Modelling the Effects of Gate Pit-Stops on Apron Congestion

MSc. Thesis

W. F. S. van Lingen

Technische Universiteit Delft

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by

W. F. S. van Lingen

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Thesis committee:	Ir. P. C. Roling,	TU Delft, supervisor
	Prof. dr. R. Curran,	TU Delft
	Dr. ir. J. Ellerbroek,	TU Delft

Abstract

Demand for air traffic is growing worldwide. As the demand for air traffic grows, the number of flight movements increases accordingly. This increase puts a strain on airport infrastructure, with gates in particular. The construction of new infrastructure with additional gate capacity is costly, and existing real estate is traditionally scarce. Therefore, gate capacity is difficult to increase, and existing gate infrastructure should be used more efficiently to cope with the increase in flights.

One of the most promising techniques to increase gate capacity through more optimal utilization of current infrastructure, is introducing gate pit-stops. With gate pit-stops, aircraft will be towed to a remote parking position between arrival and departure from the gate, in order to make space for other flights in the meantime. The main risk of introducing gate pit-stops in airport operations is that the additional towing movements will inevitably increase the number of apron movements, potentially interfering with other traffic on or near the apron. This in turn will lead to delays, which is undesirable.

An extensive literature study has identified a knowledge gap when it comes to gate pit-stops and their effect on gate utilization and apron congestion. They are currently only performed for flights with a turnaround time of three hours or longer at major hub airports, such as Amsterdam Airport Schiphol (AMS) in The Netherlands. As such, an opportunity to increase gate utilization has been identified, as the minimum required turnaround time for a pit-stop can be reduced to introduce gate pit-stops on a larger scale.

The main objective of this research is *'To assess whether gate pit-stops are a viable option to increase gate utilization for arriving flights at congested airports by creating a model that is capable of assigning aircraft to a gate and simulating the corresponding apron movements and delays'*. This objective has been accomplished by creating a model that simulates aircraft taxi movements on the apron, and assigns aircraft to a gate or remote stand. The model has been optimized for minimum delays and remote gate assignments using a Mixed Integer Linear Programming (MILP) formulation. Several simulations with varying model parameters (such as the number of gates) have been performed, to provide insight in the effectiveness of gate pit-stops for a wide range of scenarios.

Results have shown that making more use of gate pit-stops leads to better gate utilization in several cases, as the number of remotely handled flights is reduced when pit-stops are introduced. For a scenario with eight gates, a reduction in remotely handled flights is already observed when flights with an 80 minute layover are handled with a pit-stop, compared to the current 180 minute standard. It must be noted that making more use of pit-stops leads to an increase in delays. However, these can be compensated by the positive effects of parking an aircraft at a gate instead of a remote stand. Additionally, the use of new technologies such as ETS helps to reduce delays, which makes pit-stops more attractive. The results of this study can therefore be used as a starting point for both airports and airlines to determine the impact of gate pit-stops on their operations, and making more use of them in the future if this proves to be viable.

This research can be improved even further with additional research. Recommendations include modelling more aircraft types, and using real life schedule data to validate the results. Additionally, improvements could be made that enable an optimum turnaround time for pit-stops to be found for different scenarios.

Preface

With the completion of this thesis, my time at Delft University of Technology has come to an end, as this thesis completes the final requirement for the degree of Master of Science in Aerospace Engineering. Ever since I was young, I have always been interested in aviation. It therefore did not come as a surprise that I started studying Aerospace Engineering. Now that I have completed my Master's in Air Transport and Operations, I look back at an amazing time in Delft. Even though it sometimes was very tough, I am extremely glad I made it and I will never regret my decision to go and study in Delft.

Of course, I could not have done this without the help of others. First of all, I would like to thank my daily supervisor, Paul Roling, for his time and effort, and for all the insights he provided me with during this thesis project. It was great to share our passion for aviation, and to learn from him. I would also like to thank Bruno Santos for his valuable input during my mid-term and green-light meetings.

Furthermore, I would like to thank my fellow graduate students of room 3.15 for the daily dose of fun and critical review of my work. I would also like to thank my colleagues at SkyTeam for their continuous support and enabling me to bring my passion for aviation into practice in the past years.

Lastly, I would like to thank my family and friends who supported me during my entire time in Delft. I've had my ups and downs and could not have pulled this off without your unconditional support, for which I'll remain forever grateful.

W. F. S. van Lingen
Delft, May 2019

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List of Acronyms

AMS	Amsterdam Airport Schiphol, The Netherlands (IATA code)
ATA	Actual Time of Arrival
ATC	Air Traffic Control
ATD	Actual Time of Departure
APU	Auxiliary Power Unit
BRU	Brussels-National Airport, Belgium (IATA code)
cdf	Cumulative Distribution Function
CTAS	Center/TRACON Automation System
DRS	Dresden Airport, Germany (IATA code)
EASA	European Aviation Safety Agency
ETS	Electric Taxi System
ESU	Engine Start Up
ESUT	Engine Start Up Time
FAA	Federal Aviation Administration
FCO	Rome Fiumicino Airport, Italy (IATA code)
GA	Genetic Algorithm
GAP	Gate Assignment Problem
IAT	Inter-arrival Time
ICAO	International Civil Aviation Organization
ILP	Integer Linear Programming
kts	Knots (velocity)
LP	Linear Programming
MILP	Mixed Integer Linear Programming
m/s	Meters per second (velocity)
pdf	Probability Density Function
STA	Scheduled Time of Arrival
STD	Scheduled Time of Departure
TRACON	Terminal Radar Approach Control

1

Introduction

In the past years, more people were transported by air than ever before. Over 3.8 billion people took to the skies in 2016, translating into record high load factors of over 80 percent [37]. With the price of air transport continuing to fall, IATA forecasts passenger demand to nearly double to 7.2 billion annual passengers over the next 20 years [35]. As the demand for air traffic grows, the number of flight movements increases accordingly. This increase puts a strain on airport infrastructure, with some airports already struggling to keep up with the rapid growth in traffic, reflected by the fact that more and more airports are becoming slot constrained. During the (Northern) IATA Summer 2018 season, an all-time high of some 178 airports worldwide were classified as Level 3 Slot Constrained [36]. At these airports, demand for airport infrastructure significantly exceeds capacity and growth opportunities are extremely limited [34].

Gate Capacity

One of the infrastructural components that limits airport capacity is the available gate capacity. Several Level 3 airports are currently facing gate capacity issues, especially at peak times. An example of such an airport is Amsterdam Airport Schiphol in The Netherlands (AMS), which has grown rapidly over the past few years, welcoming over 71 million travellers in 2018 [4]. However, this success comes at a price, as current terminal infrastructure cannot cope with this steep increase in passenger numbers; since the onset of the Summer 2017 schedule, gate capacity restrictions have forced the dominant hub carrier KLM to handle select long-haul flights remotely on stands instead of directly at the gate [39]. The airport is not unique in this regard. Multiple airports worldwide face the same challenges as AMS, where increased traffic has prompted the construction of additional terminal real estate or even entirely new airports, as in Beijing and Istanbul. [15][14].

The construction of new terminal real estate with additional gate capacity is costly and existing real estate is traditionally scarce, which makes gate capacity difficult to increase. It is therefore imperative that gate infrastructure is utilized as efficiently as possible. The rapid growth in air traffic, coupled with the push for more efficient airport infrastructure utilization, has lead to many studies since the seventies into more efficient use of airport real estate. These studies focus on several areas, covering gates, taxiways and apron areas. Examples of this include the Gate Assignment Problem (GAP), which deals with assigning flights to a set of gates [32] and the Ground Movement Problem, which looks at optimizing all airside operations [7].

Gate Pit-Stops

In order to use existing airport infrastructure, specifically gates, more efficiently, one can look at new techniques to relieve congestion. One such technique is introducing so-called gate pit-stops. By introducing gate pit-stops, aircraft will be towed to a remote parking position between arrival and departure from the gate, in order to make space for other flights in the meantime [51]. The main risk of introducing gate pit-stops in airport operations is that the additional towing movements will inevitably increase the number of apron movements, potentially interfering with other traffic on the apron. This in turn will lead to delays, which is undesirable. To properly assess the effect of gate pit-stops on gate utilization and apron congestion, gate assignments and apron movements should be modelled. Additionally, the introduction of technological innovations such as an Electric Taxi System (ETS) needs to be investigated, as they can have a big impact on apron operations. Currently, little research has been done on gate pit-stops, and they are only performed at airports when turnaround times are three hours or longer. As such, an opportunity to increase gate utilization has been identified, as the minimum required turnaround time for a pit-stop can be reduced to introduce gate pit-stops on a larger scale.

Research Objective

Currently, there is a knowledge gap when it comes to gate pit-stops and their effect on gate utilization and apron congestion. Therefore, this research project has been performed in order to bridge this knowledge gap. The main objective is to assess whether gate pit-stops are a viable option to increase gate utilization at busy hub airports by taking into account their effect on apron congestion. This will be done by creating a model that simulates aircraft taxi movements on the apron, and assigns aircraft to a gate or remote stand. Several simulations with varying model parameters will be performed, to provide insight in the effectiveness of gate pit-stops for a wide range of scenarios. The results of these simulations can be used for both airports and airlines to determine the impact of gate pit-stops on their operations, and making more use of them in the future if this proves to be viable.

Report Structure

This report consists of seven chapters, which will be outlined below. In order to provide better insight in the current state-of-the-art on modelling taxi movements, gate assignments and gate pit-stops, a literature study has been performed which is presented in Chapter 2. The findings of this study are used to set up the simulations that will be performed to answer the main research questions. The main research questions, as well as the goals and scope of this study, are presented in Chapter 3, together with the expected outcomes. Setting up a proper model to simulate aircraft movements at an airport requires an appropriate methodology. In Chapter 4, the required model functionalities are set up and the inputs and outputs of the model are defined. With these tasks completed, a mathematical formulation is set up together with an optimization strategy, which will function to come to the results needed to answer the research questions and accomplishing the research objective.

With the model properly defined and set up, the simulations are performed and the results are analyzed in Chapter 5. Here, all outcomes of the research are set out and discussed. In order to determine model sensitivity to inputs, a sensitivity analysis is carried out. The results of this analysis are presented together with the model verification in Chapter 6.

With the aggregation of the results, the research questions can be answered, the expected outcomes can be compared to the actual outcomes of this study and relevant conclusions can be drawn. These conclusions serve to demonstrate whether airports and airlines can make smarter use of their infrastructure and what effects this has on their operations. These conclusions will be presented in Chapter 7, together with the limitations of the study, as well as recommendations for further research.

2

Literature Review

In order to assess the effectiveness of gate pit-stops and their effect on apron congestion and towing movements, a literature study has been performed which presents the state-of-the-art in the relevant fields of research. Additionally, the literature study also serves to expose the research gap in literature when it comes to gate pit-stops. The research covers three main aspects related to gate pit-stops, namely gate planning, apron operations and apron models. Section 2.1 discusses the research on gate planning, with applicable research on typical Gate Assignment Problems (GAPs). Section 2.2 elaborates on typical movements that take place on the apron, such as taxi movements, and relevant parameters required for the research into gate pit-stops. Next, Section 2.3 identifies the various methods found in literature to model apron movements. Finally, Section 2.4 presents the conclusions of the literature study.

2.1. Gate Planning

When looking at day-to-day airport operations, one of the most important aspects to ensure a smooth operation is the proper assignment of gates to arriving and departing aircraft. Creating a gate schedule that fits the needs of airlines and airport alike is very challenging. Thus, for multiple decades researchers have aimed to optimize this problem, better known as the Gate Assignment Problem. Since the early 1970s, many papers on the GAP have been published. In one of the first of such publications, the author's main objective is to investigate how gates can be used as efficiently as possible, i.e. maximizing the number of flights that can be handled at a gate [53]. As time progressed, a multitude of research with other main objectives of GAPs have emerged. The literature on GAPs therefore can be classified into different categories according to the main objective of the problem. These classifications are further discussed in the next section (Section 2.1.1). Subsequently, literature pertaining to only those gate assignment problems with objectives that are relevant for research into gate pit-stops are reviewed and discussed (Section 2.1.2) .

2.1.1. Classifications of the GAP

In available literature on Gate Assignment Problems, the main objectives discerned by [22] are as follows:

- The number of expensive aircraft towing procedures (that otherwise decrease the available time for some ground service operations on the ramp as well as in the terminal) can be reduced
- The total walking distance for passengers can be minimized
- The deviation of the current schedule from a reference schedule can be minimized in order to increase schedule attractiveness and/or passenger comfort

Alternatively, according to [13] the objectives of available studies into the GAP can be grouped under the following six categories:

- Maximizing gate utilization

- Minimizing the total number of gate conflicts
- Minimizing the number of un-gated flights
- Minimizing flight delays
- Minimizing the total passenger walking distance
- Minimizing the distance travelled by the aircraft from the runway to the gate

For the study into gate pit-stops, the research will be done from an airport owner/operator's perspective. In practice, at airports like Amsterdam Airport Schiphol in The Netherlands (AMS), gates are assigned by the airport authority and not by the airlines. As such, literature on the gate assignment problem with an objective of minimizing the total passenger walking distance or minimizing the distance travelled by the aircraft from the runway to the gate has been disregarded.

In addition to the scope outlined above, formulations of interest to the main thesis research are those GAPs that include aircraft towing movements. Taking this into account, several relevant GAP formulations have been found in literature that are discussed in the next section.

2.1.2. Selected GAP Models

An early example of a gate assignment problem that looks at the GAP from a perspective other than that of airlines (i.e. reducing walking distances, transfer times etc.), was published in 1996 [12]. In this publication, the main objective is increasing schedule robustness, where robustness equates to optimizing a schedule such that (small) deviations from the original flight schedules can be absorbed without inducing (additional) delays. In multiple studies that have been published subsequently, the authors aim to reduce the slack times (periods of time in which gates are not utilized between two flights) in order to increase schedule robustness [12][9][10] [11]. Figure 2.1 provides a visualization of schedule robustness by depicting a non-robust gate schedule.

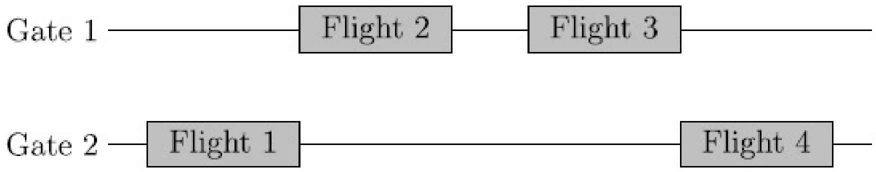


Figure 2.1: Example of a non-robust schedule [21]

Schedule robustness in the aforementioned studies is measured in two ways. The first measure is by looking at the number of aircraft that are assigned a remote parking position instead of a regular gate upon arrival. The second measure looks at the number of towing movements: if the slack time of a gate assignment is long enough, a third aircraft can be fully serviced at the gate between departure of the first aircraft and arrival of the second aircraft. If this is not the case, the aircraft needs to be towed to a remote stand. Hence, the number of required remote towing movements is a second measure for schedule robustness in this study. Although schedule robustness is not a (primary) objective of the thesis research, both approaches contain formulations that can serve as a starting point for a GAP formulation which includes towing movements and remote stand allocation. Note however that the towing movements in these studies only occur before or after a flight and not in-between flights, as is the case with gate pit-stops. A more recent study does include towing movements for split flights with gate pit-stops [22]. In this paper, flights with a long layover are modelled as three distinct parts, which allows for the modelling of flights with a gate pit-stop:

- **Flight arrival:** Aircraft arrives at the gate
- **Remote parking between flights:** Aircraft is towed away from gate and parked at a remote stand, after which it is towed back to the departure gate

- **Flight departure:** Aircraft departs from the gate

The main advantage of using this approach to schedule flights with a gate pit-stop is that gate space is freed up by towing away flights with a long turnaround. Additionally, each activity can be assigned a different gate or parking position in the model. Therefore, a flight can be modelled arrive at a fictitious gate *A*, be towed by a tow truck to a desired stand in-between arrival and departure after which it can depart from a different gate *B*. One of the main objectives in this study is reducing the number of towing movements, which is not an objective of the thesis research. However, the methodology used by splitting flights to model towing is useful to investigate the effect of gate pit-stops.

In [21], aircraft towing in-between arrival and departure is simulated by modelling pit-stops in three distinct parts. Here, every part is modelled as a separate flight, with each part similar to the three parts listed in [22]. While increasing schedule robustness is mentioned as the objective, contrary to earlier studies like [9], slack times between two flights are maximized instead of minimized to reach this objective. As the problem described in [21] takes into account the gate planning in AMS, the model has to be able to assign over 600 daily flights to more than 120 gates. Because of this complexity, the model formulation is split up into two phases. In the first phase of this model, gates of the same type are grouped and a gate plan will be set up to assign a series of flights of the same type to these gates. Since the thesis research will be modelled with far fewer gates, a model similar to this first phase can serve to assign applicable gates to flights. The mathematical model has been formulated as an ILP (Integer Linear Programming) model using CPLEX as a solver.

An important consideration for gate pit-stops is the total turnaround time of aircraft. Literature suggests that remote towing only occurs for flights with a long turnaround time. At AMS for example, only flights that stay at the gate for about three hours or longer are considered to be *long stay* flights and therefore eligible for remote towing in between arrival and departure [21][51]. However, very little research has been done on pit-stops with a shorter turnaround time, except for [51] where a minimum turnaround time of 75 minutes has been used. Nonetheless, this study does not take into account effects of pit-stops on apron congestion.

2.2. Apron Operations

Insight into the airport environment and ground movements are essential in understanding how gate pit-stops can affect delays. Therefore, in this section relevant literature and data on apron sizing, operating guidelines and movements that take place on the apron will be examined. First, detailed guidelines regarding apron design and layout are reviewed (2.2.1), after which the type of movements that take place on the apron (2.2.2) are analyzed. Lastly, literature on the development of new technology and its effect on apron movements will be reviewed (2.2.3).

2.2.1. Apron Design and Layout

Looking at airports worldwide, the layout of the apron may appear to differ significantly. However, there are regulatory bodies such as EASA, ICAO and the FAA that have set standards for airport design and engineering [25], so in effect airports worldwide have standardized dimensions. For the apron area, there are several parameters that influence its dimensions. These include:

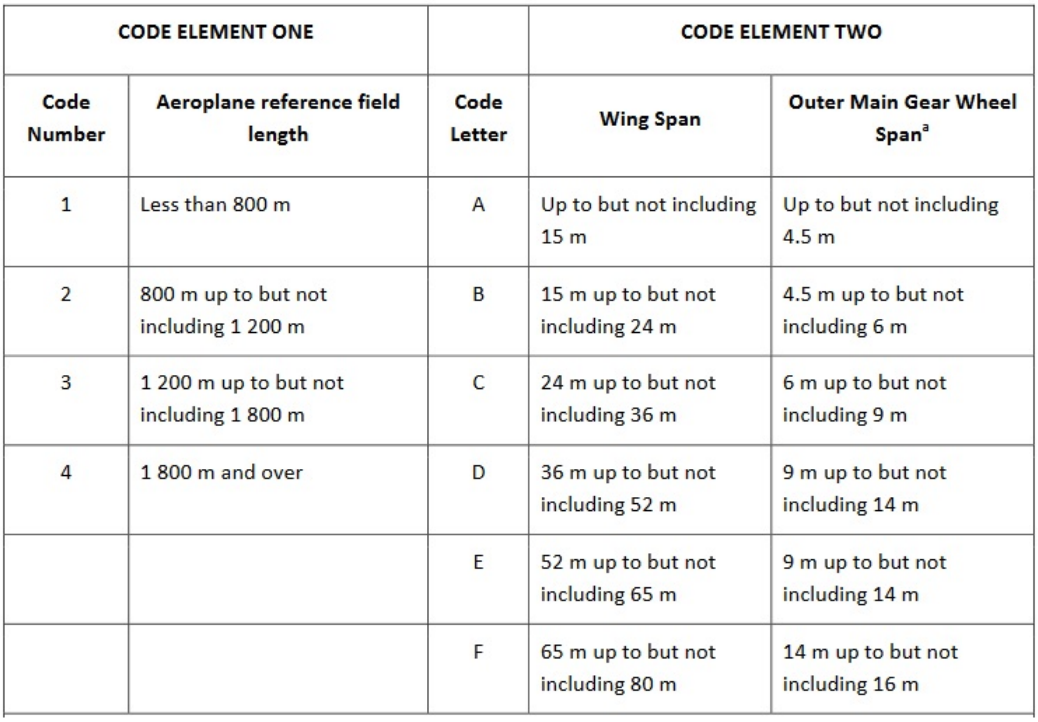
- Aircraft type
- Gate size
- Parking type
- Terminal building design type

Note that in the context of this research, these parameters pertain to the apron area (i.e. gate size on the airside apron area, and not inside the terminal building)

Aircraft Type

The aircraft type handled at an airport has a direct influence on apron capacity. Typical single-aisle

Table 2.1: Aircraft categories as defined by EASA [24]



CODE ELEMENT ONE			CODE ELEMENT TWO	
Code Number	**Aeroplane reference field length**	**Code Letter**	**Wing Span**	**Outer Main Gear Wheel Span**[a]
1	Less than 800 m	A	Up to but not including 15 m	Up to but not including 4.5 m
2	800 m up to but not including 1 200 m	B	15 m up to but not including 24 m	4.5 m up to but not including 6 m
3	1 200 m up to but not including 1 800 m	C	24 m up to but not including 36 m	6 m up to but not including 9 m
4	1 800 m and over	D	36 m up to but not including 52 m	9 m up to but not including 14 m
		E	52 m up to but not including 65 m	9 m up to but not including 14 m
		F	65 m up to but not including 80 m	14 m up to but not including 16 m

aircraft such as the Boeing 737 family and Airbus A320 series are the most commonly used aircraft at large airports like AMS [3]. For sizing and operational purposes, aircraft of similar dimensions are categorized according to dimensional and/or operational characteristics. These usually include approach speed, tail height and/or wingspan [33]. The typical guidelines used for aircraft categorization are displayed in Table 2.1 (Note that the categorization displayed is according to EASA guidelines, however the guidelines set out by ICAO are identical [33]).

The wing span of the most recent iterations of the Boeing 737 family and the Airbus A320 series aircraft (the Boeing 737MAX and Airbus A320neo) have a wing span of 35.92 and 35.8 meters, respectively [56][1]. Therefore, both aircraft fit in Code Letter Category C and thus Category C aircraft types are the most universally used.

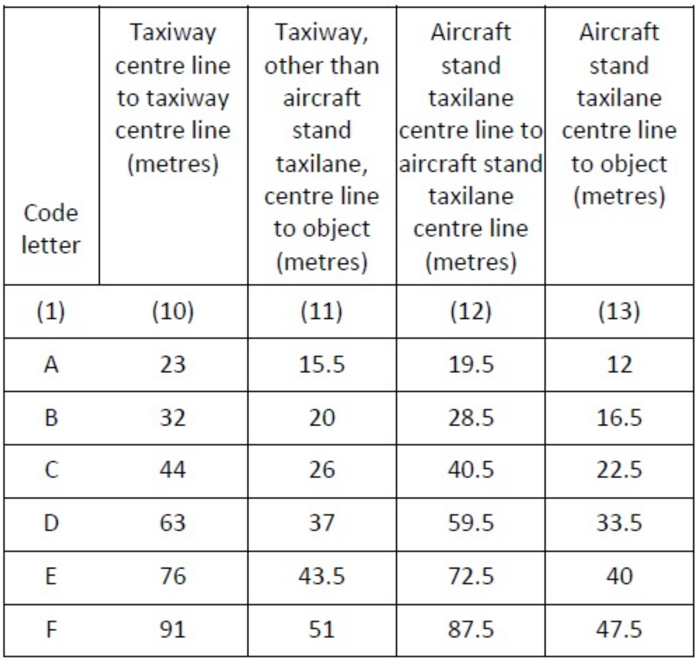
Gate Size

Using the appropriate sizing standards, the gate area can be dimensioned to fit Category C aircraft. For aircraft of this category, guidelines found in literature stipulate a minimum lateral spacing of 40.5 meters between two aircraft stand taxi lanes (see Table 2.2, column 11). This spacing is consistent with guidelines set by Airbus for apron servicing of its A320 family aircraft, as shown in Figure 2.2.

In addition to standards on lateral clearance, strict guidelines on the minimum clearance between aircraft at the gate and adjacent aircraft, buildings or other fixed objects are found in literature. These guidelines are summarized in Table 2.3. As indicated, for Category C aircraft the minimum object clearance is 4.5 meters.

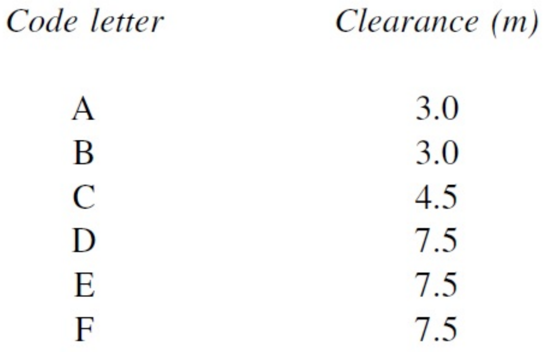
In the reviewed literature with simulations of apron movements, in most cases an extra safety margin is assumed in the total object clearance, as is often the case in real life. Although the wing span of Category C aircraft is set by regulations, the length of aircraft belonging to this category may differ. For sizing purposes of the thesis research model, it is interesting to note the difference between the shortest and longest versions of the Boeing 737 family and Airbus A320 series. The newest members of the Boeing 737 family, the Boeing 737 MAX aircraft, range in length from 33.63 meters (737 MAX 7) to 43.80 meters (737 MAX 10) [57]. Conversely, the A320neo series ranges in length from 33.84

Table 2.2: Taxiway spacing guidelines, adapted from [24]

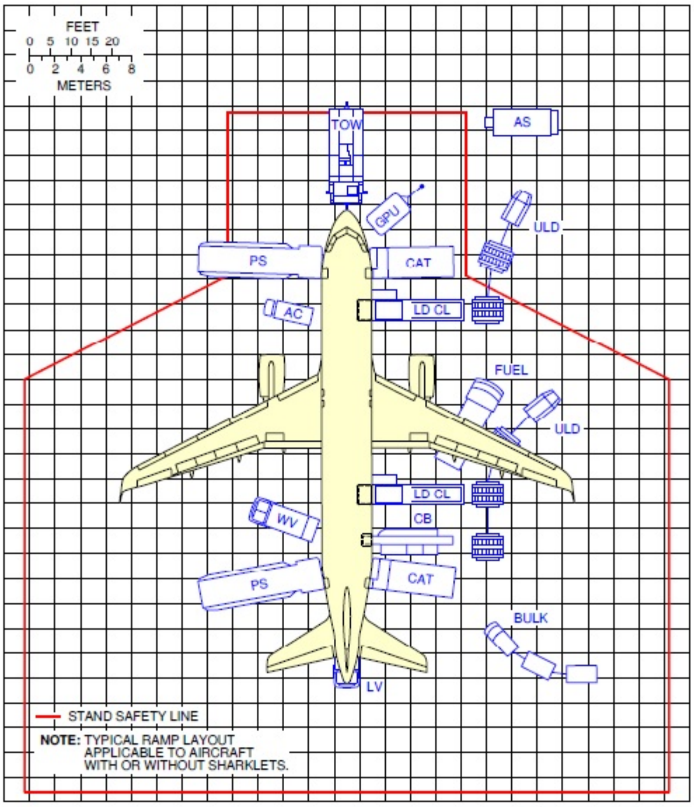


Code letter	Taxiway centre line to taxiway centre line (metres)	Taxiway, other than aircraft stand taxilane, centre line to object (metres)	Aircraft stand taxilane centre line to aircraft stand taxilane centre line (metres)	Aircraft stand taxilane centre line to object (metres)
(1)	(10)	(11)	(12)	(13)
A	23	15.5	19.5	12
B	32	20	28.5	16.5
C	44	26	40.5	22.5
D	63	37	59.5	33.5
E	76	43.5	72.5	40
F	91	51	87.5	47.5

Table 2.3: ICAO minimum clearance per aircraft category [38]



Code letter	*Clearance (m)*
A	3.0
B	3.0
C	4.5
D	7.5
E	7.5
F	7.5



NOTE: TYPICAL RAMP LAYOUT APPLICABLE TO AIRCRAFT WITH OR WITHOUT SHARKLETS.

N_AC_050102_1_0090101_01_00

Figure 2.2: A320 apron spacing requirements [1]

meters for the A319neo to 44.51 meters from nose to tail for the highest capacity A321neo [1][2] (the Airbus A318 has not been taken into account as this model will not have a successor in the A320neo series program). For safety purposes, aircraft should fit within the apron safety line. This line marks the area intended for use by ground vehicles and other aircraft servicing equipment in order to maintain a safe separation distance from moving aircraft [38].

Parking Type

The aircraft parking type refers to the orientation of the aircraft relative to the terminal building when in parking position at the gate. It affects the aircraft maneuverability at the gate and on the apron in general. From [33], it follows that there are four different aircraft parking types, namely nose-in parking, angled nose-in parking, angled nose-out parking and parallel parking. These four parking types are illustrated in Figure 2.3.

The parking type that was found in literature to be used at most large hub airports worldwide, such as AMS, is nose-in parking [54]. With this parking configuration, aircraft taxi-in under their own power and require a pushback truck or similar vehicle to be pushed out of the gate area, after which taxi out of the apron area occurs under the aircraft's own power [33].

Terminal Building Design Type

There are several ways in which terminal buildings and adjacent apron areas can be constructed. The most commonly found terminal building design types with nose-in parking are listed by ICAO [38] and depicted in Figure 2.4. Other concepts include a hybrid concept, which combines any of the depicted concepts with remote parking stands to cater to peak capacity. Each concept has distinct advantages and disadvantages, which need to be taken into account when choosing a certain terminal design type. Other considerations which (partly) depend on the chosen concept are the number of taxiways, and the obligation to meet the separation requirements listed earlier on in this section.

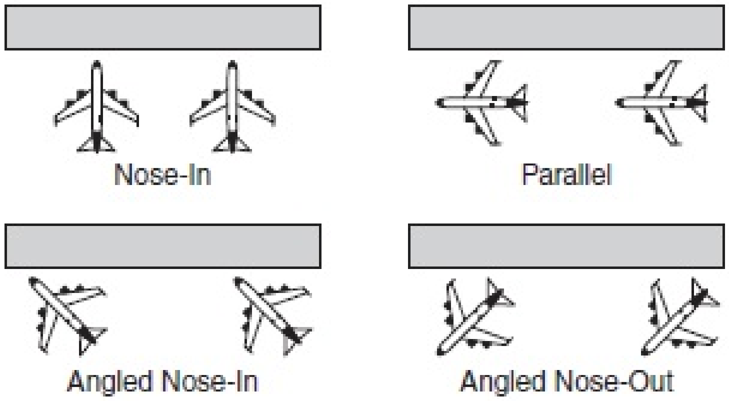
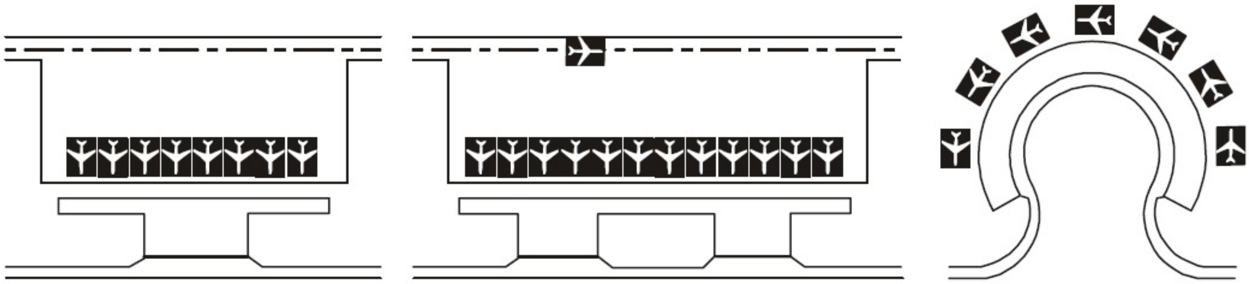
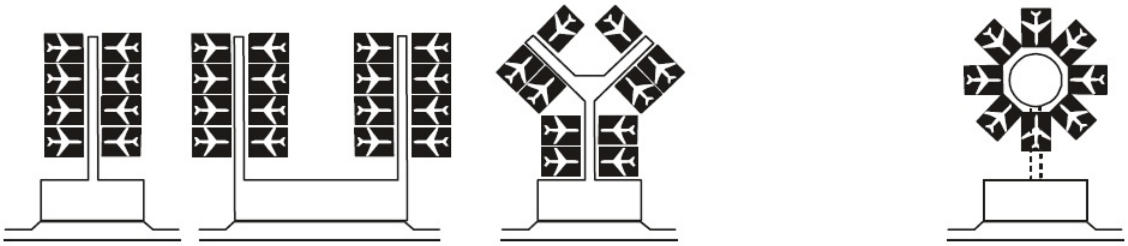


Figure 2.3: Aircraft parking types [33]



b) Linear concept and its variations



c) Pier (finger) concept

d) Satellite concept

Figure 2.4: Terminal concepts, adapted from [38]

2.2.2. Apron Movements

In this section, the aircraft ground movements that take place on the apron will be explored, and relevant information and research on these movements will be reviewed. The relevant movements and operation found in literature include:

- Taxi-in
- Turnaround
- Pushback
- Engine start up
- Taxi-out
- Towing

Each of these will be discussed separately.

Taxi-in
The taxi-in movements entails the movement of the aircraft from the moment that it enters the apron area until it has fully crossed the apron safety line at the gate. The main parameters that are of influence on the taxi-in motion are the (average) taxi speed and the total taxi-in distance. The distance depends on the chosen apron and terminal layout and will be determined once design choices have been made.

In literature, several authors use different value for the average taxi speed of aircraft. First of all, in [16], taxi speeds for different airside areas are used, e.g. stand taxi lane speeds are assumed to take place at speeds of 0 to 10 kts (about 5.1 m/s), which is lower than rapid exit taxi lane speeds. In [48], taxi movements are modelled using two average taxi speeds, namely 16 kts for fast aircraft and 8 kts for slower aircraft. In [50], the authors observe that (very) low aircraft taxi speeds rarely occur in real life situations, with the majority of aircraft observed taxiing at speeds exceeding 8 kts (about 4.1 m/s). For taxi modelling purposes, absolute minimum taxi speeds of 5 kts (about 2.6 m/s) are maintained in the same research. In [54] it is noted that at AMS, it is both an objective of the airport and the airlines alike to maintain minimum taxi speeds of 15 km/h (about 4.2 m/s) to maintain circulation and reduce congestion. For aircraft turns, literature suggest modelling this movement using the average taxi speed or using a fixed duration of 6 seconds [43].

Turnaround
After the aircraft has completed the taxi-in motion, the turnaround process at the gate will commence. This process will start from the time the aircraft is parked at the gate (on-block time) and finishes when the aircraft is ready to depart (off-block time) [61]. Typical activities that are part of the turnaround process include embarkation and disembarkation of passengers and crew (if required) as well as the loading and unloading of baggage and cargo and catering services. Additionally, technical activities that may take place during turnaround include fuelling, line maintenance and cabin cleaning [60]. For a visualization of the turnaround process, please refer to Appendix A.

