and the eventual cancellations and delays are known. So a limitation of this research and model is that it should be compared to a large real case of an operation day including the knowledge of the delays and cancellations. The LVNL has the data of the days of operation for their own research so in collaboration between the TU Delft and LVNL a further research could be performed with the correct data.

Validation of the results from the research is in somewhat way difficult because the purpose is to compare with a real operation. The research is in name of University of Technology Delft therefore historical data of the delays and cancellations of Schiphol or other airport is difficult to gather. Validation of the model itself is achieved by the use of a schiphol schedule used to determine the arrival rate, however, validate results using real data, the LVNL should be involved. Therefore the results and the model in this research is a theoretic approach on the demand management strategies.

5.2.2. Runway Variation

The implementation of an extra validation by the use of complete data set of the operational activity on the runways would also require a model which is completely build to cope with more than one runway. In the current model there is an option of increasing the capacity of the service at the airport by changing the number of the runways, however, it does not include possible differences in capacity per runway or include a ratio of the departure/arrival ratio. Adding to the model the possibility to change capacities and these ratios would be essential to use in operation at an airport such as Schiphol. Schiphol could have three runways active and in some cases one runway to use for the departure and arrival, while in this research only the arrivals on one runway are taken into account without any departures. If the model would be used for several airports it should be able to change these capacities.

6

Conclusions & Recommendations

This chapter focuses on the conclusions and recommendations that follow from this research on the effectiveness of the airport demand management strategies. As indicated the chapter will be divided into two sections; first the conclusions will be discussed in Section 6.1, followed by the recommendations on the master thesis research given in Section 6.2.

6.1. Conclusions

In this part the conclusions will be presented and discussed. The research evaluates the effectiveness of airports demand management strategies, with a focus on finding new approaches on demand management strategies. Optimising the arrival process at airports during capacity issues potentially support the operation with diversion from the planned schedule. The research is executed with a the following research objective:

Evaluation of the effectiveness and develop new insights on the Airport Demand Management Strategies

Evaluation of the effectiveness of the demand management strategies requires a method to test the effectiveness. In this research a method for evaluating the effectiveness of the different demand strategies was developed and tested for its performance.

The simulation model, based on discrete event simulation and Monte Carlo simulation method, measures the effectiveness of airport demand management strategies. The DES method was used because it is suitable method for simulating real-life logistic processes in time. This research is mainly based on the results from the delay calculations which is based on a time-delay. It is combined with a MC simulation method to guarantee an accuracy of the result of above 90%. Results from the arrival operations and optimisation of the strategies show that with a combination of delays and cancellations the effectiveness can be examined. The Pareto front of the optimisation of the strategies show an overall effectiveness of the tested strategies. Specific effectiveness of the strategies is presented by the arrival operations monitoring results. So the simulation model shows a method to obtain the effectiveness of the strategies. It is designed to be able to receive different strategies as an input as long as it is defined as a limiting factor on delays.

The advantage of the DES model is that it makes it possible to monitor the expected behaviour of the arrival operations. Visualisation are extracted from the delay calculations of the DES model resulting in information on the queue propagation and the average delay during the operation. These results can be used for deciding which specific cancellations is most effective to relief pressure from the capacity. Useful for air traffic controllers is that these results show the operational bottlenecks.

From the tested strategic approaches, the time-based delay strategy is the most efficient strategy. In the results on the comparison between the consecutive and the time-based delay strategy it shows that in all possible strategy inputs the time-based delay strategy scores best. The effectiveness of a cancellation is higher at the time-based delay strategy, a cancellation forces a greater decrease in average delay. Table 6.1 shows the results on both strategies with the corresponding amount of cancellations. For the same amount of cancellations the time-based delay strategy shows a higher decrease in average delay than the consecutive delay strategy. The average decrease in average delay per cancellation is higher for the time-based against the consecutive delay strategy, $3.2s$ against $2.8s$ respectively.

Table 6.1: Comparison between time-based and consecutive delay strategy

Cancellations %	Average delay Time-based [s]	Average delay Consecutive [s]
0	102	102
3	63	85
12	27	57
22	9	32

The standard deviation of the arrival time, shows a slight sensitive behaviour on the optimisation result. Arrival operations are stochastic processes, therefore it has the property to be sensitive in simulating such a process. Simulation with a larger standard deviation on the arrival time results in more cancellation, to achieve the same decrease in average delay. If the standard deviation is multiplied by 10, so 10 times the inter-arrival time, it shows that the cancellations required to result in the same average delay moves from 3% to 7% of the total arrivals. It can therefore be concluded that the standard deviation of the arrival time has a great influence on the result.

Optimisation of the strategies shows that by performing a number of specific cancellations, the decrease in average delay can be large. So specific targeted cancellations can make a large difference, cancelling 2.8% of the arrivals can result in up to 36% decrease in delays for the data used. It shows that with a small percentage of cancellations a large impact on the average delays can be achieved. The first cancellations have the greatest impact on the average delays, when specifically cancelled, according to the time-based delay strategy.

The moment the forecast simulation is generated is crucial in the operational decision making. The verification results show that the possibilities are much broader when the forecast moment is far before day of operation. A simulation should be made before the first planned arrivals is airborne from origin airport, so the maximum travel time including boarding buffer. The number of possible cancellations decreases when day of operation approaches. Table 6.2 shows that conducting a simulation 7 hours before operation results in lower average delays due to more possible cancellations compared to simulation at the start of operation, zero hours. So in most optimal situation the forecast moment should be at the moment all arrivals can still be cancelled.

Table 6.2: Forecast moment of one strategy input, $d_{t_{max}} = 80s$, of the time-based delay strategy

Forecast moment [hrs]	Average delay [s]	Cancellations [%]
7	22.7	15.0
0	50.9	10.2

All the conclusions separately show that different aspects of the simulation model can be used for different purposes. Also shows that the effectiveness of the demand management strategies can be tested on several aspects. It can be said for sure that on the delays and cancellations ratio the DES combined with MC simulation model gives the effectiveness of particular strategy.

6.2. Recommendations

The recommendations section is an extension on the discussion presented in Chapter 5, the recommendations follow from the topics discussed in this chapter. In the list below a number of possible improvements or follow-up researches will be presented in a concise summary of the previous discussed topics:

- Implement an extension on the optimisation of the ratio between the cancellations and the delays, by incorporating an economic aspect. Include the costs of a cancellation and delay into the result and optimise for the most cost optimal value of the cancellation and delay ratio.

- Include a broader method of the case study to increase the reliability of the validation process. Increasing the cancellation and delay data by cooperation with LVNL to increase the knowledge on the feasibility of the research.
- Variation in the runway configurations by changing the service capacity and the amount of runways. Also include the departures into the model to keep track of the whole runway operations instead of only tracking the arrivals.
- If the environmental aspect is crucial for the airport implement the possibility to optimise the result for a optimal noise or emission solution. By adding the possibility to include constraints on the noise and emission the model could obtain an optimised value for cancellation and delay ratio with respect to the environmental impact.

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Appendices

A

Research Questions and Sub-questions

In the report itself the main research question is given the sub-questions are given but to break the objective in even more smaller problems there are also sub sub questions. To make the introduction in Chapter 1 clear, these sub-sub-questions are given in this appendix and also the research question is repeated with its sub-questions.

Main Research Question:

How can the effectiveness of Airport Demand Management strategies be evaluated?

To break the problem into smaller, clearer parts of the problem sub-questions are obtained to assist in the path to the answer for the main research question. These sub-questions are given below with again sub-questions for the sub-questions. If below actors are mentioned, these are the stakeholders which are involved in the demand management procedures on an airport. Such as the airlines, airport, ground handling and other parties.

Sub questions:

- What are demand management strategies and how is it used in the landing operations?
  - How do the actors use the demand management strategies?
  - Why is it beneficial to use demand management strategies for the actors?
- What data can be used and how is it obtained?
  - What are the data distributions useful for the model?
  - How can this data can make a value for the demand management strategies?
  - What are the differences between distributions between small point-to-point airports compared to the hub-airports?
- How can the data be used in a model?
  - What models would fit the demand management problem?
  - What types of input are needed to solve the model for the required output?
  - Is it possible to use a Monte Carlo simulation approach?
  - What are the differences between the simulation and the scheduled system?
- Does the modelling techniques give a representation for the evaluation of the airport demand management strategies?
  - How do the used parameters affect the model?
  - Is it possible to perform targeted interventions in an existing schedule?
  - What is the sensitivity of the different distributions and are they robust to change?
  - What are the possibilities for verification of the model and how does the model perform?
- What would be the advantage of using such a model for the demand management problem on airports?
  - Are the inputs used for the model well chosen?
  - In what perspective does the outcome of the model give the strategies a rate on their effectiveness?

  - Does the result give a view on the best combination of delays and cancellations most effective for small and large airports?

B

Schiphol Schedule

In the following appendix a Schiphol schedule is presented from the year 2005. It is used for different calculations on the service rate. Especially to determine the probability distributions on the distances from origin to Schiphol and the Weight classes from the aircraft types in Table B.1. Only the arrivals are shown in Table B.1 because these are the only flights considered in testing the demand management strategies and these will have a priority above departures.

FSID	ID	STime	DepArr	Origin	Destination	ACType	Pax	FLType	AirlineCode
1	1	09:00	Arr	ABZ	Airport	B737700	98	NAT	KL
1	2	18:15	Arr	ABZ	Airport	B737700	98	NAT	KL
1	3	13:15	Arr	ABZ	Airport	B737700	98	NAT	KL
1	4	06:15	Arr	ACC	Airport	MD11	226	INT	KL
1	5	19:45	Arr	ADB	Airport	A300	238	INT	F2
1	6	05:15	Arr	ADD	Airport	B767200	176	INT	KL
1	7	14:20	Arr	AGP	Airport	B737700	119	NAT	HV
1	8	23:05	Arr	AGP	Airport	B737700	119	NAT	HV
1	9	06:20	Arr	ALA	Airport	B767200	176	INT	KL
1	10	13:00	Arr	ALC	Airport	B737700	119	NAT	HV
1	11	23:40	Arr	ALC	Airport	B737700	119	NAT	HV
1	12	11:00	Arr	ALP	Airport	A320	122	INT	RB
1	13	06:20	Arr	AMM	Airport	B737700	98	INT	KL
1	14	12:45	Arr	AMM	Airport	A320	112	INT	RJ
1	605	06:45	Arr	ANC	Airport	B747400	0	INT	KZ
1	606	13:00	Arr	AOK	Airport	B737800	149	NAT	HV
1	607	20:45	Arr	ARN	Airport	MD82	116	NAT	SK
1	608	09:20	Arr	ARN	Airport	MD82	116	NAT	SK
1	609	18:15	Arr	ARN	Airport	B737700	98	NAT	KL
1	610	15:05	Arr	ARN	Airport	B737700	98	NAT	KL
1	611	12:35	Arr	ARN	Airport	B737700	98	NAT	KL
1	612	08:55	Arr	ARN	Airport	B737700	98	NAT	KL
1	613	21:20	Arr	ARN	Airport	B737700	98	NAT	KL
1	614	18:05	Arr	ARN	Airport	B737600	82	NAT	SK
1	615	13:00	Arr	ARN	Airport	B737600	82	NAT	SK
1	616	06:20	Arr	ASR	Airport	B737800	124	INT	TK
1	617	11:50	Arr	ATH	Airport	B737400	117	NAT	OA
1	618	18:05	Arr	ATH	Airport	B737700	98	NAT	KL
1	619	08:45	Arr	ATH	Airport	B737700	98	NAT	KL
1	620	13:35	Arr	ATH	Airport	B737800	149	NAT	HV
1	621	07:10	Arr	ATL	Airport	MD11	0	INT	MP
1	622	08:25	Arr	ATL	Airport	B767300	156	INT	DL
1	623	09:05	Arr	ATL	Airport	B767200	176	INT	KL

