# Impact of Electric Taxi Systems on Airport Apron Operations and Gate Congestion at AAS

Msc. Thesis Study

S.M.L. Soepnel

Technische Universiteit Delft

Delft University of Technology

Challenge the future

# Impact of Electric Taxi Systems on Airport Apron Operations and Gate Congestion at AAS

## MSc. Thesis Study

by

**S.M.L. Soepnel**

in partial fulfillment of the requirements for the degree of

**Master of Science**
in Aerospace Engineering

at the Delft University of Technology,
to be defended publicly on Friday December $4^{th}$, 2015 at 15:00p.m.

| | | |
|---|---|---|
| Student number: | 1357123 | |
| Supervisors: | Ir. P.C. Roling | (TU Delft) |
| | J. Haanstra | (Schiphol Group) |
| | J. Busink | (Schiphol Group) |
| | W.J. de Wilde | (KLM Royal Dutch Airlines) |
| Thesis committee: | Prof. dr. R. Curran | (TU Delft) |
| | Ir. P.C. Roling | (TU Delft) |
| | J. Haanstra | (Schiphol Group) |
| | T.B.A. | (TU Delft) |

*This thesis is confidential and cannot be made public*



Delft University of Technology

# Preface

The world of aerospace engineering and aviation has fascinated me from a very young age. Applying for an aerospace engineering bachelors degree at the TU Delft therefore seemed a logical step to take. Throughout my bachelor, my enthusiasm for aviation, airlines, and airports grew, leading to my decision to follow a Masters in Aerospace Control and Operations. In the summer of 2014, after my internship at KLM and after completing my master courses, it was finally time choose a thesis project.

While considering potential thesis projects, this project stood out to me. During my internship at KLM I had had the opportunity to meet and talk to Wido de Wilde. He had told me he was looking into more efficient taxi systems; electric taxi systems. I remembered his enthusiasm about the topic and, therefore, this project caught my interest. I contacted the TU Delft supervisor, Paul Roling, about undertaking the project. He informed me that, since my internship, two aerospace engineering students had already started research projects on the impact and value of electric taxi systems for Schiphol and KLM. This project gave me the opportunity to continue and/or extend their research. The practical approach of the project and the ability to work on a topic of interest to both KLM and Schiphol made this project even more more appealing to me.

Schiphol was able to offer me a workspace in their main offices at the airport for the duration of this project. This has provided me with many opportunities to explore the airport operations and facilities. Even though finding my way around two large companies has been a challenge at times, it has also been a very valuable learning experience. Working on a project for KLM and Schiphol has been inspirational. It has given me the opportunity to be part of and contribute to the dynamic and innovative world of airport and airline operations.

I would like to take this opportunity to thank my supervisors for their contributions to this thesis work. I would like to thank Paul Roling for presenting me with the opportunity to undertake this project and for his continuous support and advice throughout the project. No matter how busy his schedule, every two weeks he always found the time for a meeting with me to discuss problems and progress. I would also like to thank Wido de Wilde from KLM for sharing his expertise and helping me find my way within KLM. In addition to his own feedback and knowledge on the subject of electric taxiing, his support in finding the right people to talk to and the right information within KLM has been extremely valuable to the development of the project. Furthermore, I would like to thank Jan-Otto Haanstra and Jurgen Busink for their feedback and for helping me with any questions and requests on where to find the information within Schiphol Group. They gave me the opportunity to work at Schiphol and see the ongoing operations at the airport, which has provided me with greater insight and understanding of the apron processes and has been a valuable experience. I would also like to thank Jan-Otto for taking place in my thesis assessment committee.

I would also like to thank my fellow 'SIM' students at Schiphol; Jasper, Vivian, Marnix, Justin and Nils, for their company, discussions, and lunches.

Next, I would like to thank my parents, Lilian and Niels, my sisters, Brechtje and Larske, and my brother-in-law, Michael, for their continuous love and support, not just throughout my thesis, but throughout my entire studies leading up to this project. Their unwavering encouragement, advice, and endless faith in me has helped me more than I can say. I would also like to thank my boyfriend, Peter, for his support and help every step of the way. He put up with my moments of madness and stress with admirable and reassuring calmness.

I look back on my time as a student in Delft with great pleasure. This thesis marks the end of my studies at the TU Delft and I hope the reader will enjoy reading this work.

S.M.L. Soepnel
Delft, University of Technology
28$^{th}$ of October 2015

# Executive Summary


Growth in air traffic demand and increasing attention for environmental impact of the air travel industry and airports has spurred the innovation of the Electric Taxi System (ETS).

The ETS incorporates an electric motor in the main or nose landing gear of an aircraft, powered by the auxiliary power unit (APU) of the aircraft. The system allows the aircraft to maneuver and taxi without the use of its main engines or a tow truck. Thereby, the ETS reduces fuel usage and the environmental impact during the taxi phase of flights. Additionally, the system aims to increase the gate pushback efficiency. The ETS eliminates the need for a tow truck during the pushback process as it allows for autonomous pushbacks. The studies performed on existing ETSs (the EGTS and the WheelTug systems) indicate that time can be saved with autonomous pushbacks using the ETS.

KLM Royal Dutch Airlines and Amsterdam Airport Schiphol (AAS) have instigated research to investigate the impact and potential benefits of the implementation of the ETS. This Msc. thesis research work continues the exploration of the ETS's impact at AAS by posing the following research question:

> ***What opportunities does the ETS offer for gate capacity and buffer utilization optimization, and what is the value of the impact of the ETS on apron operations at Amsterdam Airport Schiphol?***

Thus, the research attempts to draw light on the value of the ETS for operations in the apron environment. With increasing air traffic demand, the gate capacity at Schiphol Airport is nearing its maximum during the airport's peak hours. Therefore, the potential gate capacity enhancement procedures enabled by the ETS are explored in detail in this research. Additionally, the value of the ETS for the overall apron environment is investigated. The reduction in the need for tow trucks due to the ETS implementation also provides benefits for the apron environment.

However, as with any new system, the ETS presents some challenges as well. The weight of the system reduces its fuel benefits in flight. Therefore, high utilization is key for the use of the ETS. Additionally, the systems currently designed are only available for narrow body aircraft. These, and other challenges posed by the system, need to be investigated and weighed against the benefits of the system in order to determine the potential offered by the ETS and whether the system is worth investing in for airlines and airports.

This research explores the potential gate planning optimization procedures enabled by the ETS and the overall value of the ETS in the airport apron environment, through the use of a gate planning simulation model and a value model based on value operations methodology.

The ETS presents the possibility for of two gate usage optimization concepts to be implemented more widely, namely; the dispatch towing concept and the pit stop concept.

The dispatch towing concept can help prevent arrival ground delays and last minute gate changes at airports. Aircraft arriving at AAS sometimes have to wait up to 30minutes after landing in order to be able to reach an available gate because the gate is initially still occupied by another (delayed) aircraft. In some cases the aircraft still occupying the gate is fully loaded and ready for take-off, but delayed due to departure slots, en-route slots, arrival destination slots, last minute baggage loading, and/or last minute maintenance. The aircraft does not necessarily need to be occupying the gate anymore. The dispatch towing concept allows the delayed aircraft to be moved to a free buffer position in order to free up the gate for the next arriving aircraft. The concept is currently rarely applied because towing of fully loaded aircraft by tow trucks can cause structural damage to the aircraft nose landing gear. The ETS would allow for the fully loaded aircraft to be moved to a buffer position without causing structural damage.

The pit stop concept implies that arriving aircraft park at a gate in order to offload passengers and baggage. Subsequently, the aircraft moves to a free buffer for handling and turnaround services, after which the aircraft moves back to a gate for passenger and baggage loading. Therefore, the aircraft is only occupying a gate area when strictly necessary; loading and offloading of passengers. This opens up the gate for other flights to be handled during the turn around time of the pit stop aircraft on the buffer. In order to perform a pit stop, a narrow body aircraft needs a minimum turn around time of 170minutes.

The gate planning models designed in this research explore the potential of the implementation of the pit stop and dispatch towing concepts at AAS. Initially, a gate planning model is designed to graphically present the narrow body gate and buffer plan in gantt chart format. In doing so the gate and buffer planning schedule for the busiest day at AAS in 2014 is visualized. The pit stop and dispatch towing concepts are then applied to the schedule where possible.

From the visualization of the gate plans with and without the ETS enabled concepts, it can be concluded that the pit stop concept increases gate capacity at AAS by approximately six additionally aircraft on the busiest day at the airport in 2014. Furthermore, the dipatch towing concept increases gate planning efficiency and reduces ground arrival delays for six arriving aircraft on the busiest day at the airport in 2014.

The gate planning model is subsequently expanded in order to explore the effect of increased traffic and delays on the gate planning at AAS, and the usage of pit stops and dispatch towing to help increase gate capacity and solve delay conflicts, respectively.

From the extended model it becomes apparent that should the number of peak hour flights at AAS increase by 10%, and average of 25% of the additional flights can be scheduled at a gate using the pit stop concept. Should the number of peak hour flights double, an average of 8.8% of the additional peak hour flights (corresponding to 12 flights) can be scheduled using the pit stop concept.

Furthermore, the model shows that, between 10% and 12% of the ground delays caused by delayed peak hour flights at the gates can be solved through the implementation of dispatch towing. This results in an average of 17.2minutes saved for nearly 50% of the arriving delayed flights.

The gate planning models have indicated the potential of the pit stop and dispatch towing concepts enabled by the ETS for gate planning efficiency and capacity at AAS. However, the implementation of the ETS influences many key performance indicators (KPIs) of the apron area. In order to explore the value of the ETS on the apron area, a value model is developed. The value model is based on the value operations methodology (VOM). In the VOM, stakeholder values are investigated and weighed for importance in order to determine whether a design (or in this case the ETS) adds or reduces value for the environment in question (in this case the apron area).

The main stakeholders involved in the implementation of the ETS are KLM and AAS. Based on these stakeholders, four main KPIs or objectives are identified for the apron area, namely; Safety, capacity/efficiency, costs, and the environment.

The attributes of the ETS influencing the four identified objectives are explored in detail and assessed qualitatively as well as quantitatively where possible. Each attribute pertaining to an objective is weighed against the other attributes pertaining to that objective for importance. Finally, each objective in the model is also assigned a weight according to its importance to the value of the apron environment.

Apron area safety was identified is the most important objective for the stakeholders. The ETS increases the apron area and overall airport safety by reducing (and eventually eliminating) the need for tow trucks. This reduces the number of two truck incidents as well as the amount of foreign object damage (FOD). Additionally, the pushback safety may be increased by increasing the communication chain efficiency during the pushback process. However, autonomous pushbacks present a serious situational awareness problem for pilots. When navigating the aircraft backwards, pilots need the assistance of a marshaller or additional technology to help them avoid objects behind the aircraft or next to the aircraft.

The capacity and efficiency objective can be enhanced by the ETS through the implementation of pit stops and dispatch towing. Additionally, the system reduces the pushback time by up to 1minute and 50seconds.

Operational costs are also influenced by the ETS. Due to the reduction in the use (or elimination) of tow trucks, the tow truck maintenance, fuel, and personnel costs can be reduced. Furthermore, FOD and collision costs can be reduced and, through the implementation of dispatch towing, delay costs can also be avoided. It should be noted, however, that the APU and ETS maintenance costs will increase due to the extra load of the ETS. It is estimated that the ETS and APU maintenance costs amount to 15,000$/year.

The ETS also influences the airport environment. During the ETS pushback, fuel can be saved through the elimination of tow trucks. Additionally, noise on the apron is reduced to only APU noise, as opposed to APU and engine idle noise. The dispatch towing concept also allows for a reduction in fuel usage and, subsequently, emissions by reducing the time arriving aircraft need to wait with their engines still running. Due to the extra maneuvering necessary for the pit stop concept, fuel usage is increased slightly, though not as significantly as when the concept is applied with the use of tow trucks to maneuver the aircraft.
The qualitative and quantitative attribute results for the value model are shown in table 1.

| Objective: Safety | Qualitative Analysis Attribute Score | | Quantitative Analysis Attribute Score | |
|---|---|---|---|---|
| | Initial | Potential (long term) | Initial | Potential (long term) |
| Elimination Tow Truck incidents | - | - - - | -3 incidents/month | -16 incidents/month |
| Communication Efficiency | 0 | ++ | N/A | N/A |
| Situational Awareness | - - | 0 | N/A | N/A |
| **Objective: Capacity, Efficiency** | | | | |
| Pit Stops | + + + | + + + | 6 gate slots/day<br><br>Peak hour traffic increase of 10%:<br>3 additional peak hour flights | See initial impact |
| Dispatch Towing | + + + | + + + | Avg 17.2min time saved per delayed AC<br><br>10.8% peak hour flight delay conflicts solved | see initial impact |
| Pushback Time reduction | - - | - - | -1:50 min/pushback | see initial impact |
| **Costs** | | | | |
| Tow Truck Maintenance and fuel costs | - - | - - - | -978,549.-$/yr | -4,595,786.-$/yr |
| Personnel Costs | - - | - - | -163,520.-$/yr | -490,560.-$/yr |
| FOD costs | - | - | Unknown | -32,730.-$/yr |
| Ground delay costs | - | - - | -516$ per peak hour dispatch tow | see initial impact. More dispatch tows possible if more aircraft have an ETS |
| ETS and APU maintenance costs | + | + | 15,000.-$/year | see initial impact |
| **Emissions** | | | | |
| Pit Stop Extra Fuel usage | ++ | ++ | Extra Fuel used: 260.4kg<br>Fuel costs: 198.9$<br>per 6 pit stops: 12 extra taxi movements | See initial impact |
| Dispatch Towing Fuel saving | - - | - | Fuel saved: 80kg<br>Fuel costs: 61.10$<br>per dispatch tow | Fuel saved: 13kg<br>Fuel costs: 9.93$<br>per dispatch tow |
| Pushback Fuel Saving | - - | - - | Fuel saved: 9,227kg<br>Fuel costs: 7,046.50$<br>per year | See initial impact |
| Apron Noise Reduction | - - | - - | -69% | see initial impact |

Table 1: Value model objective: Emissions. Overview of objective attribute scores.

The value model qualitative assessment indicates that the ETS can enhance the safety, capacity, and efficiency of the airport apron environment, while reducing the costs and environmental impact of the apron area operations. The results of the models and the research performed can be further analyzed and developed by KLM and AAS in order to assist in the development of electric taxi systems and, eventually, enhance their competitive position within the aviation industry.

# List of Abbreviations

| | |
|---|---|
| *AAS* | Amsterdam Airport Schiphol |
| *ACMS* | Aircraft Condition Monitoring System |
| *AIBT* | Actual In Block Time |
| *ALDT* | Actual Landing Time |
| *AOBT* | Actual Off Block Time |
| *APU* | Auxiliary power unit |
| *ATC* | Air Traffic Control |
| *ATCo* | Air traffic controller |
| *CDM* | Collaborative Decision Making |
| *ECDT* | Engine Cool Down Time |
| *EGTS* | Electronic Green Taxi System |
| *ESUT* | Estimated Engine Start-Up Time |
| *ETS* | Electronic Taxi System |
| *FAA* | International Civil Aviation Organization |
| *FOD* | Foreign Object Damage |
| *ICAO* | International Civil Aviation Organization |
| *KLM* | Royal Dutch Airlines |
| *KPI* | Key Performance Indicator |
| *LVNL* | Luchtverkeersleiding Nederland (Dutch Air Traffic Control) |
| *MLG* | Main Landing Gear |
| *MoU* | Memorandum of Understanding |
| *MTOW* | Maximum Take-off Weight |
| *MTT* | Minimum Turnaround Time |
| *NLG* | Nose Landing Gear |
| *SOP* | Standard Operating Procedures |
| *TAAM* | Total Airspace and Airport Modeler |
| *TOBT* | Target Off Block Time |
| *TSAT* | Target Start-up Approval Time |
| *TTOT* | Target Take-off Time |
| *VDD* | Value Driven Design |

# Contents

# List of Figures

# List of Tables

# 1 Introduction

In 2014, Amsterdam Airport Schiphol (AAS), one of Europe's largest and busiest airports, handled 438,296 flights and 54,978,023 passengers. This is a 3% increase in the number of flight movements and a 4.6% increase in the number of passengers compared to 2013[10]. The first six months of 2015 have shown a continuation of this trend with another 3% increase in flights handled and a 5% increase in number of passengers handled in comparison to the same period in 2014[10]. Moreover, this growth in air traffic is expected to continue, or even increase, over the next decades [11].

Due to this air traffic growth, delays, congestion, and environmental problems at airports are becoming a major concern for airport operators as well as airlines. Capacity at AAS is already nearing its maximum especially during peak hours, not just for runway and airspace usage, but also for the apron and gate/ramp infrastructure. As such, the past years have shown much research dedicated to the development of new tools, systems, and procedures that will increase efficiency, capacity, and sustainability of airports and airlines [12][13].

One such system currently under development is the Electric Taxi System (ETS)[8][14][15]. The main purpose of the system is twofold: to increase the efficiency of the overall pushback and taxi processes, and to decrease the fuel usage and environmental impact of the ground-phase of a flight. Thus, both airlines and airports could potentially benefit from the implementation of such a system.

As the name suggests, the electric taxi system is designed to allow an aircraft to maneuver and taxi using electrically powered motors[8][14]. Conventionally, when an aircraft moves on the ground, it is either towed by a tow-truck or it taxis using the power from its main engines. Using the aircraft's main engines is not environmentally friendly or fuel efficient. Using a tow truck is more environmentally friendly but not time efficient. The Electric Taxi Systems allow aircraft to maneuver with limited fuel usage and also provide the opportunity for autonomous or more efficient pushback maneuvers[8][14]. Recently developed ETSs use the existing aircraft auxiliary power unit (APU) to provide power to electric motors attached to either the nose landing gear or main landing gear of the aircraft[8][14]. With the ETS, the pushback, apron, and taxiing procedures could be significantly improved.

This study will focus on the impact of the ETS on the apron operations and gate capacity at AAS. The airport apron and gate area operations form an intricate part of the overall airport operation and flight process. Congestion and delays at the airport apron and gates have a 'snowball-effect' on the overall flight and airport schedules. As such, efficient apron operations and gate planning are of the utmost importance for both airports and airlines. Additionally, environmental awareness is increasing and, consequently, environmentally friendly systems/procedures are becoming exceedingly important for ground operations as well. The ETS offers opportunities for improvement in both efficiency and environmental factors of ground operations.