In order to properly model apron operations, insight into typical aircraft turnaround times is required. The Boeing Company has published manuals specifying typical turnaround times for its 737 family of aircraft. In these manuals, Boeing distinguishes two types of stations for turnarounds: en-route stations and turnaround stations. At time of writing, no data is available yet for the 737 MAX 9 and 737 MAX 10 models, so the data considered are for 737-900ER and 737 MAX 8 models. Similarly, Airbus has published ground handling manuals for its A320 family of aircraft. Here, turnaround times are labelled as either outstation or full servicing. The turnaround times for the aforementioned models of aircraft are summarized in Table 2.4. Appendix A shows the typical turnaround schedule of a Boeing 737 family aircraft.

Table 2.4: Typical Boeing 737 and Airbus A320 family turnaround times [55][57][1]

Model	Station type	Turnaround time in min.
737-900ER	En-route / Outstation	23
737-900ER	Turnaround / Full servicing	37
737 MAX 8	En-route / Outstation	17
737 MAX 8	Turnaround / Full servicing	43
A320neo	En-route / Outstation	22
A320neo	Turnaround / Full servicing	44
A321neo	En-route / Outstation	23
A321neo	Turnaround / Full servicing	52

Pushback
Depending on the aircraft parking type, the aircraft requires pushback after the turnaround process is completed. In general, aircraft cannot reverse autonomously, hence a pushback truck or tractor is required to perform this procedure. Some aircraft, such as the Douglas DC-9 / McDonnell Douglas

MD-80, have the capability for autonomous pushbacks using reverse thrust, but these aircraft types are generally older and the number of units in service is dwindling [18].

During the pushback procedure, the aircraft is pushed back out of the gate area and positioned onto the apron taxi lane, after which it can taxi out (either under its own power or by a tug). Figure A.3 in Appendix A shows the typical actions required during pushback. According to [20], two types of pushback operations can be distinguished. The first type uses a towbar that is connected between the aircraft and a tug, whereas the second type uses a towbarless pushback tug. The type of tug used does not influence pushback speeds.

In literature, several papers have been published on pushback procedures that also touch upon pushback speeds. In [20], an average speed during pushback of 3.5 kts (about 1.8 m/s) is assumed. This leads to a total pushback procedure from off-block time to a position in which the aircraft is aligned with the taxi lane of around two minutes. However, the same article shows empirical evidence from analyzing pushback times at Dresden Airport, Germany (DRS), with an average time of three minutes to complete the pushback procedure. Other studies, such as [23] also suggest an average pushback time of three minutes. Subsequent studies have found that this time can be decreased when using new pushback technology, which will be discussed in Section 2.2.3.

Engine Start Up

Once the aircraft has been pushed back from the gate and is positioned on the taxi lane, it will taxi out. In case this is done under its own power, the engines need to be running. According to Figure A.3, engine start up (ESU) takes place during the pushback motion. In case the engine start up time (ESUT) is longer than the duration of pushback, the plane needs to hold on the taxiway, which may cause delay to other aircraft as well. In that case, ESU should take place before pushback.

Engine data found in literature has been consulted for ESUT of Category C aircraft. A very widely used engine for Catergory C aircraft is the CFM56 engine, which is built by CFM International (a joint venture between General Electric Aviation and Safran Aircraft Engines). The CFM56 powers a large part of the worldwide fleet of Airbus A320 series aircraft and it is the sole engine option for the Boeing 737 Next Generation family [17]. According to the manufacturer, the minimum ESUT for the CFM56 engine is about two minutes under normal circumstances [26]. However, in a more recent publication, the manufacturer indicated a start-up time of around one minute for the CFM56 [58].

The newest versions of the aforementioned aircraft types (the Boeing 737 MAX family and Airbus A320neo series) are powered by different engines. The 737 MAX series are exclusively powered by the LEAP-1B engine which is also manufactured by CFM International. The A320neo series are powered by either the CFM LEAP-1A engine or the PW1100G engine by Canadian manufacturer Pratt and Whitney. Looking at the LEAP-1 engine types, CFM International has indicated an ESUT that comes 'within seconds' of its predecessor, the CFM56 engine, indicating a startup time of about one minute [58]. Meanwhile, the PW1100G engine has experienced teething issues after its entry into service in 2016. Initially, the ESUT for the engine was about three minutes, though after delivering software and hardware fixes this has come down to about 90 to 100 seconds [30].
As can be seen, the time assumed in literature for pushback exceeds that of ESU for the engine types listed above. Therefore, it can be assumed that ESU takes place during pushback.

Taxi-out

The taxi-out motion is very similar to taxi-in, with the only difference being the taxi distance. This is because the taxi-out movement only entails the movement from the taxi lane (onto which the aircraft is positioned after pushback) to the apron exit. Therefore, the average taxi-out speeds are similar to the taxi-in found in literature previously.

Towing

In case an aircraft is subject to a gate pit-stop, it will have to be towed from the gate area to a remote parking position. From [45], an average towing speed of 5 kts (about 2.6 m/s) can be assumed using a tug, but this speed is relatively low. As expected, several tugs that are commercially available can reach significantly higher speeds of up to 17 kts (about 13 m/s) [27].

2.2.3. New Technologies

The Airport surface movements discussed in the previous section generally take place at low speeds using tugs or aircraft engine power. Running the aircraft engines at low speed is inefficient, and tugs are (mostly) powered by polluting fossil fuels, which is why alternatives for power during taxi are being developed. The most promising solution for an alternative taxi power source is an Electric Taxi System (ETS) [59]. An ETS consists of an electric motor which powers either the nose gear or one of the main gears of an aircraft during pushback and taxi. The motor is powered by the aircraft's Auxiliary Power Unit (APU), which uses less fuel than the aircraft's engines. Also, the need for a pushback truck during pushback is eliminated [51].

In [20], it is argued that using an ETS in lieu of conventional methods may lead to a reduction in taxi-in and taxi-out times of about 10 to 20 %. With an ETS, a maximum pushback velocity of 7 kts (about 3.6 m/s) can be attained whereas traditional pushback with a tug takes place at an average speed of 3.5 kts (1.8 m/s). Using ETS may therefore lead to a considerable reduction in the total time it takes to complete the pushback motion. Figure 2.5 shows the difference in pushback velocities between traditional pushback using a tug (left) and pushback using an ETS (right). In addition to replacing a tug during pushback, ETS may also be used as an alternative to a tug when towing an aircraft to/from a remote stand.

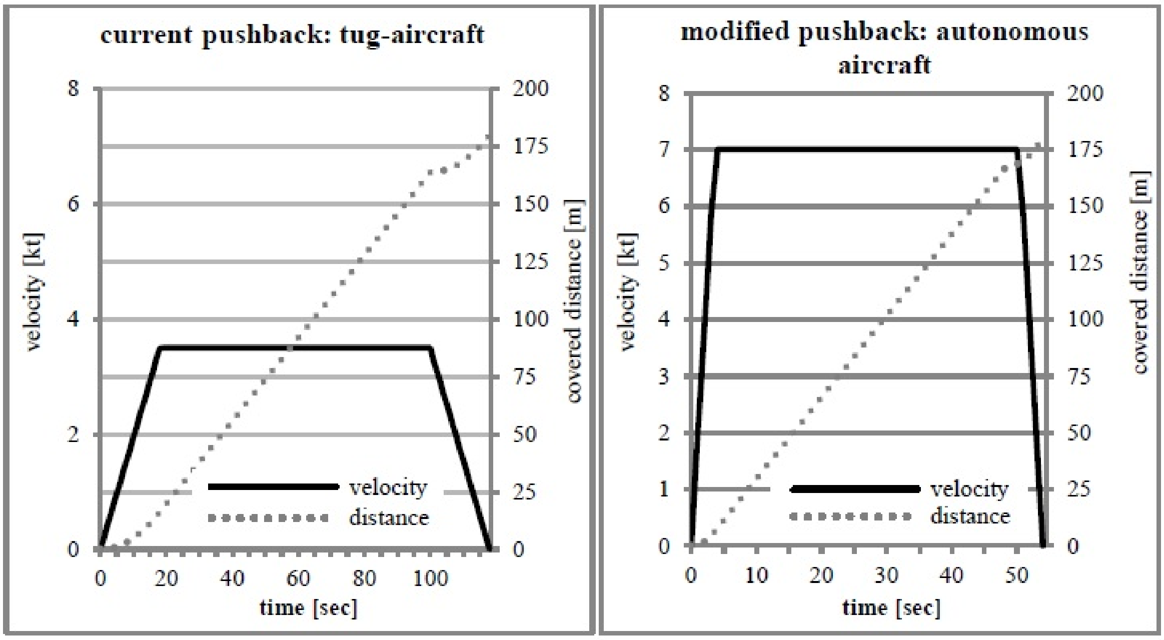


Figure 2.5: Pushback velocities: tug vs. ETS [20]

2.3. Apron Models

Airport operations are increasing worldwide [35], which leads to more congestion on airport taxiways and aprons. This congestion leads to delays, which in turn lead to financial and environmental inefficiencies [5]. Therefore, information about the predicted and exact position of aircraft is valuable to airlines and airports alike to predict and combat congestion. Multiple studies have looked at reducing delays by simulating and optimizing (expected) apron and taxi movements to relieve congestion. In this section, available literature on the various methods to model apron movements is discussed. Section 2.3.1 discusses the use of automated simulation tools, followed by Mixed Integer Linear Programming Models in 2.3.2. Section 2.3.3 examines Genetic Algorithm Models.

2.3.1. Existing Simulation Tools

Several tools are in use that simulate airborne traffic. One example of this is CTAS. CTAS, an acronym for Center/TRACON Automation System (where TRACON again is an acronym for Terminal Radar Approach Control), is a decision support tool that regulates arrival flows and predicts actual landing times up to 40 minutes before arrival [62]. However, tools that simulate ground movements are not as widespread. As a matter of fact, the ground operation (including all processes from on-block to off-block time) in most studies into air traffic is modelled as a process of constant length [5].

The available research on ground movements mostly focuses on either taxiway traffic or apron traffic. Although the simulation in the thesis research (mostly) concerns apron traffic, the techniques to model taxiway traffic may be useful as well. Hence, literature on both taxiway and apron movements has been reviewed. The ground movement simulation tools that are available concern movements on either a microscopic or a macroscopic scale. Microscopic tools are used on a short-term operational level with detailed modeling representations of actual airports, whereas macroscopic tools are mostly used for longer term decision making like the expansion of infrastructure [40]

Microscopic Simulation Tools

Multiple organisations have developed microscopic simulation tools. These include the FAA's SIMMOD Plus and SIMMOD Pro tools, Eurocontrol's RAMSPlus, TAAM by the Preston Group and Sabre's DPM. All of these programs offer the ability to fast-time simulate airside traffic, including that on the apron. Additionally, airports can be set up in very high detail, including physical and operational constraints. As such, programs like these enable airport operators to make the most efficient traffic planning decisions. An example in literature where such a tool is used can be found in [29], where the authors use SIMMOD Pro with node-link definitions of the airport layout as a decision tool for gate and taxiway assignments.

The aforementioned study shows the flexibility and power of simulation tools. However, in [5] the authors mention that calibrating and validating models of airports in simulation tools like SIMMOD is extremely difficult. Another downside of these tools is that they may lack in automatically improving operations, a feature that other optimization systems do possess [47]. In [19] the authors argue that while microscopic simulation software is very advanced and detailed, using it requires a significant amount of training.

Macroscopic Simulation Tools

A well known macroscopic simulation tool is MACAD, Mantea Airfield Capacity and Delay. Similar to the microscopic simulation tools, it considers airside traffic movements, however MACAD integrates airside models on a macroscopic level. The program has several advantages over previously discussed tools; it is fast, (relatively) easy to use and flexible [52]. In addition to that, MACAD allows the user to estimate the capacity, utilization and possible delays at every element of the entire airside area by integrating macroscopic models of each airside area element. It has been successfully evaluated at seven European airports. The main input to a MACAD simulation is a flight schedule, which can either be an existing schedule at an airport worldwide or a hypothetical schedule [52]. In Figure 2.6, the five modules which make up MACAD are displayed. These modules can be activated or not, depending on whether they are included in the model, giving it great flexibility in modelling different components and/or scenarios [19].

Although MACAD is more user-friendly than programs like SIMMOD, in-depth knowledge is still required and modelling an (hypothetical) airport requires a considerable amount of time. Another point to note is that both microscopic and macroscopic simulation tools focus heavily on visuals, which might not be required for the thesis research.

2.3.2. Mixed Integer Linear Programming Models

In most cases where simulation tools are not used for airside simulations, a Mixed Integer Linear Programming (MILP) formulation is used with a node-link network [7]. The node-link models found in literature range from fairly simple hypothetical airports to accurate representations of a real world airport. An example of the latter can be found in Figure 2.7, which is a node and link representation of

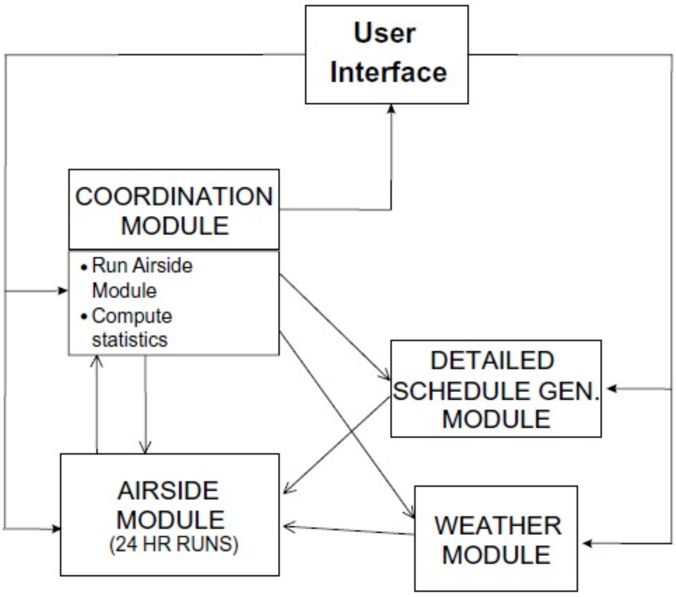


Figure 2.6: MACAD modules [52]

Rome Fiumicino Airport in Italy (FCO).

Figure 2.7: Apron graph at FCO [19]

A MILP formulation is similar to a Linear Programming (LP) formulation, which requires a linear objective function with linear constraints. However, a MILP formulation additionally requires some (but not all) variables to attain integer values [31]. A MILP formulation is exact, hence it always leads to an optimal solution [8]. The integration of integer values allows for the introduction of binary variables, such as order variables. This does come with a downside: introducing binary variables causes the search space of the solution to change from a continuous space to a discrete space, which might make the problem harder to solve. In large problems, this causes the optimization to be at risk of taking too much time for practical purposes.

In [7], the three main MILP modelling approaches are identified:

- Exact Position Approach
- Ordering Approach
- Immediate Predecessor/Successor Approach

With the first option, an exact position approach, every aircraft is allocated a set time to cover each part of its path. A network representation of an airport is used as a starting point, after which time is discretized and a network copy is allocated to each discrete time unit. Using an ordering approach, the algorithm will first sequence aircraft, after which a time schedule for each aircraft is created at every node or link in the network. The network in this case only requires binary variables as sequence constraints and time is modelled as a continuous variable. The third option is to use an immediate predecessor/successor approach, where only the immediate predecessor and successor of the aircraft at each node and edge will be simulated. As noted by the authors of [31], this approach has not been used in literature at the time of writing.

Exact Position Approach
Looking at available literature, multiple studies using an exact position approach or an ordering approach have been published. In [48], an exact position approach is used to develop a taxi-planning support tool that is able to optimize both the routing and scheduling of airside traffic. The objective is to deconflict taxi plans and delay, and total taxi time using a hypothetical airport that is modelled using a discrete time-space node-link network. In the model, aircraft may hold at the start of, or during, taxi on special nodes. In order to test the model, a planning horizon is set up to simulate the movement of eight aircraft. The problem is subsequently solved with CPLEX, a commercial software package by IBM.

In [41], taxi movements are also minimized using an exact position approach. Again, a node-link network representation of an airport is set up, including the appropriate flow conservation and capacity constraints at every node. In this example, two methodologies are used to solve the problem: both a branch and bound and a fit and relax algorithm are used. Similarly to [48], CPLEX is used to solve the problem, with results showing that the fit and relax approach leads to quicker results. However, most integer programming problems use a branch and bound algorithm since a fit and relax algorithm is harder to set up.

Ordering Approach
The ordering approach differs from the exact position approach, as the ordering approach requires the exact taxi route to be known beforehand. In return, the times for each aircraft can be modelled as continuous instead of discrete variables [7]. The ordering approach is used in [50]. The goal of the research is increasing taxi movement efficiency at AMS. In order to do this, the authors have created a node-link model of AMS, with intersecting taxiways modelled as a node, and taxiways between the nodes as an arc/link. Sets of arriving and departing aircraft are set up together with a set of taxi routes. Scheduled arrival times of aircraft at nodes are assigned, and binary order constraints are introduced to decide the best order in which subsequent aircraft will arrive at a particular node. In addition to binary constraints, regular constraints are set up and linearized (to ensure the problem can be modeled as MILP). The objective function is formulated to minimize the total sum of all aircraft taxi times. Similarly to the literature with an exact position approach, in this research CPLEX is used to solve the problem. Other research using the ordering approach expands on this research (like [46]), but the essence of the model remains the same.

2.3.3. Genetic Algorithm Models

Section 2.3.2 mentions that in the majority of literature on airport ground movements a MILP formulation is used. The other main option found in literature is using heuristics to solve the problem under study. According to [7], when heuristics are used, they are exclusively of the Genetic Algorithm (GA) type. A GA uses the survival of the fittest principle, where fitness of the offspring is measured by the value of the corresponding objective function, which in turn will converge towards an optimal solution as the fittest offspring is selected [31]. Generally, a GA is applied to problems that are too big to solve within a reasonable time frame using MILP. Since the GA is based on heuristics, there is no guarantee that an optimum will be found.

There are three main strategies when implementing a GA [7]. These include:

- Applying an initial delay/hold before pushback
- Applying a delay at a point during taxi
- Prioritizing aircraft movement

It is assumed in [7] that the first problem involving ground movements at an airport that was solved using a GA was published in 2001. Similar to previously discussed publications, the authors in [44] look to minimize total taxi time from the gate to the runway or vice versa. In this study, a single delay per aircraft is allowed at a time that is determined by the algorithm. For every pair of parent solutions, the algorithm chooses the better solution that has fewer conflicts with other aircraft in the vicinity, in order to increase the probability of finding an optimal solution. With the methodology used, a delay is applied at some point during the movement. In [7] it is argued that this is one of the three main strategies when implementing a GA. The main strategies include:

- Applying an initial delay/hold before pushback
- Applying a delay at a point during taxi
- Prioritizing aircraft movement

When applying an initial delay or hold before pushback, a delay and route will be allocated to every aircraft by the GA. The second method, applying a delay at a point during taxi, is used in [44]. Here, the delay is specified by setting a specific time for the start and end of a delay or by setting an amount of delay on a fixed position. Then, the GA will determine a position and assign a delay with start and end time where applicable. Using the third approach, prioritizing aircraft movement, the GA will investigate how to prioritize aircraft relative to each other rather than allocating a delay outright. The third option is the most frequently used approach [7].

In some cases, more traditional methods are combined with heuristics. This is the case in [28], where a branch and bound algorithm is used as a first search strategy in order to speed up the computation of the GA. In general, it must be noted that the research in which a GA is used is very complex and in a lot of cases involves the integration of various ground movements, including runways. A GA may be faster than a MILP for complex cases, but using a GA comes with a higher risk of converging to a non-optimal point, which is not the case for MILP [8]. From the literature reviewed, it has been discovered that presently no research that focuses specifically on gate pit-stops has been performed. Therefore, there is no preference in literature for using a MILP formulation or a GA when it comes to gate pit-stops.

2.4. Conclusions

The conclusions of the literature review are presented in this section, with results on apron operations and apron models discussed, followed by the synthesis of the literature gap.

Gate Planning

From the literature studied and discussed on gate planning, it can be concluded that existing formulations can be used to assign gates to aircraft with pit-stops. The objectives of most studies relating to the GAP look to optimize by creating a robust gate schedule. However, the definition of a robust schedule differs according to the author's viewpoint: it either relates to minimizing slack times or maximizing slack times. Therefore, when setting up a model with gate assignments, the main objective can be maximizing flights handled at a gate or minimizing delays. However, a combination of the two is also possible. Additionally, no research has been done into gate assignment problems with pit-stop turnaround times of less than three hours. The little research that has been done on pit-stops only take them into account on a very limited scale. A study where flights are considered for a gate pit-stop on a large scale has not been done yet, and there is therefore no knowledge available on the effect of pit-stops on gate utilization. As such, a significant research gap has been identified, and design choices in the thesis research will be made to close this gap.

Apron Operations
Looking at the literature on apron design and layout guidelines as well as the apron movements studied in this chapter, several conclusions can be drawn. First, the apron design and layout is subject to strict guidelines which depend on parameters such as aircraft type and gate size. In order to properly model an airport apron, these parameters with the corresponding guidelines need to be taken into account. Also, several design choices need to be made for the simulation of gate pit-stops, such as the aircraft type under study.

Secondly, the aircraft movements that take place on the apron are influenced by several parameters like taxi speeds and pushback times. These are also affected by design choices and may be influenced by the introduction of new technology as well. The literature reviewed provides several guidelines to model airside areas and approximate aircraft movements, however combining this all into a proper model to simulate gate pit-stops is something that has not been done before.

Apron Models
Available literature on aircraft ground movements has shown that there are multiple viable options to model ground movements. First, existing simulation tools like SIMMOD can be used. These tools are detailed and readily available, however they are complex and require a deep understanding with a steep learning curve in order to use them effectively. Another option is to create a node and link model of an airport and setting up a MILP formulation. A MILP formulation leads to an optimal solution and is the preferred option in literature to solve problems on aircraft ground movements. However, as the scale of a problem increases, computation time of a MILP formulation increases exponentially. Hence, in such cases, heuristics may be applied to solve the problem. The most commonly used heuristic in relevant studies is the GA. A GA will be faster in solving a problem than a MILP (especially for large problems), but there is no guarantee that the solution converges to an optimum.

Literature Gap
Presently, no extensive study that assesses the effect of gate pit-stops on apron congestion has been performed. The literature review confirms that some research touches upon the subject (mainly in gate planning studies), but the scope of pit-stops in these studies was limited and they were restricted to flights with very long turnaround times (roughly three hours or more) only. The method for the gate planning of flights with a gate pit-stop can serve as a starting point for the thesis research, which will be the first where gate pit-stops will be applied and their effects explicitly evaluated. Next, the guidelines on apron design and layout can be used to create an accurate representation of an airport. With the apron movements considered for gate pit-stops, the thesis research can also be used to assess the effectiveness of using an ETS for gate pit-stops. While ground movements have been modelled using various techniques, an optimization with gate pit-stops on a large scale specifically has not been done, and therefore an appropriate technique will have to be chosen and formulated, taking into account the lessons learned from the literature reviewed in this section.

3

Research Scope and Framework

This chapter discusses the scope and framework of the research on gate pit-stops. First, the problem statement is described in Section 3.1, after which the objective of the research is discussed in Section 3.2 and the main research questions are introduced in Section 3.3. Finally, Section 3.4 presents the research scope, and Section 3.5 discusses the scientific contribution of the work.

3.1. Problem Statement

Air traffic is increasing worldwide, and this trend is expected to continue for the coming 20 years, with global air traffic reaching up to 7.2 billion passengers annually [35]. This growth needs to be accommodated at airports, but current infrastructure is already (severely) constrained at several airports worldwide [36]. At the airports listed in [36], peak demand exceeds available capacity, which leads to congestion in several areas. In order to increase capacity, airports are expanding by constructing additional infrastructure, but this is both costly and time consuming. Therefore, airports and airlines together are looking into new ways to use existing airport infrastructure more efficiently in order to reduce congestion.

Congestion at airports can have several effects that negatively impact both airlines and airports. The most obvious effect is the occurrence of delays, however another major aspect is gate utilization. When peak demand exceeds available capacity, airports are unable to assign a gate to every incoming aircraft, which forces flights to be handled at a remote stand. This leads to inconveniences for passengers, airlines and airports and is therefore an undesirable side effect of the explosive increase in air traffic. This problem will only exacerbate as passenger numbers rise, so new methods of utilizing available gate capacity are required. One promising option is to introduce so called gate pit-stops. By introducing a gate pit-stop, an aircraft will be towed to a remote parking position between arrival and departure from the gate, in order to make space for another flight at the same gate in the meantime [51]. However, this will lead to an increase in apron movements, so the effect of gate pit-stops on gate utilization and apron delays needs to be assessed in order to determine whether they are a viable option to increase gate utilization.

The problem statement is summarized below:

- Air traffic is expected to double over the coming 20 years
- Airport infrastructure is already struggling to cope with current demand
- Gate utilization is a major issue: more and more flights will have to be handled remotely
- Construction of additional gate infrastructure is expensive and time consuming
- Current gate capacity needs to be utilized more efficiently
- Gate pit-stops can be introduced to reduce the number of remotely handled flights

- Introducing gate pit-stops leads to extra apron movements which may lead to additional apron delays

Currently, very little research has been done on the effectiveness of gate pit-stops, and their use is limited to flights with turnaround times of roughly three hours or longer [21][51]. This research therefore presents an interesting opportunity to look at gate pit-stops as a meaningful way to increase gate utilization for arriving flights while taking into account their effect apron movements.

3.2. Research Objective

The main objectives of the research can be traced back to the problem statement presented in the previous section. The objectives are summarized as follows:

'To assess whether gate pit-stops are a viable option to increase gate utilization for arriving flights at congested airports by creating a model that is capable of assigning aircraft to a gate and simulating the corresponding apron movements and delays'

In order to define the appropriate methodology to achieve the research objectives, the statement presented above will be dissected below.

A viable option to increase gate utilization: The goal of introducing gate pit-stops is to increase the number of flights that can be handled at a gate instead of at a remote stand. Therefore, increasing gate utilization will be measured by the number of flights in a given time period that are handled at a gate versus remotely. As the additional towing movements introduced with pit-stops lead to additional apron movements, it is possible that aircraft delays may increase. This holds for both the total system (total delay of all flights arriving and departing within a certain time frame) and individual flights (individual delay for an arriving or departing flight). Thus, it remains to be investigated whether gate pit-stops will lead to delays or not and to what extent. Viability in the context of this research is related to the total system delay and delay per aircraft as a direct result of introducing pit-stops. Naturally, whether the results show that pit-stops are viable or not is open to discussion. It is up to airports and airlines to decide whether the effects on delays are acceptable or not, and whether this makes gate pit-stops viable to them (and on what scale). However, the aim of this research is to provide insight into the operational effects, which will help decision making at airports and airlines alike.

Assigning aircraft to a gate: By creating a model that automatically assigns arriving aircraft to a gate, the exact effect of gate pit-stops on gate utilization can be analyzed. With an input schedule of arriving flights, the model will be able to determine whether a gate is occupied or not, and assign an arriving aircraft to an unoccupied gate. If no gates are available, the aircraft will be assigned to a remote stand position. Additionally, the model will assign aircraft to available gates while minimizing delays, so gates are assigned in the most optimal way.

Simulating the corresponding apron movements and delays: To determine the effect on delays, the apron movements will have to be simulated. A model will be set up that represents the taxiways of the apron and gate area. Depending on the gate that is assigned to an arriving aircraft, the exact route from and to the entrance of the apron area to the gate will be simulated. The aircraft will have to maintain minimum separation with other aircraft (both arriving and departing aircraft) on the taxiways. Delays can be assigned to individual aircraft by the model while the model will be optimized to reduce delays as much as possible. This will allow for an accurate representation of all apron movements (including those of gate pit-stops) and associated delays, which in turn will enable conclusions about ground delays due to pit-stops to be drawn.

Expected outcomes

Creating a model that assigns gates while simulating the corresponding apron movements (including those of gate pit-stops) while optimizing for minimum delays, is a novel approach. The main aspects that will be analyzed in this study are the number of flights handled at a gate instead of a remote stand and the delays associated with gate pit-stops. The expected outcome of these two aspects in the research is as follows:

- **Gate utilization**: It is expected that the introduction of gate pit-stops will lead to an increase in the number of flights that can be handled at a gate instead of at a remote stand
- **Delays**: It is expected that gate pit-stops will lead to an increase in taxi delays on the apron

The two hypotheses mentioned above will be tested and checked, by running simulations with the model and analyzing the obtained results. Looking at the first hypothesis, it is expected that the introduction of a pit-stop will reduce the time that a flight will occupy a particular gate, so it logically follows that more flights can be handled at a gate. For the second hypothesis, the effect of the increased movements due to pit-stops needs to be considered. A pit-stop inevitably leads to an increase in apron movements as aircraft need to be towed to and from the gate. Especially at busy airports where aircraft arrive in high sequence, introducing additional apron movements may prove to lead to high delays as aircraft with a pit-stop will have twice as many ground movements as aircraft without a pit-stop. Aircraft need to maintain a minimum separation and conflicts between arriving, departing and towed aircraft may arise leading to delays. For both hypotheses, the reference case will consist of simulations without pit-stops. These will then be compared to the results found for simulations which do include pit-stops, using the same input schedule and model setup. Then, conclusions can be drawn whether introducing pit-stops at airports on a broader scale will be useful or not.

3.3. Research Questions

In order to meet the objectives for the study, a main research question with sub-questions has been set up. When these questions can be fully answered, the research has reached the goals set forward earlier. The main research question has been defined as follows:

Can gate utilization at hub airports be increased by making (more) use of gate pit-stops, and what effect does this have on apron congestion?

In order to properly answer this question, the main research question has been divided into the following two more specific main sub-questions:

1. Given a certain time period, how do gate pit-stops for flights with a turnaround time of less than three hours affect gate utilization for other flights in that time period?
2. What is the effect of introducing gate pit-stops for flights with a turnaround time of less than three hours on apron delays?

These questions will be answered in the chapters that follow in this document, after which conclusions will be drawn, limitations are identified and recommendations for further research are made.

3.4. Research Scope

To answer the research questions and accomplish the research objectives within the guidelines set by TU Delft, it is imperative that the project will be appropriately scoped. By scoping the project, assumptions will be set that form the boundaries of the research project. These assumptions are listed below:

- The goal of the research is to demonstrate the effect of gate pit-stops for a generic representation of an airport. The model is not meant to resemble an existing terminal or airport. The methodology used in this research can however be applied to models of existing terminals and airports.
- Only the movements that take place on the apron will be taken into account. This implies that airborne movements, runway movements and taxiway movements outside of the apron area will not be considered.
- Interaction with ground vehicles will not be taken into account in this research
- There is no limit on remote stand capacity. Whenever an aircraft arrives and all gates are occupied, it will be assigned to a remote stand. In this research, it is assumed that this remote stand has unlimited capacity, so whenever aircraft cannot be handled at a gate, they can always be handled at a remote stand.

- There are no runway and/or taxiway limits outside of the model. Aircraft will arrive in sequence and will be able to depart regardless of any constraints outside of the apron area. Therefore, runway sequencing and effects of ATC (clearance, delays etc.) are not taken into account in this research.
- The aircraft used in the research are all of the same type, with identical dimensions and performance (taxi speeds, turnaround times etc.) unless otherwise specified.
- There are no limits on apron resources such as tow bars and tow trucks. Whenever an aircraft is ready for pushback or remote towing, sufficient equipment is instantly available and the operation will commence.
- Aircraft instantly accelerate to taxi/towing speed or decelerate to standstill where required
- Aircraft will taxi on the exact center line of the taxiway and turns are modelled as straight (90 degree) turns

3.5. Scientific Contribution

Contrary to previous studies on gate capacity and aircraft ground movements, this research will be the first of its kind that looks into the effect of gate pit-stops on ground movements and gate utilization. A model of a busy airport will be set up including apron taxiways and gates. This model will be able to assigns gates and simulate taxi movements while safeguarding aircraft separation and assigning delays where required. By including gate pit-stops, this research will be the first to demonstrate whether pit-stops are a viable option to reduce the number of flights that have to be handled remotely. The research builds upon the state-of-the-art in literature on several subjects, while expanding on topics not explored earlier, which represents the scientific contribution of this study. Below, the relevant areas of research are listed.

State-of-the-art:

- Gate assignment and gate planning
- Taxi routing optimization

Scientific contribution:

- Incorporating gate pit-stops on a large scale
- Effects of gate pit-stops on gate utilization
- Effects of gate pit-stops on apron delays

4

Methodology

In previous chapters, the state-of-the art on which the research is based, as well as the scope and objectives of the research have been presented. This chapter discusses the methodology of the research that will ultimately lead to the results and conclusions on gate pit-stops. To present the methodology in a clear and concise way, this chapter has been divided into multiple sections. First, the requirements that the model needs to fulfill are visualized and discussed in Section 4.1. Then, Section 4.2 presents the airport model used in the research. Section 4.3 discusses the input schedule used to run the model and obtain results, after which the mathematical model used to solve the problem under consideration is shown in Section 4.4. Finally, Section 4.5 presents final conclusions on the methodology.

4.1. Model Requirements

In this section, all of the model requirements will be established. These requirements will serve as a starting point for setting up a simulation of gate pit-stops and apron movements. First, functional flow diagrams for the problem under consideration have been set up, which will be discussed in Section 4.1.1. These diagrams will give a better understanding of all inputs and outputs that are required for setting up the model, and they will provide a schematic of applicable agents and servers that should be modelled together with their functionalities. Once this has been done, an overview for required inputs, outputs, functionalities and design requirements can be dissected from the functional flow diagrams. This overview will be presented in Section 4.1.2.

4.1.1. Functional Flow Diagrams

In order to fully understand the model requirements, the functional flows of the agents and servers in the model have been captured in functional flow diagrams. The main agents in the model are the aircraft, whereas the gates and apron taxiway(s) are the servers of this model. First, the main elements of the aircraft turnaround process including gate pit-stops are visualized in Figure 4.1. The main functional flow diagram consists of eight elements, which apply to each aircraft modelled. Each of these elements (except for the final element) is represented by a separate functional flow diagram, all of which will be discussed further below.

Main Functional Flow Diagram

As can be seen in Figure 4.1, the eight main elements in the model's functional flow are Arrival, Hold, Gate, Remote Stand, Pit-stop, Gate after Pit-stop, Departure and Flight Handled. The model should be able to simulate the handling of arriving aircraft, assign them to a holding position and a gate (both before and after a pit-stop) or remote stand, assign a pit-stop and round off the handling of an aircraft, either with or without a pit-stop. Both the 'hold' and 'pit-stop' modules are optional, hence aircraft modelled have the ability to hold in case of delays and to receive a pit-stop only if applicable. Additionally, the model should either assign aircraft to a gate or to a remote stand. As mentioned in Section 3.4, the scope of the model is limited to aircraft movements on the apron, which is evident from the structure of the main flow diagram, as runway movements and main taxiway movements are not included as a separate module. Next, each module will be discussed in detail to get a better understanding of what is required from the model and which agents, servers and variables are involved. Note that the module 'Flight Handled' is not discussed in further detail as this module is the concluding step and does not involve any further actions that need to be simulated.