1	624	11:20	Arr	AUA	Airport	MD11	226	INT	KL
1	625	19:00	Arr	AYT	Airport	B757300	148	INT	F2
1	626	07:05	Arr	BAH	Airport	B767200	176	INT	KL
1	627	08:50	Arr	BCN	Airport	B737700	98	NAT	KL
1	628	13:00	Arr	BCN	Airport	B737700	98	NAT	KL
1	629	21:45	Arr	BCN	Airport	B737700	98	NAT	KL
1	630	17:55	Arr	BCN	Airport	B737700	98	NAT	KL
1	631	06:10	Arr	BCN	Airport	B737700	98	NAT	KL
1	632	15:15	Arr	BCN	Airport	B737700	98	NAT	KL
1	633	17:35	Arr	BCN	Airport	B737700	119	NAT	HV
1	634	23:45	Arr	BCN	Airport	B737700	119	NAT	HV
1	635	11:20	Arr	BCN	Airport	B737700	119	NAT	HV
1	636	12:15	Arr	BCN	Airport	A320	120	NAT	IB
1	637	22:15	Arr	BCN	Airport	A320	120	NAT	IB
1	638	18:25	Arr	BCN	Airport	A320	120	NAT	IB
1	639	11:00	Arr	BEG	Airport	B737300	101	NAT	JU
1	640	05:55	Arr	BEY	Airport	B737700	98	INT	KL
1	641	07:30	Arr	BEY	Airport	B707	0	INT	7TL
1	642	12:15	Arr	BFS	Airport	B737700	119	NAT	U2
1	643	18:20	Arr	BGO	Airport	FK100	81	NAT	KL
1	644	13:20	Arr	BGO	Airport	B737700	98	NAT	KL
1	645	08:00	Arr	BGO	Airport	B737700	98	NAT	KL
1	646	23:25	Arr	BGY	Airport	B737700	119	NAT	HV
1	647	11:00	Arr	BGY	Airport	B737700	119	NAT	HV
1	648	17:35	Arr	BHX	Airport	B737300	118	NAT	WW
1	649	09:10	Arr	BHX	Airport	B737300	118	NAT	WW
1	650	19:30	Arr	BHX	Airport	FK100	81	NAT	KL
1	651	17:15	Arr	BHX	Airport	B737700	98	NAT	KL
1	652	08:40	Arr	BHX	Airport	B737700	98	NAT	KL
1	653	13:10	Arr	BHX	Airport	B737700	98	NAT	KL
1	654	10:30	Arr	BHX	Airport	FK70	64	NAT	KL
1	655	21:40	Arr	BHX	Airport	FK70	64	NAT	KL
1	656	05:30	Arr	BKK	Airport	B747200	216	INT	KL
1	657	09:40	Arr	BKK	Airport	B747400	318	INT	CI
1	658	09:45	Arr	BKK	Airport	B747400	218	INT	BR
1	659	12:50	Arr	BLL	Airport	B737500	83	NAT	DM
1	660	08:50	Arr	BLL	Airport	B737500	83	NAT	DM
1	661	16:20	Arr	BLL	Airport	B737500	83	NAT	DM
1	662	19:40	Arr	BLL	Airport	B737500	83	NAT	DM
1	663	14:25	Arr	BLQ	Airport	FK70	64	NAT	KL
1	664	18:30	Arr	BLQ	Airport	FK100	81	NAT	KL
1	665	08:20	Arr	BLQ	Airport	FK100	81	NAT	KL
1	666	13:15	Arr	BOD	Airport	EMB145	40	NAT	AF
1	667	08:15	Arr	BOD	Airport	EMB145	40	NAT	AF
1	668	18:15	Arr	BOD	Airport	EMB145	40	NAT	AF
1	669	21:30	Arr	BOH	Airport	B737500	105	NAT	TOM
1	670	06:40	Arr	BOM	Airport	DC1030	216	INT	NW
1	671	05:00	Arr	BON	Airport	MD11	226	INT	KL
1	672	17:40	Arr	BON	Airport	MD11	226	INT	KL
1	673	07:10	Arr	BOS	Airport	DC1030	216	INT	NW
1	674	18:45	Arr	BRE	Airport	FK70	64	NAT	KL
1	675	08:15	Arr	BRE	Airport	FK70	64	NAT	KL
1	676	12:40	Arr	BRE	Airport	FK50	40	NAT	KL
1	677	15:45	Arr	BRE	Airport	FK50	40	NAT	KL
1	678	12:50	Arr	BRS	Airport	FK70	64	NAT	KL
1	679	08:45	Arr	BRS	Airport	FK70	64	NAT	KL

1	680	19:15	Arr	BRS	Airport	FK70	64	NAT	KL
1	681	15:25	Arr	BRS	Airport	B737700	119	NAT	U2
1	682	18:20	Arr	BRS	Airport	FK100	81	NAT	KL
1	683	12:55	Arr	BRU	Airport	FK70	64	NAT	KL
1	684	18:30	Arr	BRU	Airport	FK70	64	NAT	KL
1	685	11:25	Arr	BRU	Airport	FK70	64	NAT	KL
1	686	07:15	Arr	BRU	Airport	FK70	64	NAT	KL
1	687	09:30	Arr	BRU	Airport	FK70	64	NAT	KL
1	688	15:25	Arr	BRU	Airport	FK50	40	NAT	KL
1	689	15:55	Arr	BSL	Airport	S2000	40	NAT	LX
1	690	19:15	Arr	BSL	Airport	S2000	40	NAT	LX
1	691	09:10	Arr	BSL	Airport	S2000	40	NAT	LX
1	692	09:50	Arr	BTS	Airport	B737500	106	NAT	NE
1	693	15:00	Arr	BUD	Airport	B737700	98	NAT	MA
1	694	13:15	Arr	BUD	Airport	B737700	98	NAT	MA
1	695	09:15	Arr	BUD	Airport	B737700	98	NAT	MA
1	696	19:45	Arr	BUD	Airport	B737700	98	NAT	MA
1	697	18:20	Arr	BUD	Airport	B737700	98	NAT	KL
1	698	09:35	Arr	BUD	Airport	B737500	106	NAT	5P
1	699	20:00	Arr	BUD	Airport	B737500	106	NAT	5P
1	700	15:00	Arr	CAI	Airport	A320	116	INT	MS
1	701	07:15	Arr	CAI	Airport	MD11	226	INT	KL
1	702	12:30	Arr	CAI	Airport	B757PW	0	INT	ET
1	703	19:55	Arr	CDG	Airport	B737500	90	NAT	AF
1	704	13:55	Arr	CDG	Airport	B737500	90	NAT	AF
1	705	17:10	Arr	CDG	Airport	MD11	228	NAT	RG
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1	707	17:40	Arr	CDG	Airport	B737700	98	NAT	KL
1	708	11:50	Arr	CDG	Airport	B737700	98	NAT	KL
1	709	10:15	Arr	CDG	Airport	B737700	98	NAT	KL
1	710	14:55	Arr	CDG	Airport	B737700	98	NAT	KL
1	711	22:05	Arr	CDG	Airport	B737700	98	NAT	KL
1	712	10:55	Arr	CDG	Airport	B737700	98	NAT	KL
1	713	16:55	Arr	CDG	Airport	A320	127	NAT	AF
1	714	12:50	Arr	CDG	Airport	A320	127	NAT	AF
1	715	19:05	Arr	CDG	Airport	A320	127	NAT	AF
1	716	08:05	Arr	CDG	Airport	A320	127	NAT	AF
1	717	09:25	Arr	CDG	Airport	A320	127	NAT	AF
1	718	08:40	Arr	CDG	Airport	A320	127	NAT	AF
1	719	18:20	Arr	CFE	Airport	S2000	42	NAT	AF
1	720	13:10	Arr	CGN	Airport	FK50	40	NAT	KL
1	721	08:15	Arr	CGN	Airport	FK50	40	NAT	KL
1	722	18:45	Arr	CGN	Airport	FK50	40	NAT	KL
1	723	13:20	Arr	CHQ	Airport	B737800	149	NAT	HV
1	724	13:30	Arr	CMN	Airport	B737800	122	INT	AT
1	725	16:20	Arr	CPH	Airport	MD87	96	NAT	SK
1	726	09:40	Arr	CPH	Airport	MD87	96	NAT	SK
1	727	21:00	Arr	CPH	Airport	MD87	96	NAT	SK
1	728	13:20	Arr	CPH	Airport	B737700	98	NAT	KL
1	729	18:25	Arr	CPH	Airport	B737700	98	NAT	KL
1	730	11:35	Arr	CPH	Airport	B737700	98	NAT	KL
1	731	07:45	Arr	CPH	Airport	B737700	98	NAT	KL
1	732	19:55	Arr	CPH	Airport	B737700	98	NAT	KL
1	733	19:20	Arr	CPH	Airport	MD81	116	NAT	SK
1	734	12:05	Arr	CPH	Airport	B737300	109	NAT	NB
1	735	08:50	Arr	CUN	Airport	B767300	218	INT	MP

1	736	10:35	Arr	CUR	Airport	B747400	320	INT	KL
1	737	09:35	Arr	CVG	Airport	B767300	156	INT	DL
1	738	21:30	Arr	CVT	Airport	B737500	105	NAT	TOM
1	739	08:15	Arr	CVT	Airport	B737500	105	NAT	TOM
1	740	08:15	Arr	CWL	Airport	FK70	64	NAT	KL
1	741	19:20	Arr	CWL	Airport	FK70	64	NAT	KL
1	742	17:15	Arr	CWL	Airport	FK70	64	NAT	KL
1	743	13:05	Arr	CWL	Airport	FK100	81	NAT	KL
1	744	07:35	Arr	DAR	Airport	B767200	176	INT	KL
1	745	06:00	Arr	DEL	Airport	MD11	226	INT	KL
1	746	12:10	Arr	DTW	Airport	DC1030	216	INT	NW
1	747	09:05	Arr	DTW	Airport	A330300	214	INT	NW
1	748	07:15	Arr	DTW	Airport	A330300	214	INT	NW
1	749	11:20	Arr	DTW	Airport	A330300	214	INT	NW
1	750	05:55	Arr	DTW	Airport	A330300	214	INT	NW
1	751	20:15	Arr	DUB	Airport	A320	120	NAT	EI
1	752	15:30	Arr	DUB	Airport	A320	120	NAT	EI
1	753	18:05	Arr	DUB	Airport	A320	120	NAT	EI
1	754	12:50	Arr	DUB	Airport	A320	120	NAT	EI
1	755	09:10	Arr	DUB	Airport	A320	120	NAT	EI
1	756	12:35	Arr	DUS	Airport	FK70	64	NAT	KL
1	757	07:55	Arr	DUS	Airport	FK70	64	NAT	KL
1	758	15:20	Arr	DUS	Airport	FK50	40	NAT	KL
1	759	18:35	Arr	DUS	Airport	FK50	40	NAT	KL
1	760	09:30	Arr	DUS	Airport	FK50	40	NAT	KL
1	761	06:20	Arr	DXB	Airport	B777200	229	INT	KL
1	762	10:20	Arr	DXB	Airport	B747300	0	INT	MH
1	763	06:25	Arr	DXB	Airport	B747400	0	INT	EK
1	764	21:00	Arr	DXB	Airport	B747400	0	INT	KL
1	765	21:40	Arr	EDI	Airport	FK70	64	NAT	KL
1	766	15:15	Arr	EDI	Airport	FK70	64	NAT	KL
1	767	12:05	Arr	EDI	Airport	B737300	119	NAT	U2
1	768	08:35	Arr	EDI	Airport	B737700	98	NAT	KL
1	769	13:20	Arr	EDI	Airport	B737700	98	NAT	KL
1	770	18:15	Arr	EDI	Airport	B737700	98	NAT	KL
1	771	12:30	Arr	EIN	Airport	FK50	40	NAT	KL
1	772	07:45	Arr	EIN	Airport	FK50	40	NAT	KL
1	773	18:20	Arr	EIN	Airport	FK50	40	NAT	KL
1	774	15:25	Arr	EIN	Airport	FK50	40	NAT	KL
1	775	18:25	Arr	EMA	Airport	B737500	105	NAT	WW
1	776	09:25	Arr	EMA	Airport	B737500	105	NAT	WW
1	777	17:30	Arr	EMA	Airport	B747400	0	NAT	7K4
1	778	22:30	Arr	ESB	Airport	B737800	124	INT	TK
1	779	06:00	Arr	ESB	Airport	A300	238	INT	F2
1	780	07:50	Arr	EWR	Airport	B767200	176	INT	KL
1	781	07:00	Arr	EWR	Airport	B767200	139	INT	CO
1	782	08:15	Arr	EWR	Airport	B767400	187	INT	CO
1	783	23:45	Arr	FAO	Airport	B737700	119	NAT	HV
1	784	23:50	Arr	FAO	Airport	B737800	149	NAT	HV
1	785	15:15	Arr	FCO	Airport	B737700	98	NAT	KL
1	786	09:10	Arr	FCO	Airport	B737700	98	NAT	KL
1	787	22:25	Arr	FCO	Airport	B737700	98	NAT	KL
1	788	13:00	Arr	FCO	Airport	B737700	98	NAT	KL
1	789	14:10	Arr	FCO	Airport	B737300	114	NAT	TV
1	790	11:45	Arr	FCO	Airport	MD88	105	NAT	AZ
1	791	19:45	Arr	FCO	Airport	A319	88	NAT	AZ