However, the implementation of an ETS also presents some drawbacks and challenges. Especially in terms of the additional weight of the system on the aircraft. Airlines and aircraft designers have put effort into reducing the weight of aircraft in order to minimize the fuel usage of the aircraft during the flight. This effort has been met with some success but the implementation of an ETS would have the opposite effect as it implies additional weight added and, consequently, a fuel penalty for the flight [7]. This fuel penalty, caused by the additional weight of the system, needs to be weighed against the benefits of the ETS to determine whether the ETS should be implemented. According to the initial research performed by Chris Wijnterp [7], utilization of the ETS system has the a large impact on the added value of the system for airlines. He suggests that with a higher ETS utilization, the benefits of the system will begin to outweigh the costs. Thus, any procedures increasing the ETS utilization could potentially prove beneficial.

On the ground, the ETSs currently available also present some limitations. Even though the ETS offers a more fuel efficient and environmentally friendly way of maneuvering aircraft, the system does have some speed limitations that could have an effect on other taxiing aircraft [16].

Furthermore, other operational and procedural challenges posed by the implementation of the ETS and ETS procedures, need to be investigated and identified to make a justified decision about whether or not the ETS should be implemented. In other words; will the benefits of the ETS on gate utilization and apron operations help the costs?

To help answer this question, this research thesis report discusses the gate planning and capacity enhancement possibilities offered by the implementation of the ETS. Furthermore, the study explores the value of the ETS for airport apron operations at AAS through the use of a value model.

## 1.1. REPORT LAYOUT

The report set-up to follow the Msc. research development. In the following sections (sections 1.2, 1.2.1, and 1.2.2), the structuring of the project and the project aims are outlined. The sections function as a more in-depth analysis of the research and problem at hand.

Once the goal of the project has been established, chapter 2 provides a concise overview of the background information and literature available pertaining to the research topic and ETS. For a more elaborate overview of the literature relating to the project please refer to the literature study relating to this Msc. Thesis.

Chapter 3 focuses on the current gate capacity and gate planning situation at AAS. The gate planning problem is defined and possible solution models are discussed. Subsequently, a capacity analysis for the narrow body gates and piers at AAS is performed, and the pit stop and dispatch towing concepts, enabled by the use of ETSs, are introduced.

Chapter 4 elaborates on the gate planning model designed in order to assess the current gate and buffer planning situation at AAS and shed light on the possibility of implementing the pit stop and dispatch towing concepts to enhance the gate capacity and efficiency at AAS.

Based on the model described in chapter 4, chapter 5 then presents the initial results obtained from the model. The initial results are subsequently analyzed leading to the development of a more extensive concept analysis model. This more extensive model is presented in chapter 6, along with the extensive model results and an analysis of those results.

After evaluation the possible impact of the ETS on gate capacity and planning, a value model is developed to further assess the impact of the ETS on the overall apron environment. The development of this value model is presented in chapter 7. The objectives and attributes pertaining to the ETS apron operations value model are discussed and analyzed in chapter 8. Furthermore, chapter 8 presents the value model outcome.

Finally, chapter 9 presents the research and project conclusions. Additionally, some recommendations for further research and development on the project topic are discussed.

## 1.2. PROJECT SET-UP

The following section elaborates on the research questions and the project goals defined in order to fill the gap in the current research on the ETS impact. First, the main research question and sub-questions are formulated to provide a global perspective of the problems at hand and to identify the main areas for improvement. Afterwards, the project goal is presented. The project is set-up such that the answers to the research questions will lead to the fulfillment of the project goal.

This MSc.Thesis project will be carried out in cooperation with Amsterdam Airport Schiphol and Royal Dutch Airlines KLM. Therefore, some sections of the study will be related specifically to these companies. However, it should be noted that many of the concepts and strategies used and presented in this Msc. research thesis can be applied to other airports and airlines as well.

### 1.2.1. RESEARCH QUESTIONS

The following main research question is formulated:

> ***What opportunities does the ETS offer for gate capacity and buffer utilization optimization, and what is the value of the impact of the ETS on apron operations at Amsterdam Airport Schiphol?***

To answer this main question, some subquestions are defined. Together, the answers to the subquestions lead to the answer of the main research question. The subquestions have been divided according to the main topics of the study.

***What system characteristics and existing operational procedures can be defined?***

- Which electric taxi systems are currently available for testing?
- What are the relevant characteristics/features of these ETSs?
- Which apron and gate procedures are in place at AAS?
- What are the constraints of the apron/gate procedures and what bottlenecks can be defined?
- What data is available regarding gate capacity and congestion at AAS?
- What data and statistics are available regarding apron movement?

***Which of the apron procedures would be affected by the implementation of an ETS and how will they be affected?***

- Which stakeholders are involved in the optimization of apron operations and the implementation of an ETS?
- Which important apron KPIs are involved with the implementation of an ETS and to which stakeholder do they relate?
- What are the areas for improvement in the current operations and how can the ETS affect these areas?
- How, and to what extent, will the implementation of the ETS have an effect on the KPIs involved?

***Which gate utilization optimization procedures and concepts can be implemented (more efficiently) through the use of ETS?***

- Why are these concepts/strategies currently (often) not used?
- How can the concepts potentially improve or enhance gate capacity and buffer utilization at AAS?
- To what extent can these procedures influence the gate capacity at schiphol?
- Which other KPIs are influenced by the procedures/concepts?

***How can the gate assignment procedures, for passenger aircraft at AAS, be modeled in order to quantitatively asses the impact of the implementation of electric taxi system (ETS) concepts on apron operations at Amsterdam Airport Schiphol?***

- How does the gate planning model at AAS work?
  - What constraints does this model work with?
  - What assumptions does the model make?
  - What are the main limitations of the model?
  - Which features of the existing model need to be changed to incorporate the ETS?
- How can a similar model be set-up in order to incorporate the ETS possibilities?
  - What data is needed in order to gain the most accurate model results?
  - What constraints does this model work with?
  - What assumptions does the model make?
  - What are the main limitations of the model?
  - how can the model be extended to include increased traffic scenarios?
  - How can the model be extended to include delays?
- How can the gate planning simulation model be used to draw comparisons between situations in which the ETS is used and situations in which the system in not used?
- What conclusions can be drawn from this comparison?

***How can a value model help to quantify the impact of the ETS on apron operations?***

- Which KPI attributes can be defined that will be affected by the ETS?
- How can these attributes be assigned weights?
- Which experts need to be consulted to define the attribute weights?
- How can constructed attributes be quantified?
- How accurate is the value model?
- What conclusions regarding the ETS can be made from the value model?

***What are the main findings of the simulation and value models?***

- What are the main benefits of the ETS for apron operations?
- What are the main challenges of the ETS for apron operations?

***How can the ETS be best utilized in the apron environment?***

### 1.2.2. PROJECT GOALS

The main objective of this Msc. Thesis project is to: ***explore and analyze the possibilities for apron gate congestion relief through the use of Electric Taxi Systems (ETS), as well as to identify and quantify the influence of the system on the apron operations for narrow body passenger aircraft at Amsterdam Airport Schiphol***. This is done through the development of a gate planning simulation model and a value model. As such, the project aims to shed light on the value of the ETSs for AAS and KLM.

The following sub-goals have been identified:

- Identify the beneficial gate allocation procedures that can be implemented with the use of the ETS at AAS.
- Explore the possibilities for these gate utilization optimization procedures through the development of a gate planning simulation model.
- Develop a value model from which the effect of the ETS on the overall apron performance can be quantified.
- Asses the impact of the ETS benefits and challenges on the airport and airline KPIs.
- Determine to what extent the ETS and ETS procedural possibilities can help alleviate gate congestion if traffic increases and/or schedule disturbances occur.

It should be noted that, due to the characteristics of the ETSs currently available (see section 2.1), the focus of the research will be on narrow body commercial passenger aircraft only. Once the ETS becomes available for wide body aircraft, the concepts presented in this research can be expanded to include these aircraft as well (for further information on this topic please refer to section 9.2).

# 2
# Background Information and Literature

In order to scope the problem at hand, the most important background information and literature pertaining to the project is presented and discussed in this chapter.
In order to assess the impact an ETS might have on the airport apron, the currently available electric taxi systems and their characteristics are discussed in Section 2.1. Section 2.2 introduces the concept of value driven decision making and provides the background theory to the value engineering concept. The Amsterdam Airport Schiphol apron design and pushback operational procedures in place are presented and discussed in section 2.3.

## 2.1. Electric Taxi Systems (ETS)

The past few years have shown significant development in electric taxi systems for commercial passenger aircraft, especially for narrow-body aircraft [17]. The three main systems under development include: the TaxiBot, the Electric Green Taxi System (EGTS), and the WheelTug. Each system offers the opportunity for reduction in fuel usage during the taxiing and pushback phases, leading to improvements with regards to emissions and noise pollution. However, some major design and operational differences between the systems leads to variations in possible benefits and challenges posed by the use of each system.

In this chapter, the three electric taxi systems are presented, discussed, and compared, based on the available research and literature.

### 2.1.1. TaxiBot

Of the three main systems, TaxiBot is the only one that is not actually integrated into the aircraft landing gear system or connected to the aircraft APU. Instead, TaxiBot functions as an external ground system [18] which is attached to the nose wheel strut of the aircraft and can be controlled by a TaxiBot driver (for pushback), as well as the pilot (for taxiing). After pushback, the TaxiBot system tows the aircraft, under control of the pilot, to the take-off runway, after which the TaxiBot is detached from the aircraft [15]. The TaxiBot system allows the pilot to steer the aircraft with existing cockpit controls. Additionally, the system uses the aircraft brakes for speed control thereby, eliminating the issue of nose landing gear fatigue experienced by conventional tow trucks over long distances. [18]

One of the main advantages of the TaxiBot system as opposed to the EGTS and WheelTug systems, is that the TaxiBot is detached from the aircraft after taxiing thus, the no additional weight is added to the aircraft during flight[15]. The TaxiBot can be attached to an aircraft without major adjustments to the aircraft (similar to a conventional tow truck). Additionally, the system can be used on wide-body aircraft as well as narrow-body aricraft, where the EGTS and WheelTug systems have thus far been designed for narrow-body aircraft only [19].
However, for airport apron and pushback operations, the TaxiBot offers only a few advantages in comparison to conventional taxi procedures. Furthermore, besides the taxi distance to or from the Polderbaan (runway 18R/36L, see appendix A), taxi distances at AAS are quite short. Therefore, research performed by KLM at AAS showed that the return on investment of the TaxiBot system would be too low to justify its implementation [19]. As such, this research will henceforth focus on the other two main electric taxi systems: the WheelTug and the EGTS.

### 2.1.2. ELECTRIC GREEN TAXI SYSTEM

The Electric Green Taxi System (EGTS) incorporates electric motors attached to the wheels of the main landing gear (MLG) in order to power and steer the aircraft from the cockpit without the use of the main engines[8]. The EGTS was developed as a joint venture between Honeywell and Safran. In a press release in 2011, the companies state that they expect the system to be installed on new and existing aircraft from 2016 onwards [20]. At the Paris and Dubai Airshow in 2013, the EGTS system was successfully demonstrated and at the end of 2013 a MoU (Memorandum of Understanding) was signed with Airbus to develop the EGTS for the A320 family [21][8].

The EGTS system makes use of the aircraft APU (auxiliary power unit) to provide power to operate the two 50kW electric engines attached to the outer right and left wheels of the MLG [22][7]. The engines are located at the back of the wheels, as shown in figure 2.1, such that they do not interfere with the breaking system and are exposed to enough air to allow them to cool properly. The EGTS was designed to be able to reach a taxi velocity of 18knts(at MTOW) in 90 seconds [22]. This acceleration is achieved by placing the engines at the MLG (as opposed to the NLG) which provides better traction[19]. On a slope of 1.5%, the taxi speed is reduced to 8.6knots but the engines are still able to provide enough breakaway torque for the aircraft to accelerate from stand-still[19]. However, for the purpose of this research the taxi characteristics will not be discussed in detail. Instead, the focus will remain on the pushback and apron operations.

Figure 2.1: EGTS motor [1]

The EGTS was designed to be implemented on narrow-body aircraft. Currently, the implementation of the EGTS on wide-body aircraft is not yet feasible or profitable for two main reasons.

Firstly, due to the weight of wide-body aircraft, the amount of power required by the EGTS may present problems with the amount of power deliverable from the aircraft's APU [19]. This problem might be mitigated as wide-body aircraft are designed to become more electrically powered (such as on the Boeing-787), thereby increasing the power deliverable by the APU.

Secondly, the utilization of the ETS for wide-body aircraft is much lower because wide-body aircraft are usually used for long-haul flights. The weight of the EGTS is carried over long flight distances with the aircraft and the system is only used for a relatively short time at the airport. Thus, the system is not yet profitable to use on wide-body aircraft [7].

Adjustments to the APU might even be necessary for the narrow-body aircraft in order to provide the required power to the engines. Additionally, the system is primarily designated for short- to medium-haul flights. As explained by wollenheit, "the cruise phases are shorter and the taxi phases represent a larger share in total utilization" (wollenheit, 2013[17]). Thus, installation of the EGTS on short- to medium-haul flights will yield the most benefits as the system utilization will be higher than for long-haul flights[23][17].

However, the EGTS does have some drawbacks. Unlike the TaxiBot system presented in the previous section (section 2.1.1), the EGTS remains attached to the aircraft even after pushback and taxiing. This means that the additional weight of the system has to be carried by the aircraft during the flight. The additional

weight causes an increase in fuel consumption during the flight. The weight of the EGTS system is estimated at 400kg[7].
The following system specifications are noted (also see table 2.1):

- 4% savings on total block fuel consumption.
- 50% $NO_x$, 60% $CO$, 75% $CO_2$ reduction compared to dual engine taxi operations.
- Reduced pushback time by up to 60% (1:15min vs. 3min normal pushback).

### 2.1.3. WHEELTUG

The WheelTug system is an electric taxi system which has been integrated into the nose landing gear (NLG) of the aircraft (as opposed to the MLG used by the EGTS). The development of the WheelTug was done in cooperation with Chorus Motors and was kick-started in 2005 with a proof of concept (in cooperation with Boeing and Chorus Motors)[14]. Since 2005, the system has been developed by the WheelTug Corporation and in 2012 an in-wheel motor design ground test was performed.

The WheelTug system is based on the same principles as the EGTS: the aircraft can be autonomously maneuvered through the use of electric engines attached to the aircraft wheels. The chorus engines used by the WheelTug system are asynchronous. This, in combination with the location of the engines at the NLG (where there is less down force than at the MLG), causes the WheelTug system to have less favorable acceleration characteristics when compared to the EGTS [19].

The WheelTug system was designed for use on narrow-body aircraft [19] and specifically for short- to medium-haul flights [18], similar to the EGTS system. The WheelTug system is estimated to weigh 140kg [19]. This weight is based only on the weight of the WheelTug motor (no wiring, controls, or attachment systems). The total weight of the WheelTug system is unknown.

WheelTug has also introduced a new maneuver to allow for a more speedy embarking and disembarking process at the gates. This maneuver is referred to as 'Twist'. The nose wheel steering and WheelTug system will allow for the aircraft to be turned (or twisted) sideways along the gates allowing for bridges to reach two aircraft doors instead of just one (as is conventionally done with nose-in parking). WheelTug suggests that the use of two doors for passenger embarking and disembarking will result in a faster boarding process and increase customer satisfaction.[14]. However, the twist maneuver would require more space along the terminal building per aircraft and no studies have yet been performed to validate or verify the value of the maneuver.

### 2.1.4. EGTS VERSUS WHEELTUG

Table 2.1 below, provides an overview of the system characteristics and predicted savings for both the EGTS and WheelTug system.
From the data presented in table 2.1 it becomes apparent that both systems show promising characteristics. For the purpose of this project, a focus will be laid on the EGTS system. The EGTS systems shows the most promising new developments and contacts with Honeywell and Safran have already been made by KLM and Schiphol.

| | EGTS | WheelTug |
|---|---|---|
| Availability | 75% overall system availability<br>95% autonomous pushback availability[7] | 95% predicted availability (not yet widely tested)[7] |
| Weight | 400kg [19] | 140kg[19] |
| Maximum speed | 20 knots[7] | 7-10knots [18] |
| Predicted fuel consumption saving | 500kg/hr during taxiing[24]<br>4% savings of total block fuel [8] | 21 lbs/min (571.5 kg/hr) during taxiing |
| emission reduction (compared to dual engine operation) | 50% $NO_x$<br>60% $CO$<br>75% $CO_2$ [8] | estimations:<br>$\sim 66\% NO_x$<br>$\sim 65-78\% CO$<br>$\sim 66\% CO_2$ [25] |
| Predicted time saving | Pushback: 60% (1:15min vs. 3min normal pushback) [8] | Pushback:~ 78% (3.5min time saving assuming a normal pushback time of 4.5 min)[14] |
| Predicted savings | Time and fuel savings per aircraft/yr: US$23.000 [8]<br>(EGTS does not provide a total system savings per aircraft/yr) | Total savings per aircraft/yr: US$500.000[14]<br>(including fuel, emissions, maintenance, time) |

Table 2.1: EGTS versus WheelTug Characteristics

## 2.2. VALUE DRIVEN DESIGN AND DECISION MAKING

The idea of value driven designs and decision making is based on the concept of value engineering which was first introduced as a methodology by Lawrence D. Miles in 1945 [26]. Since Miles' introduction, the value engineering methodology has been further exploited to allow for the development and rating of new designs. The value engineering methodology is based on assigning weights and scores to different design criterion in order to asses each design option. However, the results are usually qualitative and the accuracy of the results depends highly on the on the ability to estimate the criteria scores and weights [26]. From this basis of value engineering, the concept of Value Focused Thinking (VFT) evolved. In 1988, Ralph L. Keeney [27] presented research on the use of values as a basis for decision-making and design development [27]. Conventionally, alternatives are often used as the basis for decision-making in projects and design development. Keeney poses that in doing so, many of the values upon which the project/design is based, are not fully met or even identified. Instead, Keeney proposes starting with the establishment and identification of the values and objectives that are to be met during the project or by the design. From the establishment of these values and objectives, better alternatives can be found, leading to improved decision making opportunities. Keeney presents five main advantages of value driven decision making, namely; better identification of alternatives, evaluating the alternatives based on important values, guidance in collecting information, focusing discussions, and identifying and resolving conflicts timely [27]. Furthermore, Keeney outlines the following general steps for value driven design[28][26]:

1. Identify objectives/value
2. Structure objectives / create a value function
3. Create alternatives
4. Identify decision opportunities and rate alternatives

Thus, from the extensive research performed by Keeney[28][27], it can be established that values and objectives form key elements to good decisions and designs. This can also be applied in the case of the implementation of an ETS. In order to determine whether or not the system should be implemented, the value of the system has to be determined. Once the values and objectives have been established, different scenarios and implementation alternatives can be explored and quantified to establish the best implementation method and opportunities. Additionally, the objectives and values established will be used to develop the simulation model.