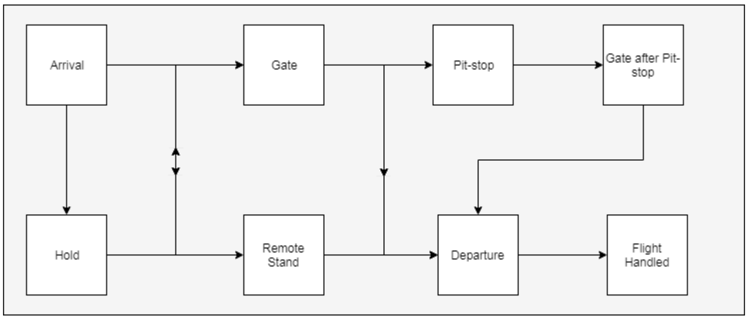


Figure 4.1: Main functional flow diagram

Legend

The modules that are discussed next contain various different agents, servers and variables. Hence, each one is colour coded (see Figure 4.2). The variables in the model are of three different types. Variables found in literature are indicated in grey, exogenous variables (i.e. those not determined by the model but used as external input) are indicated in red whereas endogenous (i.e. those determined by the model) are indicated in yellow. The exogenous variables indicate design choices as they serve as direct external inputs for the model and can be changed depending on the problem under consideration. Conversely, the endogenous variables cannot be changed directly by changing model input, as they results from the optimizations (and intermediate steps) of the model itself. The main agents and servers (aircraft, gates and taxiways) are color coded as well. Whenever an aircraft serves as an actor, this is indicated in blue. The gates and taxiways under consideration are grouped together and displayed in green.

The functional flows in each module lead to a subsequent module. This is indicated in white which corresponds to the main modules of Figure 4.1.

Figure 4.2: Legend for functional flow diagrams

Arrival

In Figure 4.3, the initial step is the arrival of the main actor(s), one or more aircraft. In order to properly model arriving aircraft, arrival times need to be determined as well as any stochastic variations. These will serve as external input to the model. Once an aircraft enters the model, appropriate taxi speed(s) and taxi distances throughout the model should be assigned. These values will come from applicable literature on the simulation of airside movements. The aircraft will then be required to taxi to a gate or remote stand. In order to do so, a gate or stand needs to be assigned, which will be done endogenously by the model. Additionally, the arrival and departure times of other aircraft need to be taken into account to determine the potential for conflicts and issue a resolution if needed. Once this can be decided in the model, the aircraft will either taxi to a gate or remote stand if available (indicated by **Y** in the diagram), or it will hold in its current position to make way for other aircraft should this be required (indicated by **N** in the diagram).

Hold

In case of a potential conflict between multiple aircraft, the model may require an arriving aircraft to

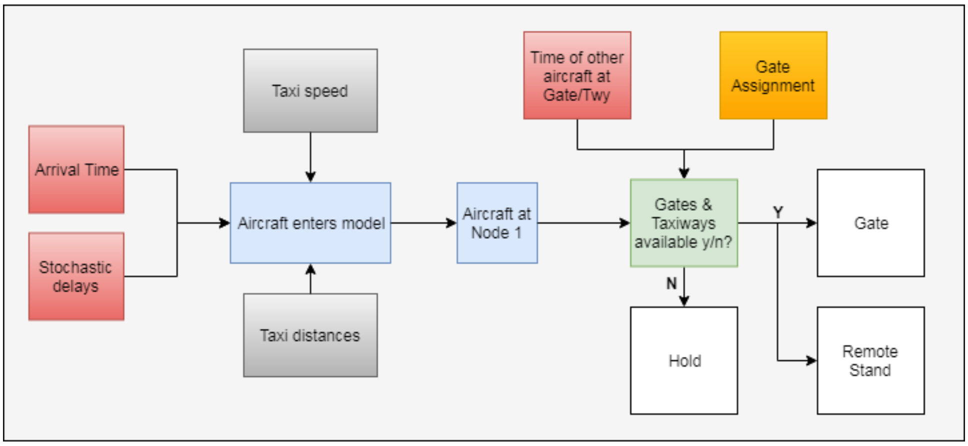


Figure 4.3: Functional flow diagram - arrival

hold before continuing to the gate or remote stand. The required functional process when this occurs is depicted in Figure 4.4. In case of a conflict because of an occupied gate, stand or taxiway, the time a conflict is resolved needs to be determined. This will be done endogenously and this in turn will lead to determining the total hold time. Additionally, when a conflict is resolved and gate or stand has become available, the model has to assign the arriving aircraft to that particular gate or stand. As such, the model must be able to determine availability of gates, taxiways and stands, assign holding delays and it must be able to provide a proper gate or remote stand assignment.

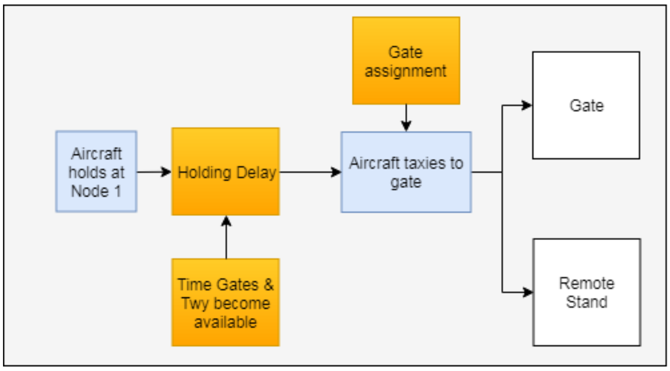


Figure 4.4: Functional flow diagram - hold

Gate

In the case that an aircraft is assigned to a gate, the required functional flow is displayed in Figure 4.5. Once the aircraft is ready to taxi to the gate, the arrival times at the gate and intermediate nodes will need be determined endogenously. Subsequently, the aircraft is parked at the gate, and the total parking time has to be determined. This will be done using data on typical turnaround times found in literature, together with the design choice to model the turnaround as a full-servicing station or as an outstation. Once this is known, the aircraft may be eligible for a pit-stop, which depends on the design input requirement for the minimum required turnaround time for a pit-stop.

If the aircraft will be towed with a pit-stop (indicated by **Y** in the diagram), first it needs to be determined whether the taxiways are available to tow the aircraft to a remote stand. This is determined endogenously, and if this is the case (again indicated by **Y** in the diagram) the aircraft will be towed and ready for a pit-stop, indicated as a separate module. If the taxiways are not available (indicated by **N** in the diagram), the time of other aircraft on the taxiways has to be established, after which a towing delay can be assigned which will both happen endogenously.

When an aircraft will not be subject to a pit-stop (indicated by **N** in the diagram), it will depart after completing turnaround at the gate. Once the aircraft is ready to depart, just like in the case of a pit-stop discussed in the previous paragraph, the model needs to determine whether the applicable taxiways are occupied or not. If this is the case (indicated by **Y** in the diagram), the aircraft will hold until it is decided that the taxiways are available (leading to a pushback delay) after which the aircraft will depart from the gate. If this is not the case (indicated by **N** in the diagram), the aircraft will depart from the gate immediately.

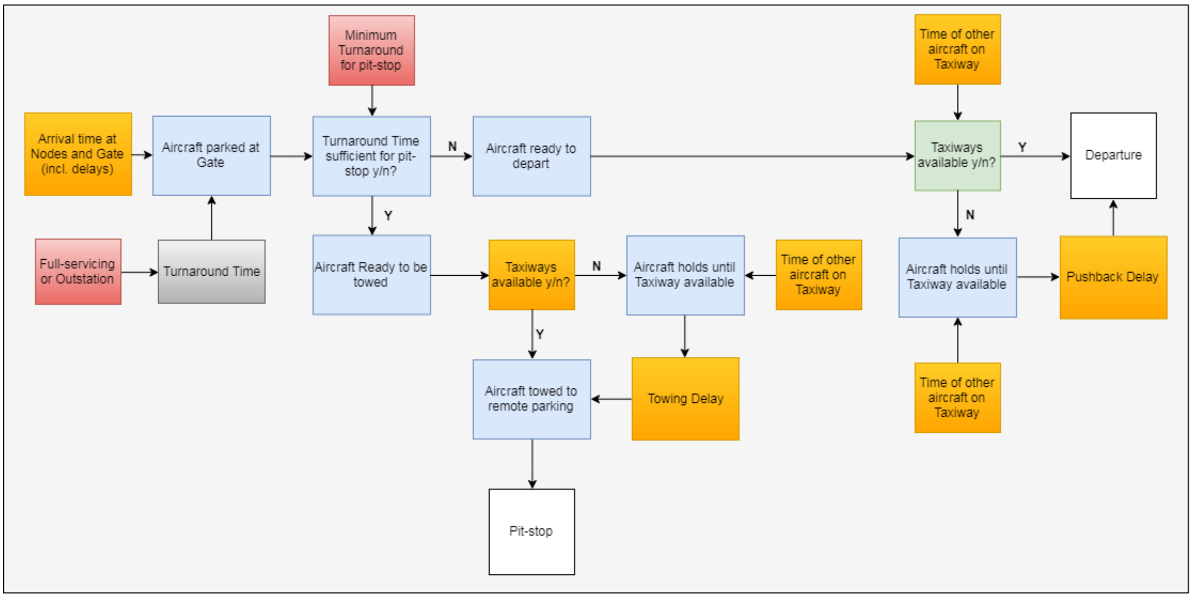


Figure 4.5: Functional flow diagram - gate

Remote Stand

When an aircraft is assigned to a remote stand, it logically follows that it is not eligible for a pit-stop. Thus, the functions described here apply to an aircraft parked at a remote stand instead of a gate for the full turnaround, and not an aircraft that is parked at a remote stand as part of a pit-stop. Pit-stops at a remote stand will be treated separately. The functional flow of aircraft parked at a remote stand is depicted in Figure 4.6. Similarly to the situation where a flight is parked at a gate, the assigned turnaround time is a combination of data from literature and the design choice to model as a full-servicing turnaround or an outstation turnaround. The endogenous variables in the remote stand module are the occupation of taxiways by other aircraft and a pushback delay if needed. When the aircraft has completed its turnaround, it is ready to depart as shown by the departure module.

Pit-stop

In case a pit-stop will be applied to a flight, the required functional flow for this procedure is displayed in Figure 4.7. The main actor, an aircraft, will be towed to a remote parking position where it will be parked for the duration of the pit-stop. This duration is a model design choice and therefore exogenous to the model. As the aircraft is ready to be towed to the gate, the model needs to determine endogenously which gate will be assigned and whether the corresponding taxiways are free of conflict. If there are no conflicts (indicated by **Y** in the diagram), the aircraft will be towed to the assigned gate, which will lead to the next module (gate after pit-stop). If the taxiways are occupied (indicated by **N** in the diagram), the aircraft will be assigned a towing delay by the model, after which it will arrive at the next module.

Gate after Pit-stop

After completing the duration of a pit-stop, an aircraft in the model has to be parked at a gate again (or in exceptional cases be assigned to a remote stand if no gates are available, however flights returning from a pit-stop are prioritized for a gate). The associated process is visualized in Figure 4.8. The gate assignment and arrival time will be determined endogenously. The turnaround time at the gate after

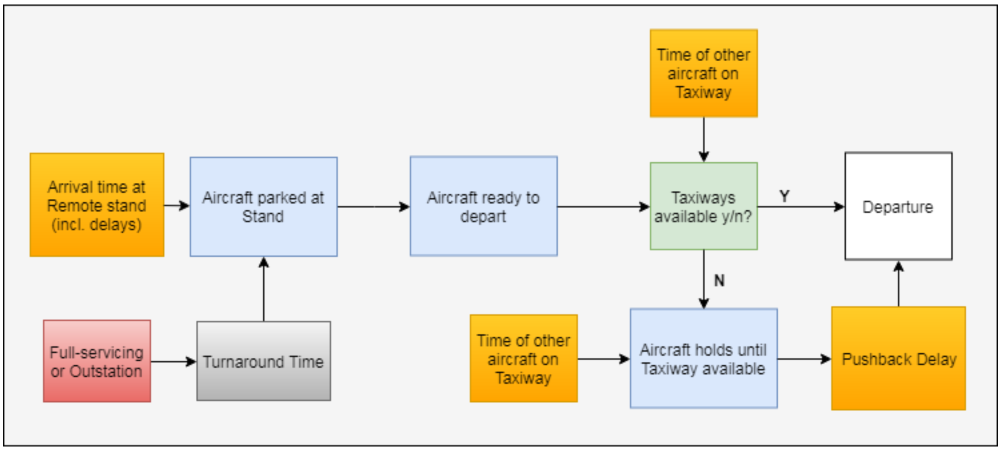


Figure 4.6: Functional flow diagram - remote stand

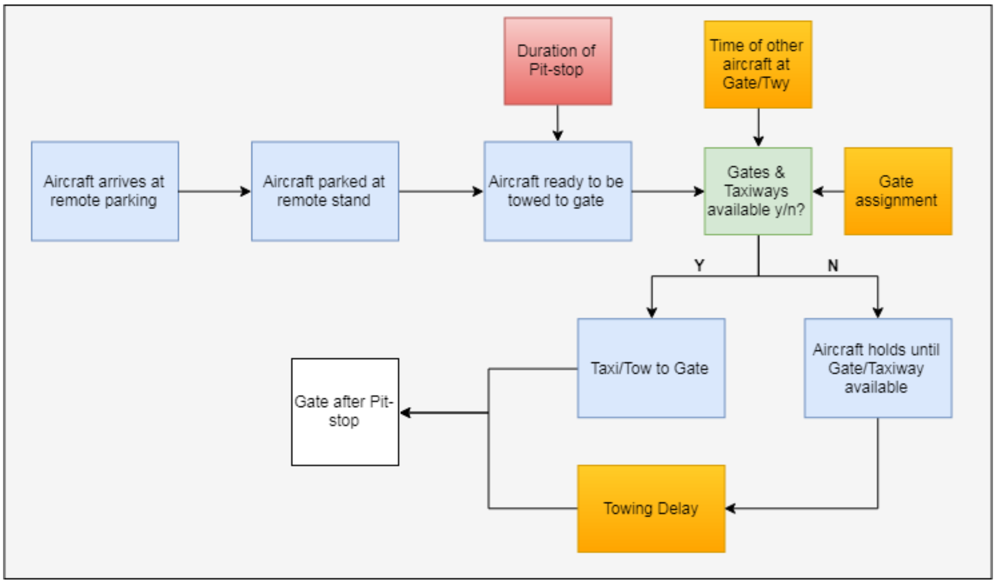


Figure 4.7: Functional flow diagram - pit-stop

returning from a pit-stop is an external input variable. Similarly to the situation in Figure 4.5, the time of other potential aircraft on taxiway as well as possible conflicts and pushback delays will be determined endogenously. Once this is complete, the aircraft can depart. This module will be explained next.

Departure

The final module that will be discussed in detail is the functional flow of the departure process, which is shown in Figure 4.9. The model will determine the actual departure time from the gate, after which the aircraft will be pushed back. The total pushback duration will be modelled using data found in literature. As pushback may occur using conventional towing or an ETS, a design choice has to be made which will influence which exact pushback duration found in literature will be used. Once pushback has been completed, the model needs to determine whether other aircraft occupy the taxiways and if conflicts can occur. Depending on whether this is the case or not, a holding delay can be assigned. Once the aircraft is ready to taxi out without conflict, it is completely handled by the model. This is indicated in Figure 4.9 by the 'aircraft handled' module.

With the required functional flows of the model fully worked out, the exact model design requirements can be distilled. This is discussed in the next section.

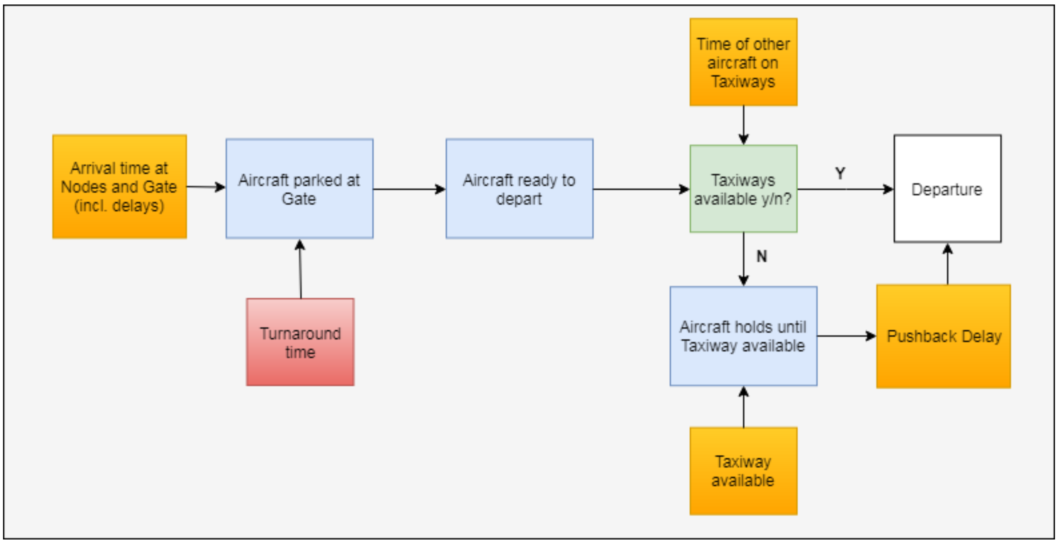


Figure 4.8: Functional flow diagram - gate after pit-stop

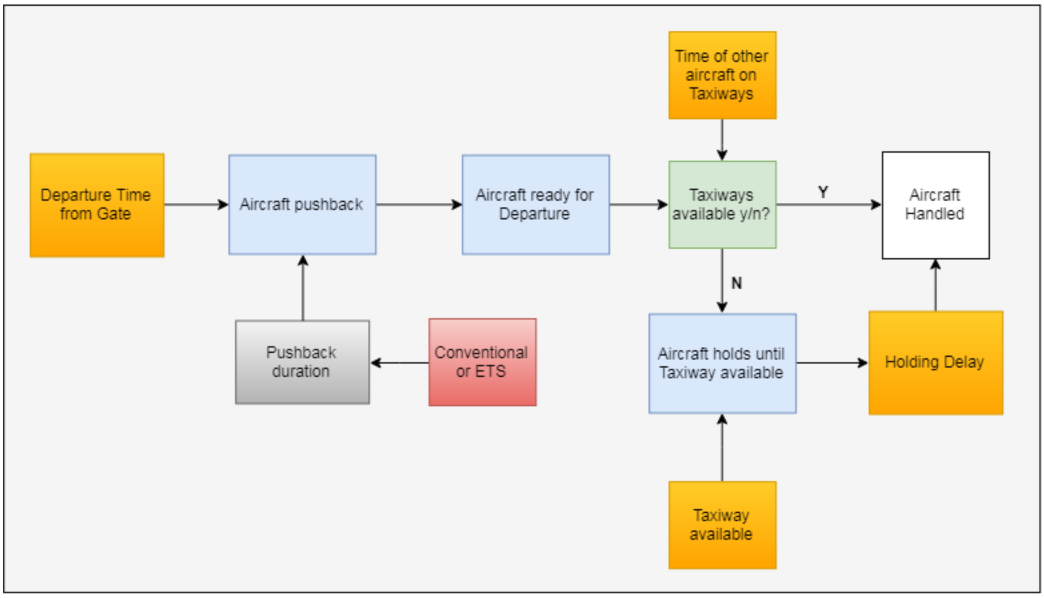


Figure 4.9: Functional flow diagram - departure

4.1.2. Design Requirements

In this section, the model design requirements found from the function flow diagrams in the previous section are discussed. Both the applicable agents, servers, required exogenous variables and endogenous variables required from the model are listed.

Agents and Servers

The aircraft in the model have been identified as the main agents. They should therefore be taken into account for the design as the only agents that will be modelled. Design choices will have to me made for these aircraft, such as the number and type of aircraft under consideration. In Section 4.2.1, this will be discussed in further detail. The servers that have been identified are the gates and taxiways. These servers should be properly sized and modelled, which will be discussed further in Section 4.2.1.

Exogenous variables

The exogenous variables required as input to the model are a combination of design choices and variables found in literature. They need to be determined *a priori*, i.e. before the simulations will commence.

All exogenous variables required are listed below, with the first four ones being variables that will be determined from literature.

- Taxi speeds
- Taxi distances
- Turnaround time
- Pushback duration
- Aircraft arrival time
- Aircraft departure time
- Stochastic variations
- Full-servicing or outstation
- Minimum turnaround time for pit-stop
- Duration of pit-stop
- Duration of turnaround before and after pit-stop
- Conventional pushback or ETS

The exogenous variables and applicable design choices are discussed in Section 4.2.2.

Endogenous variables
As mentioned previously, endogenous variables are those that are explained by the relationships and functions of the model. Therefore, the endogenous variables need to be defined by the model. The endogenous variables found from the functional flow diagrams are as follows:

- Gate assignment
- Gate utilization
- Taxiway availability
- Actual arrival and departure time of aircraft (at nodes, gates, stands)
- Holding delay
- Pushback delay
- Towing delay

Note that a gate assignment corresponds to a specific taxiway routing, which needs to be taken into account as well. The endogenous variables listed need to be defined in the model formulation. This will be done by setting up a mathematical formulation, which is explained in further detail in Section 4.4.

From the above section, it can be concluded that a model needs to be created which can provide the endogenous variables listed using the exogenous variables as input, while modelling the applicable agents and servers. The following sections will discuss in detail how this will be done.

4.2. Airport Model

Having identified the requirements that the model should fulfill, several design choices for setting up the model can be made. From the literature studied in Chapter 2, it has become clear that there are multiple methods to simulate aircraft ground movements. The three main options are using existing simulation tools (either on microscopic or macroscopic level), using a Mixed Integer Linear Programming (MILP) model or using a Genetic Algorithm (GA) model.

The use of simulation tools like SIMMOD and MACAD appear attractive as they are readily available and adaptable to the problem under consideration. It could be argued that a combination of microscopic simulation (as a decision making tool) and a macroscopic simulation tool (to model the infrastructural components) would be a viable option. However, as has been noted, these programs require expensive licenses and require considerable in-depth knowledge to operate (which in turn requires a significant amount of training). Because of both budget and time constraints, it is not feasible to use these tools for the research on gate pit-stops.

Therefore, it has been decided that the problem will be modelled using a MILP or GA formulation. The difference between using a MILP or GA formulation mainly lies in the expected complexity of the problem under review. The main advantage of using a GA in these cases is that it runs faster than MILP, however running a GA has a higher chance of converging to a non-optimal point. In the end, a MILP formulation seems most appropriate for this problem. Coupled with using a MILP formulation is the requisite to model the physical airport layout as a node-link model. The following sections will both discuss the accurate representation of an airport with its node-link model (Section 4.2.1) as well as the movements that take place and the design choices that have been made to appropriately model these movements (Section 4.2.2).

4.2.1. Physical Airport Representation

In order to create a node-link model that accurately presents an airport, several physical design choices to represent an airport have to be made. In Section 3.4, several items are listed concerning the scope of the research that need to be taken into account for the physical airport model. The first of these is the assumption that the airport under consideration will be a fictitious airport not meant to strictly resemble any other airport, however a layout will be chosen that resembles several relevant airports in operation today. In addition to that, only the apron movements will be taken into account which implies that only taxiways on the apron together with the gates will be modelled. Also, there is no limit on remote stand capacity, so remote stands will not be modelled separately. Finally, all aircraft will be of the same type, so gates and taxiways will be sized accordingly. Taking into account these limitations, design choices concerning the following aspects are made:

- Aircraft type
- Parking type
- Terminal building design type
- Gate sizing
- Taxiway sizing

Each of these aspects will be discussed below.

Aircraft Type

In order to reduce complexity, a single aircraft category has been chosen which will serve as the starting point for the physical design. As the most commonly used aircraft at airports worldwide are Category C aircraft such as the Airbus A320 series and the Boeing 737 family (see Section 2.2.1, **Aircraft Type**), the airport will be sized accordingly. This design choice has a direct influence on parameters such as the required separation of taxiways and gates.

Parking Type

The parking type of aircraft relative to the terminal building has a great influence on the apron layout.

Most large airports worldwide use nose-in parking (see Section 2.2.1, **Parking Type**) and considering the fact that other parking types generally use stairs for boarding instead of a jet bridge, this parking type is the most appropriate for for simulating gate pit-stops and gate utilization. As such, the apron and gate layout are designed and sized for this parking type exclusively.

Terminal Building Design Type

There are different terminal design types in use at airports worldwide (see Section 2.2.1, **Terminal Building Design Type**) that influence the way both gates and taxiways on the apron are modelled. As this research intends to assess the effects of gate pit-stops on apron congestion, the airport model will consists of a pier concept in a 'U'-shape. This design has been chosen as pit-stops will have the most pronounced effect on apron movements with this terminal layout. The concept will be loosely based on real-life situations at airports worldwide, such as the inner 'fork' of the D-pier at Amsterdam Airport Schiphol in The Netherlands (AMS) in Figure 4.10, or Apron 1 South/2 North at Brussels-National Airport in Belgium (BRU), with two piers in a 'U'-shape and an apron in-between (see Figure B.1 in Appendix B).

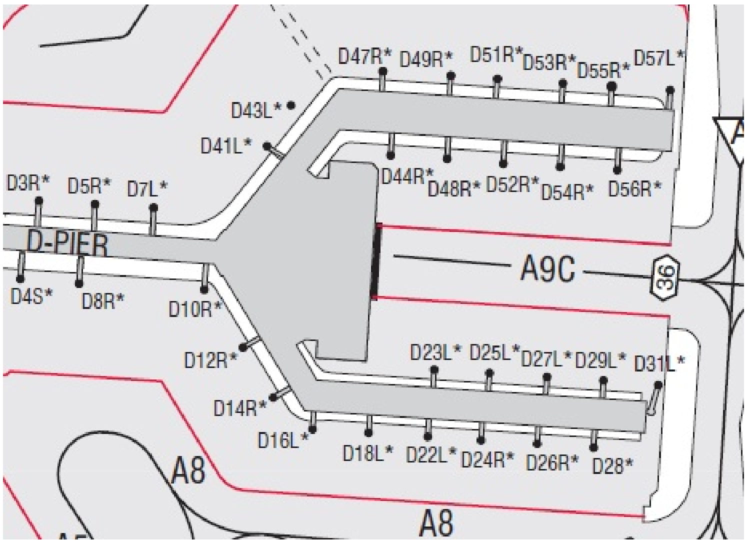


Figure 4.10: Aerodrome chart of D-Pier at Amsterdam Airport Schiphol in The Netherlands, adapted from [6]

Gate Sizing

With design choices on aircraft type, parking type and terminal building design type made, the number of gates and their sizing can be decided. In order to assess the effect of pit-stops for a varying number of gates, a design should be chosen that is flexible regarding the number of gates that can be modelled. With the aforementioned design choices, the general setup of the airport is modelled as shown in Figure 4.11. As can be seen, the model consists of multiple gate pairs of equal size running along two main piers. In the example presented, a total of eight gates is modelled. For the model, the maximum size will total eight gates, with flexibility to model for six and four gates as well. The remote stands are not modelled explicitly, however in case an aircraft is allocated a remote stand, it will arrive at the model entry and taxi to the remote stand which is located outside of the physical model, taking into account the assumption that remote stand capacity is unlimited. Design choices for the sizing and total number of taxiways and the exact number of gates are presented further on in this section.

For the sizing of the gates, the main parameter of influence is the appropriate separation for Category C aircraft. The separation requirement for Category C aircraft, listed in Table 2.2 in Section 2.2.1, stipulates a minimum clearance between two parallel taxiways at a gate of no less than 40.5 meters. A value of 40.5 meters can therefore be used for the lateral gate spacing in the physical airport model. This value is consistent with guidelines set by Airbus for its A320 family of aircraft [1]. However, the airport model is intended to resemble a large (hub) airport. Therefore, for the gate sizing alone, it is assumed that the gates are 'dual use' and can be used for larger aircraft if required. For these aircraft,

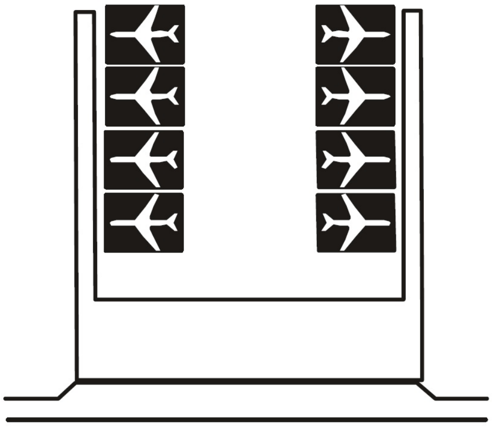


Figure 4.11: Apron and gate model with eight gates, adapted from [38]

a minimum separation between parallel aircraft stand taxi lanes will be assumed of about 61 meters (40.5 times a factor of 1.5). Adding a safety margin of 4.5 meters at each gate, the gates are located with a lateral spacing of about 70 meters.

Next to the gate width, the total length of the gate area has been set. For the largest aircraft categories, ICAO has declared the minimum clearance between aircraft and other objects at 7.5 meters (see Table 2.3 in Section 2.2.1). Therefore, the length of the gate area should encompass the total length of Category C aircraft together with the added clearance at the front and rear of 7.5 meters at minimum.

To properly size for the largest Category C aircraft, the total length of the longest aircraft of this type has been used as a reference, which is the Airbus A321/A321neo. This aircraft measures 44.51 meters from nose to tail [1]. Rounding up this length to 45 meters coupled with a margin of 8 meters at the aircraft's front and rear leads to the design of gates measuring 61 meters deep. In order to complete the physical model sizing, the taxiways are the final component that has been sized.

Taxiway Sizing

Just like other aspects of the airport model, the taxiways for the general airport setup shown in Figure 4.11 are sized for Category C aircraft. Only the taxiway leading to the apron entry and the apron taxiways with the corresponding gate taxiways is modelled. The taxiway that runs from the apron entry to the gate pair located furthest from the apron entry (referred to as the main taxiway) has been sized first. The main taxiway has been divided into four parts, which corresponds to the taxiways labeled from 1 to 4 in Figure 4.12. For the model, a design using one main taxiway has been chosen, with branches running from the main taxiway to every gate pair.

Of the four parts that make up the main taxiway, the first element (Taxiway 1) differs somewhat from the other parts and has been sized first. From Table 2.3, the minimum separation between parallel taxiway center lines for Category C aircraft is 44 meters. However, the taxiway that runs perpendicular to Taxiway 1 forms part of the larger airport outside of the model scope. As such, it can be used for larger aircraft as well. It is assumed that Category F aircraft will be present at the airport as well (though not part of the apron model), and taxiway spacing guidelines for this aircraft stipulate a distance of 91 meters between parallel taxiways. Therefore, the length of Taxiway 1 is set to 91 meters in length. As discussed previously, the gates are sized measuring 70 meters in width including safety margins. Thus, the length of the subsequent main taxiway parts (marked as Taxiway 2, 3 and 4 respectively) is set to 70 meters. Table 4.1 summarizes the length of the main taxiway elements for the model presented in Figure 4.12.

Next, the distance from the main taxiway to each gate pair has been set. In order to determine this distance, the apron taxi lane width needs to be chosen. A width of 44 meters has been chosen which corresponds to the largest spacing requirement set by ICAO for Category C aircraft. With a total stand

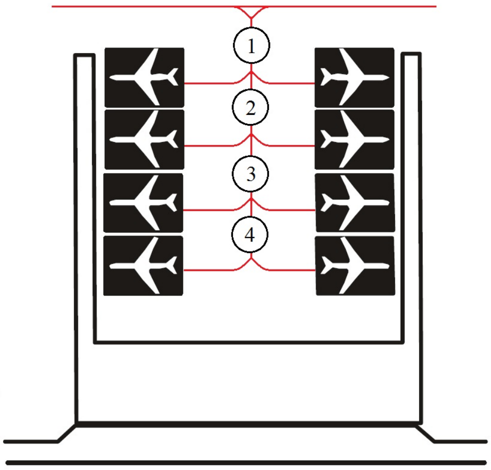


Figure 4.12: Apron and gate model with eight gates and corresponding taxiways, adapted from [38]

Table 4.1: Main taxiway length including cumulative distance from apron entry

Gate pair number	Distance (in m)	Cumulative Distance (in m)
1	91	91
2	70	161
3	70	231
4	70	301

length measuring 61 meters (see **Gate Sizing**), including an object clearance of 8 meters at the front and rear, the total distance from the main taxiway center line to the final parking position at each gate measures 75 meters. With these design parameters finalized, the total taxi distances from the apron entry to each gate pair are set. In Table 4.2, these distances are summarized.

Node-Link Representation
With the physical airport representation set up with all relevant gates and taxiways, the translation to a corresponding node-link model is made. Each gate is modelled as a node, as well as each intersection with the main taxiway and the apron entry. The links between the nodes consist of the main taxiway and the branches from the main taxiway to each gate. As the simulations are run using a model with four, six and eight gates respectively, each case has its own node-link model. However, the node-link systems are all based on the same design, so their only difference is the number of gates (i.e. taxi distances remain equal across all three situations).

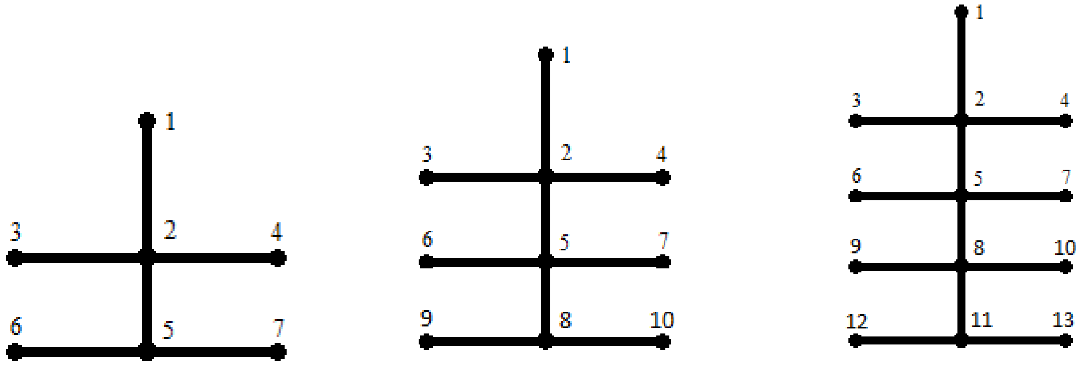
Note that as mentioned earlier, remote stands are not be modelled explicitly, instead the model will assign aircraft to a remote stand located outside of the node-link model. Therefore, an aircraft that is assigned to a remote stand will only visit Node 1 on arrival. When departing from a remote stand, it is assumed that the aircraft will taxi directly from the remote stand to the departure runway, bypassing the nodes of the model.

Figure 4.13 shows the node-link models that correspond to the physical model, with four, six and eight

Table 4.2: Total taxi in distances from the main taxi lane to each gate pair parking position

Gate pair	Distance to gate pair (in m)	Dist. apron taxi lane to park (in m)	Total dist. to park (in m)
1	91	75	166
2	161	75	236
3	231	75	306
4	301	75	376

gates respectively. Note that Node 1 in each figure corresponds to the apron entry, whereas the nodes on located on the far left and right of each figure represent the gates. The exact length of each link can be found in Table 4.3.



(a) Node-link model - 4 gates (b) Node-link model - 6 gates (c) Node-link model - 8 gates

Figure 4.13: Node-link representations for 4-6-8 gates

With the finalization of the physical airport model and the translation to a node-link model, the main agents and servers have been sized (Aircraft Type, Gate Sizing, Taxiway Sizing) and properly defined (Number of Taxiways and Gates, Layout of Taxiways and Gates). Now that the taxi distances have also been determined, the rest of the exogenous variables will be set in the next section where design choices for all of the apron movements will be made.