1	792	16:45	Arr	FCO	Airport	A320	105	NAT	AZ
1	793	19:00	Arr	FCO	Airport	B737700	98	NAT	KL
1	794	18:30	Arr	FLR	Airport	A319	106	NAT	IG
1	795	14:00	Arr	FRA	Airport	B737500	82	NAT	LH
1	796	18:40	Arr	FRA	Airport	B737500	82	NAT	LH
1	797	11:40	Arr	FRA	Airport	B737500	82	NAT	LH
1	798	19:45	Arr	FRA	Airport	B737500	82	NAT	LH
1	799	09:45	Arr	FRA	Airport	B737500	82	NAT	LH
1	800	15:20	Arr	FRA	Airport	B737500	82	NAT	LH
1	801	07:45	Arr	FRA	Airport	A330300	268	NAT	TS
1	802	17:40	Arr	FRA	Airport	A320	115	NAT	LH
1	803	19:35	Arr	FRA	Airport	FK70	64	NAT	KL
1	804	17:00	Arr	FRA	Airport	FK70	64	NAT	KL
1	805	08:30	Arr	FRA	Airport	FK70	64	NAT	KL
1	806	12:20	Arr	FRA	Airport	FK100	81	NAT	KL
1	807	09:00	Arr	FRA	Airport	B737300	98	NAT	LH
1	808	22:30	Arr	FRA	Airport	A321	146	NAT	LH
1	809	01:30	Arr	FUE	Airport	B737800	149	NAT	HV
1	810	18:05	Arr	GLA	Airport	B737700	98	NAT	KL
1	811	11:55	Arr	GLA	Airport	B737300	119	NAT	U2
1	812	09:00	Arr	GLA	Airport	FK100	81	NAT	KL
1	813	12:45	Arr	GLA	Airport	FK100	81	NAT	KL
1	814	14:05	Arr	GLA	Airport	FK100	81	NAT	KL
1	815	17:15	Arr	GOA	Airport	B737700	119	NAT	HV
1	816	08:10	Arr	GOT	Airport	B737700	98	NAT	KL
1	817	13:15	Arr	GOT	Airport	B737700	98	NAT	KL
1	818	19:50	Arr	GOT	Airport	B737700	98	NAT	KL
1	819	18:00	Arr	GOT	Airport	B737700	98	NAT	KL
1	820	15:10	Arr	GRU	Airport	B777200	229	INT	KL
1	821	08:50	Arr	GUW	Airport	B757PW	154	INT	4L
1	822	08:50	Arr	GVA	Airport	B737700	98	NAT	KL
1	823	20:35	Arr	GVA	Airport	FK70	64	NAT	KL
1	824	17:55	Arr	GVA	Airport	B737700	98	NAT	KL
1	825	14:50	Arr	GVA	Airport	FK70	64	NAT	KL
1	826	08:05	Arr	GVA	Airport	A319	125	NAT	DS
1	827	20:20	Arr	GVA	Airport	A319	125	NAT	DS
1	828	12:30	Arr	GVA	Airport	B737700	98	NAT	KL
1	829	18:35	Arr	HAJ	Airport	FK70	64	NAT	KL
1	830	12:35	Arr	HAJ	Airport	FK70	64	NAT	KL
1	831	08:00	Arr	HAJ	Airport	FK70	64	NAT	KL
1	832	15:25	Arr	HAJ	Airport	FK50	40	NAT	KL
1	833	18:30	Arr	HAM	Airport	FK70	64	NAT	KL
1	834	08:20	Arr	HAM	Airport	ATR42	37	NAT	LH
1	835	10:10	Arr	HAM	Airport	FK70	64	NAT	KL
1	836	18:55	Arr	HAM	Airport	ATR42	37	NAT	LH
1	837	15:30	Arr	HAM	Airport	ATR42	37	NAT	LH
1	838	07:55	Arr	HAM	Airport	FK100	81	NAT	KL
1	839	13:00	Arr	HAM	Airport	FK100	81	NAT	KL
1	840	15:35	Arr	HAM	Airport	FK70	64	NAT	KL
1	841	11:50	Arr	HAV	Airport	B767300	218	INT	MP
1	842	21:30	Arr	HEL	Airport	BAE146200	67	NAT	KF
1	843	07:55	Arr	HEL	Airport	B737700	98	NAT	KL
1	844	15:10	Arr	HEL	Airport	B737700	98	NAT	KL
1	845	18:25	Arr	HEL	Airport	B737700	98	NAT	KL
1	846	18:10	Arr	HEL	Airport	A320	106	NAT	AY
1	847	09:50	Arr	HEL	Airport	A320	106	NAT	AY

1	848	01:00	Arr	HER	Airport	B737800	149	NAT	HV
1	849	23:35	Arr	HER	Airport	B737800	149	NAT	HV
1	850	17:45	Arr	HKG	Airport	B747200	216	INT	KL
1	851	06:40	Arr	HKG	Airport	A340300	194	INT	CX
1	852	01:25	Arr	HRG	Airport	B737800	149	INT	HV
1	853	16:50	Arr	HUY	Airport	FK70	64	NAT	KL
1	854	08:40	Arr	HUY	Airport	FK70	64	NAT	KL
1	855	12:35	Arr	HUY	Airport	FK70	64	NAT	KL
1	856	06:55	Arr	IAD	Airport	B777200	214	INT	UA
1	857	06:55	Arr	IAD	Airport	B767200	176	INT	KL
1	858	12:20	Arr	IAH	Airport	MD11	0	INT	MP
1	859	08:20	Arr	IAH	Airport	B767200	139	INT	CO
1	860	11:55	Arr	IAH	Airport	B767400	187	INT	CO
1	861	08:00	Arr	IAH	Airport	B747200	216	INT	KL
1	862	16:50	Arr	ICN	Airport	B747200	216	INT	KL
1	863	18:55	Arr	ICN	Airport	A330200	206	INT	KE
1	864	11:00	Arr	ICN	Airport	B747400	0	INT	KE
1	865	19:20	Arr	ISB	Airport	A310	147	INT	PK
1	866	08:20	Arr	IST	Airport	B737700	98	INT	KL
1	867	17:55	Arr	IST	Airport	B737700	98	INT	KL
1	868	10:35	Arr	IST	Airport	B737800	124	INT	TK
1	869	16:30	Arr	IST	Airport	B737800	124	INT	TK
1	870	09:10	Arr	IST	Airport	B737700	98	INT	F2
1	871	08:00	Arr	JFK	Airport	B767300	156	INT	DL
1	872	12:20	Arr	JFK	Airport	B777200	229	INT	KL
1	873	07:35	Arr	JFK	Airport	B777200	229	INT	KL
1	874	09:30	Arr	JNB	Airport	B747200	216	INT	KL
1	875	06:20	Arr	KAN	Airport	B767200	176	INT	KL
1	876	09:05	Arr	KBP	Airport	B737700	98	NAT	PS
1	877	17:55	Arr	KBP	Airport	B737700	98	NAT	KL
1	878	21:40	Arr	KEF	Airport	B757PW	151	NAT	FI
1	879	12:30	Arr	KEF	Airport	B757PW	151	NAT	FI
1	880	08:30	Arr	KIV	Airport	A320	115	NAT	9U
1	881	15:15	Arr	KIX	Airport	B747200	216	INT	KL
1	882	13:20	Arr	KRS	Airport	FK70	64	NAT	KL
1	883	06:35	Arr	KUL	Airport	B747400	322	INT	MH
1	884	05:40	Arr	KUL	Airport	B747400	320	INT	KL
1	885	09:30	Arr	KWI	Airport	B747400	0	INT	SQ
1	886	06:20	Arr	KWI	Airport	B767200	176	INT	KL
1	887	11:40	Arr	LAX	Airport	B747200	216	INT	KL
1	888	18:10	Arr	LBA	Airport	FK70	64	NAT	KL
1	889	09:15	Arr	LBA	Airport	B737300	118	NAT	LS
1	890	20:15	Arr	LBA	Airport	B737300	118	NAT	LS
1	891	08:25	Arr	LBA	Airport	FK100	81	NAT	KL
1	892	12:55	Arr	LBA	Airport	FK100	81	NAT	KL
1	893	10:10	Arr	LCY	Airport	FK50	40	NAT	KL
1	894	10:10	Arr	LCY	Airport	FK50	40	NAT	VG
1	895	13:45	Arr	LCY	Airport	FK50	40	NAT	VG
1	896	17:35	Arr	LCY	Airport	FK50	40	NAT	VG
1	897	21:10	Arr	LCY	Airport	FK50	40	NAT	VG
1	898	19:00	Arr	LCY	Airport	FK50	40	NAT	KL
1	899	22:05	Arr	LCY	Airport	FK50	40	NAT	KL
1	900	10:00	Arr	LCY	Airport	FK50	40	NAT	KL
1	901	11:30	Arr	LCY	Airport	FK50	40	NAT	KL
1	902	20:30	Arr	LCY	Airport	FK50	40	NAT	KL
1	903	11:55	Arr	LCY	Airport	FK50	40	NAT	KL