## 2.3. APRON OPERATIONS

For the research to be developed it is important to provide some further information regarding Amsterdam Airport Schiphol's lay-out, configuration, and the apron area operations. The Federal Aviation Administration (FAA) provides the following definition for the airport apron area:

> Apron (ramp): A defined area on an airport intended to accommodate aircraft for purposes of loading or unloading passengers or cargo, refueling, parking, or maintenance.[29]

In this section the standard apron operating and push-back procedures are presented and discussed. As this research will be focused on and performed at AAS, the information presented will specifically pertain to the lay-out and apron operational procedures at AAS.

### 2.3.1. AMSTERDAM AIRPORT SCHIPHOL APRON OPERATIONS

Every fully operational airport has an apron area in order to connect the passenger/cargo terminal area to the aircraft and allow for aircraft parking and maintenance. However, the shape and control of this apron area is dependent on the type of airport, the runway lay-out, and the terminal configuration used.

#### AIRPORT TYPE AND RUNWAY LAY-OUT

Amsterdam Airport Schiphol is a large international airport which functions as the hub airport for KLM Royal Dutch Airlines and its partners.

As such, many of the passengers traveling to AAS are transfer passengers; they arrive at the airport and leave again within a few hours on a connecting flight to their next/final destination. In 2014, approximately 40,5% of the total number of passengers traveling through AAS were transfer passengers [30]. This implies that many of the flights arriving at AAS have passenger on board who need to catch a connecting flight. Therefore, upon arrival many aircraft are time constraint as airlines (and particularly KLM as the airline with the largest network at AAS) try to allow for as many passengers as possible to smoothly connect to their next flight. Thus, arrival delays on the ground are highly undesirable.

The large number of transfer passengers also influences the physical design of the airport terminal and thereby, the apron area. Due to time constraints and to allow for smooth connectivity, large walking distances are undesirable for transfer passengers. Thus the airport design should allow for many gates to be located in relatively close proximity. However, this also influences the amount of apron area available for aircraft maneuvering. Sections 2.3.1 and 2.3.2 provide further insight into the terminal design and operational and procedural implications at AAS.

Thus, in order to understand the complex workings of the apron operations at Amsterdam Airport Schipol, the lay-out of the apron areas, terminal buildings, taxi-ways, and runways must first be examined.

AAS has six operational runways:

- Polderbaan: 36L-18R.
- Zwanenburgbaan: 36C-18C.
- Aalsmeerbaan: 36R-18L.
- buitenveldertbaan: 09-27.
- Kaagbaan: 06-24.
- Oostbaan: 04-22.

Not all six runways can be operated at the same time but usually a combination of two or three runways is used depending on the weather (or more specifically: the wind orientation).

In appendix A, figures provide an overview of the runway and terminal building configurations. Additionally, figure 2.2 below provides an overview of the main apron area at AAS.

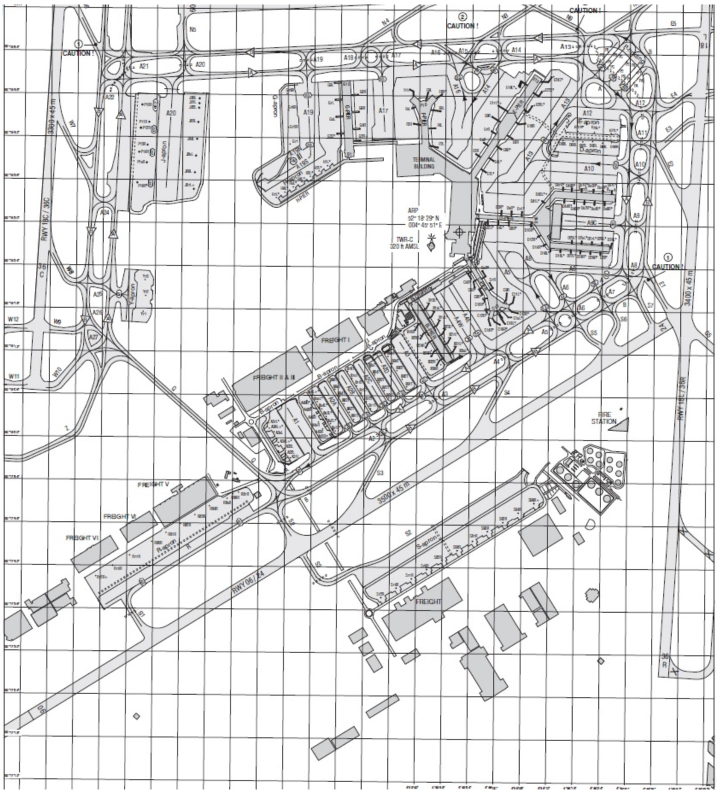


Figure 2.2: The light gray areas represent the apron, taxiways, and runways. The terminal buildings are represented in a slightly darker shade of gray [2]

### TERMINAL CONCEPTS

The terminal configuration has a very large impact on the airport ground movement, apron operations, and pushback procedures. There are five common terminal configurations, namely; linear, finger pier, satellite, midfield and transporter. As is shown in figures 2.3 and 2.2, the main passenger terminal building of Schiphol Airport has a definite finger pier terminal configuration. For the Finger pier configuration the gates of the airport are located along both sides of narrow terminal buildings (piers) which extend in the form of 'arms' or 'fingers' outward from the main terminal area. The piers can have many shapes but are most often Y-, T-, or I-shaped[31] . the AAS terminal building has seven distinct piers; the B-Pier, C-Pier, D-pier, E-pier, F-pier, G-pier, and H-pier. Four of these piers; piers B, E, G, and H are linearly shaped (or I-shaped). Piers C, D, and F are Y-shaped[2].

The main advantage of the finger pier configuration is that a larger number of gates can be located close to the central main terminal building, thereby limiting the time needed for passengers to move from one gate/area to the next. However, as the airport grows, the walking distances will increase significantly as more gates and longer piers are needed[31] .

In addition to the gates along the piers, Schiphol also has several aircraft parking positions (ramps) available on the open apron area known as the B-platform (located next to the B-pier). These ramps do not allow for a physically connection to the airport terminal building thus, the aircraft is not parked along the terminal building but some distance away from it. Buses are used to transport passengers to and from the aircraft and terminal building. This is more commonly referred to as the transporter concept.

The main advantage of the transporter concept is that the passenger terminal building does not need to be as extensive (and fewer gate houses are needed). However, the transporters are expensive to operate, leave little flexibility for delayed passengers to reach the aircraft[31], and have more negative affects on the passenger experience at the airport [32]. Thus, according to the Regulation Aircraft Stand Allocation Schiphol (RASAS), at AAS "for handling passenger flights, pier gates take priority over remote handling and transporting passengers to and from aircraft by bus" (RASAS, p6 [32]).

In total Schiphol has 98 passenger gates and 73 apron ramps[33]. Furthermore, eight main buffer platforms are available for remote handling and (relatively) long-time parking of aircraft.

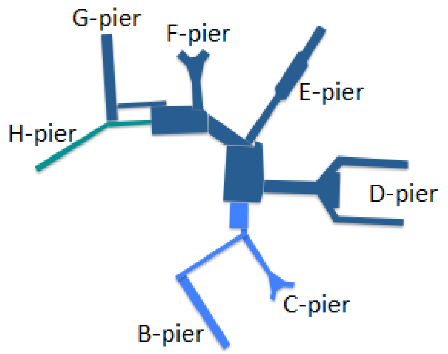



Figure 2.3: The terminal configuration of AAS [3]

For passenger handling and customs purposes the airport makes a distinct separation between Schengen, Non-Schengen, and mixed piers and/or gates. This distinction is made for passenger customs regulation purposes. The B- and C-piers are strictly used for Schengen flights. The D- and H-pier are mixed piers, implying that both Schengen and Non-Schengen flights can be handled there. The E-, F-, G-, and H-piers are used for Non-Schengen flights.

### 2.3.2. STANDARD APRON OPERATING PROCEDURES

As can be expected, the operational ground procedures at an airport depend heavily on the type of terminal building/apron area configuration in use. When a transporter concept is in use, no physical connection between the aircraft and the terminal building is made and aircraft park further away from the terminal. Therefore, a pushback truck may not be necessary as aircraft can leave their parking spot by moving forward. However, for the finger-pier configuration, aircraft are usually parked with their nose towards the terminal building (nose-in parking). The nose-in parking saves space around the building and allows for more aircraft stands along the terminal building [4]. Since aircraft generally cannot taxi backwards autonomously (without the use of reverse thrust which is preferably not used around the apron area for safety reasons), a pushback tow truck is needed to move the aircraft towards the taxi-way or runway. This pushback maneuver calls for special procedures and additional ground personnel to drive the tow truck and help maneuver the aircraft safely backwards without collisions. In his analysis of the push-back process Dieke-Meier presents the a flow diagram of the standard pushback process for nose-in parked aircraft. This flow diagram can be seen in figure 2.4. [4][34][35]

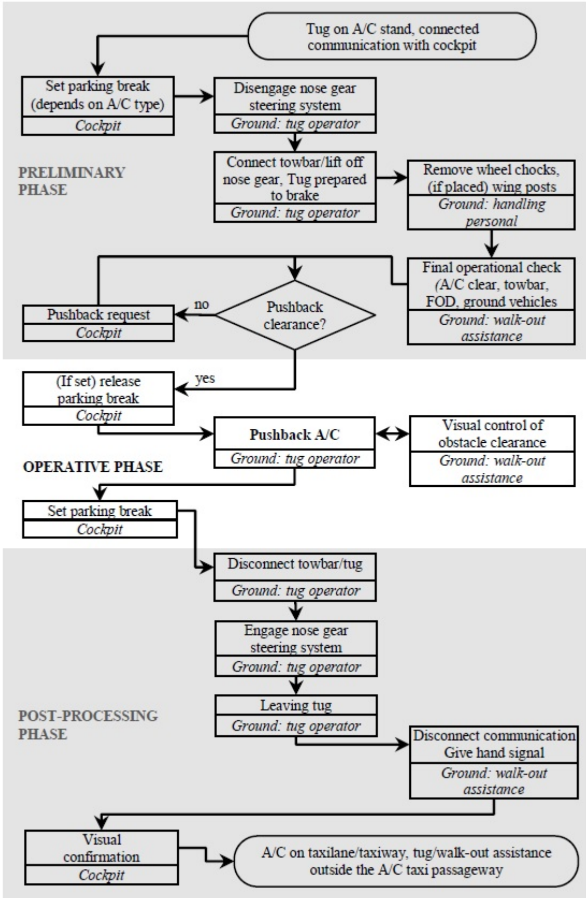



Figure 2.4: Standard pushback procedure [4]

### AAS CURRENT AIRCRAFT PARKING AND PUSHBACK PROCEDURES

Like most large airports, AAS has implemented strict aircraft parking and pushback procedures to maintain safe operations around the apron area.

After landing, the cockpit crew contacts the ground control air traffic controller (ATC) in charge and taxis towards an assigned gate. If the assigned gate is still occupied or otherwise temporarily unavailable, the ground controller will inform the cockpit crew and direct the aircraft towards a temporary holding area. Once the aircraft reaches its assigned gate, often ground staff (marshallers) will help guide the aircraft into the appropriate parking position at the gate. In addition to the marshaller, AAS has installed so called "Visual docking guidance systems". These systems make use of displays in order to present the pilot with information regarding the position of the aircraft relative to the centerline of the parking spot, as well as the aircraft closing-rate and 'stop' information through the use of sensors on the apron surface [2]. The visual docking guidance systems used at AAS are the Safegate system, the Safe Dock system, or the AGNIS/PAPA system [2]. Most aircraft parking procedures are performed without the help of a tow-truck implying that the aircraft make use of their engines to supply the power for the parking maneuver.

The pushback procedure is more complicated than the docking/parking procedure due to the fact that, for nose-in parked aircraft, a pushback truck is needed and the pilot has very limited visibility during backwards maneuvers. At AAS a power-back using reverse thrust is not permitted [2] (this could present jet blast hazards to the surrounding gates and ground crew). The pushback process for the involved personnel is outlined by Dieke-Meier and shown in figure 2.4 in section **??**. In general, this process also applies at AAS. After gaining enroute clearance, closing the aircraft doors, connecting the pushback truck and all other preparations for start-up have been made, the flight crew will request permission for Start-up from Schiphol Start-up. Once the permission for start-up is gained and it is confirmed that the ground crew is ready, the pilot will transfer to the Schiphol Ground Control channel and request pushback permission. The pushback permission provided by Schiphol Ground Control will then be valid for a 1-minute time period. After the pushback has been performed, the flight crew waits for the 'ALL CLEAR' signal from the ground handler before requesting a taxi clearance from ground control.[2]

It is important to note that throughout the gate departure and pushback process, the flight crew is part of the communication chain between the ground controller and the truck driver (or ground engineer) [2]. Thus, good communication is necessary between the flight crew and the ground controller, as well as between the flight crew and the ground engineer/tow-truck driver.

For each gate at AAS, specific pushback and taxi-out/taxi-in routes and procedures are defined.With the number of gates at AAS and the close proximity of these gates to each other, these special gate-specific pushback instructions are necessary to limit FOD and traffic congestion as well as enhancing operational safety.

### 2.3.3. COLLABORATIVE DECISION MAKING (CDM)

An important aspect of efficient ground handling at AAS is the collaborative decision making (CDM) portal. The idea of CDM was developed by Eurocontrol in an effort to reduce airport ground inefficiencies originating from bad information sharing and lack of communication between airports, airlines, ATC, and handling companies[36]. Due to the fact that so many parties are involved in the ground handling processes, a good communication and information sharing network will help reduce delays and allow scarce resources at airports to be used as efficiently as possible. Flight information such as the aircraft actual landing time (ALDT), estimated in block time (EIBT), actual in block time (AIBT), target off-block time (TOBT), actual off-block time (AOBT), target start-up aproval time (TSAT), and target take-off time (TTOT) etc. are all entered into a portal which can be accessed by the parties involved in the CDM[36]. Thus, all the parties involved can plan and predict according to accurate information.

The parties involved in the CDM at AAS are; Schiphol Group, KLM, Dutch air traffic control (LVNL), and the Schiphol Airline Operators Committee (SAOC). Since its initiation in 2010, the CDM project has been met with quite a lot of success and should be fully implemented at AAS in 2015.[36]

CDM has a large influence on gate assignments and departure sequencing, and helps mitigate the effects of delays and bad weather conditions by increasing the ground handling process predictability[36]. Should the ETS be implemented, its use will also need to be linked to systems such as the CDM portal for full optimization of ground handling processes (especially with regards to reducing gate congestion).

The standard procedures for aircraft parking, pushback, and gate assignment may be changed significantly by the implementation of the ETS. The changes that may occur are presented and discussed throughout the remainder of the report. The following chapter will elaborate on the gate capacity and planning strategies at AAS and introduce some of the gate planning optimization concepts made more readily available with the implementation of the ETS.

# 3
# AAS Gate Capacity and Assignment

In its annual report 2014, Amsterdam Airport Schiphol has indicated that, in order to meet growing air traffic demand, the airport needs to expand its operational capacity [37]. In this chapter, the gate planning concept and assignment problem/models are introduced in section 3.1. The final two sections of the chapter (sections 3.3 and 3.4) discuss the current capacity at AAS and the possible capacity enhancement concepts that may be implemented with the use of ETSs.

## 3.1. Aircraft and gate Categories

Aircraft can be divided into different categories according to weight, maximum speed, wingspan, and main gear wheel span. This is done in order to help determine the appropriate take-off and landing distances (with regards to wake turbulence) between aircraft for safe operation. Additionally, the aircraft categories can indicate the gate at which an aircraft can be handled. The size categorization is provided in figure 3.1:

| Code letter | Wingspan | Outer main gear wheel span |
|---|---|---|
| A | Up to but not including 15 m | Up to but not including 4.5 m |
| B | 15 m up to but not including 24 m | 4.5 m up to but not including 6 m |
| C | 24 m up to but not including 36 m | 6 m up to but not including 9 m |
| 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 |

Figure 3.1: The different size categories defined by ICAO into which aircraft are typically divided.[38]

Like at most airports, each of the gates at AAS was designed to handle a certain size or category of aircraft [39]. The ground indications of the aircraft parking space, available gate resources, and jet bridge are customized for use by a specific aircraft size/type. For the handling of a new aircraft category, such as the large A380, new gate configurations have to be designed. Schiphol currently uses a gate categorization system with categories 1 to 9. These categories relate to the ICAO categories approximately as shown in table 3.1.

It is possible, though not common practice, to handle smaller sized aircraft at larger category gates. However, larger category aircraft cannot be handled at smaller category gates. At Schiphol, category 4 aircraft may be handled at larger category gates if no category 4 gate is available. It should be noted that the gate planning regulations in place at the airport pose that aircraft should be handled at a gate with a category as close to the aircraft's category as possible. The most commonly occuring aircraft types per category arriving/handled at AAS are shown in figure 3.2.

| ICAO Aircraft Code Letter | AAS Gate Category |
|---|---|
| A | 1 |
| B | 2 |
| C | 3, 4 |
| D | 5, 6 |
| E | 7, 8 |
| F | 9 |

Table 3.1: ICOA Aircraft categorization and AAS gate categorization

| Cat. | Meest voorkomende vliegtuigtypes op Schiphol |
|---|---|
| 1 | Do328, EMB120, Saab340, Falcon900, Cessna Citations, Beechcraft. Alle vliegtuigen tot wingspan < 24m. |
| 2 | ATR42 / 72, BAe 146-100, CRJ100 / 200, EMB135, Saab2000, F50. |
| 3 | B737-300 t / m B737-500, BAe146-200 / 300, CRJ700-900, DASH-8, Fokker70 / 100, EMB145, EMB170-190, Global Expres BD700. |
| 4 | B717, B737-300winglets en B737-500winglets, B737-600 t / m B737-900, A318, A319, A320, A321, CRJ1000, MD81 t / m MD88, EMB195. |
| 5 | A310-200 / 300, B757-200, C130, MD90, |
| 6 | A300-600, B767-200 / 300ER, DC10, L1011, B757-300. |
| 7 | A330-200 / 300, A340-200 / 300, B747-200 / 300, B767-400, B777-200 / 200ER, B787-8 / 9, MD11, |
| 8 | A340-500 / 600, B747-400, B777-200LR / 300 / 300ER |
| 9 | B747-800F, A380, AN124, AN225. |

Figure 3.2: Most common aircraft types arriving at AAS

## 3.2. THE GATE ASSIGNMENT PROBLEM

The categorization division also presents the basis of the gate assignment problem: not every aircraft can be handled at every gate. When an aircraft lands, the gate it is assigned to needs to adhere to the requirements and size of said aircraft. In addition to size, the origin and destination of the flight, the aircraft handler, and the passenger walking distances need to be taken into account[39]. As presented in section 2.3.1, at AAS the schengen and non-schengen flights have different customs requirements and are therefore handled at different terminals of the airport[39]. Thus, even though AAS has 98 gates for passenger aircraft use [33], not every gate, even with the correct category classification, can be used by every aircraft.