Table 4.3: Length of links between nodes

Node Pair	Link Distance (in m)	Node Pair	Link Distance (in m)
1-2	91	**5-8**	70
2-3	75	**8-9**	75
2-4	75	**8-10**	75
2-5	70	**8-11**	70
5-6	75	**11-12**	75
5-7	75	**11-13**	75

4.2.2. Airport Operations

In this section, design choices are made for all the operations that take place on the apron. Together with the design choices made in the previous section, the design choices of this section will ensure that all agents, servers and exogenous variables that apply to the model are fully defined and quantified. The following operations have been taken into account:

- Taxi-in
- Turnaround
- Pushback
- Taxi-out
- Towing

With these operations treated and applicable parameters quantified, all exogenous variables are set.

Taxi-in

The taxi-in movement encompasses the entire movement from the apron entry (Node 1) up until the final parking position at the gate (Node 3,4,6,7,9,10,12 or 13 depending on the number of gates modelled). In case of a remote stand allocation, no taxi-in movement is modelled and the aircraft will only visit Node 1. The main parameters of influence for the taxi-in movement are the (average) taxi speed and the total taxi distance (see Section 2.2.2, **Taxi-in**). As the taxi distances have been set, the only remaining design choice is the (average) taxi speed that the aircraft will assume in the simulations. In order to reduce complexity, a single average taxi speed per link is assumed which is equal for all aircraft.

In literature on ground operations, various taxi speeds are observed for different airport airside areas. Apron and stand taxi lane velocities of up to 10 kts are generally used, with the majority of taxi movements taking place above 5 kts. Therefore, the taxi speed on the apron links is set to 8.0 kts (about 4.1 m/s). Usually, taxi speeds outside of the apron area are considerably higher than on the apron itself. Therefore, the taxi speed on the link connecting Node 1 and 2 is modelled to be somewhat higher than the taxi speeds on the rest of the apron, with taxi movements taking place on this particular link at 10 kts (about 5.1 m/s).

With the taxi speeds and the taxi distances set, the total travel time between the different nodes of the model can be determined for arriving aircraft. When setting up these travel times, the travel times for the links that form part of the main taxiway cover the total travel distance along these links. However, the travel time on the links that connect the main taxiway to each gate (all links except for **1-2**, **2-5**, **5-8** and **8-11**) is assumed to cover the time required to clear any possible conflicts with other aircraft. Therefore, with this travel time the aircraft covers a distance of about 50 meters, which leaves room for enough separation with any aircraft that could potentially be taxiing on the main taxiway behind it (ICAO separation of 44 meters for Category C aircraft). The taxi-in travel times can be found in Table 4.4.

Turnaround
The turnaround procedure will be modelled using typical turnaround data found in relevant literature (see Section 2.2.2, **Turnaround**). As these values differ per aircraft type and station type, a choice for a single standard turnaround time has been made to reduce complexity. Additionally, it has been decided that the turnaround will be modelled assuming a full servicing turnaround. This has been done because the arriving aircraft are intended to be handled at a gate and at a large (hub) airport. Generally, such flights are handled as full servicing turnarounds. With the decision to model for full servicing, the assumed turnaround time for the aircraft that will be modelled has been set 40 minutes. This value has been assumed as the turnaround times of the different Category C aircraft studied range between 37 to 52 minutes for full servicing. For the modelling of the aircraft movements, it is therefore assumed that arriving aircraft have a turnaround time of 40 minutes unless they qualify for a pit-stop. More details concerning flights with a pit-stop will be discussed later on in this chapter.

Pushback
After turnaround at the gate, the aircraft will be ready to depart or to be towed to a remote stand in case of a pit-stop. Due to the model design with nose-in parking, aircraft require pushback in order to depart the gate area. In the literature reviewed on this matter, a total time to complete the pushback procedure of about three minutes is suggested using conventional pushback. Therefore, the pushback procedure is simulated with a duration of 180 seconds when conventional pushback is used. It is assumed that at the departure time of an aircraft, pushback will immediately commence from the gate node (unless a hold time is allocated by the model), and exactly 180 seconds later, the aircraft is positioned on the main taxiway node that corresponds to the gate it is parked at.

The example with six gates shown in Figure 4.14 illustrates the position of an aircraft after pushback. In this example, the aircraft is positioned at Node 5 with its nose pointing towards the apron exit after it has completed the pushback maneuver from the gate positioned at Node 6. Once pushback has been completed, it is assumed that the aircraft will taxi out or be towed out instantly (i.e. the aircraft will not be modelled to hold between pushback and taxi out/towing). In case ETS is used, literature suggest a pushback duration of 120 seconds. Therefore, in order to determine the sensitivity of the simulations to faster pushback using these new technologies, separate runs with a total pushback time of 120 seconds are performed as well.

(a) Aircraft position before pushback - at gate (b) Aircraft position after pushback - on taxiway

Figure 4.14: Aircraft position before and after pushback

Taxi-out

In case an aircraft will not have a pit-stop, it will taxi out under its own power. Once the aircraft is positioned on the main taxiway after pushback, it is ready to taxi out. It is assumed that taxi out commences instantly after pushback has been completed. Similarly to the taxi in movement, the main parameters of influence for the taxi out movement are the (average) taxi speed and the total taxi distance. The taxi speeds are assumed to be similar to the taxi speeds of the taxi in movement (10 kts on the link connecting Node 1 and 2, 8 kts on all other links) and the taxi distances have been defined previously. Therefore, the total duration of the taxi out movement can be determined for every aircraft depending on its assigned gate. For an overview of the travel times between the nodes for the departing aircraft, see Table 4.5.

Towing

When an aircraft is subject to a pit-stop, it is be pushed back from the gate in the same way as other aircraft. However, once pushback is complete and the aircraft is positioned on the main taxiway, it is towed to a remote stand instead of taxiing out under its own power. The distances covered during towing are identical as for the taxi out movement, since the remote stands are located outside of the model scope. As noted earlier, towing can take place at different speeds. The most powerful tow trucks generally have a top speed of around 17 kts (see 2.2.2, **Towing**), so in order to reduce model complexity, towing movements are modelled using the same speeds as the taxi in and taxi out movements (10 kts on the link connecting Node 1 and 2, 8 kts on all other links).

With the design choices and corresponding variables for the above apron movements set, most exogenous variables have now been accounted for. Combining the taxiway distances, taxi/towing speeds and the pushback duration, the total travel time between each node can be set up. These travel times are summarized in Tables 4.4 and 4.5. These values will be used in the time-based mathematical model treated in Section 4.4. Note that these travel times hold for both taxiing aircraft and towed aircraft.

Table 4.4: Travel times between nodes - arriving aircraft

Node Pair	Travel Time (in s)	Node Pair	Travel Time (in s)
1-2	18	**5-8**	18
2-3	12	**8-9**	12
2-4	12	**8-10**	12
2-5	18	**8-11**	18
5-6	12	**11-12**	12
5-7	12	**11-13**	12

The remaining variables that still need to be defined are the aircraft arrival and departure time, stochastic variations, pit-stop duration and the duration of a turnaround before and after a pit-stop. All of these are discussed in the next section.

Table 4.5: Travel times between nodes - departing aircraft

Node Pair	Travel Time (in s)	Node Pair	Travel Time (in s)
13-11	180	**7-5**	180
12-11	180	**6-5**	180
11-8	18	**5-2**	18
10-8	180	**4-2**	180
9-8	180	**3-2**	180
8-5	18	**2-1**	18

4.3. Input Schedule

In order to create a realistic airport model with arriving and departing aircraft, an appropriate flight schedule needs to be set up that can be used as the main input to the mathematical model. In this section, the input schedules for the model is defined and described. This involves defining and varying variables such as the inter-arrival time, which is discussed in Section 4.3.1. After the initial flight schedule is set up, several variables concerning pit-stops will be quantified in order to add them to the input schedule. This is discussed in Section 4.3.2. Naturally, the aim of this study is to obtain accurate results. As real-life situations are never as perfect as predefined flight schedules due to the occurrence of, for example, delays, the flight schedule will be subject to stochastic variations. The methodology for this is presented in Section 4.3.3. In the end, the flight schedules including variations will serve as the main input for the mathematical model that will be presented in Section 4.4.

4.3.1. Flight Schedules

With the requirements for pit-stops readily defined, the initial flight schedule can be set up. The most important consideration for setting up the flight schedule is the inter-arrival time (IAT) of the aircraft in the model. The IAT is a measure for the number of arriving aircraft within a certain time frame. This is visualized in Figure 4.15, where aircraft scheduled with an IAT of 5 and 10 minutes respectively are shown.

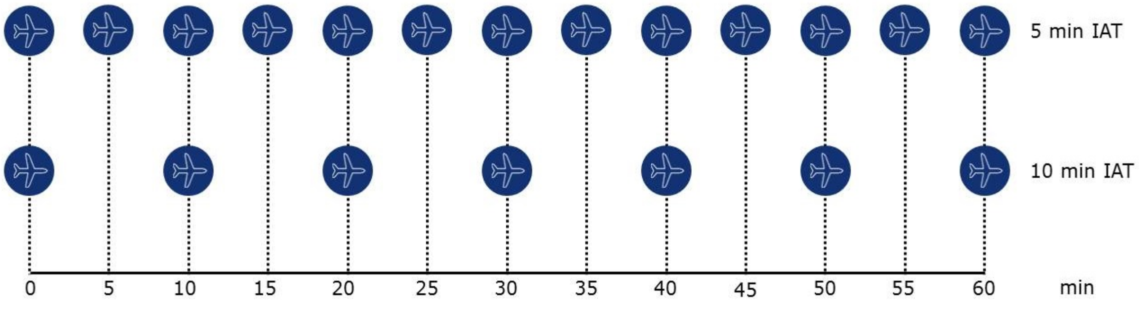


Figure 4.15: Arriving aircraft timeline with different inter-arrival times

If the IAT is low, a small number of flights will be handled and congestion will not be an issue. With a high IAT, gates will be occupied, aircraft will be allocated to remote stands and apron delays will occur due to congestion. Obviously, for this study the second scenario is of interest, and therefore a high IAT is used as a model input.

At airports worldwide, IAT is mostly dictated by arrival runway capacity. Looking at AMS, peak arrival capacity is about 68 movements per hour [63]. This corresponds to an IAT of about 53 seconds. However, this arrival capacity is provided by two runways, so the IAT is around 106 seconds per runway. Apart from the fact that an IAT of 106 seconds occurs at the absolute peak, one must consider that the model consists of a maximum of 8 gates, which makes this IAT unrealistically high for the model airport. It has thus been decided to create an input schedule with a 5 minute IAT. The total run time of the model is 2.5 hours for each run, so multiple input schedules for a 2.5 hour duration are set up.

Initially, an input schedule is created without pit-stops and delays, as these are added at later stage. This initial schedule with a 5 minute IAT is similar to the schedule displayed in Table 4.6. In this Table, the Scheduled Time of Arrival (STA) and Scheduled Time of Departure (STD) form the initial input schedule, with evenly spaced arrivals and departures, without variations and pit-stops. The initial schedule shows the 30 aircraft with their expected arrival and departure times in the model. The scheduled arrival time is defined as the time that the aircraft will be at Node 1, the scheduled departure time is the exact time that the aircraft is ready for pushback at the gate or ready for departure from the remote stand. In the next two sections, pit-stops and stochastic variations are added to make the input schedule more realistic.

Table 4.6: Input schedule example with 100 min. pit-stops - 5 min IAT - 2.5 hour duration

Input Schedule				
Aircraft	**STA (in s)**	**ATA (in s)**	**STD (in s)**	**ATD (in s)**
1a	0	60	1200	1310
2	300	299	2700	2452
3	600	645	3000	3116
4	900	1072	3300	3704
5a	1200	1214	2400	2424
6	1500	1375	3900	3864
7	1800	1677	4100	3881
8	2100	1957	4400	4514
9	2400	2640	4700	4842
10	2700	2644	5000	5318
11	3000	2994	5300	5360
12	3300	3245	5600	5579
13	3600	3456	5900	6147
14	3900	4232	6200	6595
15	4200	4194	6500	6606
16	4500	4301	6800	6883
17	4800	4964	7100	7495
18	5100	5306	7400	7496
19	5400	5326	7700	7826
20	5700	5859	8000	8473
21	6000	6134	8400	8128
1b	6000	6021	7200	7402
22	6300	6354	8700	9000
23	6600	6475	9000	9238
24	6900	6832	9300	9132
5b	7200	6897	8400	8453
25	7200	7132	9600	9839
26	7500	7306	9900	9939
27	7800	7699	10200	10069
28	8100	8138	10500	10652
29	8400	8229	10800	11002
30	8700	8761	11100	10872

4.3.2. Pit-Stops

The concept of pit-stops requires the towing of an aircraft to and from a remote stand between arrival and departure. As discovered in the literature study, at large airports pit-stops are generally performed for flights with a turnaround time of around 180 minutes or more. Additionally, gate pit-stops are only performed when the aircraft under consideration can be parked at a remote stand for at least 30 minutes [51]. In this study, the goal is to assess the viability and effect on congestion of pit-stops with a turnaround time of less than 180 minutes. Therefore, a decision on the turnaround time for which flights are eligible for a pit-stop needs to be taken. Additionally, the minimum required parking time at a remote stand needs to be determined. Three situations are modelled, all of which are discussed below.

80 minute turnaround

The first situation that has been modelled concerns a flight schedule where flights are eligible for a pit-stop if they have a total turnaround time of 80 minutes. In this case, 20 minutes are allocated to arrival and passenger disembarkation. Once this has been completed, the aircraft is towed to a remote stand. The time between the arrival and departure processes at the gate is 40 minutes in total. In theory, the aircraft should be able to be parked at a remote stand for 40 minutes, however, towing to- and from the remote stand needs to be taken into account. Assuming this takes a maximum of 5 minutes in both directions, the aircraft is parked at the remote stand for a minimum of 30 minutes (which is in line with real-life operations as mentioned in the previous paragraph). Once this time has passed, it will be at the gate for boarding for a duration of 20 minutes prior to its scheduled departure time. In the flight schedule, only the flights with a pit-stop are modelled with a turnaround of 80 minutes. The other flights are modelled with a turnaround time of 40 minutes, as discussed previously (see Section 4.2.2, **Turnaround**).

100 minute turnaround

After the simulations with pit-stops with a turnaround of 80 minutes, they are be compared to simulations that are run with turnaround times of 100 minutes. This has been done to assess the effect of different pit-stop turnaround times on both gate utilization and apron congestion. Similarly to the case of 80 minutes, 20 minutes are allocated to arrival and disembarkation of passengers and 20 minutes are allocated prior to the scheduled departure time for boarding. In this case, the time allocated to towing and parking at the remote stand is 60 minutes in total, compared to 40 minutes for the previous case. The flights that do not undergo a pit-stop have still been modelled with a turnaround time of 40 minutes.

120 minute turnaround

The final turnaround time for pit-stops that has been modelled is 120 minutes. Again, simulations are run with flights with a turnaround time of 120 minutes which will undergo a pit-stop. The results are compared to those with an 80 and 100 minute turnaround. Just like in the previous two cases, 20 minutes are allocated to arrival and disembarkation of passengers and 20 minutes for boarding. The time allocated to towing and parking at the remote stand is 80 minutes in this case, compared to 40 and 60 minutes for the previous two cases. The flights that do not undergo a pit-stop have been modelled with a turnaround time of 40 minutes.
Figure 4.16 illustrates the timeline of flights with a pit-stop with a total turnaround of 120 minutes together with the 80 and 100 minute cases.

Regardless of the pit-stop turnaround time, the aircraft movements for an aircraft with a pit-stop are modelled identically. When an aircraft is towed from the gate to a remote stand for a pit-stop, it will be treated as a regular arriving flight when it is towed back to Node 1. In that case, the aircraft is then assigned to a gate, from where it departs just like every other flight, but with a shorter parking time at the gate (only 20 minutes for boarding passengers, instead of 40 minutes for regular flights)

The pit-stops need to be accounted for in the input schedule. With a total simulation length of 2.5 hours, two flights are modelled that will be subject to a pit-stop. These flights are selected randomly. Taking into account the total length of a pit-stop (either 80 minutes, 100 minutes or 120 minutes), only those flights arriving in the initial time span that will be able to complete the full pit-stop during the total duration will be randomly selected (using MATLABs ’rand’ function). In effect, this means that out of the first five eligible flights, two will be selected for a pit-stop. In Table 4.6, two pit-stops with a total turnaround time of 100 minutes have been added. The flights that undergo a pit-stop (aircraft 1 and 5) are marked in red. As they initially arrive, they are marked as flight 1a and 5a, respectively. Once they have completed their pit-stop, they return as flight 1b and 5b. As can be seen, these two aircraft arrive in addition to the regular flights without a pit-stop, which clearly demonstrates the extra number of apron movements introduced with pit-stops.

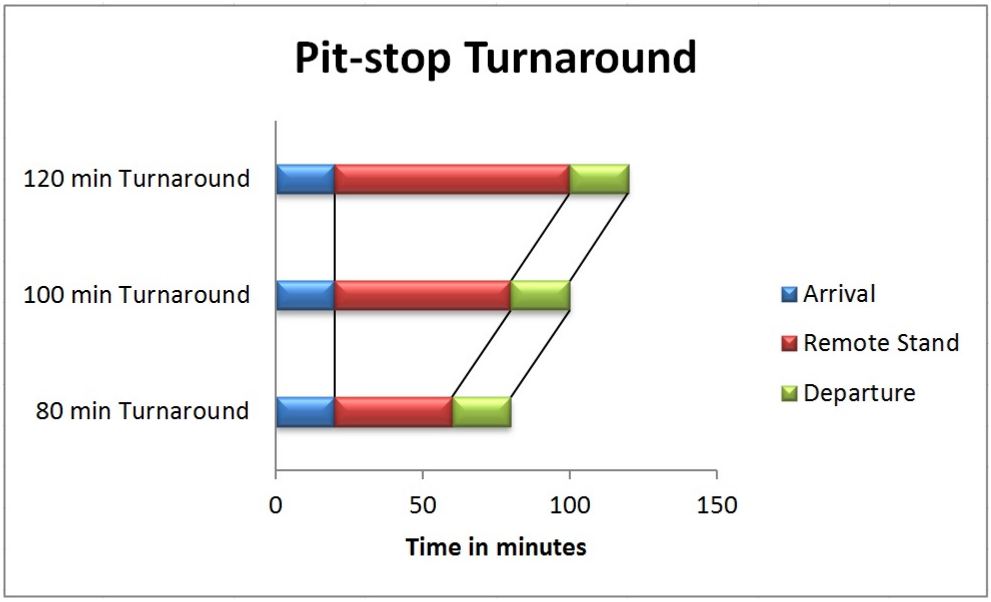


Figure 4.16: Pit-stop with 80 min., 100 min. and 120 min. turnaround time

4.3.3. Stochastic Variations

In order to make a flight schedule with a fixed inter-arrival time more realistic, stochastic variations to the flight schedule can be added. This has been done with every input schedule for the model as well. Every scheduled arrival and departure time in the input schedule is subject to a maximum variation of 5 minutes before and after the scheduled arrival/departure time. In order to model this, the input schedule is subject to a uniform distribution. The probability density function (pdf) of the uniform distribution is shown in equation 4.1, where *a* equals -300 seconds and *b* equals 300 seconds. This means that for every scheduled arrival and departure time, the actual times may vary by up to 300 seconds (or 5 minutes).

$$f(x) = \begin{cases} \frac{1}{b-a} & for \quad a \leqslant x \leqslant b \\ 0 & for \quad x < a, x > b \end{cases} \tag{4.1}$$

The cumulative distribution function (cdf) is defined by equation 4.2, where similarly to equation 4.1 *a* equals -300 and *b* equals 300.

$$F(X) = \begin{cases} 0 & for \quad x < a \\ \frac{x-a}{b-a} & for \quad a \leq x \leq b \\ 1 & for \quad x > b \end{cases} \tag{4.2}$$

As expected, the cdf with a value for *a* of -300 and for *b* of 300 looks as shown in Figure 4.17.

With the addition of pit-stops to the initial schedule completed in the previous section, the stochastic variations are added. The resulting input schedule with stochastic variations and two 100 minute pit-stops is shown in Table 4.6. As mentioned previously, the columns marked 'STA' and 'STD' show the scheduled arrival and departure times, respectively. With the schedule variations added to the evenly spaced schedule, the changes are reflected under 'ATA' and 'STD' (Actual Time of Arrival and Actual Time of Departure, respectively). The ATA and ATD serve as the model input.

With the input schedule set up, including stochastic variations and pit-stops, all agents, servers and exogenous variables are fully defined and quantified. As the model input is now complete, the endogenous variables are defined by the mathematical model which is described in the next section.

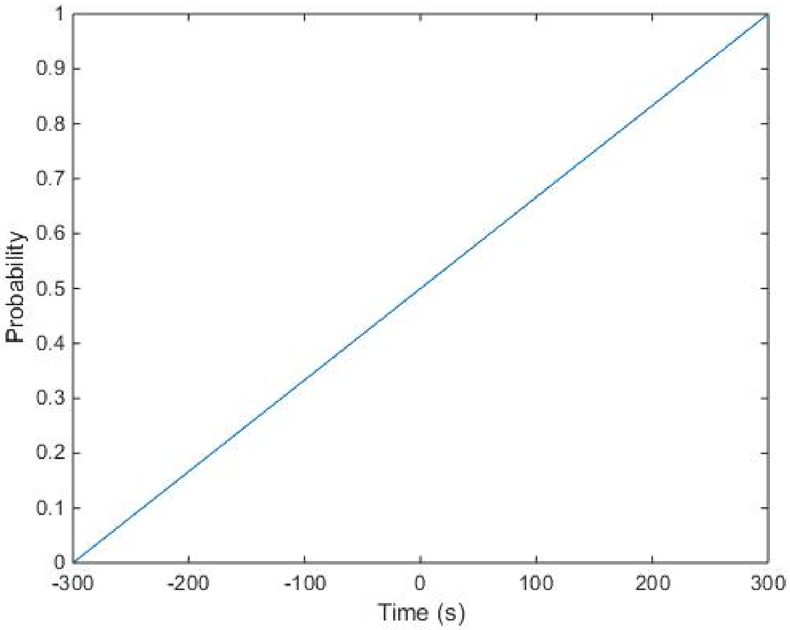


Figure 4.17: Plot of the uniform cumulative distribution function

4.4. Mathematical Model

In this section, the design choices described in the previous sections are implemented in the mathematical formulations that form the basis of the model. The mathematical model is the final step in defining all variables of the functional flow diagrams described in Sections 4.1.1 and 4.1.2, as it defines all endogenous variables.

As mentioned in Section 4.2, the mathematical model is formulated as a Mixed Integer Linear Programming (MILP) problem. The mathematical formulation of this MILP problem is discussed in three sections. In the first section (Section 4.4.1), all variables used in the MILP formulation are introduced. These variables are subject to several restrictions, which are discussed next (Section 4.4.2). In the third section (Section 4.4.3) , the full MILP formulation, including the objective function and all constraints, is explained in detail.

4.4.1. MILP Variables

Before the full MILP Formulation will be set up, all of the variables used in the mathematical formulation are listed. They consist of various time based variables, binary variables and sets.

Time Based Variables

The following time based variables are used:

- tsa_{ik}: scheduled time at node i for arriving aircraft k
- taa_{ik}: actual time at node i for arriving aircraft k
- Da_{ik}: delay at node i for arriving aircraft k
- tsd_{ik}: scheduled time at node i for departing aircraft k
- tad_{ik}: actual time at node i for departing aircraft k
- Dd_{ik}: delay at node i for departing aircraft k
- tt_{ij}: travel time from node i to node j

- tt_{ji}: travel time from node j to node i
- T_{sep}: minimum required separation time between to aircraft at a node

Binary Variables
Binary variables are variables that can either attain the value 0 or 1. The following binary variables are used:

- g_{kg}: gate assignment. Holds true if gate g is assigned to aircraft k
- r_k: remote stand assignment. Holds true if aircraft k is assigned to a remote stand
- $O_{kk'}$: order variable. Holds true if aircraft k has an actual arrival time at a node before aircraft k'
- $O_{k'k}$: order variable. Holds true if aircraft k' has an actual arrival time at a node before aircraft k

Variable Sets
The sets of variables used in the model are as follows:

- $I = \{0, .., (i, j), ..I\}$: set of all nodes in the node-link model
- $K = \{0, .., k, ..K\}$: set of all aircraft
- $G = \{0, .., g, ..G\}$: set of all gates

Next, these variables are explained in more detail and preprocessed.

4.4.2. Preprocessing

The variables introduced in the previous section are subject to several rules and restrictions, all of which will be discussed in this section. Applying these rules and restrictions to the variables presented restricts the number of variables generated, which is advantageous for the run time of the model.

Time Based Variables

- tsa_{ik}: The scheduled time of an arriving aircraft visiting a node is exclusively defined for the nodes i that are visited by aircraft k. This is fully dependent on the gate assignment. For example, an aircraft (say aircraft 1) that is assigned to the gate at Node 3 will only visit Nodes 1, 2 and 3 (and not the other nodes in the model). This implies that for this particular aircraft, this variable is only defined on those particular node as follows: tsa_{11}, tsa_{21}, tsa_{31}. For aircraft that are assigned to a remote stand, this variable is only defined on Node 1.
- taa_{ik}: Similarly to the previous variable, the actual time of an arriving aircraft k at a particular node i is solely defined for the nodes that are visited by the aircraft in question, which is dependent on the gate assignment. For aircraft that are assigned to a remote stand, this variable is only defined on Node 1.
- Da_{ik}: The delay for an arriving aircraft k at a particular node i is only defined at the nodes that are visited by the aircraft. This is dependent on the gate assignment and for aircraft that are assigned to a remote stand this variable is only defined on Node 1.
- tsd_{ik}: The scheduled time that a departing aircraft will visit a node is solely defined for the nodes i that are visited by aircraft k. This is fully dependent on the gate assignment. For example, an aircraft (say aircraft 1) that is assigned to the gate at Node 3 will only visit Nodes 1, 2 and 3 (and not the other nodes in the model). This implies that for this particular aircraft, this variable is only defined on those particular node as follows: tsa_{11}, tsa_{21}, tsa_{31}. For departing aircraft that are assigned to a remote stand, this variable is not defined.
- tad_{ik}: As with the previous variable, the actual time of a departing aircraft at a node is defined only for the nodes i that are visited by aircraft k. For aircraft that are assigned to a remote stand, this variable is not defined.

- Dd_{ik}: Delay assigned for a departing aircraft k at node i is, again, exclusively defined for the nodes that are visited by aircraft k. This variable is not defined for departing aircraft that are assigned to a remote stand.
- tt_{ij}: The travel time from node i to node j is defined only for those node pairs ij that exist in the node-link mode. For example, the travel time between Node 1 and Node 2 is defined as tt_{12} as these nodes are directly linked, however the travel time between Node 1 and Node 3 is not defined by this variable as these nodes are not directly linked. This variable is used for arriving aircraft.
- tt_{ji}: The filtering of this variable is identical to that of the previous variable. It is exclusively defined for nodes that are directly linked. This variable is used for departing aircraft.
- T_{sep}: Separation between all aircraft in the model (subsequent arriving aircraft, subsequent departing aircraft and arriving and departing aircraft) needs to be safeguarded. This variable set the minimum separation time between two aircraft at a node. For all simulations, the separation time has been set to 30s.

Binary Variables

- g_{kg}: The variable for the gate assignment holds true if gate g is assigned to aircraft k. As such, it will attain a value of 1 if this statement is true and a value of 0 if this statement is false.
- r_k: The remote stand variable holds true if aircraft k is assigned to a remote stand. As such, it will attain a value of 1 if this statement is true and a value of 0 if this statement is false.
- $O_{kk'}$: The first order variable holds true if aircraft k has an actual arrival time at a node before aircraft k'. As such, it will attain a value of 1 if this statement is true and a value of 0 if this statement is false.
- $O_{k'k}$: The second order variable holds true if aircraft k' has an actual arrival time at a node before aircraft k. As such, it will attain a value of 1 if this statement is true and a value of 0 if this statement is false.

This concludes the preprocessing of the variables of the mathematical model. With the restrictions for these variables defined, the full MILP formulation can be set up.

4.4.3. MILP Formulation

In this section, the variables introduced in Section 4.4.1 are used to formulate the Mixed Integer Linear Programming (MILP) problem in order to determine the effect of gate pit-stops on apron congestion. First, the objective function is introduced, followed by the constraints corresponding to this objective function.

Objective Function

The main objective of the model is to minimize delays while at the same time maximizing the number of aircraft that are handled at a gate instead of a remote stand. In order to accomplish this, the objective function is formulated as follows (Equation 4.3):

$$minZ = \sum_{i \in I} \sum_{k \in K} \sum_{g \in G} (Da_{ik} + Dd_{ik} + Mr_k) \tag{4.3}$$

The first two elements consist of the total arrival and departure delays summed over all aircraft and all nodes. The third element in the equation is the remote stand allocation, summed over all aircraft in the model. This variable is multiplied by a penalty M, as a remote stand allocation is undesirable. The value for M has been set to 500000. This will ensure that a remote stand is only allocated as a last resort when assigning a gate would create an infeasible solution. By choosing to minimize the variables of Equation 4.3 in brackets, it is ensured that the model will assign gates and delays as optimally as possible, keeping delays and remote stand assignments as low as possible.

Constraints

The objective function is subject to multiple constraints. They are listed below and discussed in detail.

Scheduled to Actual Time at Node

The constraints described by Equation 4.4 and Equation 4.5 ensure that the actual time of an aircraft at a node equals the scheduled time summed with the delay of the aircraft at that particular node. These constraints are set up for both aircraft arriving in the model (first line) and those departing in the model (second line).

$$tsa_{ik} + Da_{ik} = taa_{ik}, i \in I \cup k \in K \tag{4.4}$$

$$tsd_{ik} + Dd_{ik} = tad_{ik}, i \in I \cup k \in K \tag{4.5}$$

Travel between Nodes

Equation 4.6 and 4.7 describe the constraints that safeguard the travel of aircraft between two subsequent nodes for arrival and departure respectively.

$$tsa_{jk} - taa_{ik} - tt_{ij} - Mg_{kg} \geq M, i,j \in I \cup k \in K \cup g \in G \tag{4.6}$$

$$tsd_{ik} - tad_{jk} - tt_{ji} - Mg_{kg} \geq M, i,j \in I \cup k \in K \cup g \in G \tag{4.7}$$

In these equations, the gate assignment is included as it influences the routing of the aircraft. Therefore, the elements in these equations are only be generated if they form part of the routing of the aircraft that corresponds to the gate assignment. The value for penalty M has been set to 6000.

Separation - Arriving Aircraft

Arriving aircraft are required to maintain a minimum separation of 30 seconds at each node. The constraints of Equations 4.8 and 4.9 ensure this is the case for subsequently arriving aircraft. These constraints allow for a change in order between two successive aircraft if that leads to be a more optimal solution. Therefore, two equations are set up which each correspond to a different aircraft order.

$$-taa_{ik} + taa_{ik'} - MOkk' - Mg_{kg} - Mg_{k'g'} - T_{sep} \geq -3M, i \in I \cup k,k' \in K \cup g,g' \in G, k \neq k' \tag{4.8}$$

$$taa_{ik} - taa_{ik'} - MOk'k - Mg_{kg} - Mg_{k'g'} - T_{sep} \geq -3M, i \in I \cup k,k' \in K \cup g,g' \in G, k \neq k' \tag{4.9}$$

As can be seen, these equations take into account the routing associated with the gate assignment. They will only hold when all three binary variables are true. The penalty value M has been set to 6000 in both equations.

Separation - Departing Aircraft

Similar to arriving aircraft, departing aircraft are required to maintain a minimum separation of 30 seconds at each node as well. Equations 4.10 and 4.11 are similar to Equations 4.8 and 4.9, except that they hold for subsequent departing aircraft instead of arriving aircraft.

$$-tad_{ik} + tad_{ik'} - MOkk' - Mg_{kg} - Mg_{k'g'} - T_{sep} \geq -3M, i \in I \cup k,k' \in K \cup g,g' \in G, k \neq k' \tag{4.10}$$

$$tad_{ik} - tad_{ik'} - MOk'k - Mg_{kg} - Mg_{k'g'} - T_{sep} \geq -3M, i \in I \cup k,k' \in K \cup g,g' \in G, k \neq k' \tag{4.11}$$

These equations only hold when all three binary variables are true, in order to filter for the correct routing corresponding with the gate assignment of both aircraft. The penalty value M has been set to 6000 in both equations.

Separation - Conflicting Arriving and Departing Aircraft

As the separation of arriving and departing aircraft is guaranteed by the previous four equations, the final constraints that separate arriving and departing aircraft that are potentially at conflict are up. These constraints are defined by Equation 4.12 and 4.13

$$taa_{ik} - tad_{ik'} - MOk'k - T_{sep} \geq -M, i \in I \cup k,k' \in K, k \neq k' \tag{4.12}$$

$$-taa_{ik} + tad_{ik'} - MOkk' - T_{sep} \geq -M, i \in I \cup k,k' \in K, k \neq k' \tag{4.13}$$

One Aircraft per Gate
Every gate must be assigned to one aircraft at a time at most. Therefore, constraints need to be set up for all aircraft that are present in the model at a certain instance of time. Using a shifting time window of 5 minutes across the duration of the simulations, Equation 4.14 describes the constraints that are set up to guarantee that at most one aircraft is assigned to a gate. The number of variables in these constraints depends on the number of aircraft that are present in the model at the same time. In Equation 4.14, k' therefore represents an aircraft in the model that is potentially at conflict with aircraft k.

$$\sum_{k' \in K_{conflict}(k)} g_{kg} + g_{k'g} \leq 1, k, k' \in K \cup g \in G, k \neq k' \tag{4.14}$$

One Gate per Aircraft
Every aircraft may be assigned to one gate at most, or to a remote stand. Equation 4.15 shows the constraints corresponding to this requirement, where g represents all gates and r a remote stand. It follows that the variables presented need to add up to one, as the aircraft has to be assigned to one gate, or if no gate is available to a remote stand.

$$\sum_{g \in G} g_{kg} + r_k = 1, k \in K \cup g \in G \tag{4.15}$$

Subsequent Aircraft at Gate
In order to ensure that aircraft do not interfere on the links between the nodes, an additional constraint is introduced. These constraints are generated for aircraft that arrive and depart within 5 minutes of each other. It stipulates that if aircraft k' arrives within 5 minutes of the departure of aircraft k, it may not occupy the same gate. Equation 4.16 summarizes the constraints corresponding to this requirement.

$$g_{kg} + g_{k'g} \neq 1, k, k' \in K \cup g \in G \tag{4.16}$$

Order Variables
The final constraints are expressed in Equation 4.17. This equation stipulates that only one order variable holds, which logically follows from the definition of the order constraint.

$$O_{kk'} + O_{k'k} = 1, k, k' \in K \tag{4.17}$$

This concludes the mathematical formulation of the MILP problem.

4.5. Conclusions

In order to perform a thorough research, a proper methodology needs to be defined. This has been done by first defining the model requirements using function flow diagrams. These diagrams show the main agents and severs together with the required inputs and outputs for the model. The main agents for the model are the aircraft, whereas the main servers are the gates and taxiways. Several variables, both exogenous and endogenous, are identified and defined for the various functions of the model. These functions include Arrival, Hold, Gate, Remote Stand, Pit-stop, Gate after Pit-stop, Departure and Flight Handled.

The main input for the model is an input schedule, which is set up and includes stochastic variations and pit-stops. Decision have been made for the remaining exogenous variables and a mathematical model has been set up using a MILP formulation to determine the parameters for the endogenous variables. This MILP model will be used to run simulations using MATLAB and CPLEX, of which the results are presented in the next chapter.