1	904	09:15	Arr	LED	Airport	TU154	123	NAT	FV
1	905	08:25	Arr	LGW	Airport	A319	125	NAT	U2
1	906	20:25	Arr	LGW	Airport	A319	125	NAT	U2
1	907	13:55	Arr	LGW	Airport	A319	125	NAT	U2
1	908	16:50	Arr	LGW	Airport	A319	125	NAT	U2
1	909	21:45	Arr	LGW	Airport	B737700	91	NAT	BA
1	910	09:15	Arr	LGW	Airport	B737700	91	NAT	BA
1	911	11:40	Arr	LGW	Airport	B737700	91	NAT	BA
1	912	15:15	Arr	LGW	Airport	B737700	91	NAT	BA
1	913	17:30	Arr	LGW	Airport	B737700	91	NAT	BA
1	914	19:30	Arr	LGW	Airport	B737700	91	NAT	BA
1	915	20:55	Arr	LHR	Airport	A320	118	NAT	BD
1	916	08:40	Arr	LHR	Airport	A320	118	NAT	BD
1	917	13:00	Arr	LHR	Airport	A320	118	NAT	BD
1	918	22:25	Arr	LHR	Airport	A320	118	NAT	BD
1	919	18:40	Arr	LHR	Airport	A320	118	NAT	BD
1	920	10:20	Arr	LHR	Airport	A320	118	NAT	BD
1	921	16:55	Arr	LHR	Airport	A320	118	NAT	BD
1	922	20:30	Arr	LHR	Airport	B737700	98	NAT	KL
1	923	22:40	Arr	LHR	Airport	B737700	98	NAT	KL
1	924	11:05	Arr	LHR	Airport	B737700	98	NAT	KL
1	925	19:35	Arr	LHR	Airport	B737700	98	NAT	KL
1	926	18:00	Arr	LHR	Airport	B737700	98	NAT	KL
1	927	17:10	Arr	LHR	Airport	B737700	98	NAT	KL
1	928	08:55	Arr	LHR	Airport	B737700	98	NAT	KL
1	929	14:00	Arr	LHR	Airport	B737700	98	NAT	KL
1	930	12:15	Arr	LHR	Airport	B767200	176	NAT	KL
1	931	08:50	Arr	LHR	Airport	A320	119	NAT	BA
1	932	22:15	Arr	LHR	Airport	A319	101	NAT	BA
1	933	15:35	Arr	LHR	Airport	A319	101	NAT	BA
1	934	10:50	Arr	LHR	Airport	A319	101	NAT	BA
1	935	10:00	Arr	LHR	Airport	A319	101	NAT	BA
1	936	18:10	Arr	LHR	Airport	A319	101	NAT	BA
1	937	14:45	Arr	LHR	Airport	A319	104	NAT	BD
1	938	13:45	Arr	LHR	Airport	A321	146	NAT	BA
1	939	19:50	Arr	LHR	Airport	A321	146	NAT	BA
1	940	13:05	Arr	LIN	Airport	B737700	98	NAT	KL
1	941	08:45	Arr	LIN	Airport	A319	88	NAT	AZ
1	942	18:20	Arr	LIS	Airport	A320	125	NAT	TP
1	943	23:50	Arr	LIS	Airport	B737800	149	NAT	HV
1	944	09:55	Arr	LIS	Airport	B737700	98	NAT	KL
1	945	17:55	Arr	LIS	Airport	B737700	98	NAT	KL
1	946	06:30	Arr	LIS	Airport	B737700	98	NAT	KL
1	947	21:50	Arr	LIS	Airport	A319	106	NAT	TP
1	948	11:35	Arr	LIS	Airport	A319	106	NAT	TP
1	949	09:15	Arr	LJU	Airport	CRJ200	38	NAT	JP
1	950	06:10	Arr	LOS	Airport	MD11	226	INT	KL
1	951	08:30	Arr	LPL	Airport	B737300	119	NAT	U2
1	952	17:55	Arr	LPL	Airport	B737300	119	NAT	U2
1	953	12:05	Arr	LPL	Airport	B737300	119	NAT	U2
1	954	21:20	Arr	LPL	Airport	B737300	119	NAT	U2
1	955	21:30	Arr	LTN	Airport	B737700	119	NAT	U2
1	956	14:50	Arr	LTN	Airport	B737700	119	NAT	U2
1	957	08:10	Arr	LTN	Airport	B737700	119	NAT	U2
1	958	17:50	Arr	LTN	Airport	B737700	119	NAT	U2
1	959	11:25	Arr	LTN	Airport	B737300	119	NAT	U2

1	960	12:35	Arr	LUX	Airport	FK50	40	NAT	KL
1	961	17:25	Arr	LUX	Airport	FK50	40	NAT	KL
1	962	08:15	Arr	LUX	Airport	FK50	40	NAT	KL
1	963	08:35	Arr	LYS	Airport	FK100	81	NAT	KL
1	964	18:10	Arr	LYS	Airport	FK100	81	NAT	KL
1	965	13:20	Arr	LYS	Airport	B737700	98	NAT	KL
1	966	10:40	Arr	LYS	Airport	EMB145	40	NAT	AF
1	967	15:25	Arr	LYS	Airport	EMB145	40	NAT	AF
1	968	21:25	Arr	LYS	Airport	EMB145	40	NAT	AF
1	969	15:35	Arr	MAD	Airport	B737700	98	NAT	KL
1	970	17:40	Arr	MAD	Airport	B737700	98	NAT	KL
1	971	22:15	Arr	MAD	Airport	B737700	98	NAT	KL
1	972	09:05	Arr	MAD	Airport	B737700	98	NAT	KL
1	973	13:15	Arr	MAD	Airport	B737700	98	NAT	KL
1	974	22:50	Arr	MAD	Airport	B737700	119	NAT	HV
1	975	15:15	Arr	MAD	Airport	A320	120	NAT	IB
1	976	21:40	Arr	MAD	Airport	A320	120	NAT	IB
1	977	11:15	Arr	MAD	Airport	A320	120	NAT	IB
1	978	18:45	Arr	MAD	Airport	A320	120	NAT	IB
1	979	10:40	Arr	MAN	Airport	FK70	64	NAT	KL
1	980	08:35	Arr	MAN	Airport	B737700	98	NAT	KL
1	981	12:55	Arr	MAN	Airport	B737700	98	NAT	KL
1	982	10:20	Arr	MAN	Airport	B737300	118	NAT	LS
1	983	20:00	Arr	MAN	Airport	B737300	118	NAT	LS
1	984	15:10	Arr	MAN	Airport	B737300	118	NAT	LS
1	985	19:00	Arr	MAN	Airport	B737700	98	NAT	KL
1	986	21:55	Arr	MAN	Airport	FK100	81	NAT	KL
1	987	14:40	Arr	MAN	Airport	B747400	0	NAT	KA
1	988	18:00	Arr	MAN	Airport	B747400	0	NAT	CI
1	989	17:15	Arr	MAN	Airport	FK100	81	NAT	KL
1	990	15:00	Arr	MAN	Airport	FK100	81	NAT	KL
1	991	10:50	Arr	MBJ	Airport	B767300	184	INT	YZ
1	992	09:25	Arr	MCO	Airport	B767300	218	INT	MP
1	993	11:10	Arr	MEM	Airport	DC1030	216	INT	NW
1	994	14:35	Arr	MEX	Airport	B747200	216	INT	KL
1	995	12:00	Arr	MIA	Airport	B767300	218	INT	MP
1	996	19:25	Arr	MLA	Airport	A319	106	NAT	KM
1	997	12:55	Arr	MME	Airport	FK70	64	NAT	KL
1	998	18:00	Arr	MME	Airport	FK70	64	NAT	KL
1	999	08:25	Arr	MME	Airport	FK100	81	NAT	KL
1	1000	05:30	Arr	MNL	Airport	B777200	229	INT	KL
1	1001	18:15	Arr	MRS	Airport	FK70	64	NAT	KL
1	1002	14:15	Arr	MRS	Airport	FK70	64	NAT	KL
1	1003	08:55	Arr	MRS	Airport	FK70	64	NAT	KL
1	1004	18:45	Arr	MSE	Airport	FK100	86	NAT	VE
1	1005	09:15	Arr	MSP	Airport	DC1030	216	INT	NW
1	1006	12:25	Arr	MSP	Airport	DC1030	216	INT	NW
1	1007	06:30	Arr	MSP	Airport	DC1030	216	INT	NW
1	1008	07:10	Arr	MST	Airport	FK50	40	NAT	KL
1	1009	12:40	Arr	MST	Airport	FK50	40	NAT	KL
1	1010	09:55	Arr	MST	Airport	FK50	40	NAT	KL
1	1011	18:15	Arr	MST	Airport	FK50	40	NAT	KL
1	1012	20:35	Arr	MUC	Airport	CRJ100	40	NAT	LH
1	1013	08:10	Arr	MUC	Airport	CRJ100	40	NAT	LH
1	1014	16:25	Arr	MUC	Airport	CRJ100	40	NAT	LH
1	1015	22:25	Arr	MUC	Airport	CRJ100	40	NAT	LH

1	1016	18:30	Arr	MUC	Airport	CRJ700	56	NAT	LH
1	1017	11:55	Arr	MUC	Airport	B737700	98	NAT	KL
1	1018	15:15	Arr	MUC	Airport	FK70	64	NAT	KL
1	1019	17:55	Arr	MUC	Airport	B737700	98	NAT	KL
1	1020	08:20	Arr	MUC	Airport	B737700	98	NAT	KL
1	1021	21:45	Arr	MUC	Airport	FK70	64	NAT	KL
1	1022	12:25	Arr	MUC	Airport	CRJ100	40	NAT	LH
1	1023	18:40	Arr	MXP	Airport	B737700	98	NAT	KL
1	1024	08:30	Arr	MXP	Airport	B737700	98	NAT	KL
1	1025	22:45	Arr	MXP	Airport	B737700	98	NAT	KL
1	1026	15:05	Arr	MXP	Airport	B737700	98	NAT	KL
1	1027	22:20	Arr	MXP	Airport	A320	105	NAT	AZ
1	1066	14:45	Arr	OSL	Airport	B737700	98	NAT	KL
1	1067	08:35	Arr	OSL	Airport	B737700	98	NAT	KL
1	1068	12:30	Arr	OSL	Airport	B737700	98	NAT	KL
1	1069	18:30	Arr	OSL	Airport	B737700	98	NAT	KL
1	1070	08:10	Arr	OTP	Airport	B737700	98	NAT	KL
1	1071	15:25	Arr	OTP	Airport	B737700	98	NAT	KL
1	1072	17:15	Arr	OTP	Airport	B737700	98	NAT	KL
1	1073	08:45	Arr	PBM	Airport	B747400	320	INT	KL
1	1074	14:40	Arr	PEK	Airport	B747200	216	INT	KL
1	1075	17:55	Arr	PEK	Airport	B777200	304	INT	CZ
1	1076	12:25	Arr	PFO	Airport	A330300	236	INT	CY
1	1077	09:55	Arr	PHL	Airport	B767200	162	INT	US
1	1078	15:15	Arr	PRG	Airport	B737500	83	NAT	OK
1	1079	08:55	Arr	PRG	Airport	B737500	85	NAT	QS
1	1080	12:45	Arr	PRG	Airport	B737700	98	NAT	KL
1	1081	08:40	Arr	PRG	Airport	B737400	112	NAT	OK
1	1082	17:50	Arr	PRG	Airport	B737700	98	NAT	KL
1	1083	18:45	Arr	PRG	Airport	A320	120	NAT	OK
1	1084	16:35	Arr	PSA	Airport	B737700	119	NAT	HV
1	1085	17:40	Arr	PVG	Airport	B747200	216	INT	KL
1	1086	00:45	Arr	RHO	Airport	B737800	149	NAT	HV
1	1087	15:20	Arr	RIX	Airport	FK70	64	NAT	KL
1	1088	08:25	Arr	RIX	Airport	FK70	64	NAT	KL
1	1089	09:05	Arr	RIX	Airport	B737500	96	NAT	BT
1	1090	08:05	Arr	SEA	Airport	A330300	214	INT	NW
1	1091	11:35	Arr	SFO	Airport	B777200	229	INT	KL
1	1092	00:20	Arr	SHJ	Airport	B747400	0	INT	MP
1	1093	07:15	Arr	SIN	Airport	B777200	258	INT	SQ
1	1094	05:50	Arr	SIN	Airport	B747200	216	INT	KL
1	1095	13:20	Arr	SMI	Airport	B737800	149	NAT	HV
1	1096	09:00	Arr	SOF	Airport	B737300	109	NAT	FB
1	1097	09:00	Arr	SOU	Airport	Do328	25	NAT	CB
1	1098	12:45	Arr	SOU	Airport	Do328	25	NAT	CB
1	1099	20:25	Arr	SOU	Airport	Do328	25	NAT	CB
1	1100	17:00	Arr	SOU	Airport	Do328	25	NAT	CB
1	1101	15:20	Arr	SPC	Airport	B737800	149	NAT	HV
1	1102	17:10	Arr	SPC	Airport	B737800	149	NAT	HV
1	1103	09:05	Arr	STN	Airport	A319	125	NAT	U2
1	1142	07:30	Arr	TXL	Airport	B737700	115	NAT	AB
1	1143	08:20	Arr	VCE	Airport	B737700	98	NAT	KL
1	1144	14:55	Arr	VCE	Airport	B737700	98	NAT	KL
1	1145	18:25	Arr	VCE	Airport	B737700	98	NAT	KL
1	1146	22:00	Arr	VIE	Airport	A320	107	NAT	OS
1	1147	15:50	Arr	VIE	Airport	CRJ200	40	NAT	OS