In addition to the physical and customs restrictions, other factors and restrictions are also often taken into account with airport gate planning. These factors include passenger walking distances, aircraft handler locations, and pushback restrictions (such as simultaneous pushback restrictions). Many of the rules and regulations in place at AAS are described in RASAS [32].

Furthermore, dynamic and stochastic flight delays and daily fight schedule changes are common occurrences and have to be dealt with by the gate planning models in order to provide a robust gate planning schedule. This adds another factor of complexity while designing a gate planning model.

With strict flight scheduling, the constraints, and all of the restrictions and factors in place, gate assignment becomes quite a logistically complex problem. In fact the gate assignment problem is classified as an NP-Hard Problem ([40]). This implies that there is no algorithm that can provide an optimal solution to the problem within a polynomial bounded amount of time ([40]). For such complex problems, computational time needed to find an optimum is often unrealistically long. Therefore, heuristics (and meta-heuristics) are often employed in order to find satisfiable (or near-optimal) solutions.

To help find solutions to the gate planning problem, different gate planning models have been proposed in the past. Some of these models will be briefly presented in subsection 3.2.2. However, in order to introduce the models, some background information concerning the different types of models is provided in subsection 3.2.1 first.

### 3.2.1. ANALYTICAL AND SIMULATION MODELS

Models are used to represent real-life or simplified real-life situations. Thereby, they can allow for real-life situations and problems to be predicted, solved, analyzed, and/or optimized. Models are often used to answer 'What if' questions, thereby allowing strategic and tactical decisions to be made. Different models can be set-up and used to provide these simplified real-life situations.

A model often used is the mathematical model (or in a more simple form; algebraic model). Mathematical models are usually defined in the form of algorithms: numerical functions often in the form of objective functions [40]. The goal of the objective function is to be able to minimize or maximize, in other words optimize, the objective. However, is may be the case that a situation is not easily expressed in a mathematical equation or algorithm. Thus, for more complex problems, such as the gate assignment problem, mathematical models alone may not suffice.

Analytical models offer a means to describing and summing up a process in a general way. Analytical models often make use of mathematical models and objective functions to describe a process. Thereby, they aid the decision-making process on a strategic level [40]. Most Mathematical and analytical models are set-up in order to optimize processes; also known as optimization models. These optimizations may be very complex, in which case heuristics are often applied. Heuristics provide a means to implementing rules and restrictions and searching for a near-optimal solution when finding the ultimate optimal solution is too computationally complex. In the case of gate assignment, an analytical model can provide a good means to forming daily flight schedules.

Simulation models use a more detailed description of a system or process in order to analyze the impact of certain parameter changes. Thus, simulation models are not necessarily aimed at optimizing a process, but rather at performing "what-if analysis". Complex processes and systems can be explored, designed, and optimized through the use of simulation models. The impact of new processes and concepts can be evaluated using simulation models. However, simulation models are more computationally labor intensive when compared to analytical models. For good results, simulation models require complete and reliable data used to describe the system in question in detail [40].

Both analytical and simulation models, or combinations of both, have been developed in the past to assist in daily airport gate planning, to optimize (multiple) airport gate planning aspects, and to assess new processes, tools and concepts. The following section provides a brief overview of some of the airport gate assignment models that have been developed in the past.

### 3.2.2. GATE PLANNING SIMULATION RESEARCH

Early research focused on the optimization of the gate assignment and capacity problem with a focus on a single constraint: a certain aspect of the gate assignment problem would be optimized. The micro-computer based gate assignment simulation model developed by Hamzawi [41] in 1986 aims to increase gate capacity and utilization. Further research by Mirkovic [42] extends Hamwazi's model to incorporate a more flexible gate assignment system with multiple stand constraints. Both Mirkovic and Hamwazi focus on gate capacity and utilization from and aircraft gate assignment perspective. Gate ground handling activities are not optimized, and stand occupancy times and pushback times are estimated.

In the gate assignment problem, the minimization of walking distances for passengers and baggage is often considered vital. Mangoubi and Mathaisel (1985 [43]) presented a comparison between an integer linear programming solution and a heuristic solution for the problem of minimizing passenger walking distances. The heuristic solution approach was then further researched and developed by Haghani and Chen (1998 [44]). In 2001, Xu and Bailey (2001 [45]) presented a Tabu (meta-heuristic) search algorithm to find the minimum passenger walking distance gate assignment solution.

Mangoubi et al.[43], Haghani et al.[44], and Xu et al. [45] all focused on solving the gate assignment problem with the objective of minimizing passenger walking distances. However, other objective criteria (such as minimum taxi time, gate restrictions, and clustering of airlines, destinations, and handling companies.) are not optimized. Dorndorf et al. (2007 [46]) present the available literature on the development of flight gate scheduling with multi-criteria objectives, such as the work of Yan et al. (2002 [47]) who investigated the effect of stochastic delays on the gate assignment problem. Further research regarding the multiple-criteria gate assignment problem at AAS was done by Diepen et al. (2007[39]) who used a linear integer programming and column generation approach to optimizing the gate allocation at AAS.

The ETS could be used for more flexible maneuvering of aircraft around the airport. Aircraft which occupy a gate for a longer period of time could be moved to a holding area or to another more convenient gate. This capability would imply another dimension to the gate assignment problem. The gate an aircraft is assigned to when it arrives, does not necessarily have to be the same gate the aircraft departs from. Whether this feature of the ETS can be implemented into the gate assignment problem and whether it produces valuable positive effects on airport operations, needs to be researched.

Thus, the models developed by Hamwazi [41] and Mirkovic [42] provide good estimations of gate capacity, the models developed by Mangoubi et al.[43], Haghani et al.[44], and Xu et al. [45] provide good results regarding minimum passenger walking distances, and the model proposed by Diepen et al.[39] provides a good solution for the gate-assignment problem at Schiphol.

The existing airport apron simulation models fall into three main categories, namely; event-driven (discrete) models, network-based models, or rule-based models [48].

The event-driven simulation models are the most common mathematical models used[48]. They are discrete models (as opposed to continuous models), implying that they develop step-wise, based on the occurrence of an instantaneous event. The SIMMOD and TAAM tools are examples of event-driven simulation models. Event-driven simulations are the most common models used as they present the easiest way to model the complex dynamic environment of the apron in a mathematical way [48]. However, even though the event-driven simulation models are less complex, they are also less accurate and effective than the network-based or rule-based models[48].

Yu Cheng performed research regarding a network-based model for apron simulation in order to solve pushback conflicts [49]. The network-based model proposed, works on the principle of nodes and arcs in a network. The established nodes are based on the arrival and departure of aircraft and the arcs are based on sequences established by the relationships and constraints of time and resources. As indicated by Cheng: "simulation was done by calculating the longest path to every node in the network along a sequence" (Cheng, 1998 [48]). The network-based model is however, primarily focused on solving conflicts efficiently which makes the model less adaptable to the ETS possibilities.

In addition to the network-based model, Cheng also suggests the use of a rule-based model for apron simulation[48]. The rule-based model provides a means to combine mathematical/analytical models with knowledge-based models [48]. Thus, allowing the model to be more easily verified and represent a real-life complex situation more accurately by being embedded in a knowledge-based system. The model can handle large-scale dynamic and inter-linked problems. The rule-based models essentially work with the principle that if a certain condition occurs then a rule is applied to form the conclusion (If-Then structure). Cheng suggests the establishment of a network-based model first, which can be expanded to a rule-based model[48]. However, the rule-based model proposed by Cheng is relatively complex and requires significant computing time.[48].

Besides these models, some extensive airport simulation models have also been developed for research purposes. Two of the most developed models are SIMMOD and TAAM (Total Airspace and Airport Modeler).

SIMMOD was developed by Honeywell and the FAA. It is a discrete-event simulation model by which the system's state(s) change at discrete points in time based on a mathematical model and instantaneous events.[50]

TAAM is a fast-time gate-to-gate simulation model developed by Jeppesen. The model was developed in order to provide detailed ground simulations and allow for analysis of the impact of new airport operations/procedures/systems. As such, TAAM provides the user with the ability to compare a base-line situation with a new situation.[51]

Both models have advantages and disadvantages. SIMMOD is less complex than TAAM and can therefore be more easily used. It allows for appropriate and powerful 2D simulations of ground operations. However, TAAM provides a more accurate and realistic 3D simulation environment.[52]

For the purposes of this research both models were considered but neither was used. Due to the specific nature of the research and focus on ETS, the use of either SIMMOD or TAAM would have been costly and inefficient.

#### SOLUTION METHODS AAS GATE PLANNING

Unlike the optimization and analytical models, the rule-based simulations models can more accurately describe the complex gate planning process. As such, most gate planning models used at large complex international airports (such as AAS), are rule-based models. The model uses if...then rules to plan aircraft and a score list to optimize the gate at which an aircraft is planned [40]. The gate planning model shows a gantt chart time-line overview of a gate per day. Each afternoon the gate planners at AAS and KLM plan the next day's flights through the use of the gate planning model. Any flights with special requests/needs are modified manually by the gate planners. Additionally, during the day's operations, delays and gate changes are implemented and checked by AAS and KLM gate planners. The human factor in the gate planning process is still needed due to the stochastic (unpredictable) behavior of the gate planning and airport environment. No computer system has the ability to completely handle and adapt to the changes posed by the airport environment, in a timely manner, yet. However, the human factor in the gate planning environment can also cause errors and inefficiencies.

Thus, even though the gate assignment problem at Schiphol is being solved using some of the most advanced technology available, gate congestion is still a concern. The ETS may be able to offer some opportunities in relieving gate congestion due to increased maneuverability of aircraft. The following sections will elaborate on the current capacity at AAS (3.3) and the possible capacity enhancement concepts (3.4).

## 3.3. CURRENT CAPACITY AND PEAK HOUR ANALYSIS

Based on the data available for the busiest day in 2014 (July $21^{st}$), the following capacity calculations are made per narrow body pier during the peak hours at the pier. Two different approaches are used to indicate the current capacity at each pier during peak hours. First, the number of gates needed in order to handle the given set of flights is calculated. This is done according to the following formula:

$$G = A(T+S) \tag{3.1}$$

Where G is the number of gates, A is the arrival rate of aircraft at the pier (aircraft per minute), T is the average or minimum turnaround time (TAT), and S is the separation margin between the aircraft. Using the minimum TAT will provide and indication of the maximum capacity. The minimum TAT of the aircraft at the pier is calculated by determining the minimum TAT of the aircraft types handled at the pier, the number of aircraft of each type handled at the pier on July $21^{st}$ and, subsequently, taking the weighted average of the minimum TATs. The average TAT is calculated by taking the average of all the TATs at the pier on July $21^{st}$.

Secondly, the maximum number of flights that can be handled at a gate is calculated. This is done using both the average actual turnaround times of all the aircraft at the pier and the minimum turnaround time of the aircraft types at pier during the peak. This minimum turnaround time is calculated using data provided by KLM and the data provided in the "Aircraft characteristics for Airport Planning" documents published by the aircraft manufacturers. A weighted average of the minimum turnaround times of the aircraft types at the pier is calculated and used to represent the minimum turnaround time at the pier during the peak (for the given set of flights).

Finally, in order to shed light on the occupancy of the gates at a pier, the percentage of time the gates are occupied for is determined. This is done by considering the number of operations that take place at the pier during the peak hour(s). In this case, the time a flight spends at a gate is divided into an arrival phase and a departure phase. Each phase is referred to as an 'operation'. Thus, the average time needed per operation is half of the turnaround time of the flight. The total time needed to complete the operations during the peak hour is then determined using the following formula:

$$\text{Time to complete peak hour operations}(T) = \left(\frac{TAT}{2}\right) * \#\text{ofOperations} \tag{3.2}$$

To determine the occupancy of the gate during the peak hour, the following formula is subsequently applied:

$$\frac{\left(\frac{T}{\text{number of gates}}\right)}{\text{duration of the peak}} = \%\text{time gate occupied} \tag{3.3}$$

### 3.3.1. B-PIER CAPACITY

The B-pier has type 4 classified gates along one side of the pier and type 3 classified gates along the opposite side of the pier. A capacity calculation is therefore performed separately for each side of the B-pier.

For the side of the B-pier with type 3 classified gates, five gate arrival peaks can be defined throughout the day. These peaks occur at: 08:00 A.M., from 10:00-12:00, at 13:00P.M., at 15:00 P.M. and at 19:00P.M.. This can be seen by the orange columns in figure 3.3. Additionally, figure 3.3 provides an overview of the number of operations (aircraft arrivals and aircraft departures) that occur at the gate per hour (blue columns).

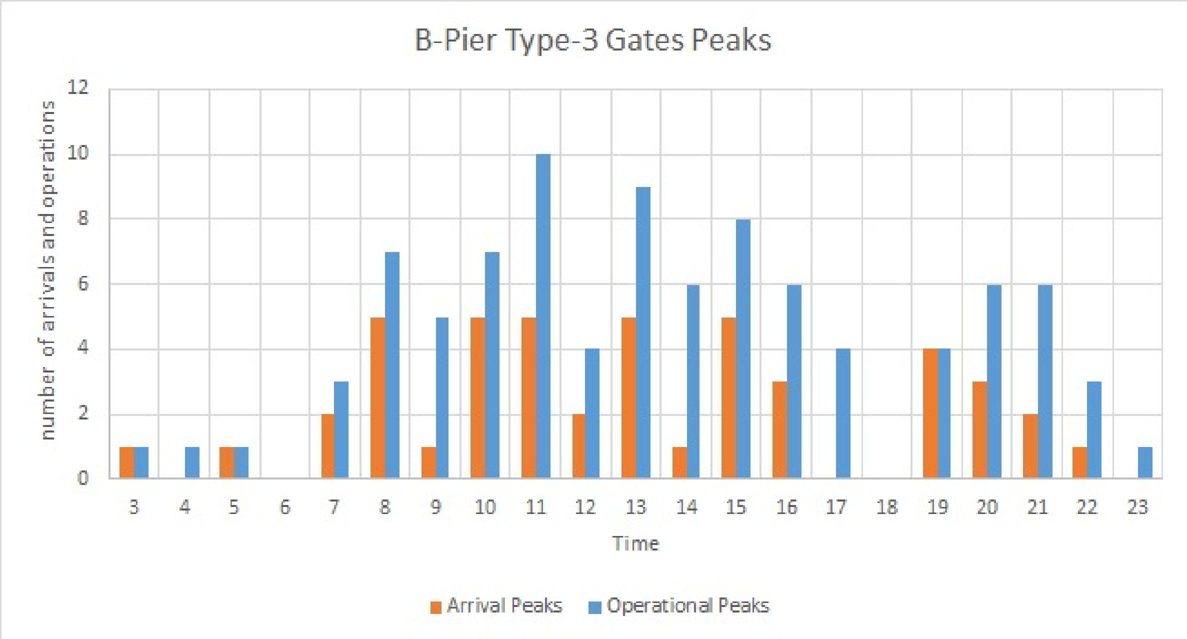



Figure 3.3: Type 3 classified gates B-pier peaks July $21^{st}$ 2014

Table 3.2 presents pier data used to calculate the peak capacity:

| | |
|---|---|
| Average TAT | 67.78 minutes |
| Minimum TAT | 55.26 minutes (including a margin of 20 minutes separation between flights) |
| Number of gates available | 7 gates |

Table 3.2: B-pier type-3 classified gates data used for capacity calculations

Table 3.3 shows the number of gates needed per peak.

| Peak | A (aircraft per minute) | Gates needed with minimum TAT | Gates needed with average TAT | Gate Occupancy (avg TAT)(%) |
|---|---|---|---|---|
| Peak 1 | 0.083 | 4.6 | 5.65 | 56.5 |
| Peak 2 | 0.083 | 4.6 | 5.65 | 68.6 |
| Peak 3 | 0.083 | 4.6 | 5.65 | 72.6 |
| Peak 4 | 0.083 | 4.6 | 5.65 | 64.6 |
| Peak 5 | 0.067 | 3.68 | 4.58 | 32.3 |

Table 3.3: Number of gates needed to handle the peak hour flights and gate occupancy at the 3-Type classified gates of the B-Pier

Table 3.4 provides an overview of the number of flights handled during the peak hours and the average and maximum number of flights that could be handled during the peak hours.