5

Results

The results of the simulations run using the model that was completed in Chapter 4 are discussed in this chapter. Three airport scenarios have been simulated, with four, six and eight gates, respectively. Additionally, for each of these scenarios, three distinct pit-stop turnaround times have been simulated. In Section 5.1, the results of the simulations with four gates are discussed. Next, the simulation results with six gates are presented in Section 5.2, after which the results with eight gates are examined in Section 5.3. In Section 5.4, the results for the different scenarios are compared and conclusions are drawn. Some considerations for the analysis of the results need to be made, which are explained below.

Considerations for Analysis of Results
In order to be able to make a valid comparison between the three scenarios, the simulations in each scenario have been performed with similar input variables and using similar assumptions, which are listed in each section detailing the different scenarios. Before the simulations of which the results are presented in this chapter could be performed, one final design choice had to be made regarding delay assignment to applicable aircraft. As the model possesses the functionality to assign delays to aircraft both on arrival and departure, it needs to be considered whether airlines and airport operators will recognize gate pit-stops as a viable option to increase the number of flights handled at a gate instead of a remote stand. The option to incorporate pit-stops on a larger scale will only be considered if it makes operational sense, and not lead to delays in stages of flight outside of the model scope. Therefore, looking at delay assignment by the model, it has been decided that for these simulations, only arrival delays will be assigned. The reason for this is quite straightforward: if an arriving aircraft is delayed, eventual delays may be absorbed during turnaround, whereas departing aircraft at busy airports are bound by departure slots. If the model dictates an aircraft to hold at the gate before departing, it may miss its departure slot at the runway, which will lead to (a build up of) delays outside of the model scope. For this reason, it has been decided to assign delays to aircraft solely on arrival.

With this final consideration taken into account, the simulations have been performed for the various scenarios. The results of the simulations are captured in bar charts and box plots, which show the total arrival delay and number of remote gate assignment for the simulations. The bar charts show the average total delay across all runs of each simulation. For the box plots which show the number of remote stand assignments, the median value of each plot is indicated by a red dash and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The upper and lower values of the whiskers are those points that are not deemed outliers. All points outside of this range are considered outliers and they are marked by a ’+’ symbol.

5.1. Scenario 1: Four Gates

The airport model with four gates serves as the basis for the simulations discussed in this section. The node-link model that represents this scenario is depicted in Figure 5.1 (exact information on model sizing can be found in Section 4.2.1).
In order to investigate the effect of introducing pit-stops on apron congestion and gate availability, six

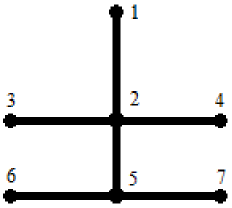


Figure 5.1: Node-link model for Scenario 1 (4 gates)

simulations have been performed for the scenario with four gates. All simulations have been run with a total time period of 2.5 hours (150 minutes) and an inter-arrival time of five minutes. This resulted in a total of 30 unique arriving aircraft in the schedule period. The turnaround time for the aircraft handled has been set to 40 minutes, except for two aircraft in each simulation. For each simulation, two flights were randomly selected from the first eight flights by MATLAB using the built-in 'randn' function. These two flights were assigned a longer turnaround time, which resulted in two aircraft being parked at the gate for a longer time (long stay flight) or these two aircraft being subjected to a pit-stop. For the simulations with pit-stops, the total number of aircraft movements equals 32 (with 30 unique aircraft), as the two flights with a pit-stop will return after being parked at a remote stand as additional movements.

The simulations can be grouped in three pairs, where the main difference between each simulation pair is the total turnaround time for the two flights with a longer turnaround. The first pair of simulations were run with a turnaround time of 80 minutes for the two randomly selected flights, the second two simulations were done with a turnaround time of 100 minutes for these two flights whereas the third pair of simulations were run with a long turnaround time of 120 minutes. All simulations consist of 50 runs in order to get accurate results and reduce the impact of any outliers if applicable. The input schedule parameters used in all simulations can be found in Table 5.1 and the parameters that are unique to each simulation can be found in Table 5.2. The results for a long turnaround of 80 minutes are presented in Section 5.1.1, the results for 100 minutes can be found in Section 5.1.2 while the results for 120 minutes are discussed in Section 5.1.3.

Table 5.1: Input parameters for all simulations - Scenario 1

Input Schedule	
Parameter	*All Simulations*
Number of Gates	4
Schedule duration (min)	150
Inter-arrival Time (min)	5
Number of Unique Aircraft	30
Regular Turnaround Time (min)	40
Number of Runs	50

Table 5.2: Input parameters for each unique simulation - Scenario 1

Input Schedule						
Parameter	*Simulation 1*	*Simulation 2*	*Simulation 3*	*Simulation 4*	*Simulation 5*	*Simulation 6*
Movements	30	32	30	32	30	32
Long stay/Pit-stop	2 Long stay	2 Pit-stop	2 Long stay	2 Pit-stop	2 Long stay	2 Pit-stop
Long Turn. (min)	80	80	100	100	120	120

5.1.1. Long Turnaround: 80 Minutes

The input parameters for the first two simulations can be found in Table 5.1 and Table 5.2 under *Simulation 1* and *Simulation 2*. Evidently, the main difference between these simulations is the handling of the two flights with a longer turnaround time of 80 minutes. In the first simulation, these flights are handled like any other flight, which means that they are assigned to a gate or remote stand, depending on which is available (see '2 Long stay' in Table 5.2). In the second scenario, the two flights will undergo a pit-stop (see '2 Pit-stop' in Table 5.2). With two pit-stops, the total number of movements increases from 30 to 32. For both simulations, the total number of remote gate assignments and the total delays have been determined. This enables one to compare the effect of including pit-stops or not on similar input schedules.

Simulation 1

Of all Simulations that have been performed, Simulation 1 shows the least delays. This is visualized in Figure 5.2, which shows box plots for the delays per aircraft arrival movement. The box plots show a median arrival delay of zero seconds for the first nine arriving aircraft. Therefore, in all 50 runs, none of the first nine arriving aircraft experienced any delay. However, aircraft 10 to 14 all experienced delays to a varying degree. After the arrival of aircraft 14, the median delays are reduced to zero again for the remaining flights. The increase in delays between flights 10 and 14 roughly corresponds with the departure of the first six flights, so this result is in line with expectations as the departing flights conflict with arriving flights. This phenomenon repeats itself somewhat between flight 18 and 24, however the exact flights assigned to a gate are more spread out by the model to reduce delays, which is evident from the fact that the median delays are all zero even though the boxes and whiskers show non-zero delays. As can be seen, maximum delays (not taking into account outliers) for aircraft 19 are comparatively high at 362 seconds, however, considering the low median delays, the model runs smoothly despite the high IAT and schedule variations of up to 5 minutes. The median non-zero delay values are summarized in Table 5.3.

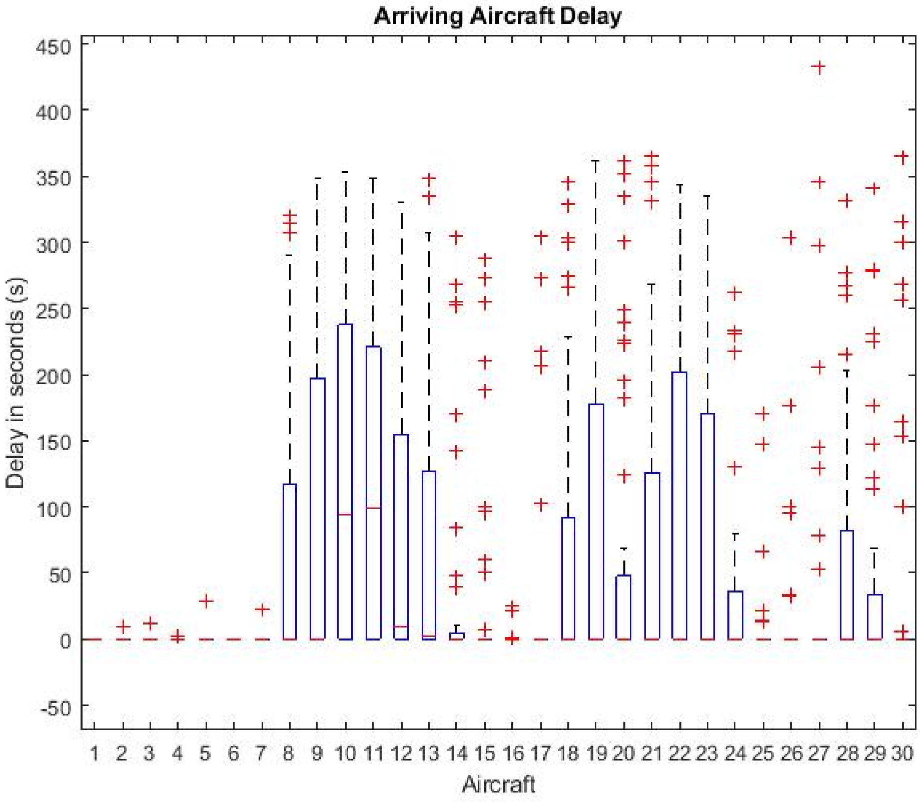


Figure 5.2: Arrival delays - 4 gates - 80 min - 2 long stay flights

Table 5.3: Median delay values - 80 min - 2 long stay flights

Aircraft	**10**	**11**	**12**	**13**
Median Delay (s)	94.5	99	9.5	2.5

The mean number of aircraft handled at a remote stand equals 17.18, whereas the mean total delay is 1316 seconds or about 43.9 seconds per movement.

Simulation 2
The results of Simulation 2 show similar results to Simulation 1. In this case however, the addition of two pit-stops does lead to a slight increase in delays. However, the general pattern of delays is similar to the previous simulation without pit-stops. Figure C.1 in Appendix C shows the delays for all arriving aircraft movements. The maximum 75th percentile delay observed with two 80 minute pit-stops is 389 seconds for aircraft 21. As can be seen in Table 5.4, the additional movements of the pit-stops do lead to an increase in median delays and there is a noticeable increase in delays around flight 18 to 23, which coincides with the additional movements due to the two pit-stops.

Table 5.4: Median delay values - 80 min - 2 pit-stops

Aircraft	**9**	**10**	**11**	**21**
Median Delay (s)	109.5	181	35.5	15.5

The mean number of aircraft handled at a remote stand equals 18.02, whereas the mean total delay is 1593 seconds or about 49.8 seconds per movement. Therefore, the addition of two pit-stops with 4 gates and a long turnaround of 80 minutes leads to an increase in remote gate assignments and delays.

5.1.2. Long Turnaround: 100 Minutes

For the second pair of simulations of Scenario 1, the input parameters can be found in Table 5.1 and Table 5.2 under *Simulation 3* and *Simulation 4*, respectively. Similarly to the two simulations in Section 5.1.1, the main difference between these two simulations is the way of handling the two flights with a longer turnaround time of 100 minutes. In Simulation 3, these flights are handled as regular flights (see '2 Long stay' in Table 5.2) whereas in Simulation 4 these flights will undergo a pit-stop (see '2 Pit-stop' in Table 5.2).

Simulation 3
In Simulation 3, the long turnaround for two flights has increased from 80 minutes to 100 minutes. Therefore, two flights have been randomly selected as long stay flights with a 100 minute layover. Figure C.2 in Appendix C shows the box plots of the arrival delays for these movements. Similarly to Simulation 1 with two long stay flights, the first nine arriving aircraft have a median delay of zero, and the general pattern of delays is comparable as well. The number of aircraft that have a non-zero median delay is lower than for simulation 1, but the median non-zero delay values are higher as can be seen in Table 5.5. The maximum 75th percentile delay is considerably higher at 429 seconds for aircraft 27, compared to 362 seconds for aircraft 19 in Simulation 1. Delays for arriving flights 27 to 29 are noticeably higher, which coincides with the departure of the two long stay flights, so the effect of these longer turnaround have a definite effect on the arrival delays for later flights.

Table 5.5: Median delay values - 100 min - 2 long stay flights

Aircraft	**10**	**11**	**12**
Median Delay (s)	205	75.5	62

The average number of remote stand assignments for this simulation is 17.12 and the mean total delay equals about 1321 seconds or 44 seconds per movement, which is only slightly higher than the delays for Simulation 1 with 80 minute long stay flights.

Simulation 4

The arrival delays from Simulation 4 are visualized in Figure 5.3. Except for some outliers, the first seven flights do not experience any delays. The spread of the delay across the movements is akin to that of Simulation 3, with an apparent increase in delays between flight 18 and 23 compared to the previous runs. This peak corresponds to the return of the two flights with a pit-stop from the remote stand, and it can be seen that these movements cause additional delays. The maximum 75th percentile delay equals 376 seconds for aircraft 10, but it should be noted that in this case there are multiple 75th percentile peaks of around the same values, as average delays are higher but more spread out than in the previous case. The median non-zero delay values are summarized in Table 5.6.

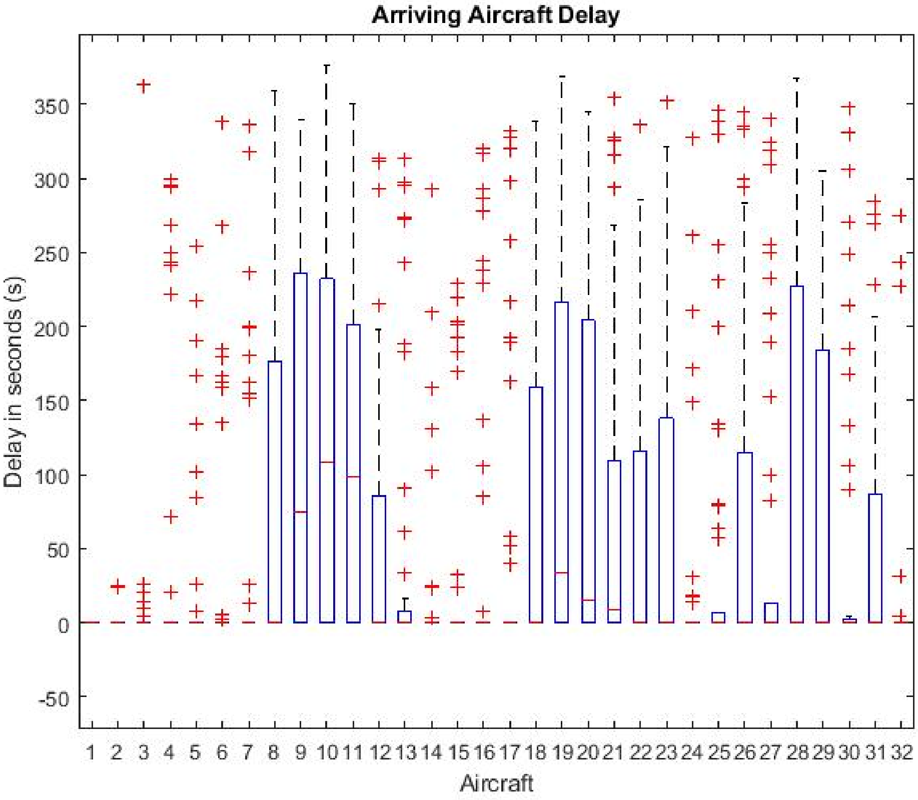


Figure 5.3: Arrival delays - 4 gates - 100 min - 2 pit-stops

Table 5.6: Median delay values - 100 min - 2 pit-stops

Aircraft	**9**	**10**	**11**	**19**	**20**	**21**
Median Delay (s)	74.5	108.5	99	33.5	15	9

As can be seen, adding pit-stops does not increase the total median delay (342.5 versus 339.5), but because of a higher spread of delays, the mean delay for Simulation 4 equals 1778.9 seconds or just under 56 seconds per movement. The average number of remote stand assignments is 17.32. Therefore, the addition of pit-stops for a scenario with four gates and a long turnaround of 100 minutes is ineffective as delays increase and the number of remote stand assignments is not reduced.

5.1.3. Long Turnaround: 120 Minutes

For the final pair of simulations with four gates, the input parameters can be found in Table 5.1 and Table 5.2 under *Simulation 5* and *Simulation 6*. In these two cases, the first simulation will be run with two long stay flights with a 120 minute turnaround time (see '2 Long stay' in Table 5.2) while the second simulation will be run with two randomly selected pit-stops with a total duration of 120 minutes (see '2 Pit-stop' in Table 5.2).

Simulation 5

Looking at the arrival delays for a schedule with two long stay flights with a turnaround of 120 minutes, a similar pattern as in Simulation 3 (2 long stay flights with a 100 minute turnaround) can be discerned. (See Figure C.3 in Appendix C). The main difference is that the delays are spread out more across all movements for the case with a 120 minute long turnaround. Like all other simulations with four gates, for the first nine flights the median delay remains zero, confirming that the model runs smoothly until the first departing flights start to interfere with the continuous arrivals. The highest observed 75th percentile delay is 366 seconds for aircraft 11. Table 5.7 displays the median non-zero delay values.

Table 5.7: Median delay values - 120 min - 2 long stay

Aircraft	**10**	**11**
Median Delay (s)	99.5	22.5

Table 5.7 confirms that the delays are spread out more than in the other simulations, as only two aircraft have a non-zero median delay whereas the average total delay is higher than the other simulations with two long stay flights at 1431 seconds (or 48 seconds per movement). The average number of remote gate assignments is 17.22.

Simulation 6

The final simulation with four gates is performed with two pit-stops with a total duration of 120 minutes. The delays per movement are shown in Figure 5.4. This simulation shows the highest spread of delays across all aircraft, with a peak in delays for the final flights (aircraft 25 to 30) compared to the previous simulation without pit-stops. This peak corresponds to the returning flights with a pit-stop, hence the appearance of these delays contrary to the previous simulation. The highest recorded 75th percentile delay is 362 seconds for aircraft 10. The median delays are listed in Table 5.8.

Table 5.8: Median delay values - 120 min - 2 pit-stops

Aircraft	**9**	**11**	**20**	**28**	**29**
Median Delay (s)	30.5	14	33.5	21	32.5

The average total delay with two pit-stops is 1792.8 seconds with an average of 56 seconds per movement. This simulation proved to be the only scenario with four gates where the introduction of pit-stops lead to a decrease in remote stand allocations, as the average number of remote stands equals at 16.80 compared to 17.22 for the similar scenario with two long stay flights.

Conclusions

In order to draw conclusions on the simulations with four gates, the number of unique aircraft assigned to a gate and the average delay of every simulation needs to be compared. In Figure 5.5, box plots of the number of flights handled at a remote stand are displayed. Looking at the x-axis, the numbers indicate the duration of the long turnaround times in minutes, whereas the letter indicates whether long stay flights or pit-stops were applied (for example, 80L refers to a scenario with 2 long stay flights with an 80 minute turnaround). As can be seen, the number of remotely handled flights is only reduced when pit-stops are introduced in lieu of long stay flights with turnaround time of 120 minutes. In this case, the mean number of remote gate assignments is reduced from 17.22 to 16.80. In all other scenarios, introducing pit-stops does not lead to a reduction in remote stand allocations.

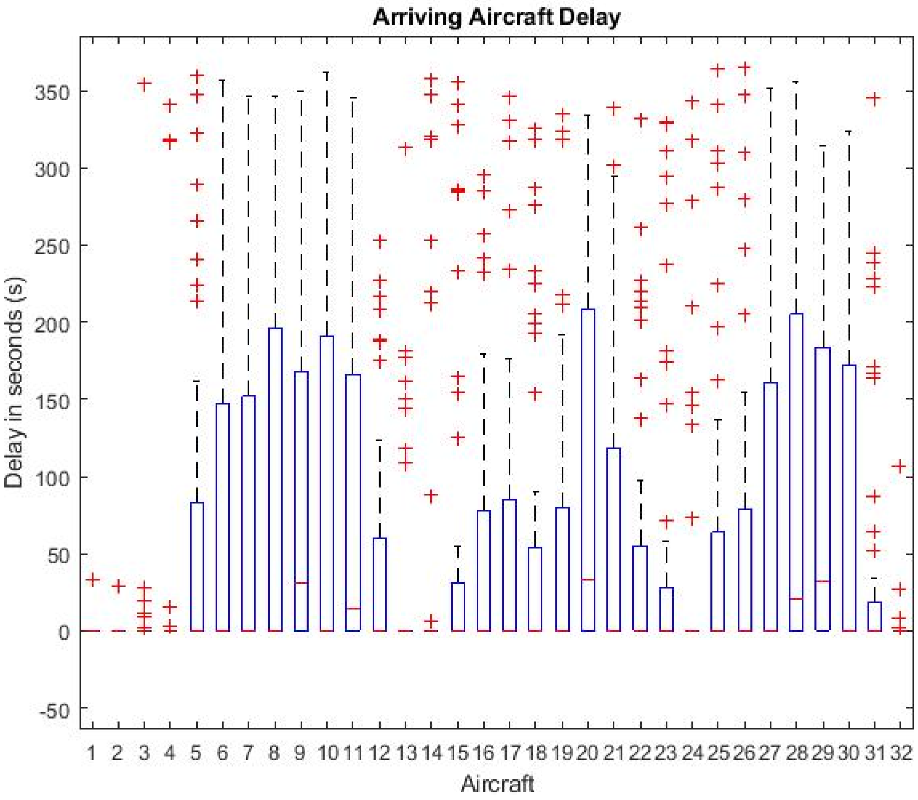


Figure 5.4: Arrival delays - 4 gates - 120 min - 2 pit-stops

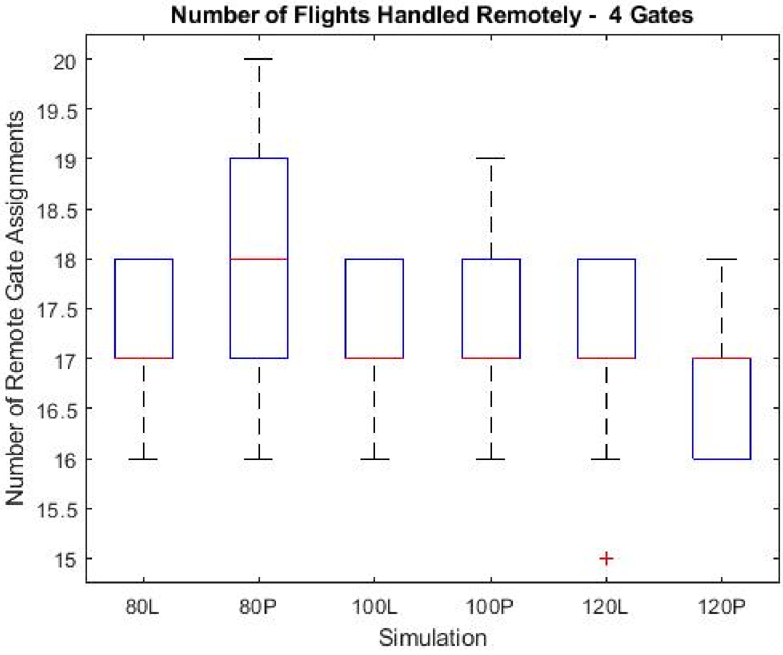


Figure 5.5: Number of remotely handled flights - 4 gates

Figure 5.6 shows the total average delays for all simulations of Scenario 1 with four gates. It follows that in all cases, the addition of pit-stops leads to an increase in delays. This confirms that additional delays are an inevitable side effect of gate pit-stops. Looking at the simulations with a 120 minute long turnaround, the average delay per aircraft increases from 48 seconds per aircraft without pit-stops to 56 seconds with pit-stops.

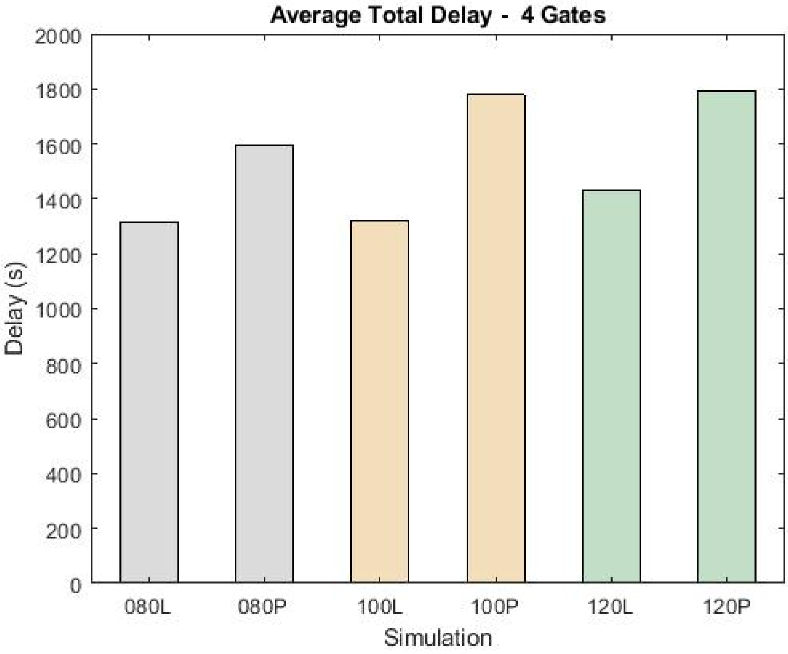


Figure 5.6: Average total delays - 4 gates

Another aspect that can be taken into account is the run time for each of the simulations. For the scenario with four gates, Simulation 6 was the simulation with the longest run time. This simulation took 3623 seconds (about one hour) for all 50 runs to complete.

5.2. Scenario 2: Six Gates

In this section, the results of the simulations with six gates are presented. The node-link model that represents the airport model is shown in Figure 5.7.

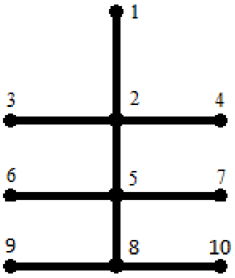


Figure 5.7: Node-link model for Scenario 2 (6 gates)

Just as in Section 5.1, six simulations have been performed. These simulations using the six gate model were run in a similar fashion to the simulations with the four gate model, which implies a total schedule duration of 2.5 hours (150 minutes) and an inter-arrival time of five minutes, with 30 unique arriving and departing aircraft (thus the total number of aircraft movements equals 32 movements with 30 unique aircraft for the simulations with two pit-stops). Again, for each simulation two flights were randomly selected from the first eight flights and assigned a longer turnaround time. The first pair of simulations have two long stay flights or flights with a pit-stop with a total duration of 80 minutes, the second pair of simulations were run with two long stay flights or pit-stops of 100 minutes in total and the final two simulations were run with a 120 minute long turnaround for the long stay flights or pit-stops. For each simulation, a total of 50 runs were performed to achieve accurate results.

The input parameters used in all six simulations can be found in Table 5.9, whereas the input parameters that are unique to each simulation are listed in Table 5.10. In Section 5.2.1, the results for the simulations with a long turnaround of 80 minutes are presented. For the simulations with 100 minute long turnarounds, the results can be found in Section 5.2.2 and the results for the 120 minute case are treated in Section 5.2.3.

Table 5.9: Input parameters for all simulations - Scenario 2

Input Schedule	
Parameter	*All Simulations*
Number of Gates	6
Schedule duration (min)	150
Inter-arrival Time (min)	5
Number of Unique Aircraft	30
Regular Turnaround Time (min)	40
Number of Runs	50

Table 5.10: Input parameters for each unique simulation - Scenario 2

Input Schedule						
Parameter	*Simulation 1*	*Simulation 2*	*Simulation 3*	*Simulation 4*	*Simulation 5*	*Simulation 6*
Movements	30	32	30	32	30	32
Long stay/Pit-stop	2 Long stay	2 Pit-stop	2 Long stay	2 Pit-stop	2 Long stay	2 Pit-stop
Long Turn. (min)	80	80	100	100	120	120

5.2.1. Long Turnaround: 80 Minutes

In this section, the results of the simulations with six gates and long turnarounds of 80 minutes will be discussed. For the appropriate input parameters, please refer to Table 5.9 and Table 5.10 under *Simulation 1* and *Simulation 2*. The input parameters are generally the same, however the main difference between the two simulations is that in the first simulation the two flights with a long turnaround remain parked as a long stay flight (see ’2 Long stay’ in Table 5.10), whereas in the second simulation these flights will go through a pit-stop (see ’2 Pit-stop’ in Table 5.10). The effect on delays and the number of remote stand assignments has been assessed and the results are presented below.

Simulation 1

The delays displayed in Figure 5.8 show a larger spread of delays than the similar scenario with two 80 minute long stay flights with four gates. Additionally, the delays are considerably higher than with four gates, which is in line with expectations, as the aircraft require more time to taxi to- and from the furthest gates across the single apron taxiway. The first seven aircraft do not experience any delays except for some outliers. After the arrival of the seventh flight, all aircraft experience delays to a certain degree. The general pattern of the delays is akin to that of the similar simulation with four gates, which means that two delay peaks can be observed. These peaks correspond to the departures of the flights that are assigned to a gate, coupled with the continued arrival of incoming flights. The median non-zero delay values can be found in Table 5.11. The highest observed 75th percentile delay occurs for aircraft 25 and is equal to 1100 seconds. Comparing the values for the delays to Simulation 1 in Section 5.1.1 confirms that the addition of two extra gates leads to a considerable increase in congestion as aircraft separation needs to be maintained.

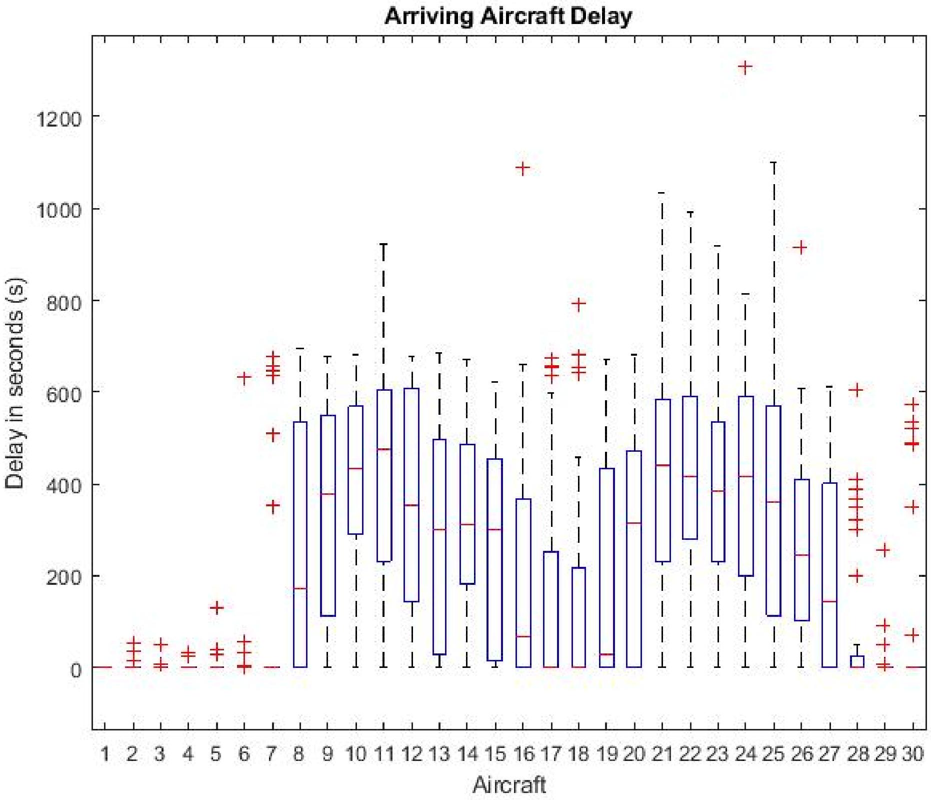


Figure 5.8: Arrival delays - 6 gates - 80 min - 2 long stay flights

Table 5.11: Median delay values - 80 min - 2 long stay flights

Aircraft	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**19**	**20**
Median Delay (s)	173	379	432.5	474.5	354	299.5	311.5	301	68	28	314
Aircraft	**21**	**22**	**23**	**24**	**25**	**26**	**27**				
Median Delay (s)	440.5	415	385.5	414.5	359	244	143				

The average total delay equals 6358.4 seconds, or some 212 seconds per movement. The average number of remote stand assignments is 12.02.

Simulation 2

Simulation 2 is similar to Simulation 1, except for the introduction of pit-stops. The two randomly selected flights that were parked as long stay flights in the previous simulation will now both undergo a pit-stop. Figure C.4 in Appendix C shows the arrival delays per aircraft. Compared to Simulation 1, the addition of pit-stops leads to an increase in delays, especially around flight 21 to 26, which coincides with the return of two flights with a pit-stop to the gate. Therefore, the occurrence of these delays is in line with expectations. The highest delay measured within the 75th percentile is 1070 seconds for aircraft 24, which is comparable to the identical situation without pit-stops, but average delays are significantly higher as pit-stops are introduced. The average total delay is 7198.5 seconds per run for this simulation which is equal to about 225 seconds per movement. For a list of median non-zero delay values, see Table 5.12. The average number of remote stand assignments is 13.18 (up from 12.02), so this confirms that for six gates, the addition of pit-stops with a turnaround of 80 minutes is not feasible.

Table 5.12: Median delay values - 80 min - 2 pit-stops

Aircraft	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Median Delay (s)	104.5	248.5	449	444.5	481.5	426	422	282	242	108	98
Aircraft	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
Median Delay (s)	79	186	183.5	344	321	312.5	255	315	234.5	139.5	181.5

5.2.2. Long Turnaround: 100 Minutes

The second pair of simulations of Scenario 2 are performed with a longer turnaround time of 100 minutes for two randomly selected aircraft. In Simulation 3, these aircraft are handled as long stay flights, while they are handled with a pit-stop in Simulation 4. The full list of input parameters can be found in Table 5.9 and in Table 5.10 under *Simulation 3* and *Simulation 4*.

Simulation 3

For Simulation 3, two aircraft are assigned a long turnaround of 100 minutes. These aircraft are handled as long stay flights. The arrival delays for the aircraft in this simulation are displayed in Figure C.5 in Appendix C. The results are very similar to Simulation 1, as the only difference is the duration of the long stay flights. The average total delay is somewhat higher at 6570.1 seconds and 219 seconds per movement. Looking at the highest 75th percentile delay, a value of 1350 seconds was assigned to aircraft eight. Table 5.13 shows the median delays for all aircraft with a non-zero median delay.

Table 5.13: Median delay values - 100 min - 2 long stay flights

Aircraft	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Median Delay (s)	461	477.5	508.5	410	405	369	399	221	139
Aircraft	**17**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
Median Delay (s)	17	375.5	432	434.5	374	365	360.5	361.5	102.5

Looking at the remote stand assignments, an average of 12.18 aircraft are assigned to a remote stand for each run of this simulation. As expected, this value is higher than for the comparable simulations with an 80 minute long turnaround, as in this simulation the long stay flights occupy the gates for a longer period of time.

Simulation 4

As expected after analyzing the previous simulations, the introduction of pit-stops leads to additional delays compared to Simulation 3 without pit-stops. In Figure 5.9, the delays per aircraft movement are presented. Two distinct peaks in the delay values can be distinguished which correspond to the first departures from the gate and the return of the flights with pit-stops respectively. The three highest 75th percentile values correspond to the second peak, which is a direct effect of the pit-stops. The maximum recorded delay value that is not considered an outlier equals 995 seconds for aircraft movement 24. This value is lower than the highest 75th percentile value found in the previous simulation with two long stay flights. The average total delay for this simulation equals 7378.1 seconds, which comes down to an average of around 231 seconds per movement. In Table 5.14, the median delay values are displayed. Concluding from the above results on delays, it can be seen that the addition of 100 minute pit-stops in a 6 gate model leads to higher overall delays, but peak delays appear to be lower than with two long stay flights.