1	1148	21:20	Arr	VIE	Airport	FK70	64	NAT	KL
1	1149	08:45	Arr	VIE	Airport	B737700	98	NAT	KL
1	1150	18:15	Arr	VIE	Airport	B737700	98	NAT	KL
1	1151	13:00	Arr	VIE	Airport	FK100	81	NAT	KL
1	1152	19:20	Arr	VIE	Airport	A319	101	NAT	OS
1	1153	09:20	Arr	VIE	Airport	A319	101	NAT	OS
1	1154	17:55	Arr	VNO	Airport	B737700	98	NAT	TE
1	1155	09:05	Arr	VNO	Airport	B737700	98	NAT	TE
1	1156	23:15	Arr	VRN	Airport	B737700	119	NAT	HV
1	1157	09:45	Arr	WAW	Airport	EMB145	38	NAT	LO
1	1158	22:00	Arr	WAW	Airport	EMB145	38	NAT	LO
1	1159	09:05	Arr	WAW	Airport	B737700	98	NAT	KL
1	1160	15:00	Arr	WAW	Airport	B737700	98	NAT	KL
1	1161	18:25	Arr	WAW	Airport	B737700	98	NAT	KL
1	1162	19:00	Arr	WAW	Airport	EMB170	56	NAT	LO
1	1163	08:30	Arr	YEG	Airport	B767300	218	INT	MP
1	1164	06:45	Arr	YUL	Airport	MD11	226	INT	KL
1	1165	07:40	Arr	YVR	Airport	MD11	226	INT	KL
1	1166	12:20	Arr	YYZ	Airport	B767200	158	INT	AC
1	1167	07:15	Arr	YYZ	Airport	B747400	320	INT	KL
1	1168	10:30	Arr	ZAG	Airport	A319	106	NAT	OU
1	1169	16:50	Arr	ZAG	Airport	A319	106	NAT	OU
1	1170	14:05	Arr	ZRH	Airport	BAE1463	78	NAT	LX
1	1171	19:00	Arr	ZRH	Airport	A320	134	NAT	LX
1	1172	12:15	Arr	ZRH	Airport	B737700	98	NAT	KL
1	1173	14:05	Arr	ZRH	Airport	FK100	81	NAT	KL
1	1174	18:25	Arr	ZRH	Airport	FK100	81	NAT	KL
1	1175	20:10	Arr	ZRH	Airport	B737700	98	NAT	KL
1	1176	08:45	Arr	ZRH	Airport	B737700	98	NAT	KL
1	1177	08:55	Arr	ZRH	Airport	A319	101	NAT	LX
1	1178	21:40	Arr	ZRH	Airport	A319	101	NAT	LX
1	1028	11:05	Arr	MXP	Airport	A320	105	NAT	AZ
1	1029	17:00	Arr	MXP	Airport	MD88	105	NAT	AZ
1	1030	18:10	Arr	NAP	Airport	B737700	119	NAT	HV
1	1031	18:10	Arr	NBO	Airport	B777200	258	INT	KQ
1	1032	05:35	Arr	NBO	Airport	B777200	229	INT	KL
1	1033	18:35	Arr	NCE	Airport	B737700	98	NAT	KL
1	1034	12:50	Arr	NCE	Airport	FK70	64	NAT	KL
1	1035	08:30	Arr	NCE	Airport	B737700	98	NAT	KL
1	1036	11:25	Arr	NCE	Airport	B737700	119	NAT	HV
1	1037	23:35	Arr	NCE	Airport	B737700	119	NAT	HV
1	1038	18:35	Arr	NCE	Airport	B737700	119	NAT	HV
1	1039	15:30	Arr	NCL	Airport	FK70	64	NAT	KL
1	1040	13:00	Arr	NCL	Airport	B737700	98	NAT	KL
1	1041	18:25	Arr	NCL	Airport	FK100	81	NAT	KL
1	1042	08:40	Arr	NCL	Airport	FK100	81	NAT	KL
1	1043	21:20	Arr	NCL	Airport	FK100	81	NAT	KL
1	1044	12:30	Arr	NDR	Airport	B737500	87	INT	AT
1	1045	15:15	Arr	NRT	Airport	B777200	229	INT	KL
1	1046	17:45	Arr	NRT	Airport	B747400	261	INT	JL
1	1047	12:40	Arr	NUE	Airport	FK70	64	NAT	KL
1	1048	17:30	Arr	NUE	Airport	FK70	64	NAT	KL
1	1049	08:20	Arr	NUE	Airport	FK70	64	NAT	KL
1	1050	08:20	Arr	NWI	Airport	FK70	64	NAT	KL
1	1051	18:25	Arr	NWI	Airport	FK70	64	NAT	KL
1	1052	12:05	Arr	NWI	Airport	FK70	64	NAT	KL

1	1053	15:45	Arr	NWI	Airport	FK50	40	NAT	KL
1	1054	13:25	Arr	OPO	Airport	A320	125	NAT	TP
1	1055	12:40	Arr	OPO	Airport	FK100	76	NAT	NI
1	1056	09:15	Arr	ORD	Airport	B767300	170	INT	UA
1	1057	08:00	Arr	ORD	Airport	B747400	0	INT	SQ
1	1058	08:40	Arr	ORD	Airport	MD11	0	INT	MP
1	1059	07:35	Arr	ORD	Airport	B747200	216	INT	KL
1	1060	19:40	Arr	ORK	Airport	A320	120	NAT	EI
1	1061	09:35	Arr	ORK	Airport	A320	120	NAT	EI
1	1062	14:45	Arr	OSL	Airport	B737600	82	NAT	SK
1	1063	19:35	Arr	OSL	Airport	B737600	82	NAT	SK
1	1064	09:35	Arr	OSL	Airport	B737600	82	NAT	SK
1	1065	20:55	Arr	OSL	Airport	B737700	98	NAT	KL
1	1104	16:35	Arr	STN	Airport	A319	125	NAT	U2
1	1105	21:05	Arr	STN	Airport	A319	125	NAT	U2
1	1106	03:55	Arr	STN	Airport	MD11	0	NAT	MP
1	1107	17:15	Arr	STR	Airport	FK70	64	NAT	KL
1	1108	15:40	Arr	STR	Airport	FK70	64	NAT	KL
1	1109	19:35	Arr	STR	Airport	FK70	64	NAT	KL
1	1110	07:50	Arr	STR	Airport	FK100	81	NAT	KL
1	1111	12:45	Arr	STR	Airport	FK100	81	NAT	KL
1	1112	18:05	Arr	SVG	Airport	FK100	81	NAT	KL
1	1113	13:15	Arr	SVG	Airport	FK100	81	NAT	KL
1	1114	08:05	Arr	SVG	Airport	FK100	81	NAT	KL
1	1115	12:10	Arr	SVO	Airport	A319	93	NAT	SU
1	1116	17:45	Arr	SVO	Airport	B737700	98	NAT	KL
1	1117	12:55	Arr	SZG	Airport	Do328	25	NAT	A6
1	1118	17:55	Arr	SZG	Airport	Do328	25	NAT	A6
1	1119	08:05	Arr	SZG	Airport	Do328	25	NAT	A6
1	1120	06:05	Arr	TBS	Airport	B737700	98	NAT	KL
1	1121	09:00	Arr	TLL	Airport	B737500	86	NAT	OV
1	1122	15:25	Arr	TLL	Airport	FK70	64	NAT	KL
1	1123	18:25	Arr	TLS	Airport	FK100	81	NAT	KL
1	1124	08:50	Arr	TLS	Airport	FK100	81	NAT	KL
1	1125	14:45	Arr	TLS	Airport	FK100	81	NAT	KL
1	1126	08:50	Arr	TLV	Airport	B767200	165	INT	LY
1	1127	09:35	Arr	TLV	Airport	B737700	98	INT	KL
1	1128	02:45	Arr	TLV	Airport	B747400	0	INT	75C
1	1129	20:25	Arr	TLV	Airport	B747400	0	INT	LY
1	1130	20:50	Arr	TLV	Airport	B747400	0	INT	LY
1	1131	04:00	Arr	TLV	Airport	B747400	0	INT	LY
1	1132	15:10	Arr	TRD	Airport	FK70	64	NAT	KL
1	1133	08:40	Arr	TRD	Airport	FK70	64	NAT	KL
1	1134	08:40	Arr	TRF	Airport	FK70	64	NAT	KL
1	1135	18:10	Arr	TRF	Airport	FK70	64	NAT	KL
1	1136	18:20	Arr	TSF	Airport	B737700	119	NAT	HV
1	1137	17:35	Arr	TXL	Airport	FK100	81	NAT	KL
1	1138	19:35	Arr	TXL	Airport	FK100	81	NAT	KL
1	1139	07:45	Arr	TXL	Airport	B737700	98	NAT	KL
1	1140	10:30	Arr	TXL	Airport	FK70	64	NAT	KL
1	1141	13:05	Arr	TXL	Airport	B737700	98	NAT	KL

Table B.1: Schiphol schedule from 2005, only the arrivals are in the schedule

C

Great Circle Distance

The Great Circle Distance calculation method for obtaining the distance between two locations on a sphere is used in the calculation for the service rate. Distance is calculated by the location of the airports of a origin and destination of a flight, the coordinates in latitude and longitude are used for this calculation. By the use of these coordinates the distance could be determined, and used for the probability distribution used to assign distances to the random generated service rate. These distances are then used for the weight class distribution of the different flights. Is is based on the Schiphol schedule given in Appendix B in combination with a list of locations, latitude and longitude coordinates, of the airports in the world.

The following part will be about the calculation of the great circle distance between two locations on a sphere, assumed that the earth is a smooth sphere. Which in a real life situation is not the case but for the scope of this research it gives a good estimation of the distances. The great circle distance is based on a combination of the Cartesian coordinate system and the earth's radius[4, 51]. In the Equations C.1, C.2 and C.3 the distances in the X, Y and Z direction are shown respectively. These equations are based on the latitude, ϕ, and longitude, λ, and a location one and two of the two airports, origin indicated as one and destination as two. Also an illustration is added to give an idea of the angles and the variables in Figure C.1.

$$\Delta X = \cos\phi_2 \cdot \cos\lambda_2 - \cos\phi_1 \cdot \cos\lambda_1 \tag{C.1}$$

$$\Delta Y = \cos\phi_2 \cdot \sin\lambda_2 - \cos\phi_1 \cdot \sin\lambda_1 \tag{C.2}$$

$$\Delta Z = \sin\phi_2 - \sin\phi_1 \tag{C.3}$$

The difference in X, Y and Z direction will give the three axis distances from the origins to the destinations location. Next is determine the cross distance of these three distances over the three axis' combined, as shown in Equation C.4 and called the great circle chord length, C.

$$C = \sqrt{(\Delta X)^2 + (\Delta Y)^2 + (\Delta Z)^2} \tag{C.4}$$

Using the great circle chord length it is possible the determine the angle over the sphere from origin to destination, this angle is called the central angle indicated as $\Delta\sigma$. Next step is to determine the actual length of the arc over the sphere. In Equation C.6 it is shown how the arc length is obtained by the use of the radius of the sphere, which in this situation is the earth's radius, $R_E = 6378.631 km$[30, 38].

$$\Delta\sigma = 2 \arcsin \frac{C}{2} \tag{C.5}$$

$$d = r\Delta\sigma = R_E\Delta\sigma \tag{C.6}$$

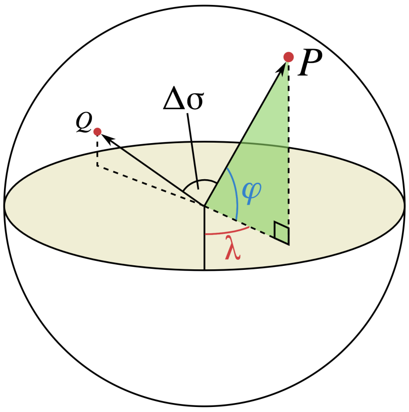


Figure C.1: Illustration of the variables in the Great Circle Distance method, P and Q indicate the origin and destination, as an example the latitude and longitude are indicated for the origin, P, and the central angle $\Delta\sigma$ is also indicated

D

Discrete Event Simulation

In this appendix a brief and concise explanation will be given on the discrete event simulation(DES) Approach. This approach is used to obtain a realistic image of the arrival pattern resulting from the generated arrival rate and service rate. Before getting the application of the airport arrival operations it is best to obtain some knowledge on the DES approach itself.