Similar calculations can be made for the 4-type classified gates of the B-pier. Figure 3.4 shows the peak hours of arrival flights at the type-4 classified B-pier gates as well as the total operations at the pier per hour. From the figure it becomes clear that the pier has three distinct arrival peaks from 8:00-10:00, from 16:00-17:00, and at 19:00. Additionally it can be noted that the pier has a distinct operations peak at 19:00.

| Peak | # of flights handled | Peek duration | Average number of flights that can be handled at the pier | maximum number of flights that can be handled at the pier |
|---|---|---|---|---|
| Peak 1 | 5 | 60 min | 6.2 | 7.6 |
| Peak 2 | 10 | 120 min | 12.4 | 15.2 |
| Peak 3 | 5 | 60 min | 6.2 | 7.6 |
| Peak 4 | 5 | 60 min | 6.2 | 7.6 |
| Peak 5 | 4 | 60 min | 6.2 | 7.6 |

Table 3.4: Number of flights that can be handled during the peak hours at the 3-Type classified gates of the B-Pier

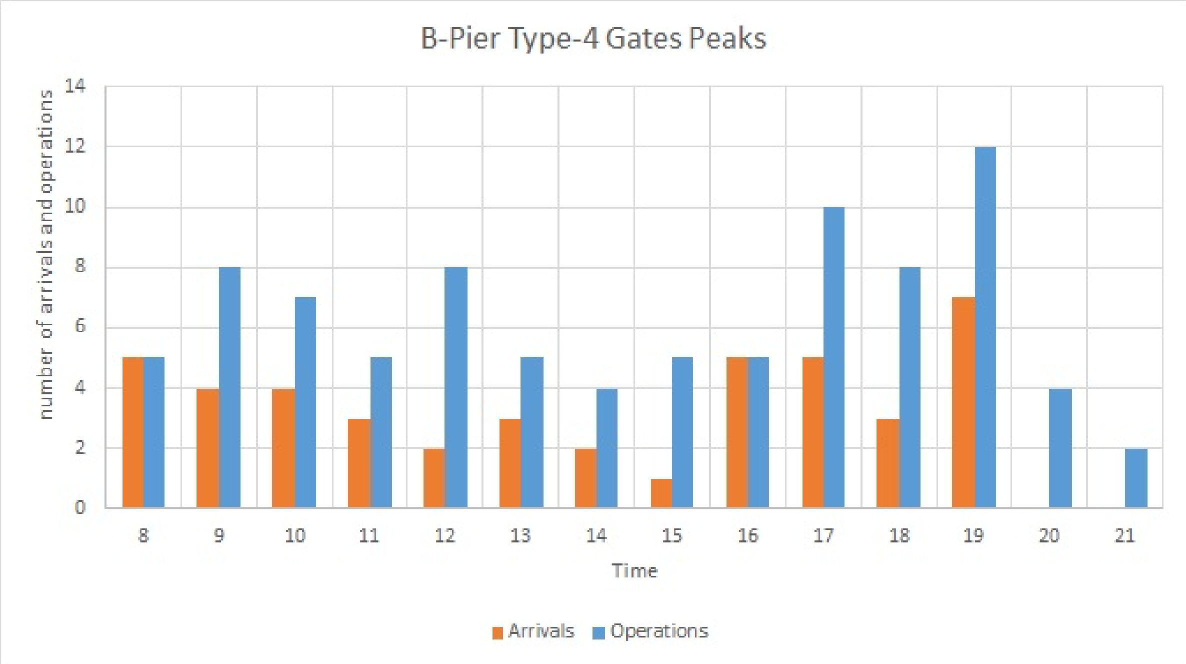



Figure 3.4: Type 4 classified gates B-pier peaks July $21^{st}$ 2014

Table 3.5 presents pier data used to calculate the peak capacity:

| | |
|---|---|
| Average TAT | 76.8 minutes |
| Minimum TAT | 67.12 minutes (including a margin of 20 minutes separation between flights) |
| Number of gates available | 6 gates |

Table 3.5: B-pier type-4 classified gates data used for capacity calculations

Table 3.6 shows the number of gates needed per peak and the occupancy of these gates during the peak hours.

| Peak | A (aircraft per minute) | Gates needed with minimum TAT | Gates needed with average TAT | Gate Occupancy (avg TAT)(%) |
|---|---|---|---|---|
| Peak 1 | 0.072 | 4.85 | 5.55 | 71.1 |
| Peak 2 | 0.072 | 5.6 | 6.4 | 80 |
| Peak 3 | 0.072 | 5.6 | 6.4 | 128 |

Table 3.6: Number of gates needed to handle the peak hour flights and gate occupancy during peak hours at the 4-Type classified gates of the B-Pier

Table 3.7 provides an overview of the number of flights handled during the peak hours and the average and maximum number of flights that could be handled during the peak hours.

| Peak | # of flights handled | Peek duration | Average number of flights that can be handled at the pier | maximum number of flights that can be handled at the pier |
|---|---|---|---|---|
| Peak 1 | 13 | 180 min | 14 | 16 |
| Peak 2 | 10 | 120 min | 9.4 | 10.7 |
| Peak 3 | 5 | 60 min | 4.7 | 5.4 |

Table 3.7: Number of flights that can be handled during the peak hours at the 4-Type classified gates of the B-Pier

As can be seen from the data presented in the tables, the type-3 classified gates of the B-pier are close to their maximum capacity and the type-4 classified gates are already reaching their maximum capacity during peak hours. At the type-3 classified gate, the highest operational peak is experienced between 13:00 and 14:00, with gates occupied for 72.6% of the time. The type-4 classified gates are already reaching their maximum capacity (especially with the current average turnaround times), especially during the evening peak hour (between 19:00 and 20:00). During the 19:00 peak hour, the gates are occupied 128% of the time considering the average TAT. This implies that flights have to be handled as closely to their minimum TAT as possible and there is very little room for unexpected delays.

### 3.3.2. C-PIER CAPACITY

For the C-pier four arrival peaks are identified throughout the day of July 21$^{st}$ 2014. However, as shown in Figure 3.5, two maximum arrival peaks can also be easily identified. These peaks occur at 08:00A.M. and at 11:00A.M..

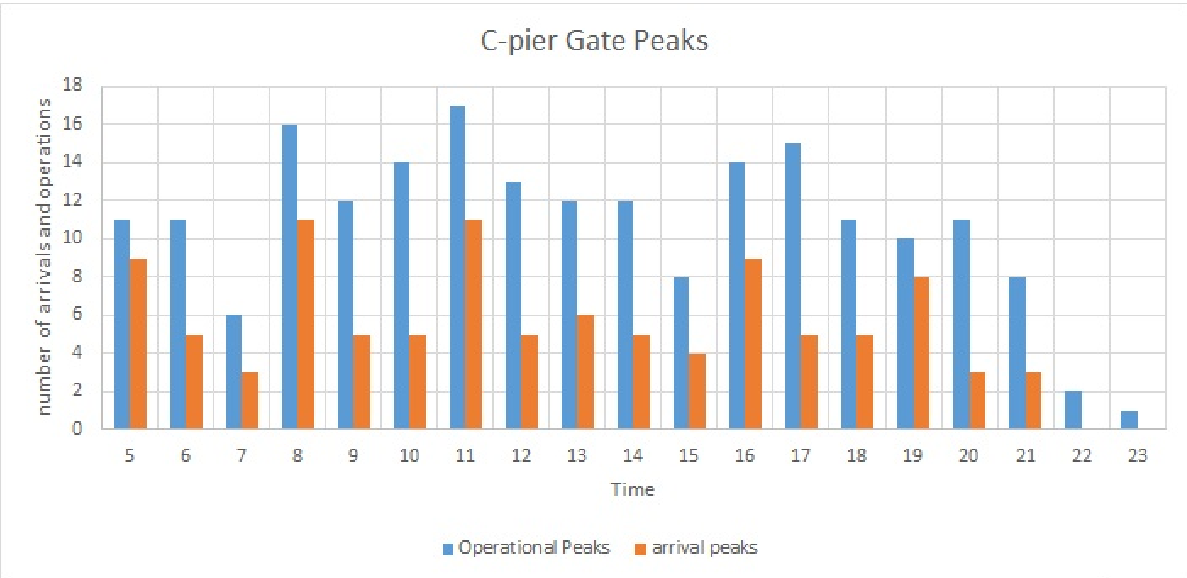



Figure 3.5: C-pier peaks July 21$^{st}$ 2014

During these peaks the following capacity calculations can be made using the data presented in table 3.8. Table 3.9 shows the number of gates needed per peak.

Table 3.10 provides an overview of the number of flights handled during the peak hours and the average and maximum number of flights that could be handled during the peak hours.

From this data it can be concluded that the C-pier is also close to its maximum capacity during its peak hours. During the peak between 11:00a.m.-12:00p.m., the C-pier gates are occupied 76.6% of the time. With

| | |
|---|---|
| Average TAT | 75.74 min |
| Minimum TAT | 66.93 min (including a margin of 20 minutes separation between flights) |
| Number of gates available | 14 gates |

Table 3.8: C-pier gate data used for capacity calculations

| Peak | A (aircraft per minute) | Gates needed with minimum TAT | Gates needed with average TAT | Gate Occupancy (avg TAT)(%) |
|---|---|---|---|---|
| Peak 1 | 0.183 | 12.3 | 13.9 | 72.1 |
| Peak 2 | 0.183 | 12.3 | 13.9 | 76.6 |

Table 3.9: Number of gates needed to handle the peak hour flights and gate occupancy during peak hours at the C-pier

| Peak | # of flights handled | Peek duration | Average number of flights that can be handled at the pier | maximum number of flights that can be handled at the pier |
|---|---|---|---|---|
| Peak 1 and 2 | 11 | 60 min | 11.1 | 12.5 |

Table 3.10: Number of flights that can be handled during the peak hours at the C-pier

five additional operations during this peak hour (a 30% increase in number of operations) the gate will be at its maximum capacity. Additionally, from the calculations it can be concluded that with the current average TAT of aircraft at the pier, the number of gates needed is 14 (equal to the current number of gates available).

### 3.3.3. D-PIER CAPACITY

The D-pier has three arrival peaks (blue columns figure 3.6) throughout the day of July 21$^{st}$ 2014. From figure 3.6, the three main arrival peaks are identified at 08:00, at 12:00, and at 19:00. The maximum peaks occur at 08:00 and 13:00. It should be noted that in the morning the D-pier has 19 narrow body gates available. In the afternoon, however, it has 23 narrow body gates available.

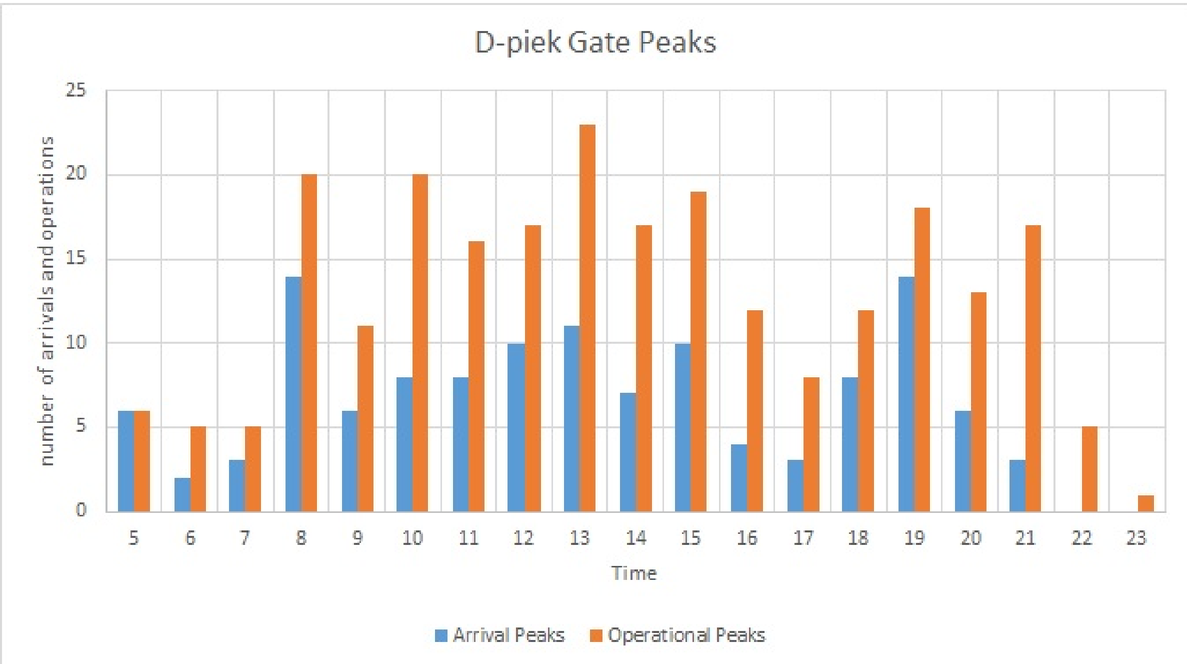



Figure 3.6: D-pier peaks July 21$^{st}$ 2014

During these peaks the following capacity calculations can be made using the data presented in table 3.11. Table 3.12 shows the number of gates needed per peak and the percentage of time the gate is occupied during

| | |
|---|---|
| Average TAT | 85.53 min |
| Minimum TAT | 61.61 min (including a margin of 20 minutes separation between flights) |
| Number of gates available morning | 19 gates |
| Number of gates available Afternoon (after 13:00) | 23 gates |

Table 3.11: D-pier gate data used for capacity calculations

the peak hours.

| Peak | A (aircraft per minute) | Gates needed with minimum TAT | Gates needed with average TAT | Gate Occupancy (avg TAT)(%) |
|---|---|---|---|---|
| Peak 1 | 0.23 | 14.4 | 19.96 | 75 |
| Peak 2 | 0.183 | 11.3 | 15.7 | 86.3 |

Table 3.12: Number of gates needed to handle the peak hour flights and gate occupancy during peak hours at the D-pier

Table 3.13 provides an overview of the number of flights handled during the peak hours and the average and maximum number of flights that could be handled during the peak hours.

| Peak | # of flights handled | Peek duration | Average number of flights that can be handled at the pier | maximum number of flights that can be handled at the pier |
|---|---|---|---|---|
| Peak 1 | 14 | 60 min | 13.3 | 18.5 |
| Peak 2 | 11 | 60 min | 13.3 | 18.5 |

Table 3.13: Number of flights that can be handled during the peak hours at the D-pier

The data shows that the D-pier is at its highest operational capacity from 13:00-14:00 and at its highest arrival capacity at 08:00. Even though the number of new arrivals during the peak hour from 13:00-14:00 is not as high as during the morning peak from 08:00-09:00, the gates are occupied 86% of the time from 13:00 until 14:00. This is due to the higher number of departures from 13:00-14:00. Thus, the number of operations at the gates is high compared to the number of arrivals from 13-14. It can thereby be concluded that the D-pier is also nearing its maximum capacity similarly to the C and B-piers.

### 3.3.4. H-pier Capacity

The H-pier has three distinct arrival peaks as shown in figure 3.7 (from 08:00-10:00, at 18:00, and at 21:00). The maximum peak, for both arrivals and operations occurs at 21:00. Table 3.14 provides an overview of the data used to calculate the capacity at the H-pier.

| | |
|---|---|
| Average TAT | 41.92 min |
| Minimum TAT | 31.5 min (including a margin of 10 minutes separation between flights) |
| Number of gates available | 7 gates |

Table 3.14: H-pier gate data used for capacity calculations

Table 3.15 shows the number of gates needed at the maximum peak, as well as the percentage of time the gates are occupied during the maximum operational peak hour.

Table 3.16 provides an overview of the number of flights handled during the peak hours and the average and maximum number of flights that could be handled during the peak hours.
The H-pier is mostly use by EasyJet which, as a low-cost carrier, employs very short turnaround times. The minimum turnaround time is, therefore, very close to the actual average turn around time. This also helps

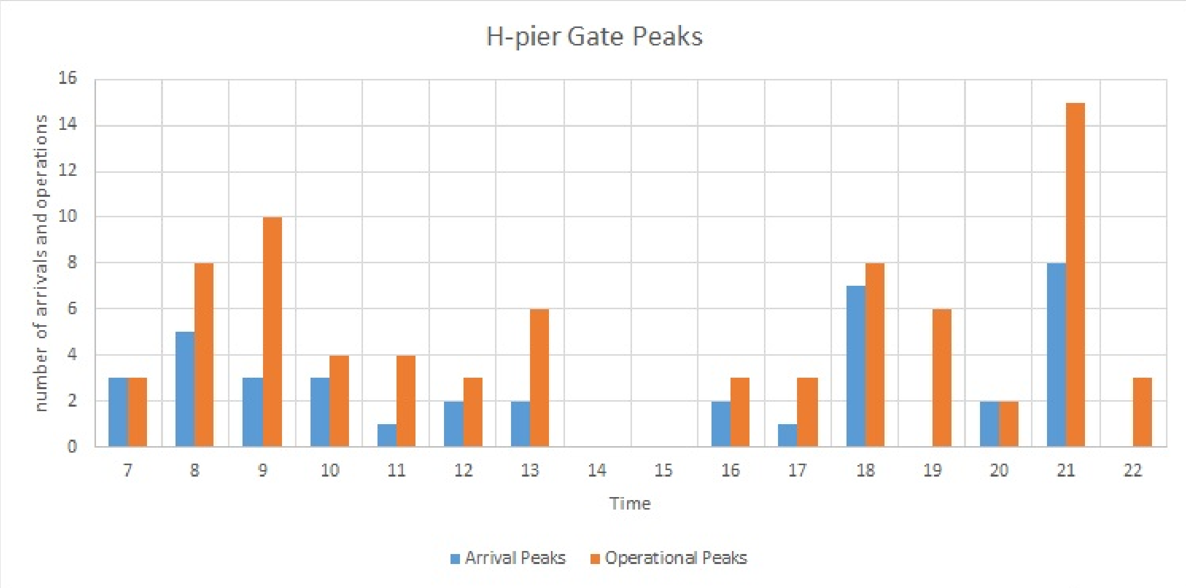



Figure 3.7: H-pier peaks July 21$^{st}$ 2014

| Peak | A (aircraft per minute) | Gates needed with minimum TAT | Gates needed with average TAT | Gate Occupancy (avg TAT)(%) |
|---|---|---|---|---|
| Peak 3 | 0.13 | 4.2 | 5.6 | 74.9 |

Table 3.15: Number of gates needed to handle the peak hour flights and gate occupancy during peak hours at the H-pier

| Peak | # of flights handled | Peek duration | Average number of flights that can be handled at the pier | maximum number of flights that can be handled at the pier |
|---|---|---|---|---|
| Peak 3 | 8 | 60 min | 10 | 13.3 |

Table 3.16: Number of flights that can be handled during the peak hours at the H-pier

increase the capacity of the pier. Similarly to the D-pier, the H-pier is nearing its maximum capacity during its peak hours but it is not yet at its maximum capacity.

The current capacities presented in this section show that many of the narrow body gates at AAS are near their maximum capacity. During peak hours, most gates are occupied for more than 70% of the hour. The predicted air traffic growth is, therefore, expected to cause capacity problems at AAS during peak hours[37]. The following section presents two concepts, enabled by the implementation of the ETS, that may allow for enhanced gate capacity, more efficient buffer usage, and decreased aircraft ground delays upon arrival.

## 3.4. DISPATCH TOWING AND PIT STOP CONCEPTS

Dispatch towing and pit stops are existing concepts that aim to improve the efficiency and flexibility of airport gate planning and enhance the gate capacity. However, the procedures are not yet widely used due to towing inefficiencies and restrictions. The ETS could eliminate or reduce these inefficiency and restrictions, thereby presenting the opportunity for more widespread use of the dispatch towing and pit stop procedures.