The average number of remote stand assignments is 12.76, which is higher than for the similar simulation without pit-stops. Pit-stops of a duration of 100 minutes or less are therefore not effective in increasing gate utilization for a model with six gates.

5.2.3. Long Turnaround: 120 Minutes

The last two simulations of Scenario 2 (6 gates) both have a long turnaround of 120 minutes for the two flights that are either long stay flights or flights with a pit-stop. The first of the two, Simulation 5,

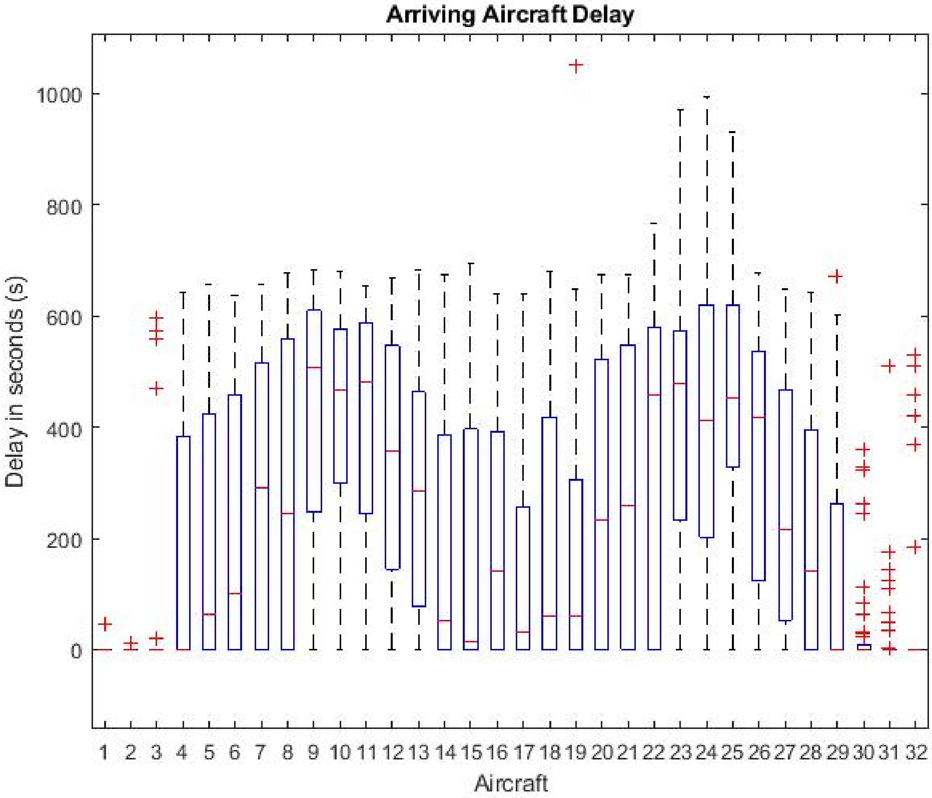


Figure 5.9: Arrival delays - 6 Gates - 100 min - 2 pit-stops

Table 5.14: Median delay values - 100 min - 2 pit-stops

Aircraft	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Median Delay (s)	62	100	291	245	508	467	480	356
Aircraft	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Median Delay (s)	284	52	15	141	32	60	60	233
Aircraft	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Median Delay (s)	259	459	478	412	451	419	215	142

contains two long stay flights whereas the second simulation, Simulation 6, has two flights with a pit-stop. Below, the results of both situations will be analyzed and compared.

Simulation 5

In order to analyze the delays, box plots for the delays of all runs and aircraft have created. They can be found in Figure C.6 in Appendix C. The delay pattern observed is very similar to Simulation 1 and 3 (2 Long stay flights with 80 and 100 min. turnaround, respectively). The delays for the last few flights around the second peak are slightly higher (especially for aircraft 27 and 28) as the long stay flights depart around the time that these movements arrive. At 1398, the 75th percentile value for aircraft 23 is the highest of all simulations with two long stay flights and 6 gates. At 6286.1 seconds and 210 seconds per movement, average delays are comparable to Simulation 1 and 3. The number of remotely handled flights averaged 12.68 per run. For the median delay values, please refer to Table 5.15.

Simulation 6

For the final simulation with six gates, the delays are presented in Figure 5.10. It can immediately be seen that significant delays occur for all movements after the arrival of the fourth movement. Comparing this Figure to that of Simulation 5, it becomes clear that the pit-stops in combination with the

Table 5.15: Median delay values - 120 min - 2 long stay flights

Aircraft	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Median Delay (s)	22.5	315	292	355	393	444.5	479	403	109
Aircraft	**17**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
Median Delay (s)	13.5	320	330.5	345	442.5	410	424.5	330.5	98

high sequence of arriving flights leads to a build up of delays. Comparing Figure 5.10, with 120 min. pit-stops, to Figure 5.9, with 100 min. pit-stops, one can see that the effect of increasing the pit-stop duration also leads to a quicker build up of delays. However, the median delay values remain more constant with 120 minutes compared to 100 minutes, where in the second case more fluctuations can be seen. On average, total delays with 120 minute pit-stops equal 7987.3 seconds or 250 seconds per movement, which is the highest delay for all six simulations in this section. The median delay values can be found in Table 5.16.

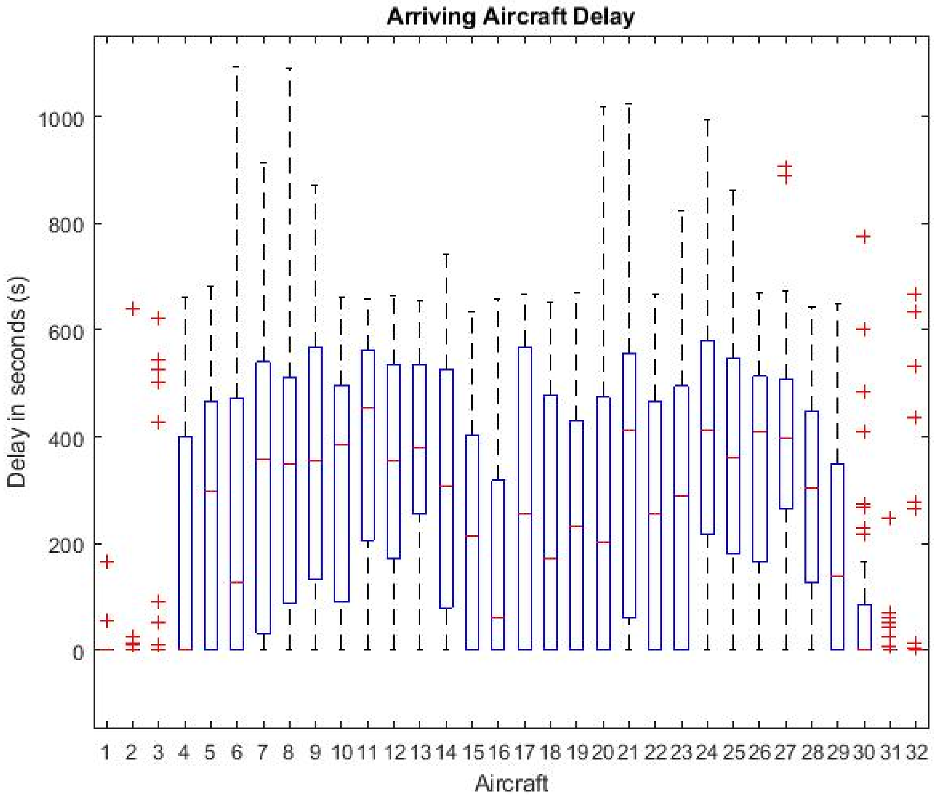


Figure 5.10: Arrival delays - 6 gates - 120 min - 2 pit-stops

Table 5.16: Median delay values - 120 min - 2 pit-stops

Aircraft	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Median Delay (s)	297.5	127.5	358.5	350	354.5	384	453	354.5	379
Aircraft	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Median Delay (s)	305.5	215	61	257	171.5	231.5	201.5	413	256
Aircraft	**23**	**24**	**25**	**26**	**27**	**28**	**29**		
Median Delay (s)	287.5	413	361	408.5	397.5	305	139		

With two pit-stops of 120 minutes, the average number of remote gate assignments is 12.34, which is lower than for two 120 minute long stay flights (12.68).

Conclusions

The results found in this section reinforce the previously found results in Section 5.1, where it was determined that pit-stops are effective only when they have a turnaround time of 120 minutes or more. Looking at Figure 5.11, it is evident that this hold for a scenario with six gates as well, as the number of remote stand assignments is only reduced in the cases with a 120 minute long turnaround.

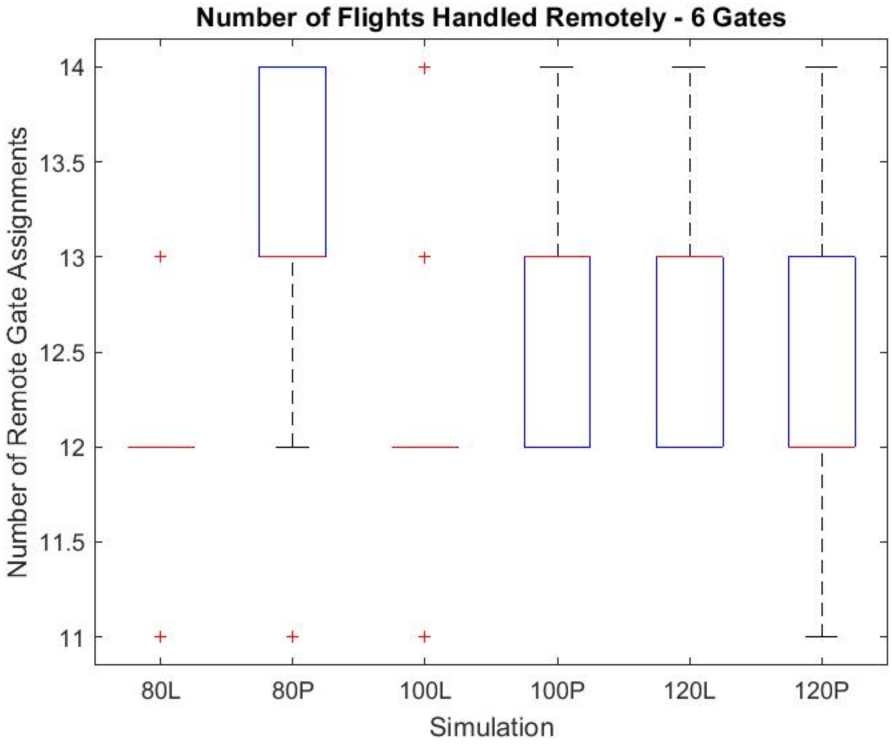


Figure 5.11: Number of remotely handled flights - 6 gates

Taking into account the average total delays, from Figure 5.12 it becomes clear that the addition of pit-stops is always accompanied by an increase in delays. As the delays without pit-stops are already significant, the additional delays due to the pit-stops are relatively minor. In the case of Simulation 5 and 6, where the pit-stops lead to a decrease in remotely handled flights, the increase in total delays is about 27%.

The simulation with the longest run time was Simulation 6, just like the scenario with four gates in Section 5.1. A total of 11595 seconds (about 193 minutes) were needed to complete all 50 runs of Simulation 6.

5.3. Scenario 3: Eight Gates

The results of the final scenario will be presented in this section. All simulations in this section will be run with eight gates, of which figure 5.13 shows the node-link model.

Six simulations have been run with a similar setup as in Sections 5.1 and 5.2. All simulations have been run with a duration of 2.5 hours (150 minutes) and a five minute inter-arrival time. In total, 30 unique aircraft arrive and depart in each distinct simulation, where a total of 32 movements take place with these 30 aircraft for the simulations with two pit-stops. All aircraft have been assigned a turnaround time of 40 minutes, except for two randomly selected flights. These two flight have been assigned a

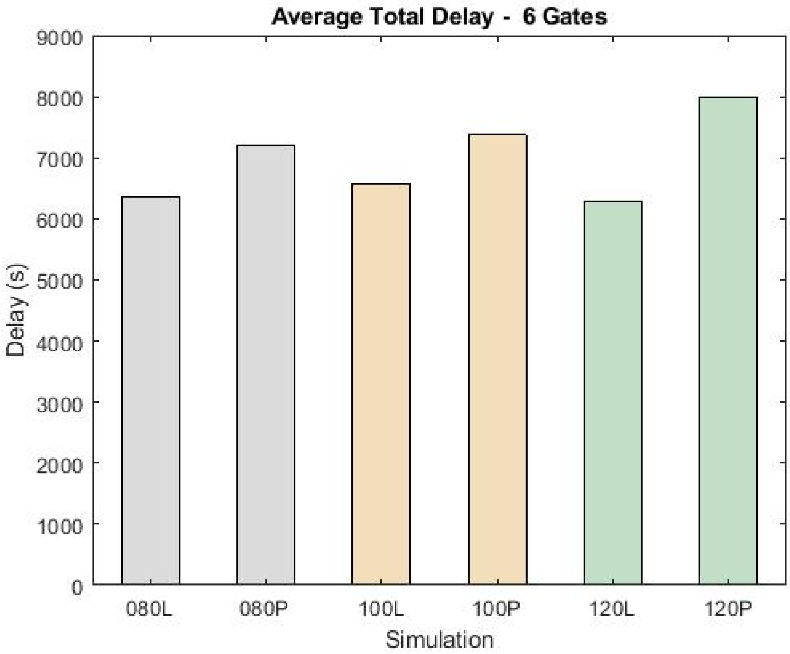


Figure 5.12: Average total delays - 6 gates

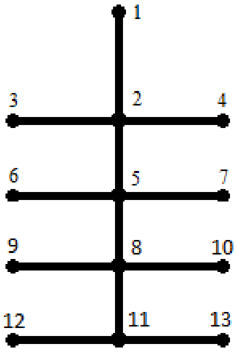


Figure 5.13: Node-link model for Scenario 3 (8 gates)

longer turnaround, during which they remain at the gate (Simulation 1, 3 and 5) or undergo a pit-stop (Simulation 2, 4 and 6). Each simulation consists of 50 unique runs in order to obtain accurate results and identify any potential outliers. The results of the simulation are presented by identifying delays per aircraft and the total number of remote stand assignments.

An overview of the input parameters used for all simulations can be found in Table 5.17, and the parameters unique to each simulation are listed in Table 5.18. In Section 5.3.1 Simulation 1 and 2 will be discussed, after which the results of Simulation 3 and 4 will be discussed in Section 5.3.2. The results of the final two simulations, Simulation 5 and 6, will be treated in Section 5.3.3.

5.3.1. Long Turnaround: 80 Minutes

The parameters used for the simulations in this section can be found in Table 5.17 and Table 5.18 under *Simulation 1* and *Simulation 2*. The only difference between these simulations is the application of the longer turnaround time for two randomly selected aircraft. For the first simulation, these aircraft are parked as long stay flights whereas for the second simulation these aircraft are selected to undergo a pit-stop. Below, the results of these simulations are shown.

Table 5.17: Input parameters for all simulations - Scenario 3

Input Schedule	
Parameter	*All Simulations*
Number of Gates	8
Schedule duration (min)	150
Inter-arrival Time (min)	5
Number of Unique Aircraft	30
Regular Turnaround Time (min)	40
Number of Runs	50

Table 5.18: Input parameters for each unique simulation - Scenario 3

Input Schedule						
Parameter	*Simulation 1*	*Simulation 2*	*Simulation 3*	*Simulation 4*	*Simulation 5*	*Simulation 6*
Movements	30	32	30	32	30	32
Long stay/Pit-stop	2 Long stay	2 Pit-stop	2 Long stay	2 Pit-stop	2 Long stay	2 Pit-stop
Long Turn. (min)	80	80	100	100	120	120

Simulation 1

The delays assigned by the model to the aircraft are visualized using box plots in Figure 5.14. The first seven movements all have a median delay of zero, as the model smoothly assigns these flights to a gate. However, once the eighth movement arrives, delays start building up and all subsequent flights experience a non-zero median delay. This is different from similar cases with four and six gates, where delays reduce after an initial peak. The reason for this can be explained by the 'depth' of the model: aircraft that are assigned to a gate further down the main taxiway (for example the gates located at Node 12 and 13 in Figure 4.13c) take longer to clear the apron than flights parked close to the apron entry (Node 1). If an aircraft departs from one of these gates, arriving aircraft have to hold longer before the apron taxiway is clear. The average total delay is therefore high at 9256.7 seconds or some 309 seconds per aircraft movement. The median delay values are also high across all movements (see Table 5.19). In total, an average of 8.26 aircraft per run is assigned to a remote stand.

Table 5.19: Median delay values - 80 min - 2 long stay flights

Aircraft	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Median Delay (s)	238	414	400	447	457	420	433	444
Aircraft	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Median Delay (s)	473	451	261	161	358	510	402	439
Aircraft	**24**	**25**	**26**	**27**	**28**	**29**	**30**	
Median Delay (s)	427	492	503	298	189	147	330	

Simulation 2

The effect of pit-stops compared to keeping flights parked at the gate for a turnaround time of 80 minutes will now be examined. Figure C.7 in Appendix C shows the delays for the arriving aircraft. When comparing these results to the results of the previous simulation, the effect of the pit-stops is apparent especially around movement five to seven. These flights show a zero median delay without pit-stops, however with the addition of pit-stops they all experience a delay. This can be explained by the fact that their arrival times roughly coincide with the departure of the two flights with a pit-stop. For subsequent flights, the same two peaks can be noticed and overall median delays remain high for all arrivals, as can be seen in Table 5.20. The increase in average delay with pit-stops is substantial at 46%, with a total average delay of 13506.6 seconds or some 422 seconds per movement. Looking at the average number of remote gate assignments, 8.20 flights are handled remotely on average, which is lower

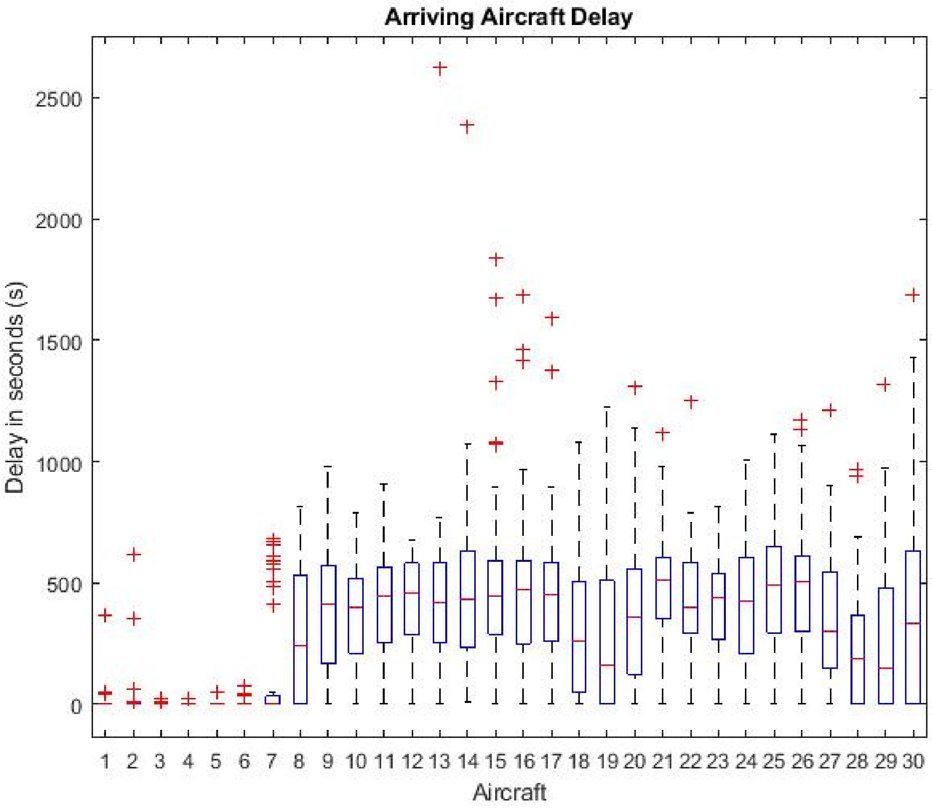


Figure 5.14: Arrival delays - 8 gates - 80 min - 2 long stay flights

than the value found in Simulation 1. Therefore, contrary to the other scenarios, for a scenario with 8 gates pit-stops do lead to a decrease in remotely handled flights for simulations with an 80 minute long turnaround.

Table 5.20: Median delay values - 80 min - 2 pit-stops

Aircraft	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Median Delay (s)	223.5	345	234	399	388.5	428.5	420.5	364
Aircraft	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Median Delay (s)	376	609	548	538	541	546.5	581.5	524.5
Aircraft	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
Median Delay (s)	529	426	213	239	291	333.5	434	524.5
Aircraft	**28**	**29**	**30**	**31**	**32**			
Median Delay (s)	445.5	353	242	112.5	257			

5.3.2. Long Turnaround: 100 Minutes

Two simulations have been performed with a long turnaround of 100 minutes assigned to two selected aircraft. In the first of these (Simulation 3), the two flights with a long turnaround are modelled as long stay flights. In Simulation 4, these flights undergo a gate pit-stop. All relevant input parameters for these simulations can be found in Table 5.17 and Table 5.18 under *Simulation 3* and *Simulation 4*. The results presented in this section will be used to support the conclusions on delays and remote stand assignments for an airport model with eight gates.

Simulation 3

The arrival delays per aircraft for Simulation 3 are visualized using box plots in Figure C.8 which can be found in Appendix C. The results are very similar to the results of Simulation 1 (two long stay flights, 80 min.), with the second peak in delays having shifted by about four flights, which corresponds to the longer turnaround time for the two long stay flights. The highest 75th percentile delay was measured at 1438 seconds for aircraft 30. Table 5.21 lists the median non-zero delays for this simulation. The total delay averages 9332.1 seconds, which equals some 311 seconds per movement. These delays are only slightly higher than the delays measured in Simulation 1, which indicates that the effect of a longer turnaround time for long stay flights does not have a significant impact on delays with an eight gate model. The average number of remote gate assignments is 7.94.

Table 5.21: Median delay values - 100 min - 2 long stay flights

Aircraft	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Median Delay (s)	244	435	452	478	450	433	383	458
Aircraft	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Median Delay (s)	516	432	275	302	383	398	491	462
Aircraft	**24**	**25**	**26**	**27**	**28**	**29**	**30**	
Median Delay (s)	499	488	458	377	103	21	282	

Simulation 4

The box plots for the delays of Simulation 4 are presented in Figure 5.15. As can be seen, significant delays start to build up after the fourth arrival movement. Median delays remain high throughout the arrival sequence, with a spike in delays around movement 22 to 26. These arrival movements correspond to the aircraft that return from the remote stand after a pit-stop, which explains the high delays. Looking at the median delays in Table 5.22, the high delay values show that the delays are relatively evenly spread across all movements. The total delay averages 11562.9 seconds across all runs, which is equivalent to about 361 seconds per movement. On average, 7.50 aircraft were assigned to a remote stand across all runs, which is a lower value than that found for Simulation 3. Therefore, with eight gates, pit-stops with a duration of 100 minuts are effective, contrary to the cases with four and six gates.

Table 5.22: Median delay values - 100 min - 2 pit-stops

Aircraft	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Median Delay (s)	91	236	409.5	466	505	439	399.5	373
Aircraft	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Median Delay (s)	455.5	495	467	441.5	400	312	317	420.5
Aircraft	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Median Delay (s)	502	520	478.5	593	552	555.5	398.5	280.5
Aircraft	**29**	**30**	**31**	**32**				
Median Delay (s)	93	73.5	31.5	418.5				

5.3.3. Long Turnaround: 120 Minutes

The final two simulations that are presented have been performed with an eight gate model and two flights with a long turnaround of 120 minutes. The input parameters for the simulations in this section can be found in Table 5.17 and Table 5.18 under *Simulation 5* and *Simulation 6*, respectively.

Simulation 5

Simulation 5 was performed with two long stay flights with a total turnaround time of 120 minutes for each of these two flights. This leads to the delays visualized in Figure C.9 in Appendix C. The results for this simulation are very similar to the previously discussed simulations with 2 long stay flights and 8 gates (Simulation 1 and 3). Total delays averaged 8192.8 across 50 runs (approximately 273 seconds per movement). Median delay values are listed in Table 5.23. The average number of remote stand assignments equals 8.56.

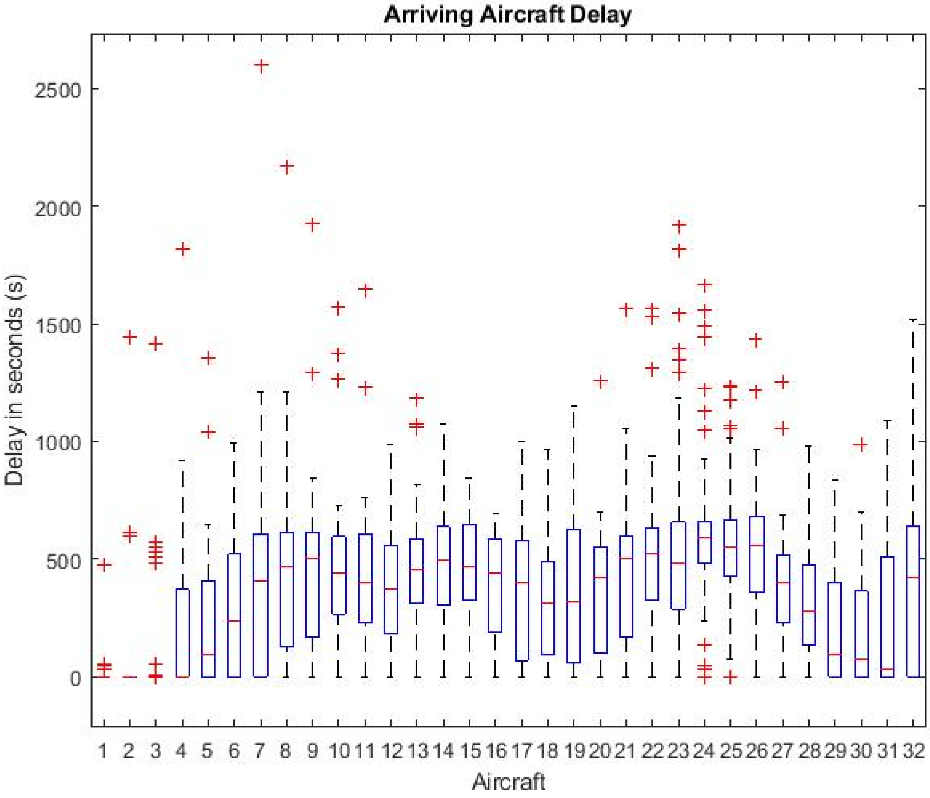


Figure 5.15: Arrival delays - 8 gates - 100 min - 2 pit-stops

Table 5.23: Median delay values - 120 min - 2 long stay flights

Aircraft	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Median Delay (s)	281.5	395.5	443.5	463.5	393	489	499	438.5
Aircraft	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Median Delay (s)	410	363	313	298.5	299	188	341.5	498.5
Aircraft	**24**	**25**	**26**	**27**	**28**	**29**	**30**	
Median Delay (s)	480	413	437.5	345	48.5	8.5	39	

Simulation 6

For the final simulation, the delays are captured in box plots shown in Figure 5.16. Looking at the results, after arrival movement number four, median delays are rather constant. Of all simulations with pit-stops, the distribution of delays is smoothest for this simulation. This can be explained by the fact that overall delays are high and approximately evenly distributed after the arrival of aircraft eight in Simulation 5, which serves as a basis for Simulation 6, where the only difference is the addition of pit-stops. Simulation 5 shows a drop in delays around aircraft 21, however in Simulation 6 this coincides with the return of the flights with a pit-stop. As such, this dip is not observed in Simulation 6. With the addition of pit-stops in Simulation 6, delays remain constant at median values of around 400 to 500 seconds (see Table 5.24). The average total delay for this simulation is 12135.0 seconds (379 seconds per movement) with an average of 7.88 remote stand assignments per run. Therefore, the results for eight gates show a reduction of remote gate assignments for all simulations with pit-stops.

Conclusions

In the previous two sections, it was determined that pit-stops are an effective way to increase gate utilization solely for cases with a 120 minute turnaround. The results in this section underline the ef-

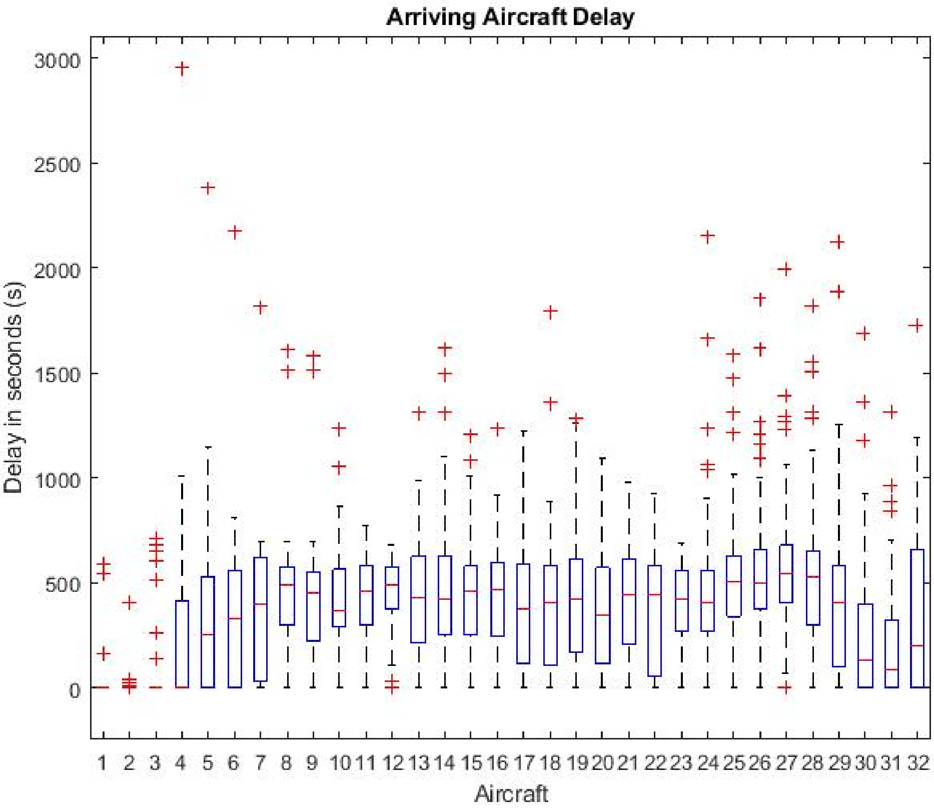


Figure 5.16: Arrival delays - 8 gates - 120 min - 2 pit-stops

Table 5.24: Median delay values - 120 min - 2 pit-stops

Aircraft	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Median Delay (s)	255	332	400	494.5	455.5	371	461.5	493
Aircraft	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Median Delay (s)	430	423	464.5	472	373.5	408	422	344
Aircraft	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Median Delay (s)	446.5	443	423.5	411	505.5	501.5	547	527.5
Aircraft	**29**	**30**	**31**	**32**				
Median Delay (s)	410	135.5	87	201				

fectiveness of 120 minute pit-stops, but it has been shown that for a larger model with eight gates, pit-stops become effective with a shorter turnaround as well as simulations for both 80 and 100 minutes have shown. This is reinforced by Figure 5.17, which shows the remote stand assignments for all six scenarios with eight gates.

Looking at average delays in Figure 5.18, the observations from the previous scenarios of pit-stops inevitably leading to an increase in delays is confirmed with eight gates as well.

Simulation 6 again took the longest to complete. In total, in 28368 seconds all 50 runs were done, which equals about 473 minutes, or just under eight hours.

5.4. Conclusions

In this chapter, the results of three distinct scenarios have been analyzed. Each scenario consists of six simulations, where the only difference between each scenario is the number of gates of the model.

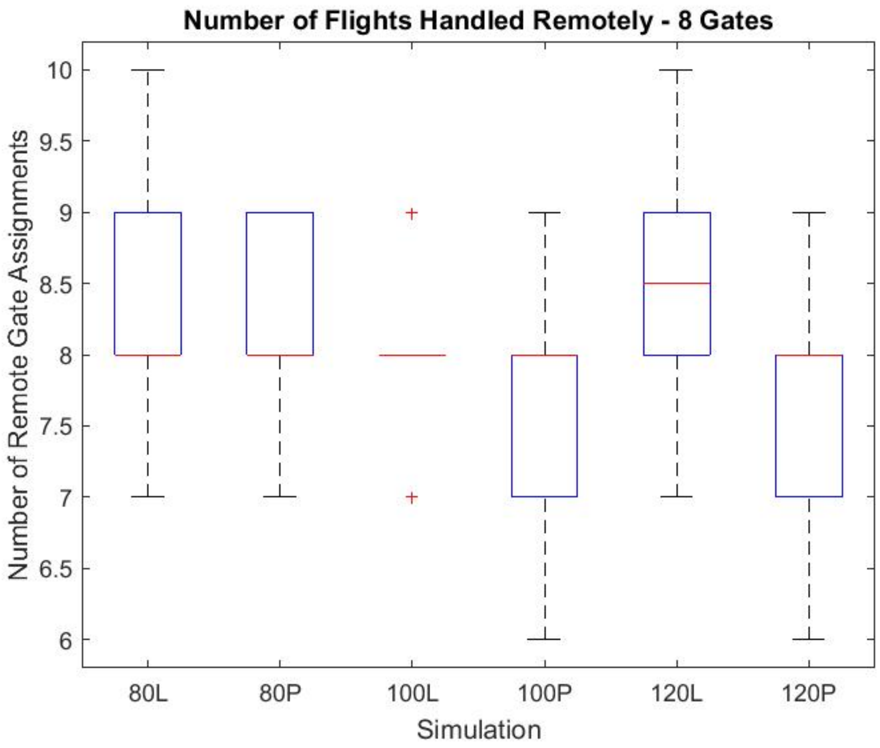


Figure 5.17: Number of remotely handled flights - 8 gates

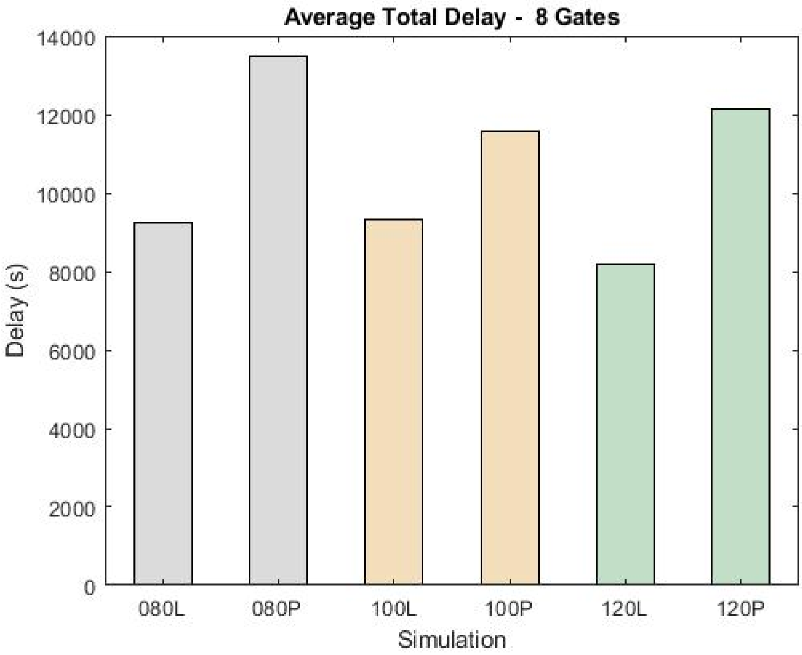


Figure 5.18: Average total delays - 8 gates

Scenario 1 and 2

For Scenario 1 and 2 (four and six gates, respectively), assigning a pit-stop to flights with an 80 minute layover did not lead to an increase in flights handled at a gate instead of a remote stand. Apparently, the extra gate space that comes available in this time cannot be used effectively. Additionally, in both cases the application of pit-stops lead to a increase in delays as a result of an increase in apron movements. For airports and airlines, it is therefore not recommended to introduce pit-stops with a turnaround of 80 minutes in case of a pier with four or six gates. The results with a long turnaround of 100 minutes for both scenarios show similar results as the 80 minute case: pit-stops in these cases cause an increase in delay whereas the number of remotely handled flights is not reduced.