The discrete event simulation method is based on modelling the discrete sequence of events. An event is indicated as the time at which the handling occurs and the type of handling occurring. The queuing system is an example of a discrete event system where an arriving object at a counter is an event following by the next event where the object got serviced and the next event is that the object leaves the system. Every change in the system has certain duration in time which is called these events. It can be explained most easily by a figure or flow diagram, simulating the basic arriving events, serviced events and leaving events.

In the situation in Figure D.1 a queuing model is given as the DES example. The first event occurring in the flow diagram is the arriving object, the next event is enter or skip the queue:

1. Enter the queue - In this case there are already objects waiting for service and therefore those objects are in the queue. The event of being in the queue will take the time till the object can enter one of the service places.
2. Skip the queue - In this case the object actually enters the queue but there are no object in the queue and there is a service spot available. So the time of the object in the queue equals zero.

The next event is the service event, the object gets from the queue into one of the spots where it gets service. The event of service takes the time it needs to deliver service to one object. In Figure D.1 three service points are given where each object can get service, it depends on the situation and the operation if there is chosen to use more service points. After the event of the service is done the object leaves the operation indicated as leaving.

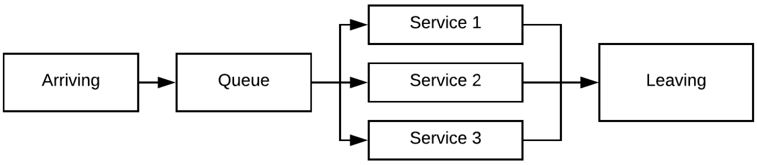


Figure D.1: Discrete Event Simulation example, a Queuing model

As given in this explanation, every event takes a certain amount of time. The purpose of using the Discrete Event Simulation for logistic issues is to model and predict the time it takes for an object to get it from arrival to finish the service and leaves the operation. This system can be very useful for operating in handling traffic or in factory service.

E

Monte Carlo Simulation

In this Appendix a short explanation is given on the Monte Carlo simulation method. It mainly focuses on the application of in the modelling of the uncertainties and what the outcome will be of the simulations. Therefore it discusses the application of probability distribution in forecasting models, which is also used for the research on the effectiveness of demand management strategies.

The Monte Carlo simulation is used for forecasting models to cope with a combination of probability distributions. So it can be said that the method is for forecasting uncertainty in the models. It is used for the evaluation of the effectiveness of the airport demand management strategies because several different probability distributions are used, the normal probability distributions for the arrival time and service time and the uniform distribution for the selection of the arrival rates.

Forecasting models always have to cope with different uncertainties and risks therefore certain assumptions are made in such a model. Because the method is based on executing the model for a number of simulation runs the Monte Carlo simulation gives an estimation of the area given by the input. In the several probability distributions used for obtaining a forecast or risk analysis boundaries are given to the distributions. Within the boundaries the models generates certain values according to the distribution used in the model. If more distributions are used in the forecast the whole model is executed a number of simulation runs to incorporate all the used probability distributions and obtain the result from all the distributions combined. By running the model a number of times it generates for every run a new value within the given boundaries, therefore more runs are needed. The input is given in boundaries and not in absolute values, by running the model hundreds or thousands of times the most probable value can be generated by averaging the outcome of the multiple runs.

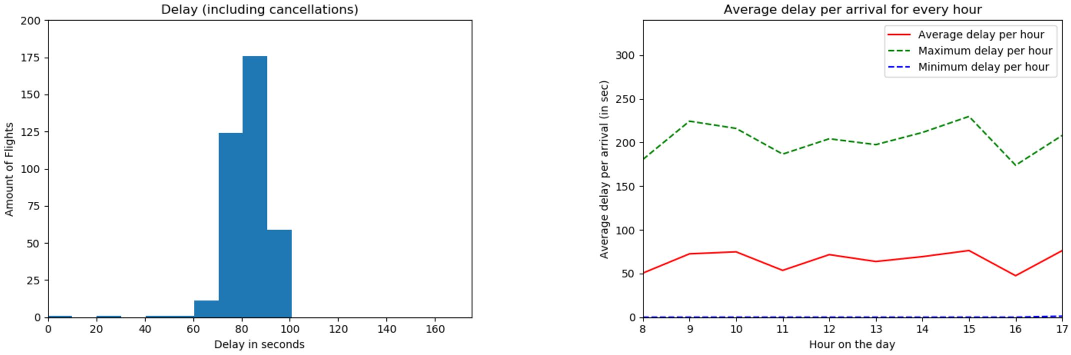
In the application of the Monte Carlo simulations into logistic issues is mostly because of incorporating the stochastic behaviour at the logistic behaviour. Also in this research the probability distributions are used to generate the values for some of the inputs, therefore it is required to use Monte Carlo simulations to cope with the uncertainties of these probability distributions. These logistic processes are modelled with a different approach and this approach will then be repeated a number of times, the result of every run separately will be conserved and at the end of the repetitions this result will be averaged, which is the result of the MC simulation. It is in these cases just used for minimising the uncertainty of the use of the stochastic implementation by the probability distribution.

F

Results: Arrival Operations of the Strategies

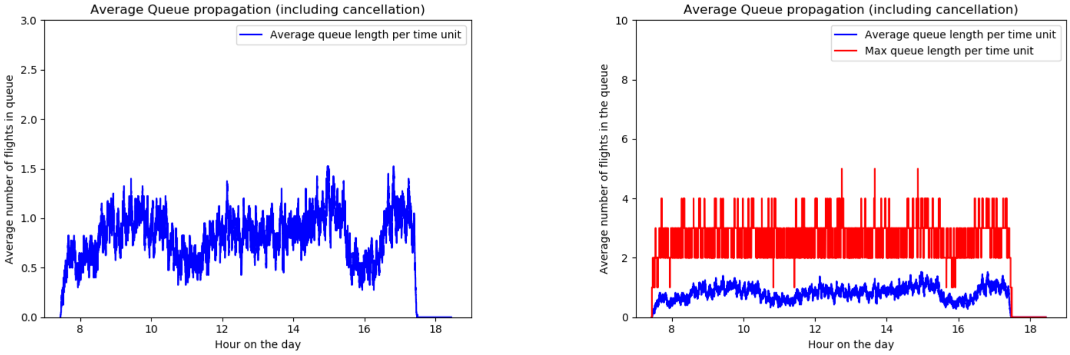
In this appendix a number of results are presented on the arrival operations of the strategies. Several strategy inputs are used, first results on the time-based delay strategy will be given in Section F.1 followed by the results on the consecutive delay strategy in Section F.2. These results show the monitoring results of the operational simulated hours.

F.1. Time-Based Strategy



(a) Average waiting time distribution

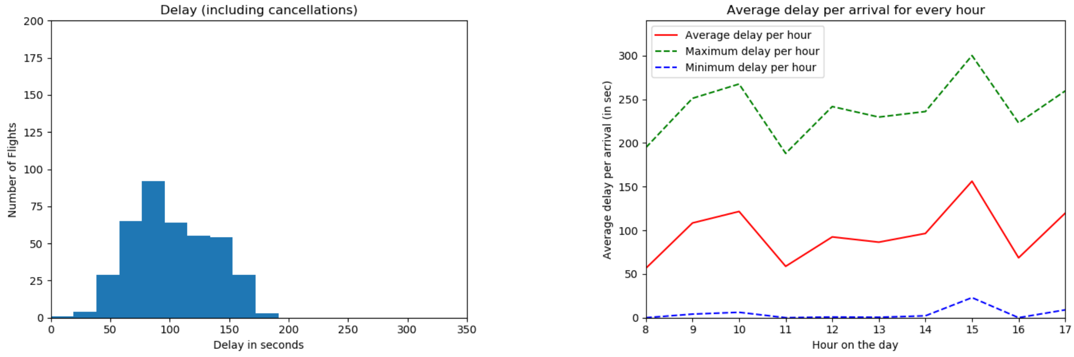
(b) Average delay per arrival through the operation



(c) Average queue propagation

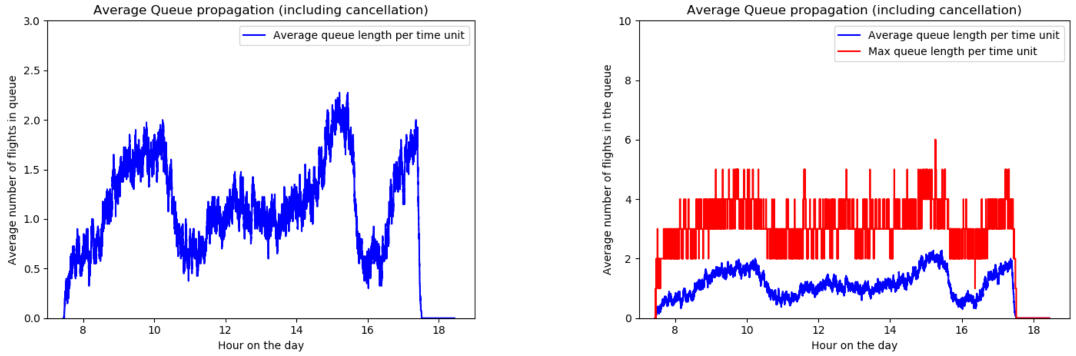
(d) Average and maximum queue propagation

Figure F.1: Operational monitoring results of simulation for $d_{t_{max}} = 200$s



(a) Average waiting time distribution

(b) Average delay per arrival through the operation

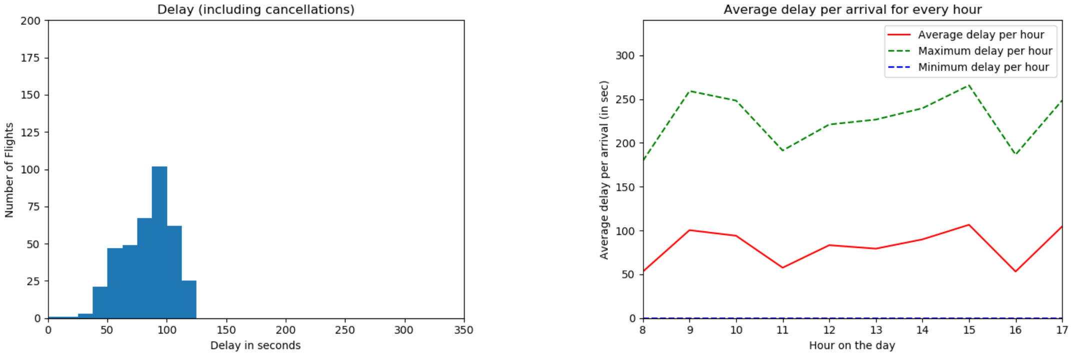


(c) Average queue propagation

(d) Average and maximum queue propagation

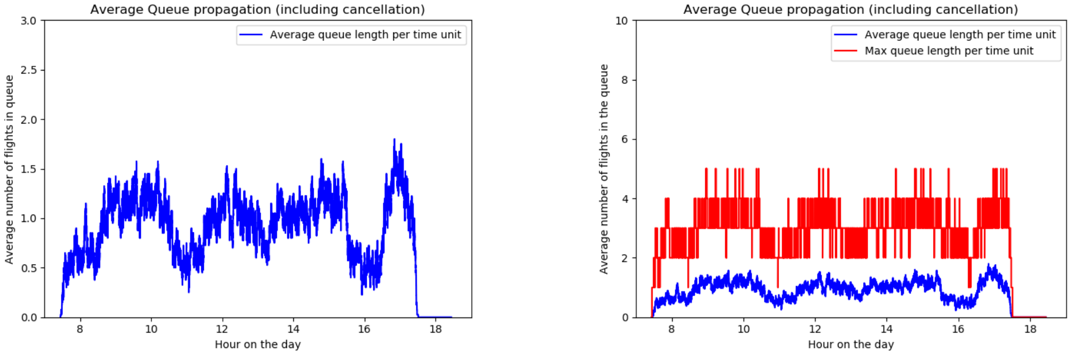
Figure F.2: Operational monitoring results of simulation for $d_{t_{max}} = 350$s