Dispatch Towing refers to the concept of moving a fully loaded but delayed aircraft from the gate to a buffer position to wait for its departure slot, in order to free up the gate for the next arriving aircraft. As Schiphol airport is near its maximum gate capacity, on peak days there is a chance that an arriving flight has to wait more than five minutes before being able to park at its assigned gate due to another aircraft still occupying that gate. Schiphol allocates its gates with a 20 minute margin between any departing and arriving flights. However, flights can be delayed significantly such that this 20 minute margin is overstayed. The reason for flight delays at the gate varies, but during the summer peak period the delays are most often caused by aircraft waiting for their destination arrival slots, en-route slots, departure slots, and/or last minute aircraft services. If an aircraft is ready for departure but still parked at the gate because it is waiting for a slot, it could be moved away from the gate to a buffer to spend its time waiting there. This way the gate would be free on time for the next arriving aircraft. Additionally, the burden of the planning disruption thereby falls on the flight causing the disruption instead of on another flight. Assuming that the gate planned schedule made by Schiphol (in cooperation with KLM)each day is an optimized schedule, schedule changes are generally undesirable. Sometimes the aircraft waiting for a gate may receive a gate change. This gate change may have further impact on the gate allocation of other flights as well. Thus, the delay of one aircraft at the gate can impact multiple flights and force the gate planning schedule to deviate from the optimal schedule. This deviation can be avoided by using dispatch towing.

Therefore, Dispatch Towing could be the answer to solving some of the congestion occurring at Schiphol during peak hours. The main reason dispatch towing is often not put into practice today is because it requires a fully loaded aircraft to be towed by a tow truck to a buffer. Towing of fully loaded aircraft by a tow truck can lead to structural fatigue on the nose landing gear of aircraft. Therefore, many aircraft manufacturers (including Boeing and Airbus) often forbid the towing of fully loaded aircraft unless, for instance, a very specific tow truck can be used. The ETS would be a good solution for this problem. The ETS is designed to allow a fully loaded aircraft to taxi, thus the structural integrity of the aircraft no longer suffers when the fully loaded aircraft is moved from the gate to buffer. Thereby, dispatch towing may become a very beneficial procedure if the ETS were to be implemented.

A pit stop procedure can be used to free up a gate during the servicing and turn around of an aircraft. An aircraft is parked at a gate to offload the passengers and their baggage, afterwards the aircraft is towed to a buffer where the rest of the ground handling is performed. Once it is time for the aircraft's next flight, the aircraft is towed back to a gate and the passengers are boarded. During the time the aircraft spends on the buffer, the gate it was planned at is free for another aircraft (with a shorter turnaround time) to use. Thus the same gate is now handling two aircraft instead of just one.

This procedure is already used sometimes at schiphol airport. However, pit stops do imply an increase in towing movements. During peak hours when the tow truck schedule is also near its maximum capacity, extra towing movements are often avoided. With the implementation of the ETS however, the tow trucks would no longer be needed to perform pit stops and the inefficiencies of the extra pushbacks can be reduced.

# 4
# Gate Assignment Model Set-up

AAS is nearing its gate capacity during peak hours at the gates. The ETS may allow for the use of the pit stop and dispatch towing concepts to increase capacity and absorb delays during the peak hours at AAS. In order to investigate the impact of these concepts, a simplified AAS gate planning model is set-up. The model aims to shed light on the current gate and buffer planning situation at AAS, as well as on the impact that the implementation of the dispatch towing and pit stop concepts with ETS might have.

The model is therefore set-up to allow for the implementation of a flight schedule and the visualization of said flight schedule in time-line format. Through the visualization of the gate planning, comparisons between situations with and without the dispatch towing and pit stop concepts can be drawn more easily.

## 4.1. Model Build-up

The Gate Planning Model is set up to produce a graphic representation of the gate planning at Schiphol Airport for narrow body gates and buffers (similarly to the gate model currently in use at AAS). Thereby, different scenarios, and the effect of pit stops and dispatch towing, can be brought to light through a comparison of the gate planning graphs.
The Gate Planning Model is developed using Excel VBA in order to be able to process the data and produce the gate planning graphs. The model comprises of two separate sub-models; the Customized gate planning model and a model based on real-life data.

### 4.1.1. Customized Gate Planning Model

The Customized gate planning model is developed to simulate new gate planning scenarios that may arise with the implementation of dispatch towing and pit stop concepts.
The model consists of a flight scheduling user form (a Macro). Via this form the user can enter flights and flight data into a schedule. The data entered includes:

- The flight number (of the flight departing from the gate)
- The aircraft registration code
- Whether the aircraft is a narrow body aircraft or a wide body aircraft
- The aircraft category
- The aircraft type
- Whether the aircraft is arriving from (or departing to) a schengen or non-schengen destination
- The arrival and departure time of the aircraft

Figure 4.1 provides a screen shot of the user form macro used by the Customized gate planning program to form a flight schedule or add flights to an existing flight schedule.
The Information provided to the user form is then entered in an excel sheet to form a schedule of flights for one day.

Next, the turn around time of each flight is calculated and entered to the same sheet. Another user form can now be used to plan the flights in the schedule at an available gate. In order for the gate planning user form to be able to assign gates to the scheduled flights, a second sheet is created in the excel workbook. This sheet contains a list of the available gates, as well as the category aircraft that can be handled at the gate, and whether the gate is a Schengen, Non-Schengen, or mixed gate. Additionally, for each gate, the neighboring

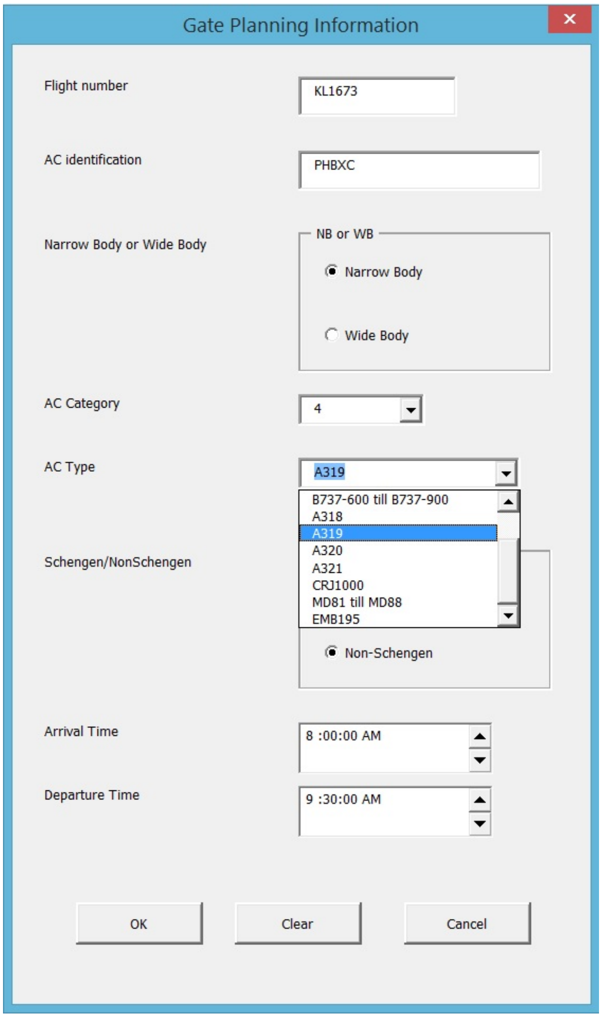
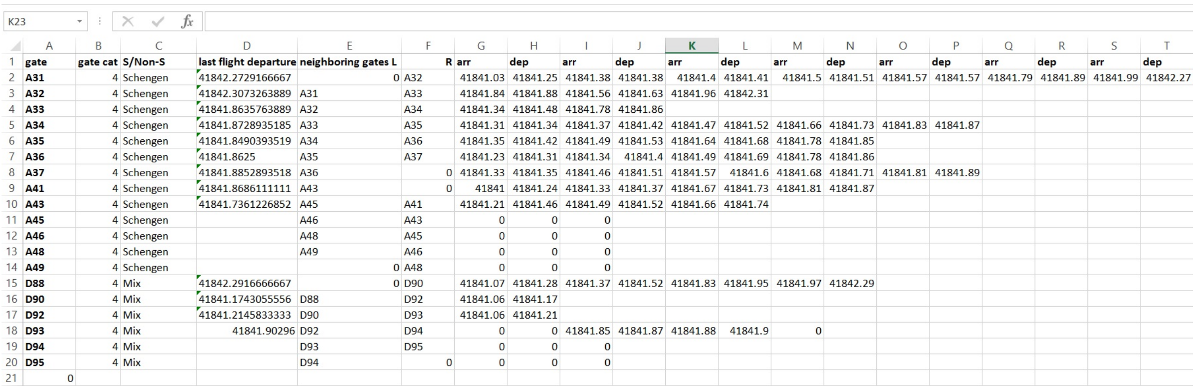



Figure 4.1: Screen Shot of the Model data entry user form

gates are noted to ensure that the program does not assign aircraft with identical departure or arrival times to neighboring gates. A screen shot of the gate sheet used for scheduling flights at the buffer 'gates' is shown in figure 4.2. It should be noted that the arrival and departure times shown in the image are in general excel format.



| gate | gate cat | S/Non-S | last flight departure | neighboring gates L | R | arr | dep | arr | dep | arr | dep | arr | dep | arr | dep | arr | dep | arr | dep |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A31 | 4 | Schengen | 41842.2729166667 | 0 | A32 | 41841.03 | 41841.25 | 41841.38 | 41841.38 | 41841.4 | 41841.41 | 41841.5 | 41841.51 | 41841.57 | 41841.57 | 41841.79 | 41841.89 | 41841.99 | 41842.27 |
| A32 | 4 | Schengen | 41842.3073263889 | A31 | A33 | 41841.84 | 41841.88 | 41841.56 | 41841.63 | 41841.96 | 41842.31 | | | | | | | | |
| A33 | 4 | Schengen | 41841.8635763889 | A32 | A34 | 41841.34 | 41841.48 | 41841.78 | 41841.86 | | | | | | | | | | |
| A34 | 4 | Schengen | 41841.8728935185 | A33 | A35 | 41841.31 | 41841.34 | 41841.37 | 41841.42 | 41841.47 | 41841.52 | 41841.66 | 41841.73 | 41841.83 | 41841.87 | | | | |
| A35 | 4 | Schengen | 41841.8490393519 | A34 | A36 | 41841.35 | 41841.42 | 41841.49 | 41841.53 | 41841.64 | 41841.68 | 41841.78 | 41841.85 | | | | | | |
| A36 | 4 | Schengen | 41841.8625 | A35 | A37 | 41841.23 | 41841.31 | 41841.34 | 41841.4 | 41841.49 | 41841.69 | 41841.78 | 41841.86 | | | | | | |
| A37 | 4 | Schengen | 41841.8852893518 | A36 | 0 | 41841.33 | 41841.35 | 41841.46 | 41841.51 | 41841.57 | 41841.6 | 41841.68 | 41841.71 | 41841.81 | 41841.89 | | | | |
| A41 | 4 | Schengen | 41841.8686111111 | A43 | 0 | 41841 | 41841.24 | 41841.33 | 41841.37 | 41841.67 | 41841.73 | 41841.81 | 41841.87 | | | | | | |
| A43 | 4 | Schengen | 41841.7361226852 | A45 | A41 | 41841.21 | 41841.46 | 41841.49 | 41841.52 | 41841.66 | 41841.74 | | | | | | | | |
| A45 | 4 | Schengen | | A46 | A43 | 0 | 0 | 0 | | | | | | | | | | | |
| A46 | 4 | Schengen | | A48 | A45 | 0 | 0 | 0 | | | | | | | | | | | |
| A48 | 4 | Schengen | | A49 | A46 | 0 | 0 | 0 | | | | | | | | | | | |
| A49 | 4 | Schengen | | 0 | A48 | 0 | 0 | 0 | | | | | | | | | | | |
| D88 | 4 | Mix | 41842.2916666667 | 0 | D90 | 41841.07 | 41841.28 | 41841.37 | 41841.52 | 41841.83 | 41841.95 | 41841.97 | 41842.29 | | | | | | |
| D90 | 4 | Mix | 41841.1743055556 | D88 | D92 | 41841.06 | 41841.17 | | | | | | | | | | | | |
| D92 | 4 | Mix | 41841.2145833333 | D90 | D93 | 41841.06 | 41841.21 | | | | | | | | | | | | |
| D93 | 4 | Mix | 41841.90296 | D92 | D94 | 0 | 0 | 41841.85 | 41841.87 | 41841.88 | 41841.9 | 0 | | | | | | | |
| D94 | 4 | Mix | | D93 | D95 | 0 | 0 | 0 | | | | | | | | | | | |
| D95 | 4 | Mix | | D94 | 0 | 0 | 0 | 0 | | | | | | | | | | | |
| 0 | | | | | | | | | | | | | | | | | | | |

Figure 4.2: Screen shot of the sheet used for gate planning

When a flight is selected for planning in the user form, the characteristics concerning the flight's Schengen status, aircraft type category, and arrival and departure times are checked against the list of gates available. If the Schengen status of the flight matches and the aircraft type category is less than or equal to that of the gate, the arrival and departure times of the flight are checked against the arrival and departure times of other aircraft at the gate. If a time slot is found to be available at the gate, the arrival and departure times of the flight are checked against those of the gate's neighboring gates (to ensure no arrivals and/or departures occur simultaneously). If there are no conflicts with neighboring gates, the flight is scheduled at the gate. Should any of the constraints not be met, the next gate in the gate list is selected and the same constraints are checked for this gate. Figure 4.3 provides a screen shot of the gate planning user form as described above.

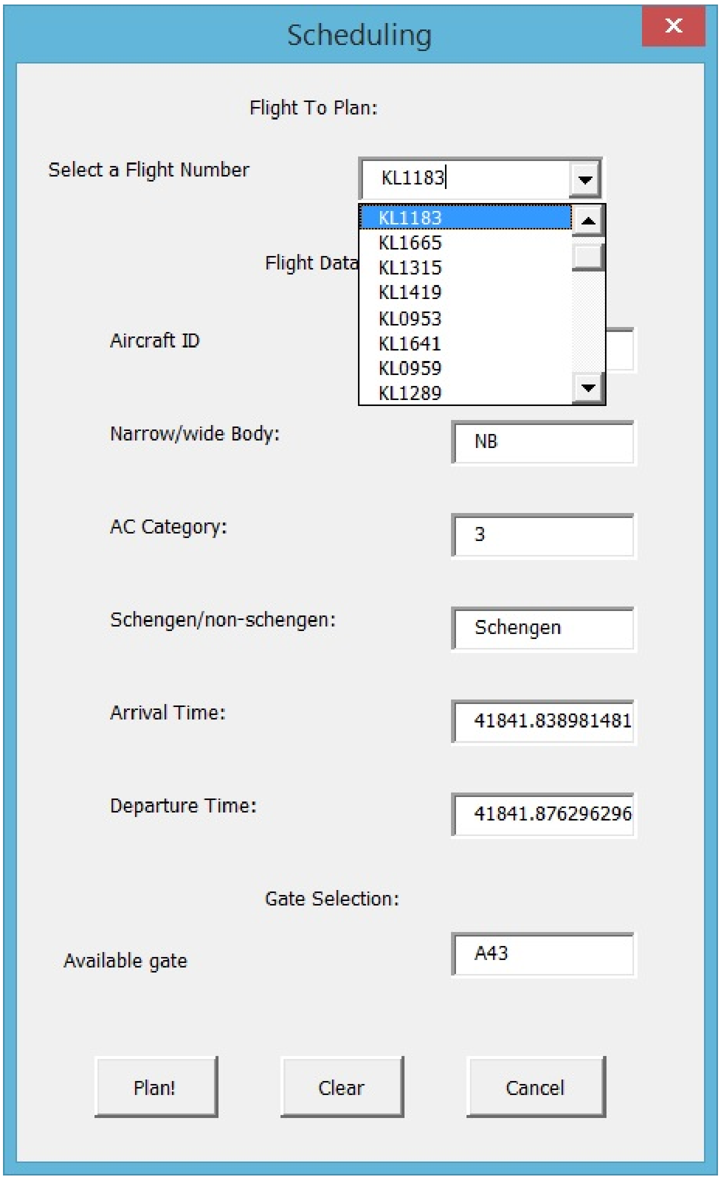



Figure 4.3: Screen shot of the user form used to plan aircraft at available gates and form a gate schedule.

The gate assigned to the flight is entered into the flight data sheet via the gate planning user form. The data can now be rearranged such that it can be graphically presented in the form of a gate planning chart. For these initial results please refer to section 5.

The actual gate schedules made by Schiphol airport and KLM include optimizations for passenger transfers and walking distances, as well as aircraft ground handling services. The simulated schedules created by the

Customized gate planning model do not include these optimizations; therefore, they vary somewhat from the actual gate schedules. However, even without these optimizations, the Customized gate planner can still be used in order to measure the impact of the new procedures (dispatch towing and pit stops) on gate planning and capacity, especially in conjunction with the gate planning model based on real-life data.

### 4.1.2. MODEL BASED ON REAL-LIFE DATA

The gate planning model based on real-life data is, as the name suggests, based on an existing gate schedule that was implemented in the past. The data is obtained from the Schiphol database 'APC-Dashboard'. It includes;

- The gate the aircraft is located at
- The aircraft registration code
- The aircraft arrival time at and departure from the gate
- The flight number of the flight departing from the gate

Additional data from the APC-Dashboard can be obtained concerning aircraft that had to wait more then 3 minutes upon arrival because their gate was still being occupied by another aircraft. This data is of particular interest for investigating the dispatch towing concept. If dispatch towing were to be employed some of the aircraft waiting for their gate would no longer have to do so.

With the data obtained from the APC-Dashboard the real-life gate planning graphic can be made similarly to that of the Customized gate planning model (using excel VBA). The Results of the real-life model represent the actual situation and can be used to verify the results of the Customized model. Additionally, a combination of the two models can be used to produce graphs showing comparisons between the current situation and what the gate planning could look like with the implementation of the pit stop and dispatch towing concepts.

### 4.1.3. MODEL ASSUMPTIONS AND CONSTRAINTS

Certain constraints and assumptions are taken into account for the model to be set-up.