Scenario 3

The results of Scenario 3 (eight gates) show that as the number of gates increases beyond a certain number (six gates for the input variables in this research), pit-stops become more effective in reducing the number of remotely handled flights. With eight gates, introducing pit-stops lead to more flights at a gate for flights with a long layover of 80 minutes, which was not the case in the other two scenarios with less than eight gates. As the turnaround time of the flights with a longer layover increases, the effect of pit-stops become more pronounced. Again, more flights can be handled at a gate but this does lead to an increase in delays.

Final Results

The results of all scenarios are summarized in Table 5.25 and Table 5.26. The results in Table 5.25 show the average number of remote assignments per scenario. Table 5.26 displays the average delay per unique aircraft for all scenarios. Looking at these values, the number of remotely parked aircraft goes down with around 5 when the number of gates is increased from 4 to 6. This number goes down by another 4 aircraft if the number of gates is increased further to 8 in total. Because of congestion on the apron, it appears that adding an additional gate pair becomes less effective further away from the apron entry. The delays increase significantly with the addition of each gate pair, both for long stay flights and pit-stops. As overall delays increase for this reason, the incremental effect on delays due to pit-stops is somewhat mitigated, making pit-stops a more viable option as the number of gates increases. As for the effect on computation times, the increase in total run times between the different scenarios is significant (see Table 5.27). The longest simulation for Scenario 1 took about 60 minutes to complete, whereas the longest run time of Scenario 3 was about 473 minutes (an increase of 688%). This shows the exponential increase in the scale of a problem when a MILP approach is used, and is something to be taken into account should the model be expanded further.

Table 5.25: Average number of remote gate assignments - all scenarios

	Long Turnaround					
Number of Gates	*80 Minutes*		*100 Minutes*		*120 Minutes*	
4	17.2	18.0	17.1	17.3	17.2	16.8
6	12.0	13.2	12.2	12.8	12.7	12.3
8	8.3	8.2	7.9	7.5	8.6	7.9

Table 5.26: Average delay per movement in seconds - all scenarios

	Long Turnaround					
Number of Gates	*80 Minutes*		*100 Minutes*		*120 Minutes*	
4	43.9	53.1	44.0	59.3	47.7	59.8
6	211.9	239.9	219.0	245.9	209.5	266.2
8	308.6	450.2	311.1	385.4	273.1	404.5

Table 5.27: Longest computation time in minutes - all scenarios

Scenario	**Duration**
1 (4 Gates)	60
2 (6 Gates)	193
3 (8 Gates)	473

6

Verification and Sensitivity Analysis

In order to ensure that the model complies with the requirements, verification of the model needs to take place. Section 6.1 discusses the verification of the model. In addition to the model verification, a sensitivity analysis has been performed. This analysis has been done to assess the effect of the aircraft inter-arrival time on the model results, as well as the effect of introducing new pushback technologies like ETS. The results of the sensitivity analysis can be found in Section 6.2.

6.1. Verification

During verification, the model will be checked to determine whether the mathematical model functions correctly and whether the output is both consistent and logical. Generally, this process is split up into two parts. In the first part, the code that represents the mathematical model is verified, and in the second part the calculations are verified [42].

The code that represents the model has been verified by using input of which the expected outcomes (gate assignment, delays, time at nodes etc.) were calculated a priori. The times of aircraft at each node, gate / remote stand assignments and eventual delays were calculated by hand. The results produced by the model proved to be identical to the calculations, which verified correct functioning of the mathematical model. Several runs were initially performed with a test case of 4 gates, with a schedule time of 2 hours. In this test case, an inter-arrival time of 7 minutes was used and every aircraft (18 in total) was assigned a turnaround time of 40 minutes. No pit-stops or long stay flights were added to this model yet. The model was then verified to determine whether the mathematical inputs functioned correctly. Once it was determined that this is case, the model was expanded. Every expansion was again tested and verified in the same way.

In order to guarantee consistency and logic of the calculations, several runs with the final model scenarios have been performed and manually checked. These analytical solution checks were performed to determine whether the output is consistent and whether the output adheres to all constraints set forward in the mathematical model. This was done by analyzing each aircraft with its corresponding gate assignment and the time of each aircraft at every node. The exact times that each aircraft in the model visited a node and/or a gate were reviewed and compared to the other aircraft in the model to ensure that all constraints were functioning correctly. For the scenarios reviewed, it was found that the constraints set functioned correctly, as the aircraft maintained sufficient separation and no aircraft were assigned to the same gate or link at any time.

6.2. Sensitivity Analysis

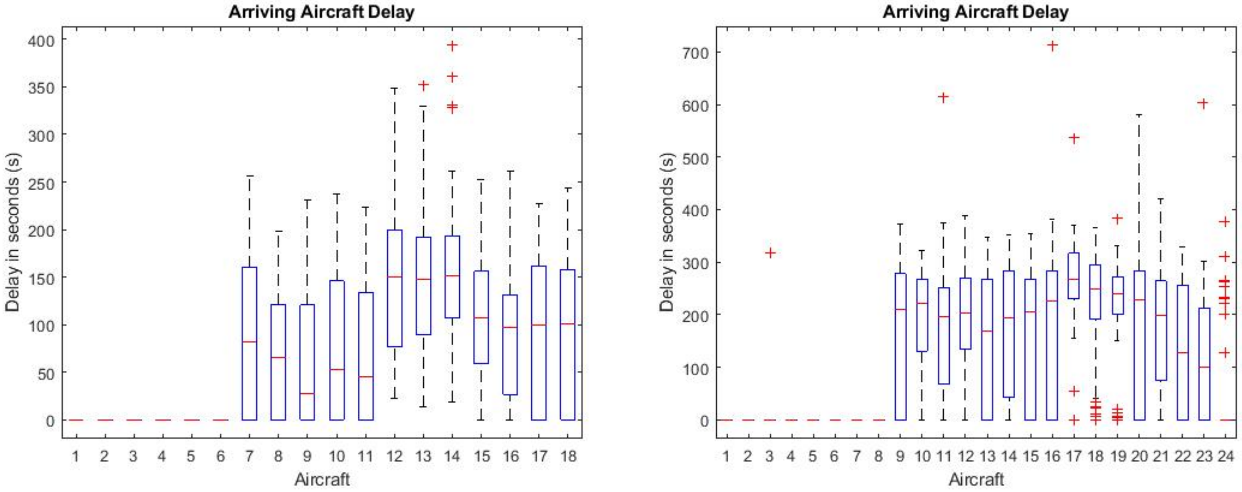
The sensitivity analysis for the model has been performed by taking into account two important input parameters. In the first scenario discussed in Section 6.2.1, the effect of the inter-arrival time on the model results are analyzed. In Section 6.2.2, the second scenario is discussed in which the effects of introducing new pushback technology on delays and gate assignments are analyzed.

6.2.1. Inter-arrival Time

The inter-arrival time used to come to the results of Chapter 5 was set to five minutes. However, as was noticed in Section 5.3 in particular, the high sequence of arriving aircraft has an adverse effect on delays. Therefore, simulations have been performed with a longer IAT of 7 minutes instead of 5 minutes.

Two Long Stay Flights

In Figure 6.1, the results for the arrival delays for different inter-arrival times are displayed. In both cases, an eight gate model was used and 2 flights were randomly selected to serve as a long stay flight with a turnaround time of 80 minutes for a total schedule duration of 2 hours (120 minutes).

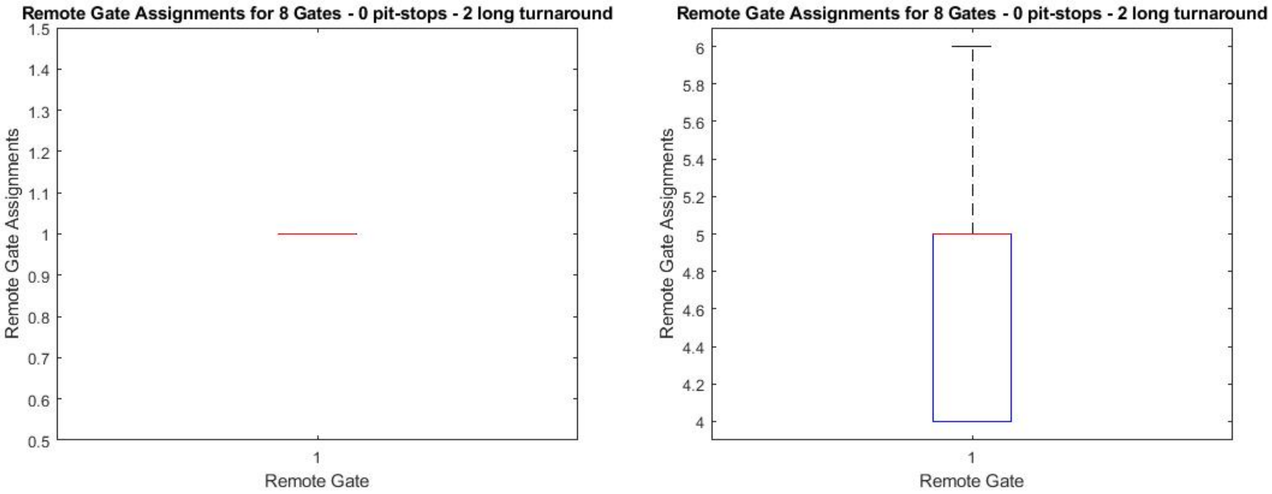


(a) 7 minute IAT - 2 long stay flights

(b) 5 minute IAT - 2 long stay flights

Figure 6.1: Delays for 7 and 5 minute inter-arrival times - 8 gates - 2 long stay flights

From Figure 6.1, there is a significant increase in delays when the inter-arrival time is decreased from 7 to 5 minutes. The median total delay with a 7 minute IAT is 1129 seconds, whereas this value equals 3040 seconds for the scenario with a 5 minute IAT. This represents an increase of 169%, whereas the number of flights increases by 33% (from 18 to 24).



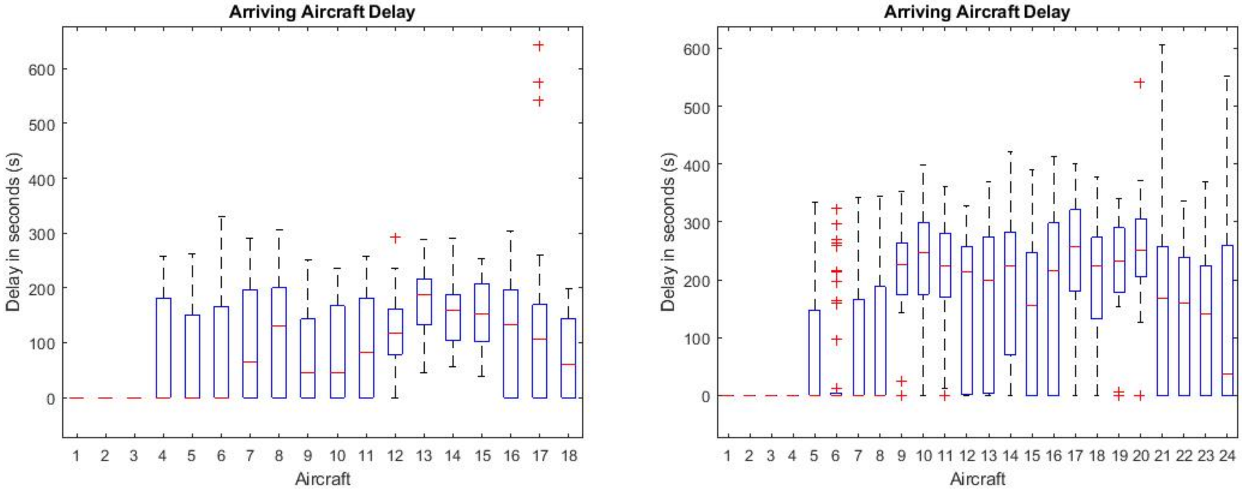
(a) 7 minute IAT - 2 long stay flights

(b) 5 minute IAT - 2 long stay flights

Figure 6.2: Remote stand assignments for 7 and 5 minute inter-arrival times - 8 gates - 2 long stay flights

Looking at the number of remote assignments in Figure 6.2, the median number of remotely handled flights equals one for the 7 minute IAT which increases to a median of five for the simulation with a 5 minute IAT. Thus, for a 7 minute IAT, a total of 94% of flights (17 out of 18) can be handled at a gate, which decreases to 79% (19 out of 24) flights with a 5 minute IAT.

Two Pit-stops
The same analysis has been performed for the two different inter-arrival times where two flights will undergo a pit-stop. Figure 6.3 shows the delays for a 7 and 5 minute IAT where two flights experience a pit-stop.



(a) 7 minute IAT - 2 pit-stops

(b) 5 minute IAT - 2 pit-stops

Figure 6.3: Delays for 7 and 5 minute inter-arrival times - 8 gates - 2 pit-stops

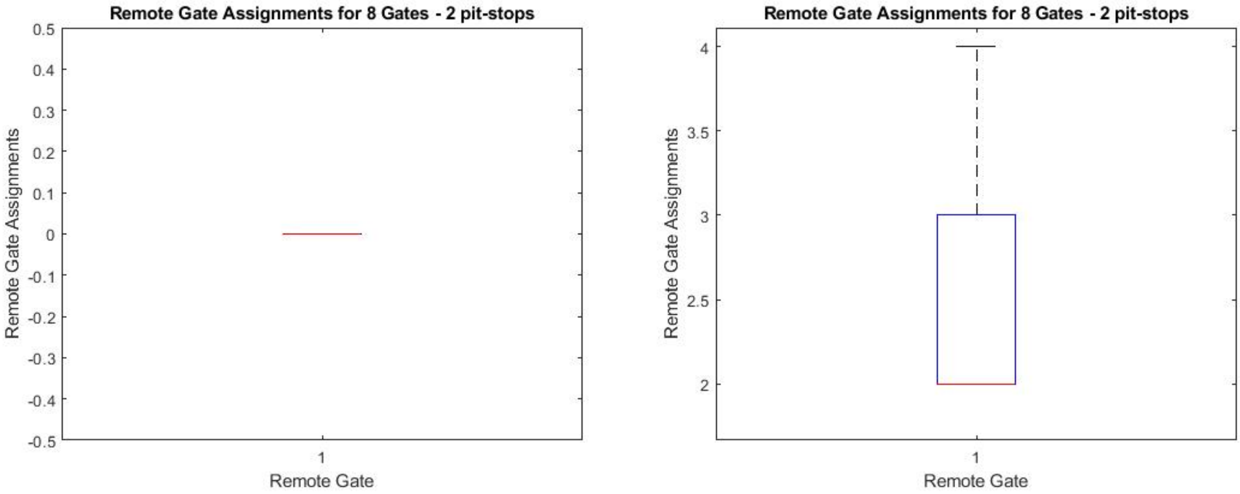
From Figure 6.3, delays increase significantly when the inter-arrival time is reduced to 5 minutes, which is a similar results compared to the simulations with two long stay flights. The median total delay with a 7 minute IAT equals 1285 seconds. The median delays increase to 3175.5 seconds when the inter-arrival time is reduced to 5 minutes. This represents an increase of 147%, whereas the number of flights increases by 33% (from 18 to 24).

Figure 6.2 shows the number of remote gate assignments for the different inter-arrival times. The median number of remotely handled flights equals zero for the 7 minute IAT which increases to a median of two for the simulation with a 5 minute IAT. With a 7 minute IAT, 100% of all unique flights can be handled at a gate, whether only 90% (20 out of 22) flights with a 5 minute IAT can be handled at a gate.

6.2.2. New Pushback Technology

In Chapter 2, it was found that new pushback technologies such as ETS can be used to reduce the total pushback time. In all previously discussed simulation, a pushback duration of 180 seconds was used. If ETS is introduced, this can be reduced to 120 seconds. In order to assess whether the introduction of ETS has a pronounced effect on apron delays and gate assignments, several runs with a reduced pusbhack duration of 120 seconds have been performed. For these simulations, an inter-arrival time of 5 minutes is used. The first simulations compare the results with a six gate model, whereas the second simulations compare the results using an eight gate model.

Six Gates
For the simulations with six gates, the results found in Section 5.2.3 for flights with pit-stops are compared to a simulation with identical input parameters (two pit-stops, 120 minute long turnaround) except for a pushback duration of 120 seconds instead of 180 seconds. Figure 6.5 compares the number of



(a) 7 minute IAT - 2 pit-stops (b) 5 minute IAT - 2 pit-stops

Figure 6.4: Remote stand assignments for 7 and 5 minute inter-arrival times - 8 gates - 2 pit-stops

remote gate assignments for both scenarios, where '120C' stands for the simulation with a conventional pushback duration of 180 seconds and '120E' indicates a simulation using ETS, which reduces pushback to 120 seconds.

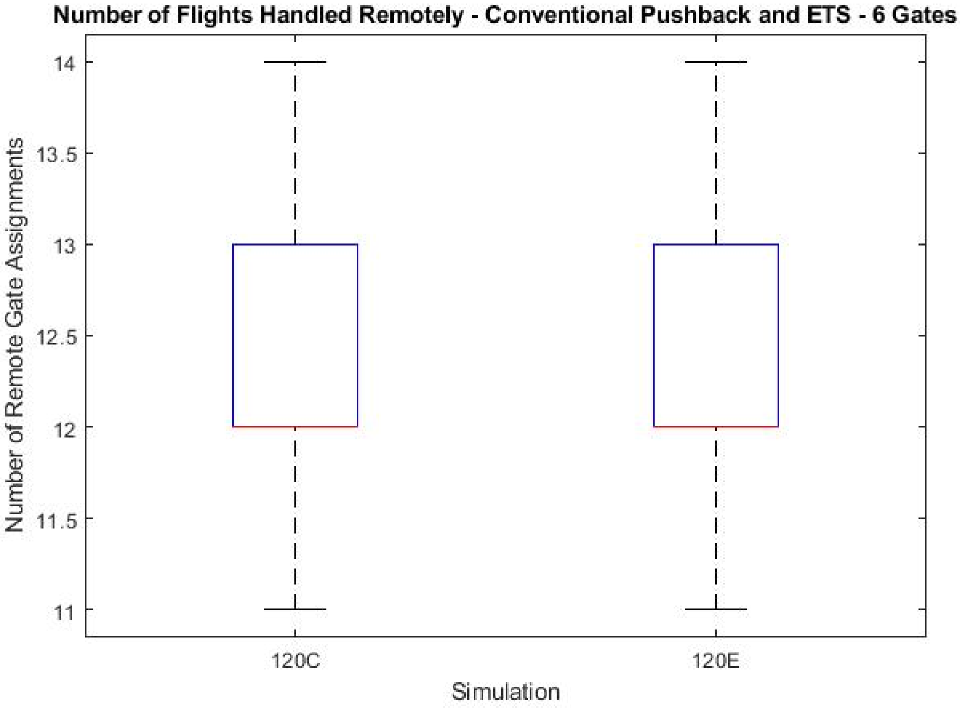


Figure 6.5: Remote gate assignments - 6 gates - conventional pushback vs. ETS

The introduction of ETS does not lead to a noteworthy reduction in remotely handled flights, as the average number of remote assignments reduces from 12.34 with conventional pushback to 12.28 using ETS. However, using ETS does have a positive effect on delays, as average total delays are reduced from 7987.3 seconds to 6935.2 seconds (about 13%) using ETS. Figure 6.6 shows this reduction in delays.

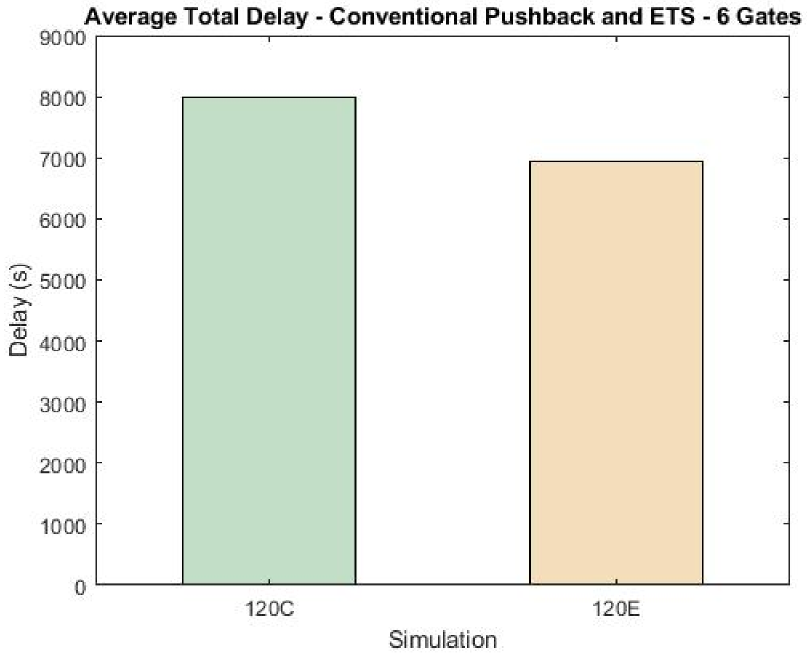


Figure 6.6: Average total delay - 6 gates - conventional pushback vs. ETS

Eight Gates
Like the analysis on the usage of ETS with six gates, for the simulations with eight gates simulations with conventional pushback and ETS are compared using previously found results in Section 5.3.3. The usage of ETS is compared to conventional pushback for simulations with 2 pit-stops and 120 minute long turnarounds. The results in 6.5 show the effect on remote stand assignments when using ETS ('120E') compared to conventional pushback ('120C').

With an eight gate model, the introduction of ETS has a somewhat more pronounced effect on remote gate assignments compared to a six gate model, as the average number of remote assignments drops from 7.88 to 7.70 when ETS is used. However, as can be seen in Figure 6.8, the main advantage of using ETS is the reduction in delays. Average total delays are reduced by about 7% compared to conventional pushback. This is somewhat less than for the six gate model, which saw a reduction of 13%. A reason for this could be that the eight gate model has significantly higher overall delays, so the effect of switching from conventional pushback to ETS is less pronounced in this case.

The above results show that the introduction of new technologies, such as ETS, can be very useful in decreasing delays, especially when gate pit-stops are used. Its effect on reducing the number of remote stand assignments is limited, but they can still aid in making pit-stops more effective, as pit-stops become more attractive when the inherent effect of increased delays is mitigated by the use of ETS. These results therefore present an interesting opportunity for further research, where the investment in ETS can be traded-off with the reduction in delays and flight handled at a remote gate.

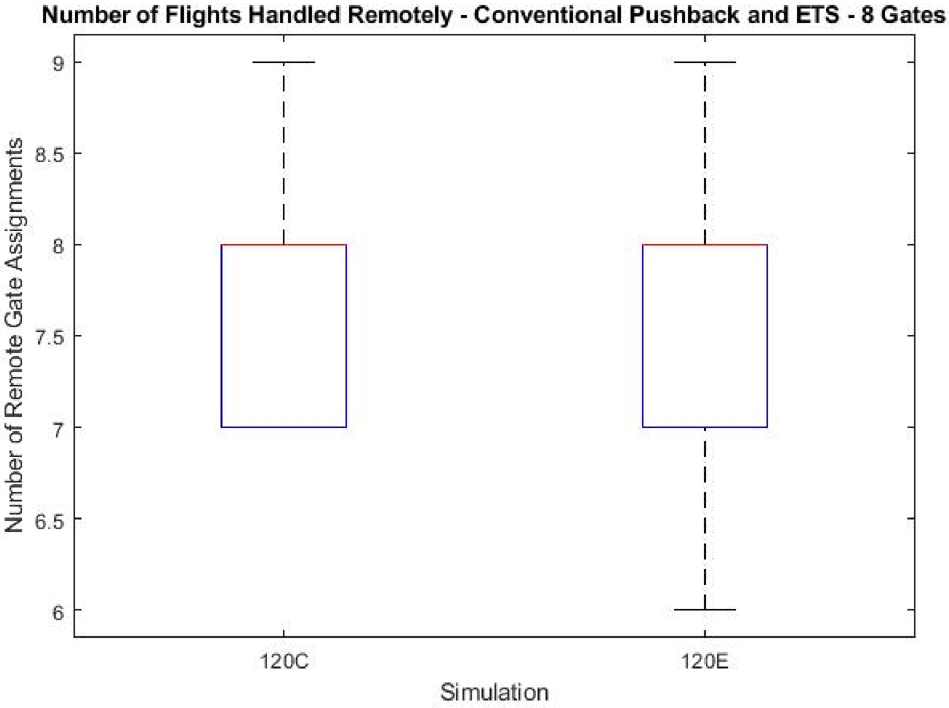


Figure 6.7: Remote gate assignments - 8 gates - conventional pushback vs. ETS

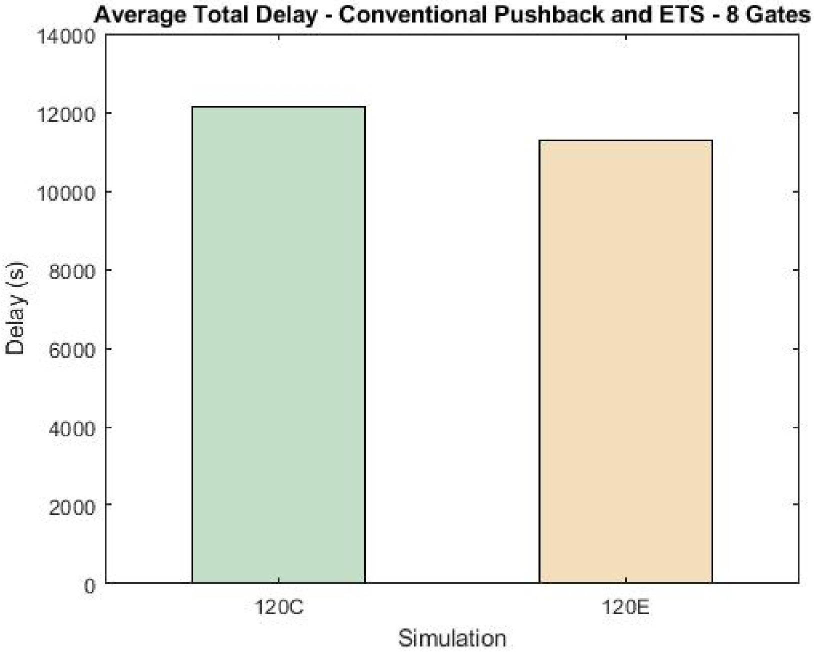


Figure 6.8: Average total delay - 8 gates - conventional pushback vs. ETS

7

Conclusions, Limitations and Recommendations

This chapter discusses the conclusions, limitations and recommendations for the work presented in the previous chapters. Section 7.1 gives an overview of all the conclusions that follow from the results and Section 7.2 presents the limitations of the work. Finally, Section 7.3 makes recommendations for future research.

7.1. Conclusions

The main objective of the research is to assess whether gate pit-stops are an effective way to increase gate utilization at busy airports by taking into account the effect of pit-stops on apron congestion. To accomplish this objective, a model representing the airport apron area with gates has been created, and aircraft ground movements have been simulated based on a MILP formulation. These movements were optimized to minimize delays and remote stand assignments. The simulation results provide insight in gate usage and delays, in order to answer the main research question. The main research question is formulated to investigate whether gate utilization can be increased by making (more) use of gate pit-stops, and what the effect is of pit-stops on apron congestion. The sub-questions of the research focus on the two elements of the main question, namely gate utilization and apron congestion. Therefore, the findings of each of these elements will be presented separately, after which the main research question will be answered. The conclusions on gate utilization will be discussed first in Section 7.1.1. Thereafter, the conclusions on apron congestion will be presented in Section 7.1.2. With the conclusions on both sub-questions, the final conclusions that answer the main research question are given in Section 7.1.3.

7.1.1. Gate Utilization

The first sub-question focuses on the effect of pit-stops on gate utilization for flights with a turnaround time of less than three hours. The expected outcome is that the introduction of gate pit-stops will lead to an increase in the number of flights that can be handled at a gate instead of a remote stand.

The results from all of the simulations performed in Chapter 5 show that this hypothesis is partly true. For some of the scenarios that have been tested, the introduction of pit-stops leads to a decrease in flights assigned to a remote stand and therefore an increase in the number of flights handled at a gate. However, this does not hold true for all scenarios. In some cases, results show that pit-stops do not lead to a decrease in remote stand assignments at all.

Looking at the model with four gates, pit-stops only lead to an increase in flights handled at a gate when the total turnaround time is 120 minutes or more. The cases with a turnaround time of 80 and 100 minutes, respectively, actually show an increase in remote stand allocations. However, as has been stated earlier, flights are currently eligible for a pit-stop only when they have a turnaround time of 180 minutes or more. Therefore, the results with a 120 minute turnaround already show an improvement over current procedures. It must be noted that the decrease in remote stand allocations is marginal (from 17.2 to 16.8 on average), but the run time for these simulations is only 2.5 hours because of computational constraints. Thus, in practice, a more meaningful reduction is expected when pit-stops are introduced for a full day schedule.

The findings of the research using a six gate model are very similar to those of the four gate model. When pit-stops are introduced for a six gate model, the number of aircraft handled at a gate only increases with a total duration of 120 minutes. As long stay flights with a 120 minute turnaround are replaced by two flights with a pit-stop, a modest decrease in remote stand allocations is observed (from 12.68 to 12.34 on average). Again, it must be acknowledged that these results are found for a total schedule duration of 2.5 hours. For a full day schedule the results are expected to have a more substantial impact. The sensitivity analysis performed in Chapter 6 shows that using an Electric Taxi System (ETS) in lieu of conventional pushback has a negligible effect on gate utilization, as average remote stand assignments are hardly reduced when ETS replaces conventional pushback.

Results for the model with eight gates show that gate pit-stops become more effective in reducing remote stand assignments as the model size increases. For the eight gate model, simulations have shown that replacing long stay flights with pit-stops has a positive effect on gate utilization for flights with an 80 minute layover or longer. As this model most closely resembles a section of a large airport compared to the other two models, these results confirm that airport and airlines can increase the number of flights handled at a gate by using gate pit-stops on a larger scale. The largest reduction in remote stand assignments is observed for the case with a 120 minute turnaround. This turnaround duration is already significantly shorter than the 180 minute guideline currently in place for gate pit-stops at major airports worldwide.

7.1.2. Apron Congestion

The second sub-question for the research concerns the effect of pit-stops on apron congestion for flights with a turnaround time of less than three hours. As gate pit-stops are introduced, the number of apron movements increases, which can lead to delays. As such, it is expected that gate pit-stops lead to additional apron delays.

Looking at the simulations performed with a four gate model, the introduction of pit-stops leads to an increase in total delay time in all cases. With this model, the only scenario in which pit-stops are effective in increasing gate utilization is with a 120 minute turnaround. The increase in average delay per aircraft associated with this scenario is about 12 seconds only, and the maximum median delay observed is actually lower with pit-stops than in the simulation with two 120 minute long stay flights. These results indicate that smooth apron operations are feasible with the addition of pit-stops, proving that pit-stops are an effective solution to increase gate utilization.

The scenario with six gates exhibits the same pattern of delays as shown in the scenario with four gates. In all simulations with six gates, adding pit-stops leads to an increase in total delays. Results show that without pit-stops, average delays per aircraft are significant, which is a result of the high rate of arrivals coupled with the required separation on the apron. Therefore, for this model, the addition of pit-stops has a comparatively small effect on the average delay per aircraft, with an increase of about 57 seconds per aircraft with 120 minute pit-stops. The sensitivity analysis shows that this can be reduced further to about 22 seconds, in which case replacing two 120 minute long stay flights with two pit-stops makes even more sense from an operational perspective.

The aircraft in the final scenario with eight gates experience very high delays for the simulations with two long stay flights. This shows that adding an additional gate pair in the ’fork’ becomes less effective further away from the apron area. The addition of pit-stops leads to the largest relative increase in delays with 120 minute long turnarounds, as the average delay per aircraft increases by about 48% or 131 seconds per aircraft. However, with a 100 minute turnaround this reduces to just under 24%, with an average of 74 seconds per aircraft. The effects of introducing ETS with 120 minute pit-stops show that the increase in delays can be reduced to some 102 seconds per aircraft, as discussed in Chapter 6. This scenario shows the largest decrease in remote stand assignments. Introducing pit-stops with shorter turnaround times together with ETS can therefore be an effective way to increase gate utilization at busy hub airports. This comes at a small delay penalty of under 2 minutes per aircraft on average, which can be largely compensated by the positive effects of parking an aircraft at a gate instead of a remote stand.

7.1.3. Final Conclusions

This research shows that making more use of gate pit-stops can lead to better gate utilization, as they can be used more effectively to combat the phenomenon of (unwanted) remote handling. This in turn leads to higher passenger satisfaction, shorter passenger and baggage connecting times and ultimately more profits for airlines and airports. It must be noted that making more use of pit-stops leads to an increase in delays. However, these can be compensated by the positive effects of parking an aircraft at a gate instead of a remote stand. Additionally, the use of new technologies such as ETS helps to reduce delays, which makes pit-stops more attractive. The results must be considered in the context of this research, which means that several limitations of the model need to be considered, as discussed in the next section.

7.2. Limitations

The results presented are bound by the limitations of the research. These limitations stem from simplifications of the scope and the model, and time constraints. The following limitations should be taken into consideration when interpreting the findings of this research:

- **Airport representation**: The model used to test the effect of pit-stops on apron congestion was set up using existing guidelines. However, it is not an exact copy of an actual airport, as modelling a large airport would be too time consuming. Therefore, the simulations do not represent movements at an existing airport. Additionally, only the gates and apron taxiways have been modelled, as other airside elements (such as runways) are outside of the research scope. Hence, effects on delays outside of the apron area have not been determined. It is expected that the effect of pit-stops on delays outside of the apron area are minimal, as the taxiways outside of the apron area have a higher capacity than the apron taxiway, so the increased number of movements due to pit-stops can be absorbed without delays.

- **Aircraft type and characteristics**: The simulations have been run with the assumption that all aircraft are of the exact same type with identical turnaround times. In real life situations, aircraft size and type vary, which has implications on input parameters such as taxi speeds and turnaround times. All speed changes have been assumed to take place instantaneously, which clearly differs from real world conditions. Performing pit-stops with different aircraft types and more realistic speed changes may lead to a slight increase in observed delays.

- **Gate assignment**: The model prioritizes gate assignments over remote stand assignments. However, delays are kept to a minimum as well. The consequence of this is that due to the high arrival rate, aircraft are not delayed by the model until a gate becomes available. Rather, the model may assign an arriving aircraft to a remote stand to keep delays to a minimum, and the next arrival will be assigned to a gate instead. In real life situations, there might be a preference for certain flights to be handled at a gate over other flights (due to a high number of critical connections, a high number of passengers with reduced mobility, etc.) while incurring a nominal delay. If this is the case, higher delays should be expected in real life situations.