F.2. Consecutive delay Strategy



(a) Average waiting time distribution

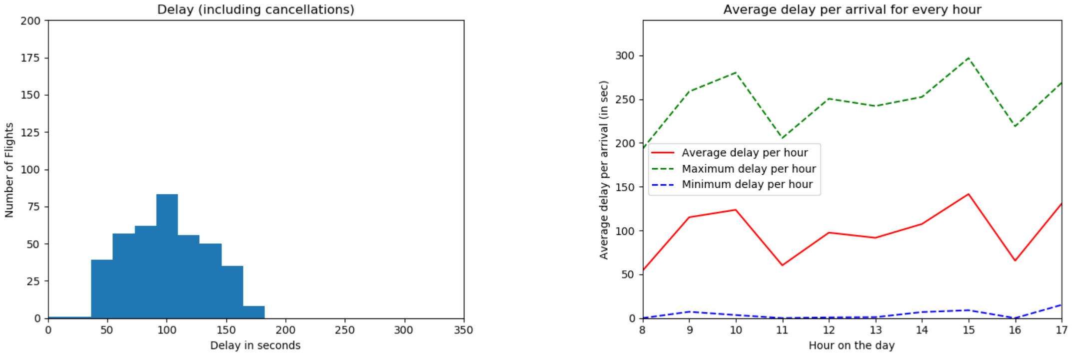
(b) Average delay per arrival through the operation



(c) Average queue propagation

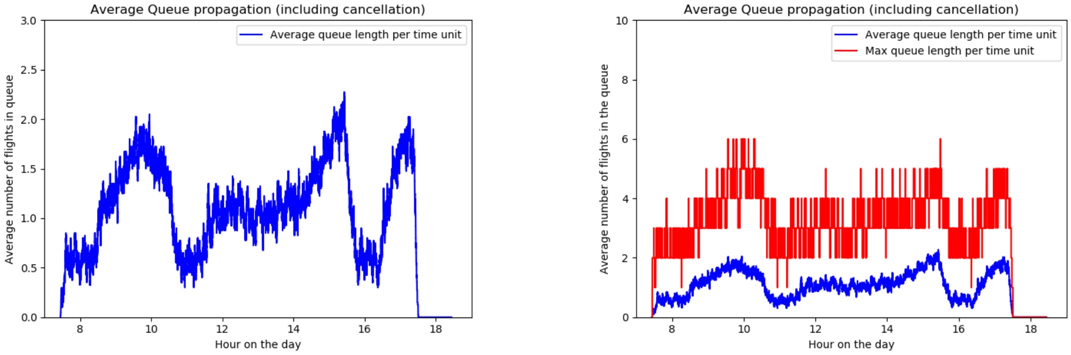
(d) Average and maximum queue propagation

Figure F.3: Operational monitoring results of simulation for $d_{c_{max}} = 20$ consecutive delayed arrivals



(a) Average waiting time distribution

(b) Average delay per arrival through the operation



(c) Average queue propagation

(d) Average and maximum queue propagation

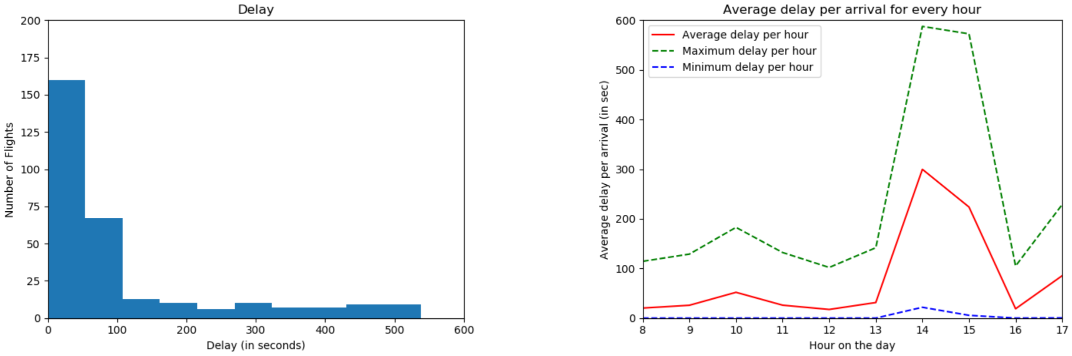
Figure F.4: Operational monitoring results of simulation for $d_{c_{max}} = 50$ consecutive delayed arrivals

G

Results: Case Study Amsterdam Airport Schiphol

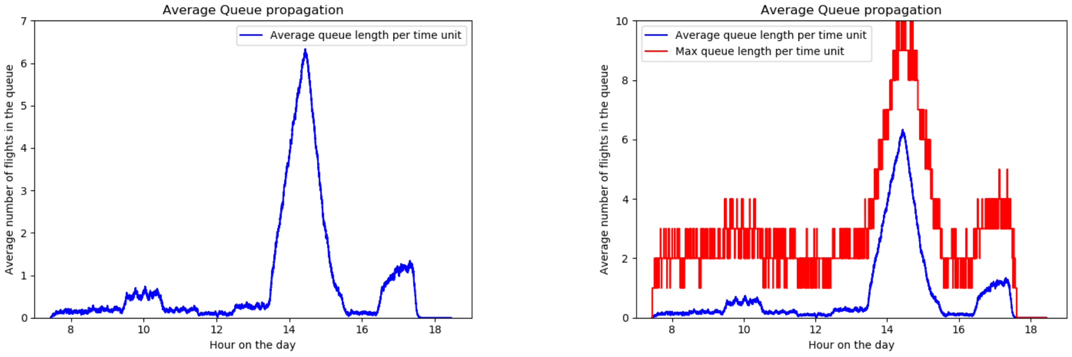
In this appendix a number of results are presented on the arrival operations of the strategies subjected to the data of a real life Schiphol schedule. First results of no strategy input will be given in Section G.1 followed by the time-based delay strategy in Section G.2 and at last the consecutive delay strategy will be presented in Section G.3. These results show the monitoring results of the operational simulated hours.

G.1. No Strategy



(a) Average waiting time distribution

(b) Average delay per arrival through the operation

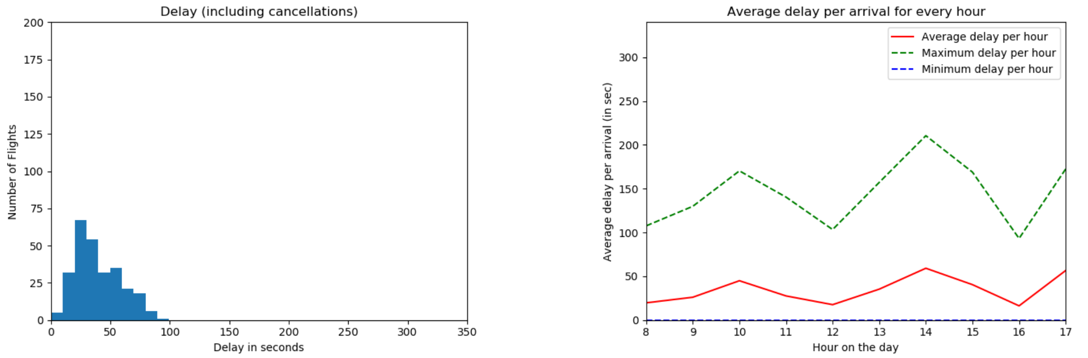


(c) Average queue propagation

(d) Average and maximum queue propagation

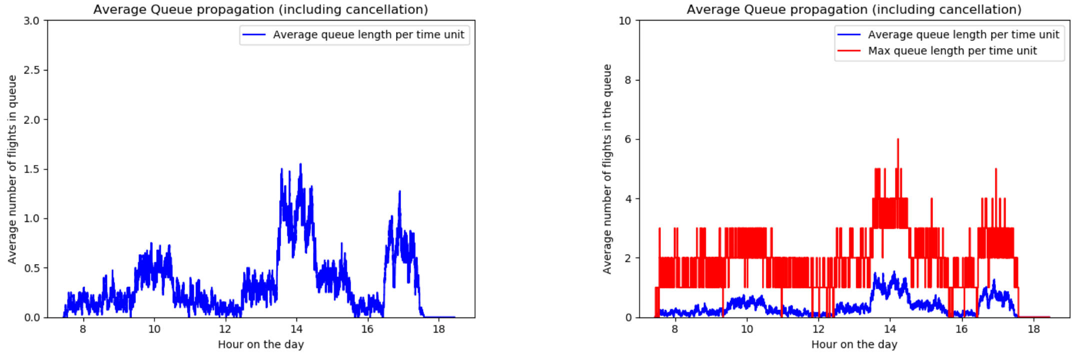
Figure G.1: Operational monitoring results of case study no strategy

G.2. Time-Based Delay Strategy



(a) Average waiting time distribution

(b) Average delay per arrival through the operation

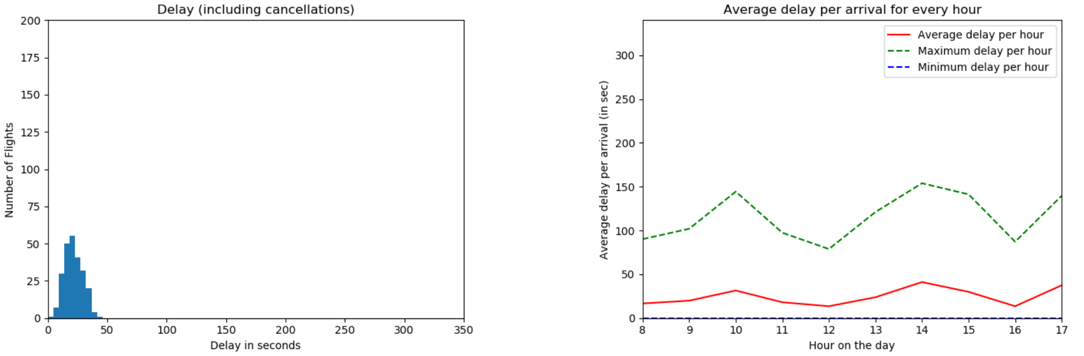


(c) Average queue propagation

(d) Average and maximum queue propagation

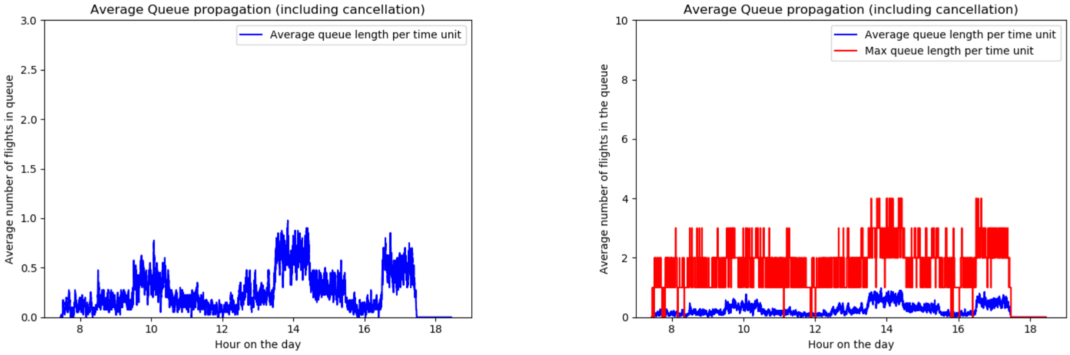
Figure G.2: Operational monitoring results of case study time-based delay strategy of $d_{t_{max}} = 100$s