#### CONSTRAINTS

The main gate planning constraints in place at Schiphol are defined in the 'Regulations for Aircraft Stand Allocation Schiphol' or RASAS [32]. The document aims to outline the rules that the gate assignment model used by Schiphol and the gate planners working at the airport adhere to. The regulations and rules that are taken into account in the gate planning models developed during this thesis research are based on those defined in RASAS. These include:

- Schengen and Non-Schengen clasification matches between the gate and the flight.
- The aircraft type matches that of the aircraft types that can be handled at the gate.
- For the dispatch towing and pits stop procedures only the buffers that are a maximum of 10 minutes taxi time away from the flight's gate are considered. For the narrow body gates in question these buffers include: the A-apron, the D-apron, and the R-apron.
- Aircraft leaving or arriving at two adjacent gates cannot do so at the same time.
- A margin of 20 minutes (10 minutes for the H-pier) is taken between each consecutive departing and arriving aircraft at a gate. This is done in order to be able to handle any short stochastic delays.
- RASAS defines a minimum narrow body turnaround time of 170 minutes for a pit stop to be considered. Additionally, if the aircraft is towed away from the gate it has to be able to be parked on the buffer for at least 30minutes.
- For dispatch towing, the flights disturbing the planned operations are never favored. This implies that an aircraft will not be dispatch towed from its gate because the next aircraft arrived early. Furthermore, this implies that from the time the gate is planned to become available for the arriving aircraft, the delayed departing aircraft may be towed to a remote parking place to await its departure. This is only done if the departing aircraft will spend more than 5 minutes on the buffer.

### Assumptions

It is assumed for now that the ETS will only be available for narrow body aircraft. Therefore, only narrow body gates and buffers are considered in the models. Additionally, the assumption is made that each narrow body aircraft is equipped with an ETS and can therefore perform the Dispatch towing and pit stop procedures.

As indicated in section 3.2, the gate assignment problem is highly complex. For the purpose of this study, and in order to reduce the complexity of the problem while maintaining verifiability of results, transfer passengers, passenger walking distances, and aircraft ground handling service provider locations are not taken into account in the models. This should have little effect on the model's validity, as the effect that dispatch towing and pit stops may have can still be measured by using real-life data and the real-life model for comparison.

In the Customized gate planning model it is assumed that all narrow body gates and buffers are available for use. In actual everyday planning situations it is often the case that a few gates may not be available due to gate maintenance or other construction/maintenance activities at the airport.

Furthermore, it is assumed that the taxi time from the gate to a buffer amounts to a maximum of 10 minutes.

# 5
# Concept Application and Initial Simulation Results

In order to produce the initial results, data from the busiest day in 2014 was used. According to the data from the APC dashboard, week 30 (July $21^{st}$ until July $27^{th}$) was the busiest week in 2014. During this week July 21st experienced the highest gate occupancy. Thus, the initial results are made using the data from July $21^{st}$ 2014.

## 5.1. Real-life Data Buffer Planning

The following graphs show the buffer gate planning on July $21^{st}$. Figure 5.1 shows the buffer planning based on real-life data (made with the real-life gate planning model). Figure 5.2 shows the buffer planning made using the Customized gate planning tool with the same set of flights as the real-life data model. The yellow bars on the graph/time-line represent the flights scheduled at the gates. the gates are listed along the y-axis.

Essentially, the schedules look very similar but the flights are planned on different buffers due to the way the Customized gate planning model is set-up (the assumptions and constraints applied: see section 4.1.3). The buffer planning made using the real-life gate planning model reflects the actual buffer occupancy situation of July $21^{st}$ 2014. This real-life planning includes the possible daily maintenance constraints or servicing preferences of the airline. The customized gate planning model does not take these constraints into account. It is a simplified version of the gate planning model used at Schiphol.

It is important to note, however, that the flights planned at the D-buffers in the real-life situation are also planned at the D-buffer according to the customized gate planning model. Similarly, the flights planned at the A-buffer in the real-life representation are also planned at the A-buffer by the customized gate planning model. This is an indication that the customized gate planning model adheres to the correct gate planning constraints and rules imposed at AAS (defined by RASAS [32]).

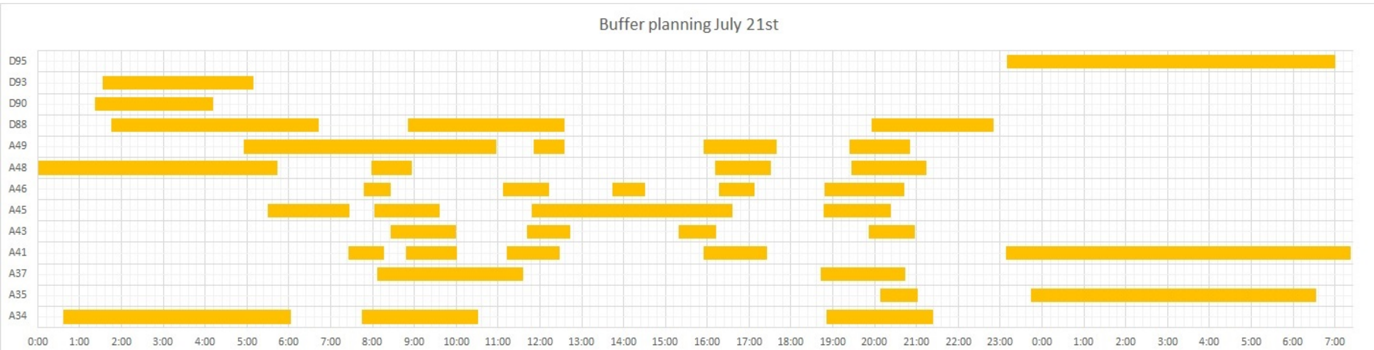



Figure 5.1: Buffer Planning July $21^{st}$. Made using the Real life gate planning model

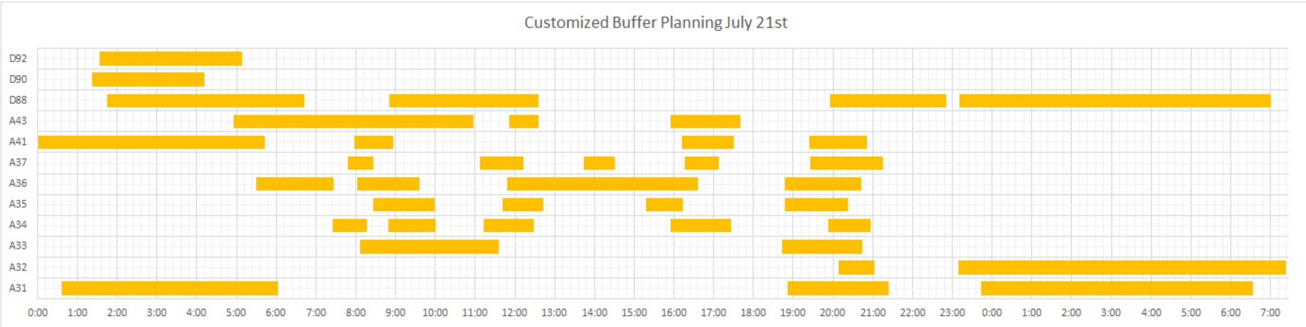



Figure 5.2: Buffer Planning July $21^{st}$. Made using the Customized gate planning tool

## 5.2. EXAMPLE GATE PLANNING WITH AND WITHOUT DISPATCH TOWING

In order to obtain insight into the possibilities of dispatch towing, two separate example gate planning graphs are presented with and without dispatch towing. In the first graph 5.3, without dispatch towing, the arriving aircraft would have had to wait 17 minutes before being able to park at its assigned gate. In the second graph 5.4, without dispatch towing, the aircraft would have had to wait 22 minutes before receiving a ramp change and parking at a different gate from its assigned gate.

In the figures, the arriving flights are indicated in red, the departing flights are indicated in green, the flights influenced by the dispatch towing are indicated in blue, and all other flights planned at the gate are indicated in orange. For the two example graphs shown, the buffers involved are D93 and A31, respectively.

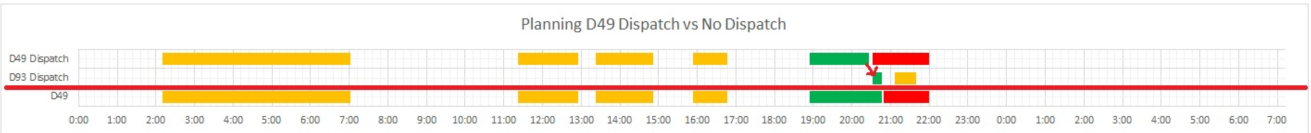



Figure 5.3: Gate planning D49 with and without dispatch towing

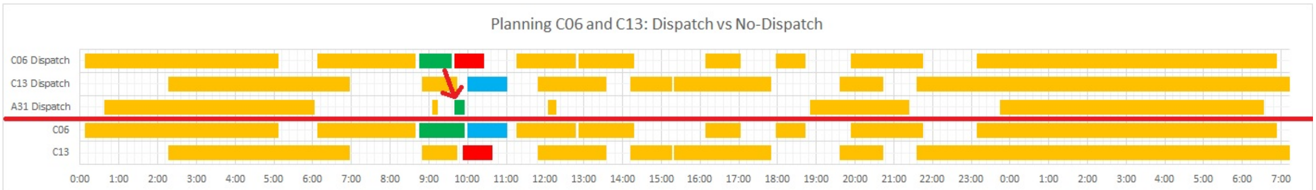



Figure 5.4: Gate planning C06 and C13 with and without dispatch towing

For the dispatch towing graphs, real data was entered into the Customized gate planner to determine the buffer availability for the departing aircraft. Then, the real-life gate planning model was used to graphically present the gate planning of the C06 and C13 gates without dispatch towing. Subsequently, the dispatch towing data adjustments were entered into the real life model to graphically present the gate planning with dispatch towing.

There were four more dispatch towing candidates on July $21^{st}$ 2014. The gate planning graphs created for these candidates can be found in appendix B. Thus, in total there were 6 dispatch towing candidates during the peak day of July $21^{st}$ 2014. There was enough space on the nearby buffers to accommodate the dispatch tows. Thereby, an average of 16minutes of arrival ground delay for arriving flights could have been saved per dispatch tow.

## 5.3. GATE PLANNING WITH PIT STOPS

Figure 5.5 provides a graphical view of the gate planning with pits stops for the relevant flights on July $21^{st}$. In the graphs, each different color represents one aircraft, except for orange which is used to indicate all other flights at the gates on July $21^{st}$ 2014.

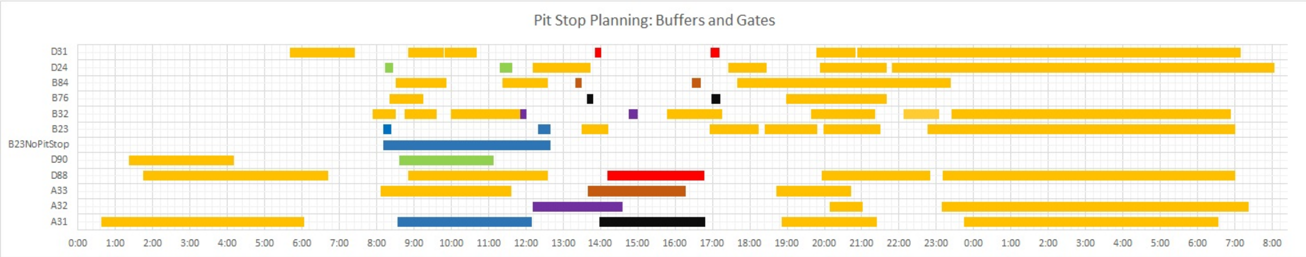



Figure 5.5: Gate planning with Pit Stops. Gate B23 also shows the planning without pitstops for comparison.

From the graph it can be seen that six flights during the day of July $21^{st}$ 2014 were pit stop candidates. During the time that the pit stop candidates are not occupying the gate, six other/additional flights could have been accommodated at the gates. The buffer availability for the pit stop model shown in figure 5.5 is based on the buffer planning produced by the Customized model. It can be seen from the planning model that there is enough room on the buffers for the six pit stops to be performed.

## 5.4. INITIAL RESULTS ANALYSIS

From graphical representation of the gate planning (see sections 5.1,5.2,5.3) some initial conclusions can be made.

The buffer planning graphs shown in section 5.1, indicate that, unlike the gates at AAS, there is quite a lot of planning room left in the buffer schedule. The buffers are not being used to their full capacity. Of course, it would be a bad idea to plan the buffers to their full capacity. However, the fact that they are not extremely busy, leaves room for the dispatch towing and pit stop concepts to be implemented. Without buffer space these concepts cannot be used.

The graph in section 5.2 provides insight into how the dispatch planning works and what it would look like for the gate planners at AAS. From the graph, it can be observed that the dispatch towing concept would create efficient room at the gate for the aircraft arriving to avoid delays, and the departing delayed aircraft can easily be accommodated at a buffer.

The Pit stop graph provided in section 5.3 shows that the dispatch planning concept can create a lot of room at overly congested gates. Thus, creating the ability for more aircraft to be handled at a gate. Especially those pit stop flights occurring during the peak hours are of interest.

Based on these initial promising results, Chapter 6 will elaborate on the impact of the dispatch towing and pit stop concepts. The focus will be put on the peak hours as during these hours the gates are at their highest capacity and, therefore, the dispatch towing and pit stop concepts will have the most effect.

# 6 EXTENDED MODEL AND CONCEPT ANALYSIS

The capacity calculations shown in section 3.3 provide insight into the current capacity at Schiphol airport. Most of the piers at schiphol airport are at or near their maximum capacity during the peek hours. With the implementation of the ETS dispatch towing and pit stop procedures, some of the gate congestion can be alleviated (as shown in Chapter5).

The pit stop concept essentially frees a gate for an additional flight to be handled. From figure 5.5 in chapter 5, it can be seen that for July $21^{st}$ 2014, if the pit stop concept were to be applied, a total of 6 extra aircraft could be handled at the airport's narrow body gates.

Even though dispatch towing does not necessarily allow for more aircraft to be handled at a gate, it does help alleviate ground congestion at the airport, reduce ground delays upon arrival, and provide a means to absorbing stochastic delays at airports. Aircraft waiting for a long time to be able to park at their gates, no longer have to wait if dispatch towing is implemented. This implies that the optimized gate planning is less often distorted due to delayed aircraft at a gate, resulting in a more optimal gate allocation and more robust scheduling.

The initial results are promising but they are only based on data from the busiest day of 2014. What would happen if traffic increased even further (as predicted)? What would happen to the gate planning schedule if more flights were to be delayed? The scale of the impact of the implementation of the concepts (via the use of the ETS) still needs to be investigated. With the predicted air traffic growth, it is of interest to known to what extent the pit stop and dispatch towing concepts can help increase capacity and efficiency at the airport. In order to investigate this, the models described in chapter 4 have been extended. This chapter outlines set-up, assumptions, and constraints of the extended models in section 6.1. Additionally, the results of the models are presented and then analyzed in sections 6.2 and 6.3.

## 6.1. EXTENDED MODEL SET-UP

Similarly to the initial models, the extended model is made up of two separate sub-models. One sub-model aims to shed light on the impact of pit stops on gate planning and schedules, and the other sub-model aims to shed light on the impact of dispatch towing on gate planning and delay absorption. Both models are based on (and use) data from the busiest day at AAS in 2014: July $21^{st}$ 2014. In the following sections, each model is outlined and described.

Essentially, both of the models are set up by determining the overall peak hours for the day of July $21^{st}$ (or any other day if so needed and flight schedule data is available). AAS experiences multiple operational peaks during the day with two main peaks: one in the morning and one in the early evening. From the capacity analysis provided in section 3.3 it can be concluded that all narrow body piers have a peak hour that starts at or includes 08:00a.m.. Logically, this results in the main morning peak hour from 07:00 until 09:00. The second peak runs from 18:00 until 22:00. The focus is put on the two main peak periods because during these hours capacity is of the highest concern and delays have the most impact on the overall flight schedule. For example, a 10% increase in the overall number of flights arriving at AAS throughout the day will not have as much of a direct impact on the gate capacity as a 10% increase in the number of flight arriving during a peak hour. Therefore, for the purpose of this research, extra flights are only added during peak hours and only peak hour flights are delayed.

### 6.1.1. PIT STOP ANALYSIS MODEL

The pit stop procedure may become particularly useful when more flights are expected to arrive at AAS. As mentioned previously, this is in fact what is expected to happen at the airport. The pit stop maneuver may be able to free up gates during the peak hours, thereby allowing more flights to be handled at the airport. To analyze the extent to which pit stops may be able to enhance capacity, a predefined percentage of flights is added to the peak hour flights in the schedule.

In order to add flights, a given percentage of existing peak hour flights are randomly selected and duplicated by the model. To make the schedule more realistically possible and the duplicated flights unique, a random number of minutes (according to a normal distribution with a mean of 2 minutes and a standard deviation of 4minutes) are added to the selected and duplicated flights. Thereby, random and unique flights are added to the peak hour schedule.

However, the newly added flights have not yet been assigned to a gate. The next process undertaken in the model is to schedule the added flights at the available gates if possible. the additional scheduled flights are subsequently added to the overall flight schedule. Some of the added flights will not be able to be scheduled, the model will attempt to reschedule these flights through the use of pit stops later on.

After forming the new flight schedule, the pit stop candidates are determined. For pit stop candidate qualification a flight must meet the same requirements as defined in RASAS and applied in the initial model (see section 4.1.3). That is: the flight has a turnaround time of at least 170 minutes and if the aircraft is towed away from the gate it has to be able to be parked on the buffer for at least 30 minutes. If a flight is selected as a pit stop candidate, it is split into a start phase at the planned gate, a middle phase at a buffer, and a final phase back at a gate (not necessarily the same gate the flight started from).

After the pit stop implementation, the model tries to reschedule the additional flights that had originally been left unplanned.

Finally, the number of added flights, the initial unplanned flights, the number of Pit Stop Candidates, the number of flights rescheduled after Pit Stop implementation, and the final number of unplanned flights is stored. Additionally, the number of initial gate operations, the number of gate operations with the additional flights and the number of final gte operations with the rescheduled flights is stored.

Subsequently, a monte carlo simulation process is applied by running the model a significant number of times to let the averages of the data stored converge. Thereby, resulting in an overview of the impact of the pit stop procedure for a certain percentage of flights added. The results of the pit stop model are presented and discussed in sections 6.3 6.2, respectively.