- **Input schedule**: The schedule, which serves as input for the simulations, has a constant arrival rate with limited variations of up to five minutes. In reality, arrival rates are not constant and delays are more stochastic than the variations presented. Ideally, an input schedule with actual arrival and departure times from a busy hub airport is used, as this will give a better validation for the results presented in this research.

- **Running time**: The running time increased dramatically as more gates are added to the model. Therefore, running simulations with a total schedule period of more than 2.5 hours proved to be impractical due to time constraints. Opportunities to reduce the running time should be explored so that the schedule period can be increased, and a full day can be run to better assess the impact of pit-stops.

7.3. Recommendations for Further Research

There are several recommendations for further research based on the results and limitations discussed in the preceding sections. They are listed below.

- **The effect of taxiways and apron entries**: The research is based on a model with a single main apron taxiway. However, an extra taxiway can be added in order to make the gates located furthest away from the apron entry more easily accessible. This would benefit circulation and would lead to a reduction in delays. Alternatively, the effect of adding an extra entry to the apron area should be investigated, as this would reduce the distance from the gates to the apron area. It is expected that this will reduce delays and increase pit-stop effectiveness

- **Multiple aircraft and gate types**: As explained in the previous section, one of the main assumptions for the simulations of apron movements is the use of a single aircraft type. In order to make the simulations a more accurate representation of reality, the effect of having multiple aircraft types should be investigated. This also has an effect on gates, as different aircraft have different requirements for gate sizing.

- **Validation using real data**: As explained in Chapter 4, the model airport was based on specific segments of airports worldwide, such as the D-Pier at AMS. In order to properly validate the model accuracy, it should be investigated whether real life flight data can be used. Unfortunately, this data was not available for this research, but future research would benefit from the usage of actual flight data. This would also allow for a more accurate representation of delays instead of the method used in this research.

- **Optimal turnaround for pit-stops**: The results presented in this research show that pit-stops can be effective in cases with a turnaround time of less than 180 minutes, which is the current norm. For every tested scenario, pit-stops are effective from 120 minutes (and less in the case of eight gates). An interesting proposal for future research would be to determine the minimum turnaround time for several scenarios for which pit-stops become effective in reducing remote handling.

- **Cost-benefit analysis**: In aviation, the main incentive for operational decisions is cost. Therefore, the research into gate pit-stop effectiveness would benefit from a cost-benefit analysis to underline the results and aid airlines and airports in decision making regarding pit-stops.

A

Appendix

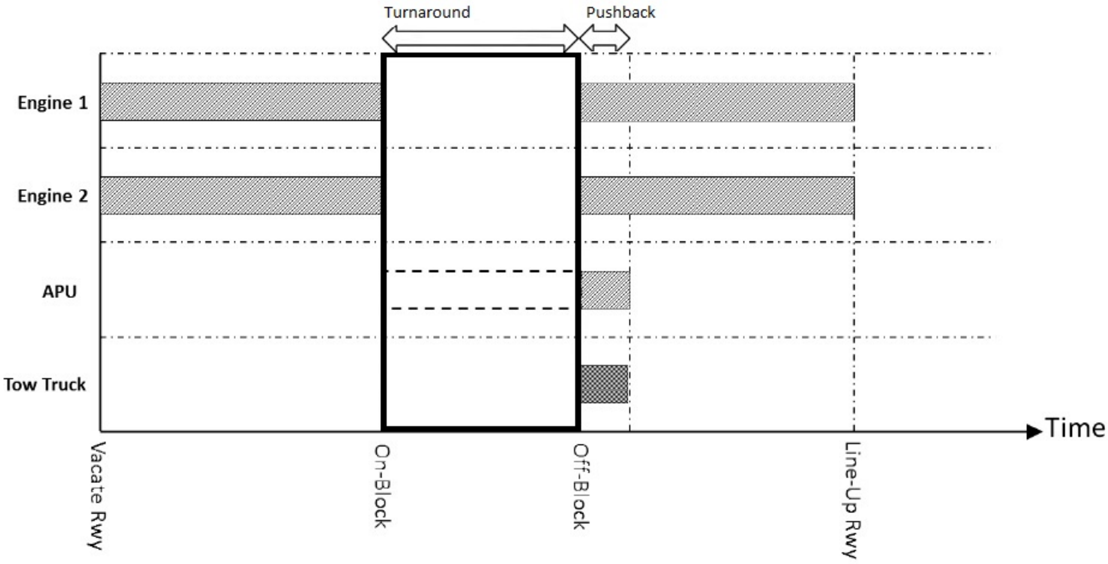


Figure A.1: Turnaround process chart, adapted from [23]

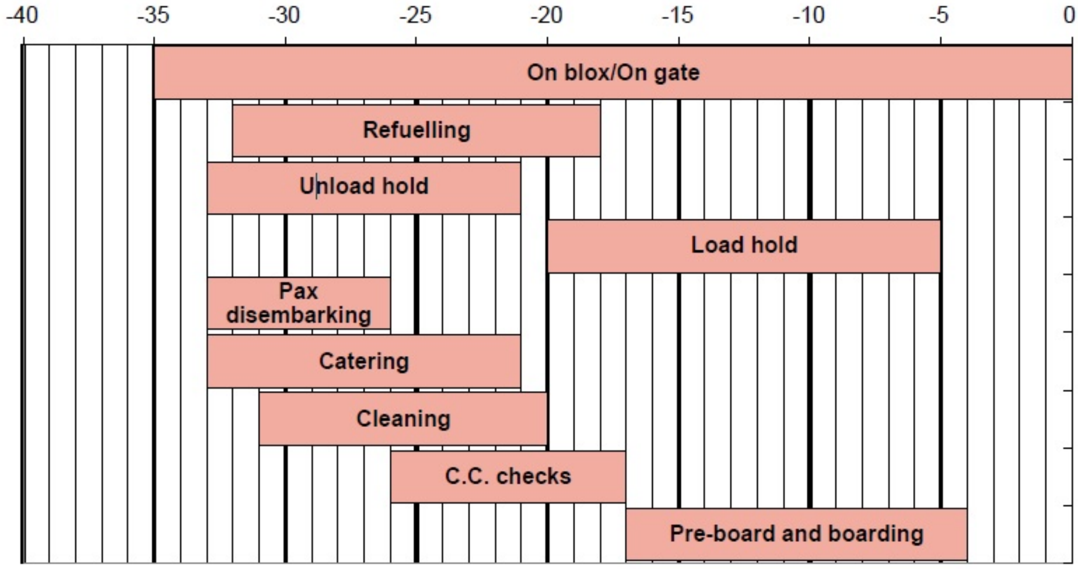


Figure A.2: Typical turnaround schedule for a Boeing 737 aircraft [60]

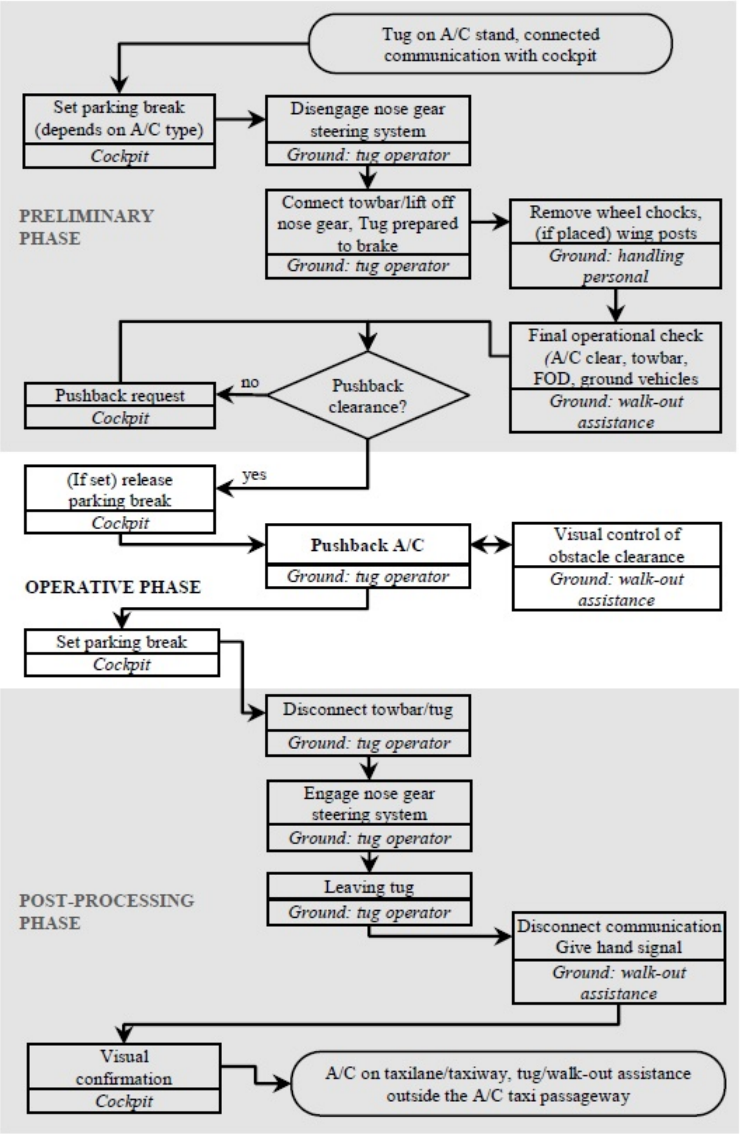


Figure A.3: The standard pushback procedure [20]

B

Appendix

Table B.1: Length of links between nodes

Node Pair	**Link Distance (in m)**	**Node Pair (in m)**	**Link Distance (in m)**
1-2	66	**5-8**	40.5
2-3	75	**8-9**	75
2-4	75	**8-10**	75
2-5	40.5	**8-11**	40.5
5-6	75	**11-12**	75
5-7	75	**11-13**	75

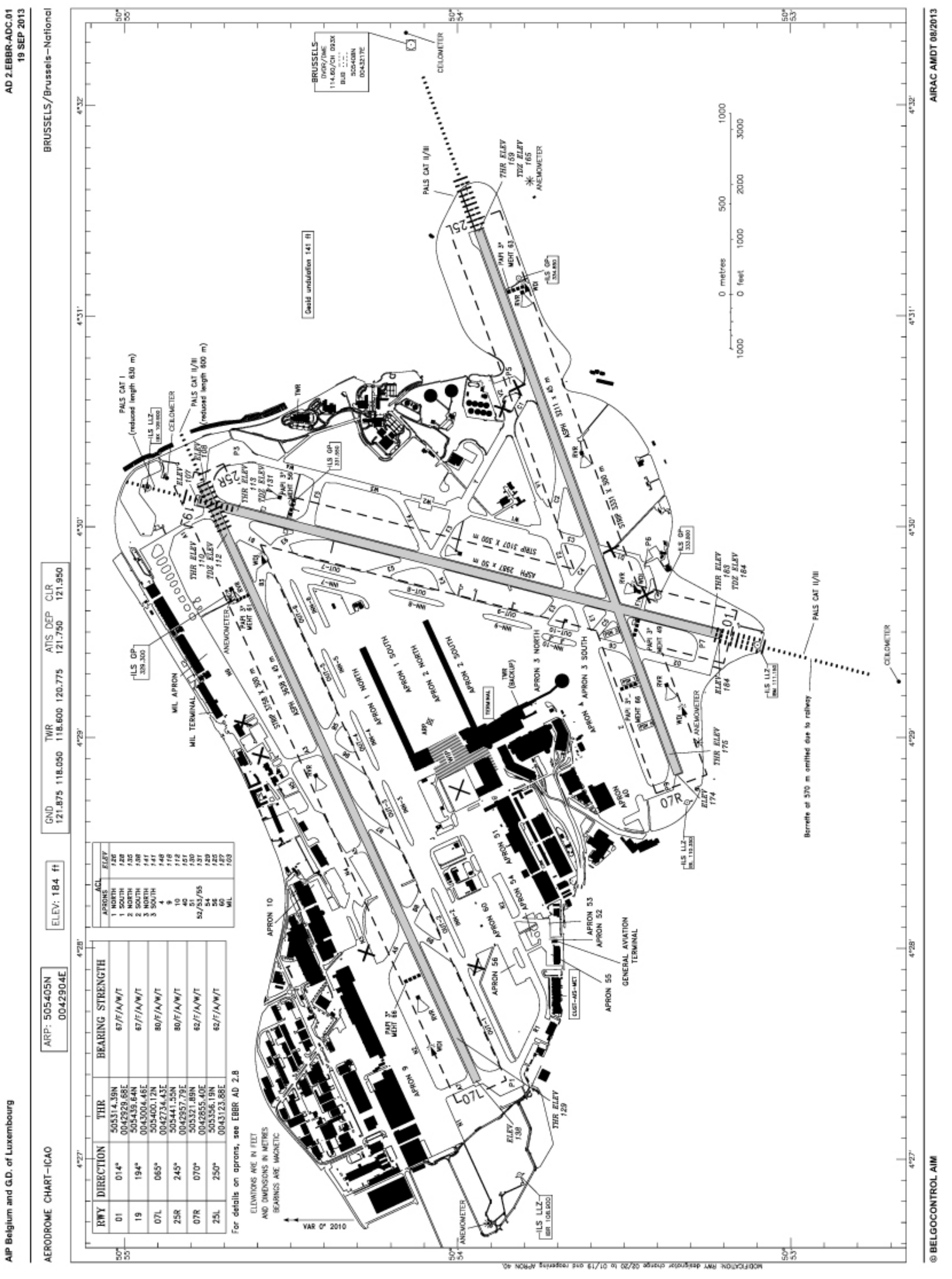


Figure B.1: Brussels-National (Zaventem) Airport chart [49]

C
Appendix

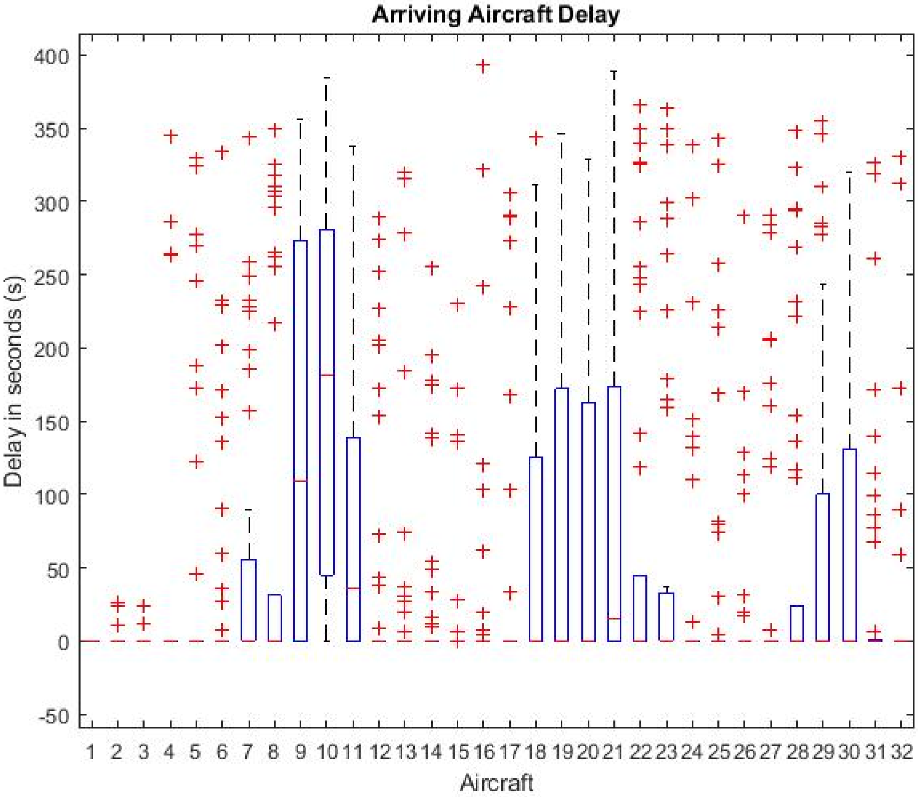


Figure C.1: Arrival delays - 4 gates - 80 min - 2 pit-stops

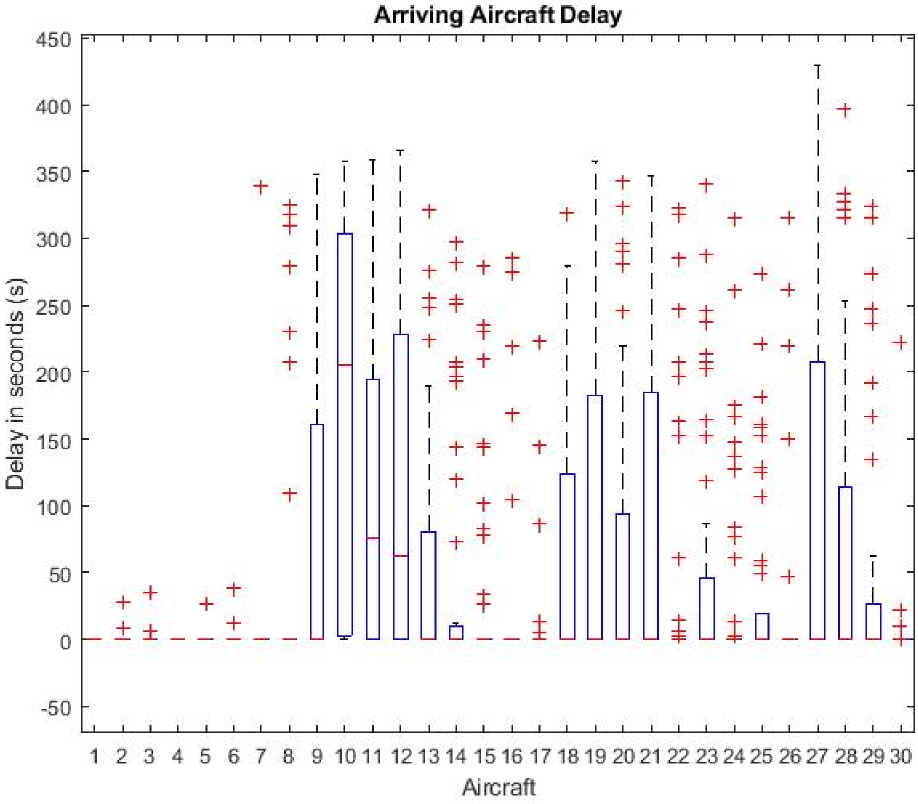


Figure C.2: Arrival delays - 4 gates - 100 min - 2 long stay flights

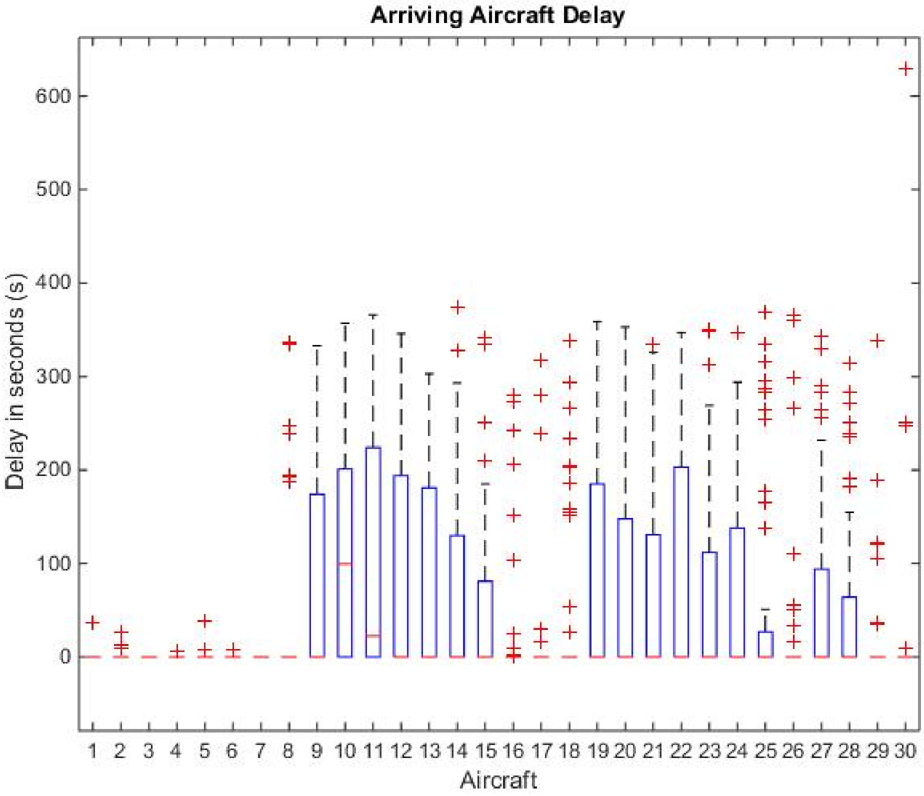


Figure C.3: Arrival delays - 4 gates - 120 min - 2 long stay flights

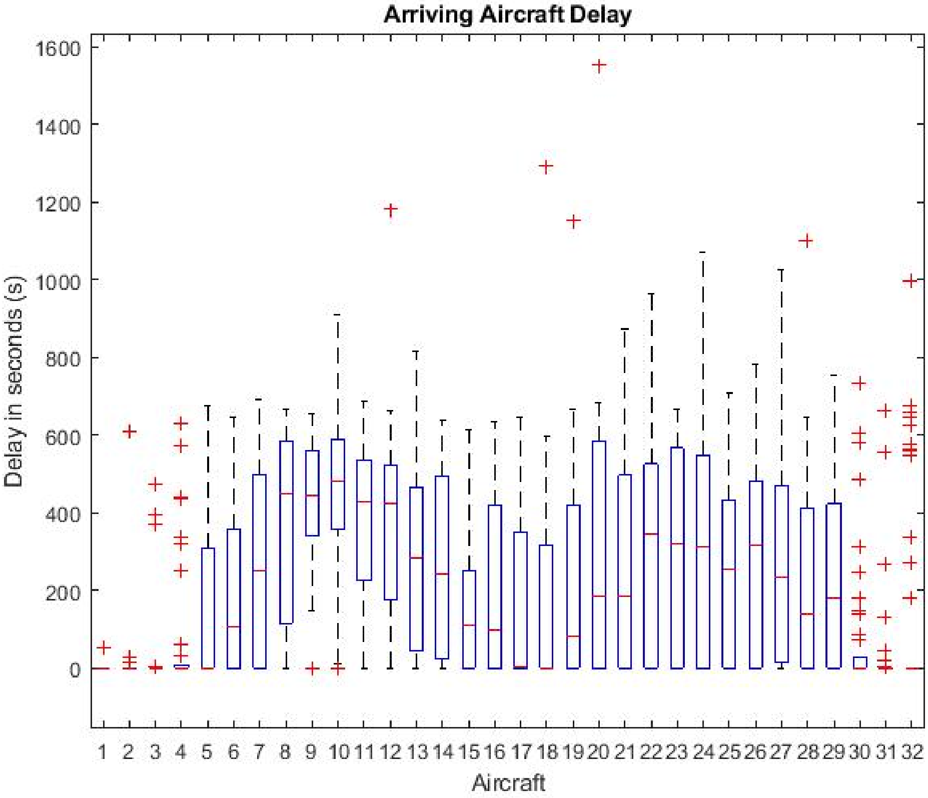


Figure C.4: Arrival delays - 6 gates - 80 min - 2 pit-stops

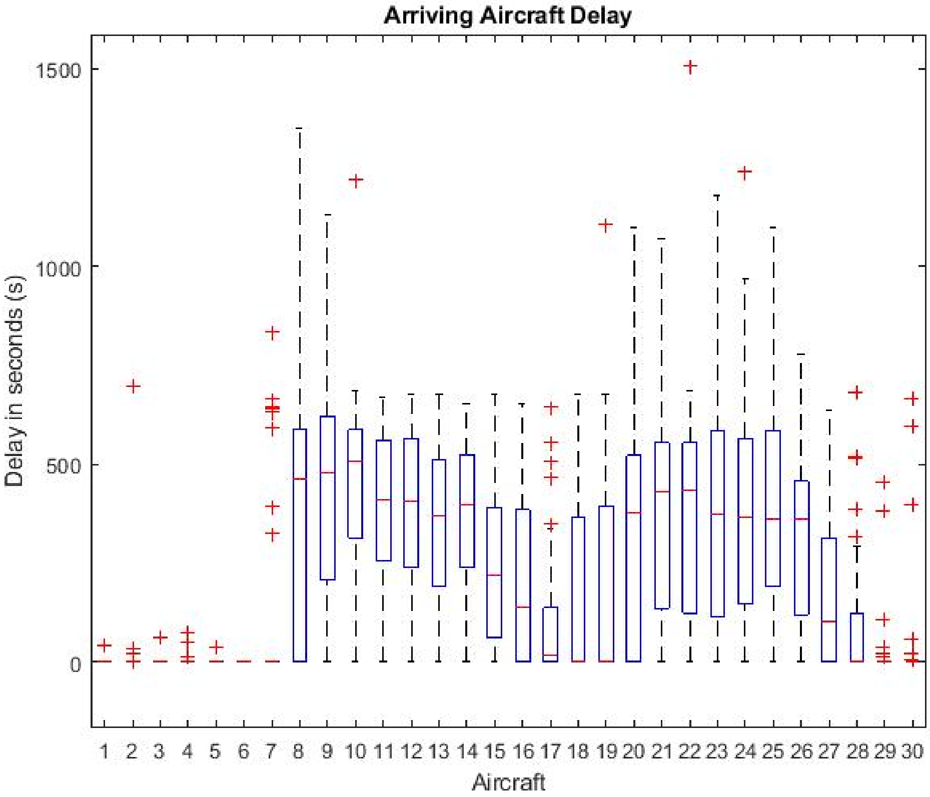


Figure C.5: Arrival delays - 6 gates - 100 min - 2 long stay flights

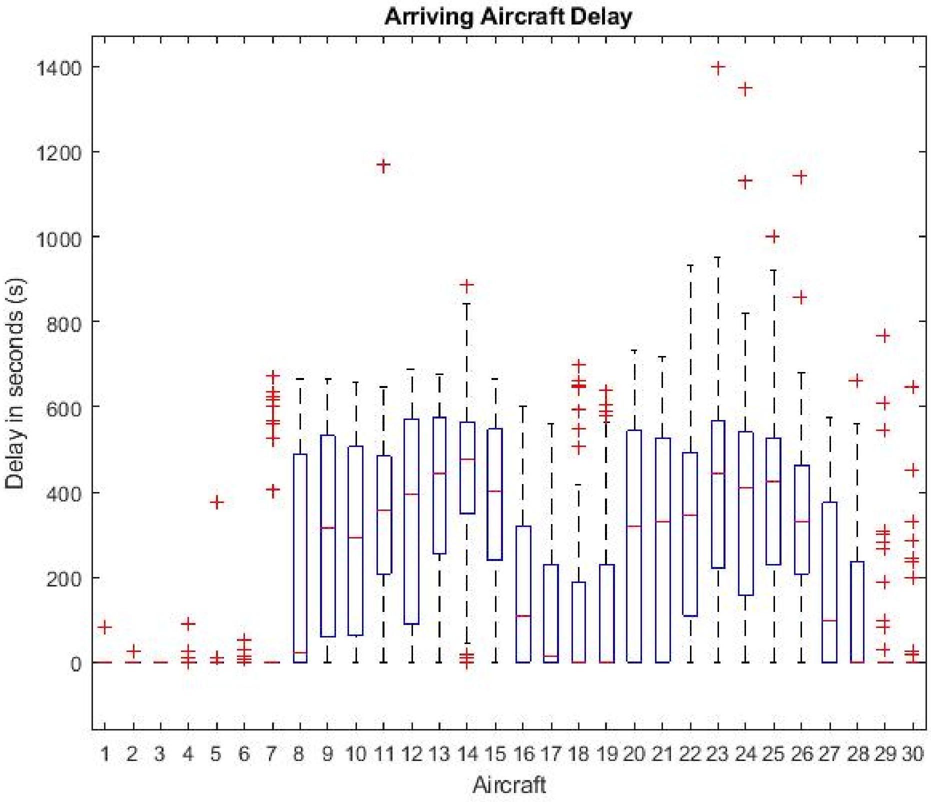


Figure C.6: Arrival delays - 6 gates - 120 min - 2 long stay flights

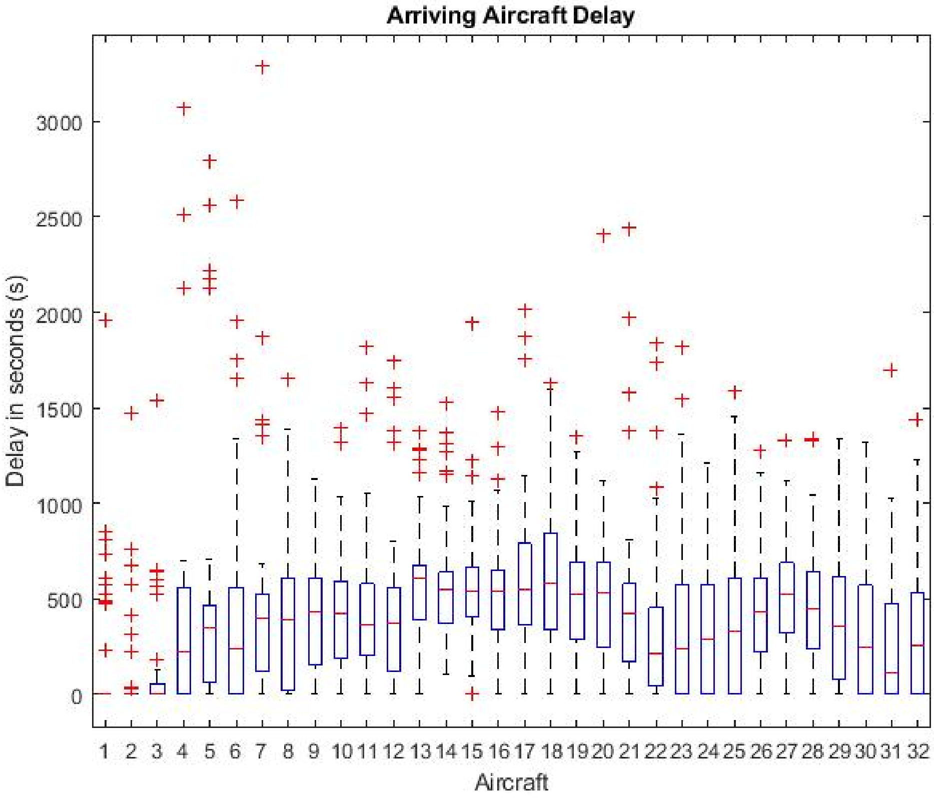


Figure C.7: Arrival delays - 8 gates - 80 min - 2 pit-stops

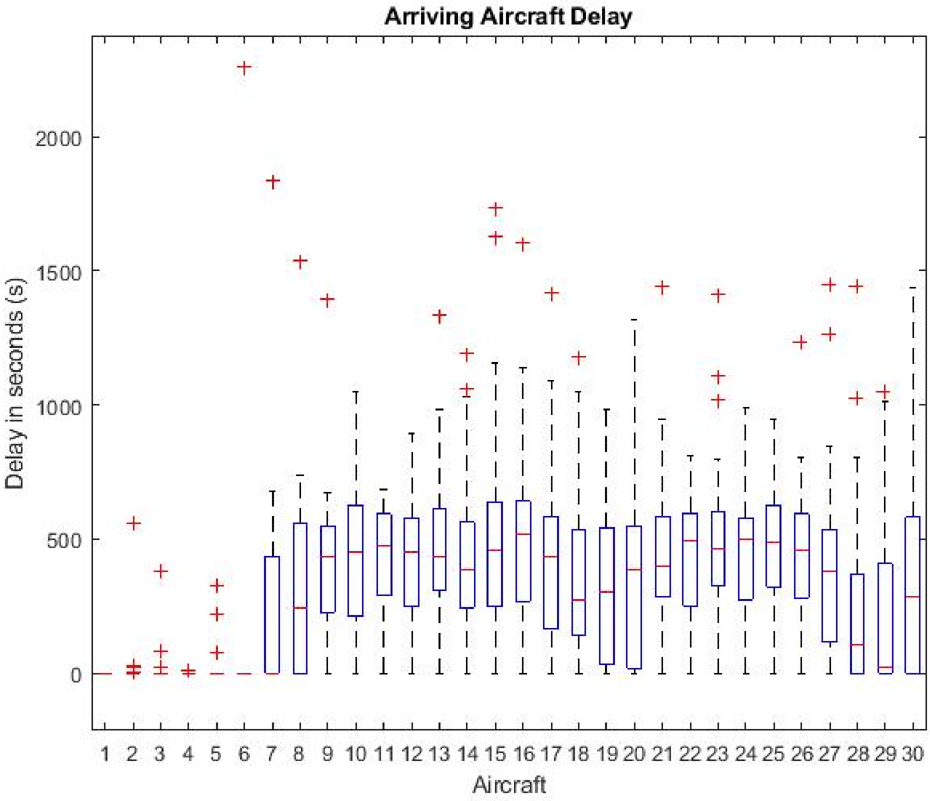


Figure C.8: Arrival delays - 8 gates - 100 min - 2 long stay flights

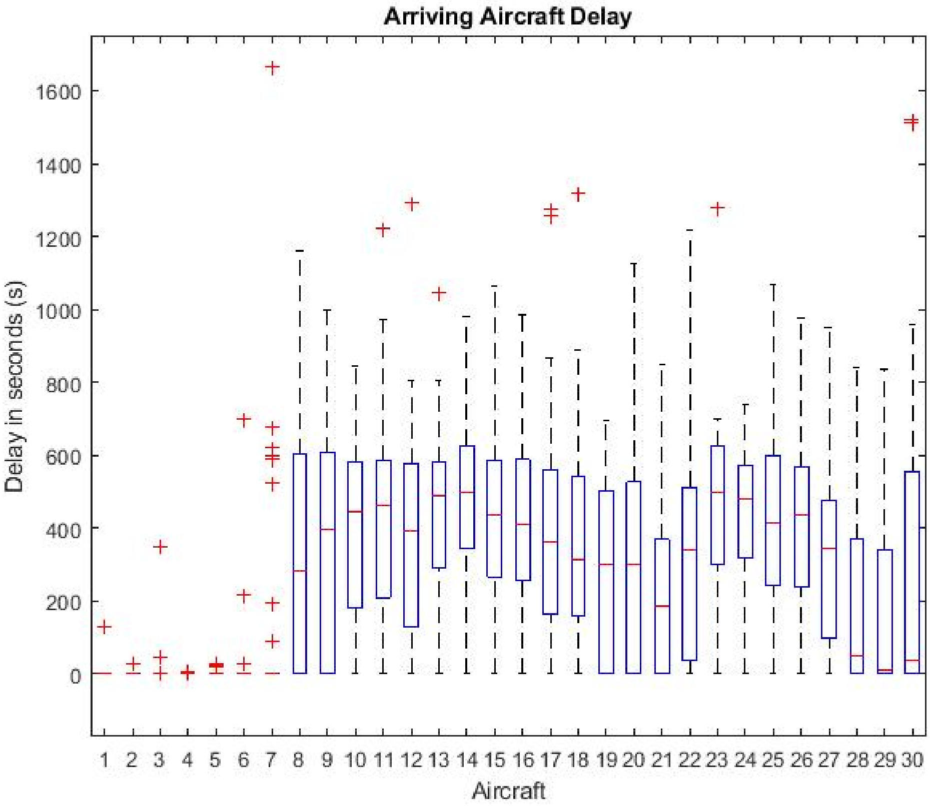


Figure C.9: Arrival delays - 8 gates - 120 min - 2 long stay flights

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