G.3. Consecutive Delay Strategy



(a) Average waiting time distribution

(b) Average delay per arrival through the operation



(c) Average queue propagation

(d) Average and maximum queue propagation

Figure G.3: Operational monitoring results of case study time-based delay strategy of $d_{c_{max}} = 5$ consecutive delayed arrivals

H

Cost of a delaying Aircraft

The cost of the delay is not researched into detail but from the data found and presented in Table H.1 and H.2 a visualisation on the cost is obtained. Figure H.1 shows the relation between the delay in minutes and the corresponding cost of the delay. Also a division is made between the en-route and the at-gate delays, as can be seen the difference between the at-gate and the en-route delays is not large compared to the differences between the medium size aircraft and the heavy size aircraft. So it can be said that the profit can be achieved at the heavy aircraft. The cost figure has an exponential growth of the cost per minute of delay until the 120 minutes of delay and from that point the cost per extra minute are in linear relation. The cost of the delay of an aircraft is divided into several parts and one of those parts increases a lot in the beginning, this is most probably the cost of repayment to the passengers of the ticket price.

Table H.1: The At-gate delay cost given for different aircraft types delaying for different amounts of time[15]

Aircraft	Weight class	5	15	30	60	90	120	180	240	300
B733	Medium	€110	€710	€2.800	€14.110	€39.300	€77.120	€96.000	€121.530	€154.780
B734	Medium	€130	€800	€3.130	€15.860	€44.250	€86.690	€107.780	€136.130	€172.760
B735	Medium	€110	€650	€2.540	€12.720	€35.320	€69.430	€86.520	€109.770	€140.250
B738	Medium	€150	€890	€3.510	€17.750	€49.530	€96.840	€120.310	€151.700	€191.960
B752	Medium	€150	€1.020	€4.100	€21.210	€59.660	€116.380	€144.390	€181.620	€228.980
B763	Heavy	€400	€1.840	€6.050	€26.850	€71.550	€153.610	€210.290	€251.840	€304.210
B744	Heavy	€540	€2.640	€9.030	€41.360	€111.610	€241.220	€330.050	€393.750	€472.750
A319	Medium	€120	€730	€2.870	€14.630	€40.910	€80.010	€99.660	€126.210	€160.710
A320	Medium	€130	€820	€3.260	€16.650	€46.660	€91.140	€113.350	€143.190	€181.640
A321	Medium	€140	€950	€3.860	€19.960	€56.170	€109.440	€135.940	€171.250	€216.350
AT43	Medium	€50	€300	€1.110	€5.360	€14.630	€29.270	€37.140	€48.640	€65.050
AT72	Medium	€70	€400	€1.490	€7.350	€20.220	€40.140	€50.500	€65.200	€85.410
DH8D	Medium	€70	€420	€1.590	€7.850	€21.640	€42.840	€53.850	€69.360	€90.570
E190	Medium	€90	€550	€2.100	€10.410	€28.820	€56.740	€70.960	€90.530	€116.610
A332	Heavy	€420	€1.980	€6.620	€29.630	€79.260	€170.570	€233.510	€279.370	€336.920

Table H.2: The En-route delay cost given for different aircraft types delaying for different amounts of time[15]

Aircraft	Weight class	5	15	30	60	90	120	180	240	300
B733	Medium	€320	€1.320	€4.010	€16.540	€42.950	€81.980	€103.300	€131.250	€166.940
B734	Medium	€330	€1.400	€4.340	€18.280	€47.890	€91.540	€115.050	€145.820	€184.880
B735	Medium	€290	€1.210	€3.650	€14.930	€38.640	€73.850	€93.150	€118.610	€151.310
B738	Medium	€350	€1.510	€4.750	€20.230	€53.260	€101.810	€127.770	€161.630	€204.380
B752	Medium	€420	€1.840	€5.730	€24.490	€64.580	€122.940	€154.220	€194.720	€245.370
B763	Heavy	€790	€3.020	€8.410	€31.560	€78.610	€163.030	€224.420	€270.690	€327.760
B744	Heavy	€1.320	€4.980	€13.700	€50.690	€125.610	€259.890	€358.050	€431.080	€519.410
A319	Medium	€310	€1.310	€4.020	€16.930	€44.350	€84.600	€106.550	€135.380	€172.180
A320	Medium	€330	€1.410	€4.440	€19.010	€50.190	€95.860	€120.430	€152.630	€193.440
A321	Medium	€370	€1.640	€5.240	€22.720	€60.310	€114.960	€144.220	€182.290	€230.150
AT43	Medium	€90	€430	€1.360	€5.860	€15.370	€30.260	€38.620	€50.620	€67.520
AT72	Medium	€130	€570	€1.850	€8.050	€21.280	€41.550	€52.620	€68.020	€88.930
DH8D	Medium	€150	€650	€2.040	€8.740	€22.970	€44.620	€56.510	€72.910	€95.010
E190	Medium	€230	€980	€2.960	€12.120	€31.390	€60.170	€76.100	€97.380	€125.180
A332	Heavy	€860	€3.310	€9.280	€34.950	€87.250	€181.210	€249.470	€300.660	€363.530

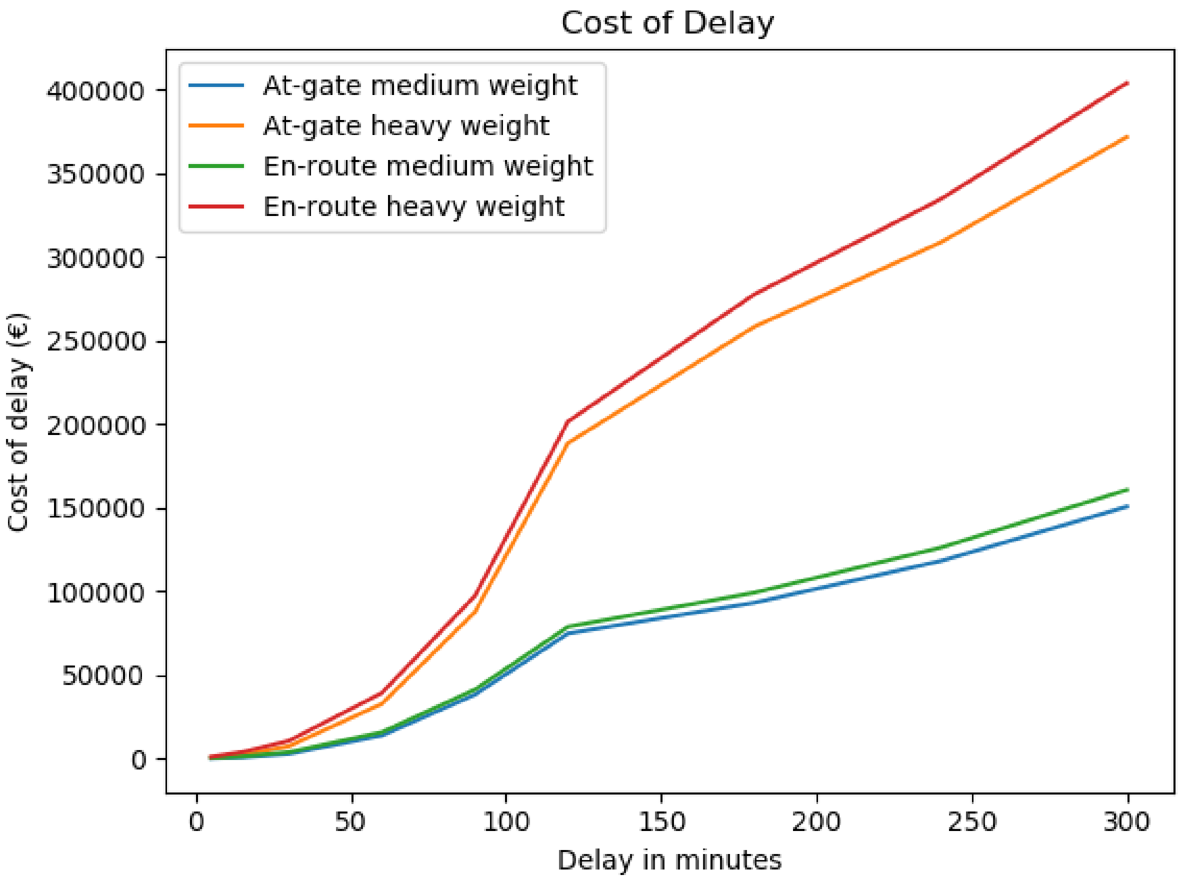


Figure H.1: Cost of the delay of one aircraft over time

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Travel-time distribution

The travel-time distribution is used for the priority in which an aircraft can be cancelled and which aircraft are always delayed or diverted. Travel-time distribution can help in finding the high probabilities that an aircraft can be cancelled, and it is also used in finding the distribution for the weight classes and distances. In Figure I.1 the amount of aircraft over the amount of time the aircraft need to travel towards Schiphol airport and in Figure I.1 the distance towards schiphol against the amount of aircraft is given. Both figures have the same distribution, as expected.

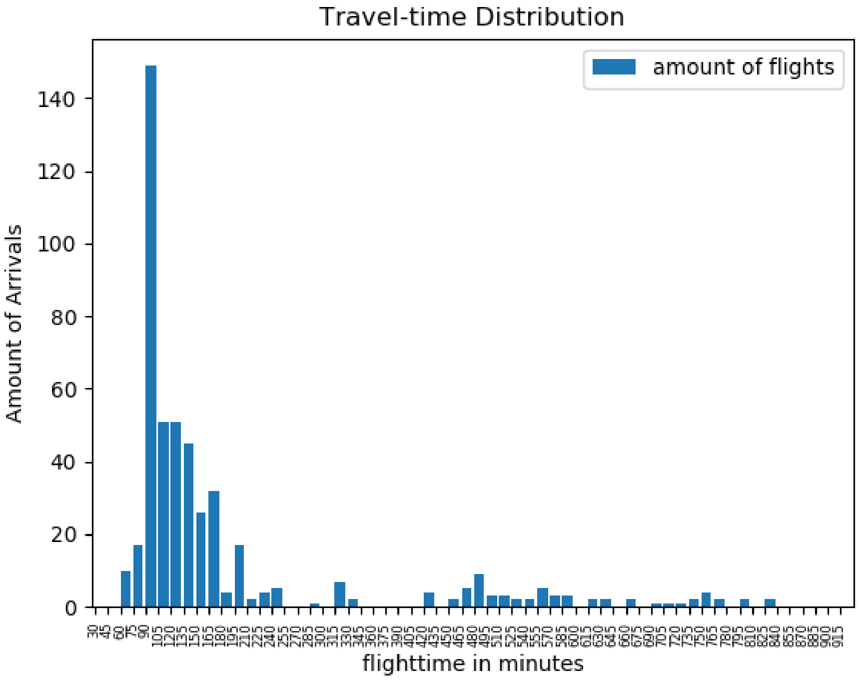

Figure I.1: Travel-time of the arrivals at Schiphol