In order to gain insight into the set-up and workings of the pit stop analysis model, figure 6.1 provides a flow chart overview of the model.

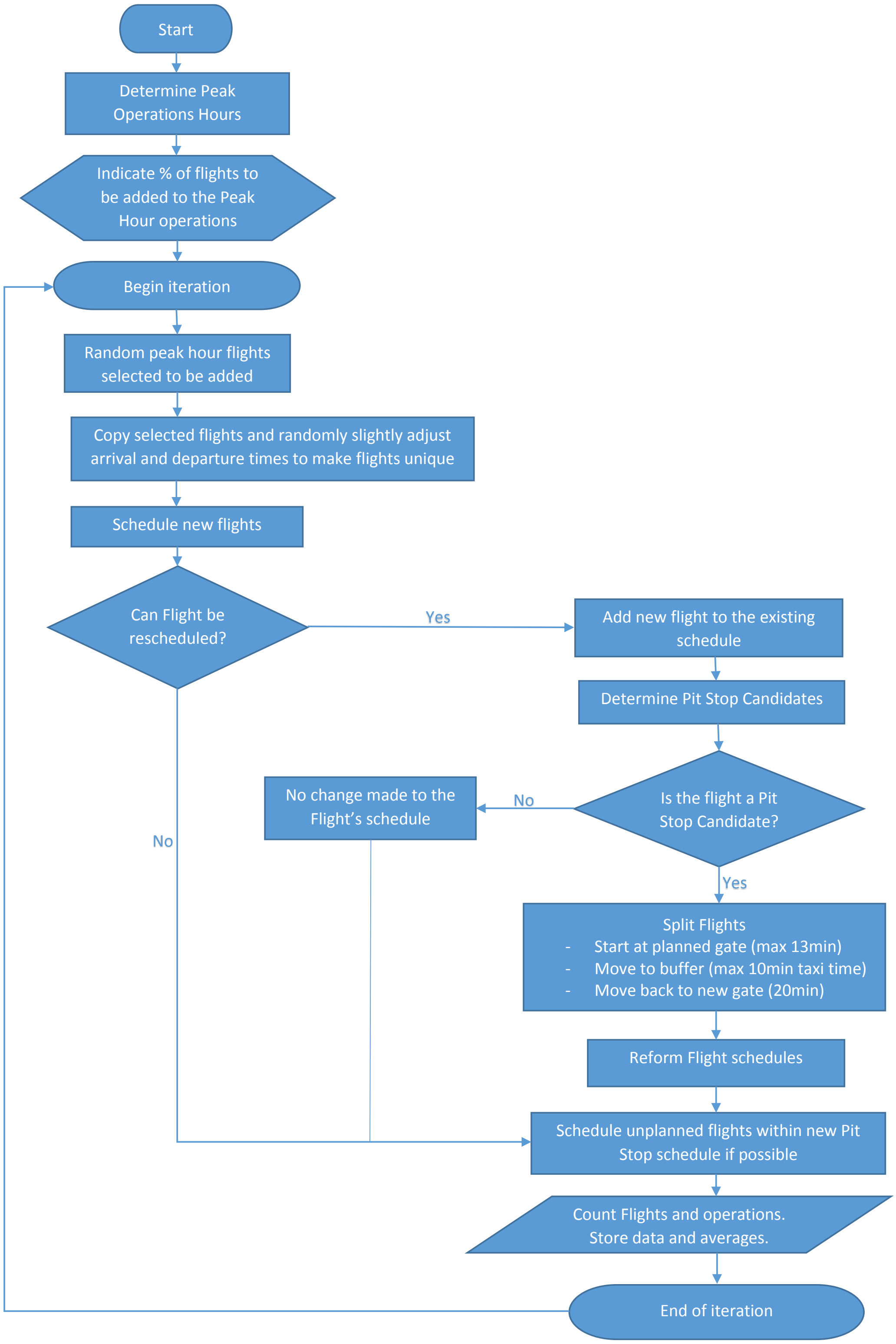



Figure 6.1: Flow chart of the pit stop analysis model

### 6.1.2. DISPATCH TOWING ANALYSIS MODEL

Besides additional flights, delays can also cause a strain on capacity and gate scheduling at airports. As shown previously (see chapter 5), the dispatch towing concept may offer some means to absorb/resolve delays and enhance the efficiency of buffer usage. The analysis model aims to shed light on the extent of the impact of dispatch towing.

After determining the peak hour flights, the percentage of peak hour flights to be delayed is indicated at the start of the iteration runs. Based on this percentage, a number of randomly selected peak hour flights are delayed. The amount (in minutes) by which the flights are delayed is determined by a random number according to a normal distribution with a minimum of 5 minutes, a maximum of 180 minutes, a mean of 25 minutes, and a standard deviation of 10 minutes. The mean of 25 minutes is based on delay data and information obtained from KLM for dispatch towing candidates over 2014.

Some of the delayed flights may have caused conflicts in the flight schedule. The model assesses whether a conflict with the next flight was caused and the extent of the conflict caused in minutes overlap with the next flight. Should the overlap caused be greater than 5 minutes and the entire delay of the flight be greater than 9 minutes, the flight qualifies as a dispatch towing flight. The reason the entire delay of the flight needs to be greater than 9 minutes is so that with a minimum taxi time of 5 minutes, the flight still spends at least 4 minutes on the buffer. Otherwise, the movement of the delayed flight to a buffer is inefficient. The maximum time between the buffer and the gate the delayed flight comes from is 10 minutes. Therefore, for any delay less than 14 minutes long, the delayed flight is towed to a buffer less than 10 minutes taxi time away.

Another aspect to consider when determining the impact of dispatch towing is the fact that not every aircraft that is delayed at a gate is actually able to move to a buffer; this depends on the reason for the delay. For example, if an aircraft is delayed because it is waiting for missing passenger or crew, then the aircraft cannot move away from the gate yet. However, if the aircraft is fully loaded but waiting for an ATC slot somewhere along its route or last minute baggage loading, then it can leave the gate and wait on a buffer. Every delayed aircraft is given a delay code according to the type of delay or reason for the delay. Based on these delay codes for a set of delayed and potential dispatch candidate flights over 2014, it was found that approximately 51% of delayed flights had delay reasons that would allow for dispatch towing. These reasons include:

- Departure slots
- Arrival slots at destination airports
- En-route slots (especially prevalent during the summer over European airspace)
- Last minute baggage loading
- Last minute minor aircraft maintenance

Basically, if passengers and crew have boarded the aircraft and the bridge/gate area is no longer needed, the aircraft can become available for dispatch towing if it is delayed.

The model takes these delay reasons into account by randomly selecting 51% of the potential dispatch candidates to perform a dispatch tow. These flights are then rescheduled to leave the gate at the original designated time and then move to an available buffer for the remainder of the delay.

Finally, per run, the model stores the data pertaining to the number of conflicts caused by the delays, the number of potential dispatch towing candidates, the number of solved conflicts, the number of unsolved conflicts, and the average amount of time saved for the arriving flights through the implementation of dispatch towing.

In order to gain insight into the set-up and workings of the dispatch analysis model, figure 6.2 provides a flow chart overview of the model.

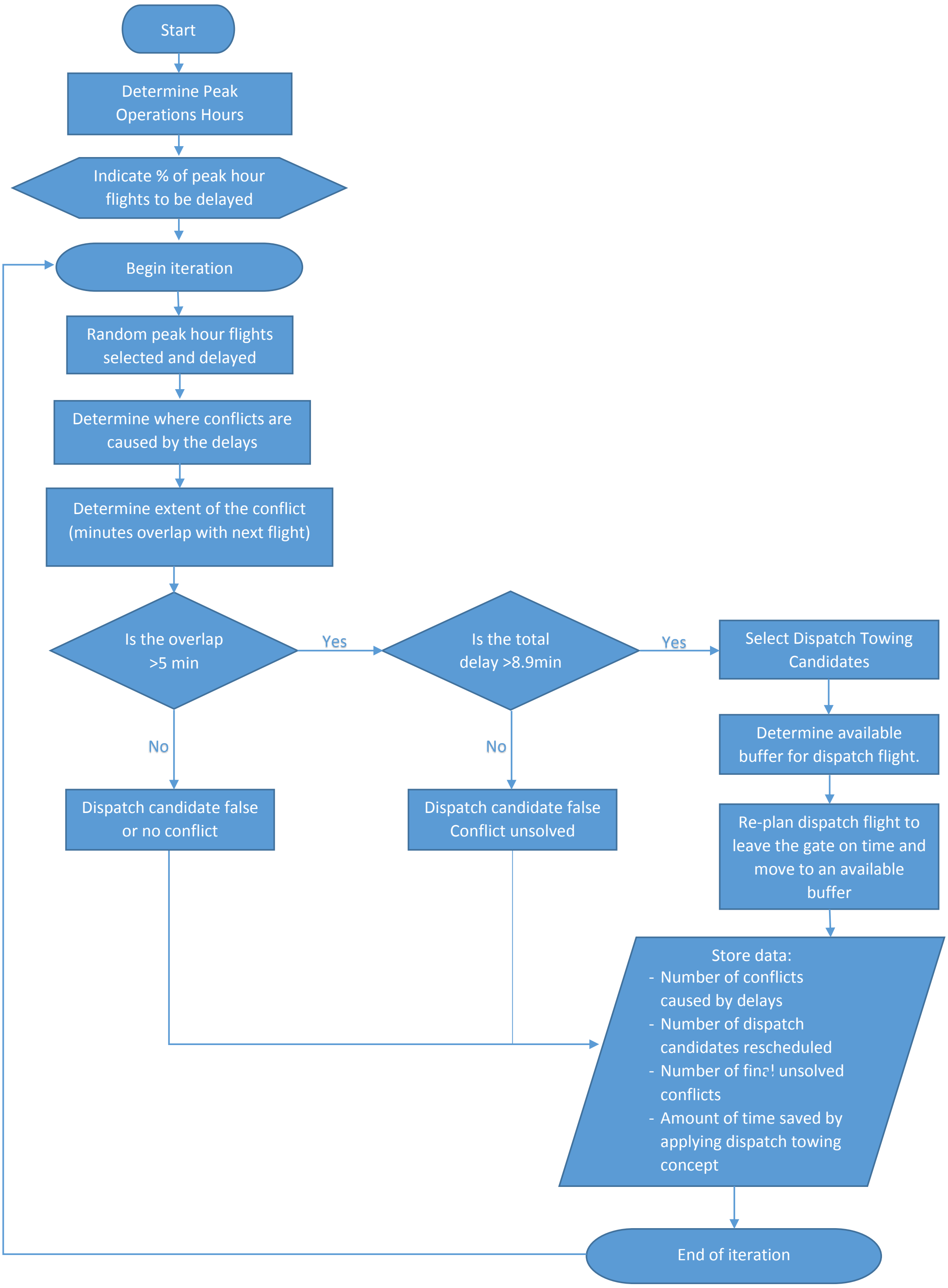



Figure 6.2: Flow chart of the Dispatch analysis model

### 6.1.3. ASSUMPTIONS

As the extended model is based on the initial model and the initial results, many of the same assumptions and constraints have been applied. These assumptions include:

- The ETS is only available for narrow body aircraft. Thus, only narrow body gates and aircraft are considered in by the extended model.
- Each narrow body aircraft that is a candidate for a pit stop or dispatch towing maneuver is equipped with an ETS.
- Transfer passengers, passenger walking distances, and aircraft ground handling service provider locations are not taken into account or optimized in the models. The assignment of flights to gates is, however, based on real-life data and constraints in order to maintain verifiability.
- All narrow body gates and buffers are assumed to be available for use.
- the minimum taxi time from a gate to a buffer is 5 minutes. The maximum taxi time between a gate and a buffer is set at 10 minutes.

The constraints applied to both models include:

- Schengen and Non-Schengen clasification matches between the gate and the flight.
- The aircraft type matches that of the gate type.
- For the dispatch towing and pits stop procedures only the buffers that are a maximum of 10 minutes taxi time away from the flight's gate are considered. For the narrow body gates in question these buffers include: the A-apron, the D-apron, and the R-apron.
- Aircraft leaving or arriving at two adjacent gates cannot do so at the same time.
- RASAS defines a minimum narrow body turnaround time of 170 minutes for a pit stop to be considered. Additionally, if the aircraft is towed away from the gate it has to be able to be parked on the buffer for at least 30minutes.
- For dispatch towing, the flights disturbing the planned operations are never favored. This implies that an aircraft will not be dispatch towed from its gate because the next aircraft arrived early. Furthermore, this implies that from the time the gate is planned to become available for the arriving aircraft, the delayed departing aircraft may be towed to a remote parking place to await its departure. This is only done if the departing aircraft will spend more than 4 minutes on the buffer.

Some additional assumptions and constraints are also applied to the extended model.

The pit stop model (or extra flight model) makes a few assumptions regarding the handling time at the gates and on the buffer. For the narrow body flights arriving at AAS the maximum time taken to offload passenger and luggage (as defined by the aircraft's characteristics for airport planning) is 13 minutes. After these 13 minutes the aircraft can leave the gate and the rest of the handling can be performed on the buffer until the loading of passengers and baggage commences. The flight then spends at least 30 minutes on the buffer. Subsequently, the flight moves back to a gate for the last 20 minutes of its turn around time. The 20 minutes loading time for passengers and final checks is also based on the narrow body aircraft characteristics for airport planning. For some aircraft the processes may take shorter than 13 or 20 minutes because the aircraft are smaller. However, for the purpose of this model, it is assumed that every pit stop flight spends at least 13 minutes at a gate upon arrival and 20 at a gate upon departure.

The extended pit stop model no longer assumes the aircraft performing the pit stop has to return to the same gate from which it left. However, the flight does have to return to a gate at least 20 minutes before its departure to avoid delays.

The extended dispatch towing model (or delayed flights model) also applies some additional constraints and assumptions. As described in the section 6.1.2, it is assumed that dispatch towing candidate flights are delayed by 25 minutes on average. This is based on data regarding dispatch towing candidate flights over 2014.

Additionally, the flights are assumed to be delayed a minimum of 5 minutes in order for the delay to be considered significant. Therefore, the overlap with the succeeding flight also has to be more 5 minutes in order for the delay caused to the succeeding flight to be considered significant.

Furthermore, the model assumes that the total delay has to be at least 9 minutes for the dispatch tow to be worth while. The model assumes that any total delay less than 14 minutes will be towed to a buffer no more than 5 minutes away from the gate. For all the flights with a total delay of more than 14 minutes, a buffer less than 10minutes away is designated (conforming with the rules set by AAS).

## 6.2. Extended Model Results

The following section will present the results obtained from the two extended analysis models. The models, as outlined in the previous sections, are run multiple times for different scenarios and each scenario undergoes multiple iterations. During each iteration, data is stored and averaged in order to check for convergence and obtain a final result.

For the Pit Stop extended analysis model the following scenarios are set up:

- 10% peak hour flights added
- 20% peak hour flights added
- 30% peak hour flights added
- 40% peak hour flights added
- 50% peak hour flights added
- 100% peak hour flights added

For each scenario the model is run at least 600 times to obtain a converging result. The results per scenario are shown in the tables 6.1 and 6.2. Table 6.1 provides an overview of the initial settings and steps of the pit stop extended analysis model. Subsequently, table 6.1 sheds light in the final situation results per scenario run. It should be noted that the initial number of operations at the gates (before any flights are added) is equal to 832 operations. An operation refers to either an arrival handling phase at a gate/buffer of a departure handling phase at the gate or buffer.

| Scenario | # Added Flights | # Unplanned flights initial | # pit stop candidates |
|---|---|---|---|
| 10 | 14 | 5.7 | 11.3 |
| 20 | 27 | 14.7 | 11.5 |
| 30 | 41 | 25.6 | 11.6 |
| 40 | 55 | 36.7 | 11.7 |
| 50 | 68 | 47.2 | 11.8 |
| 100 | 137 | 107 | 13 |

Table 6.1: Initial situations per scenario for the pit stop extended analysis model.

| Scenario | Final # re-planned flights (due to pit stop implementation) | Final # unplanned flights | Final # of Operations |
|---|---|---|---|
| 10 | 3.5 | 2.2 | 889.6 |
| 20 | 5.8 | 9 | 920.5 |
| 30 | 7.5 | 18.1 | 952.2 |
| 40 | 8.6 | 28.1 | 982.6 |
| 50 | 9.3 | 37.9 | 1010.2 |
| 100 | 12 | 95 | 1156 |

Table 6.2: Final situations per scenario for the pit stop extended analysis model.

The Dispatch towing extended analysis model is run for a minimum of 700 iterations per scenario run. The scenarios set up for the dispatch towing models are as follows:

- 10% peak hour flights delayed
- 20% peak hour flights delayed
- 30% peak hour flights delayed
- 40% peak hour flights delayed
- 50% peak hour flights delayed
- 100% peak hour flights delayed

Tables 6.3 and 6.4 provide and overview of the results of the dispatch towing analysis model.

| Scenario | # Flights delayed | # Conflicts caused | # Dispatch Candidates |
|---|---|---|---|
| 10 | 14 | 3.6 | 1.7 |
| 20 | 27 | 6.9 | 3 |
| 30 | 41 | 10.4 | 4.4 |
| 40 | 55 | 13.9 | 5.8 |
| 50 | 68 | 17.2 | 7.1 |
| 100 | 137 | 33.9 | 13.8 |

Table 6.3: Initial situations per scenario for the Dispatch towing extended analysis model.

| Scenario | # Flights rescheduled (due to dispatch towing) | # unsolved conflicts | Average amount of time saved (min) |
|---|---|---|---|
| 10 | 1.7 | 2 | 17 |
| 20 | 3 | 3.9 | 17.3 |
| 30 | 4.4 | 6 | 17.4 |
| 40 | 5.8 | 8.1 | 17.2 |
| 50 | 7.1 | 10 | 17.2 |
| 100 | 13.7 | 20.1 | 17.2 |

Table 6.4: Final situations per scenario for the dispatch towing extended analysis model.

## 6.3. ANALYSIS OF EXTENDED MODEL RESULTS

The results of the extended analysis models for the dispatch towing and pit stops are shown in section 6.2 and can now be analyzed in order to draw some conclusions.

### 6.3.1. PIT STOP EXTENDED MODEL ANALYSIS

Given the number of added flights and the number of initially unplanned flights, the number of initially rescheduled flights can be determined. This refers to the flights that could be added to the gate schedule with out the need for pit stops to be made. Thereby the percentage of flights that were initially planned and the percentage of flights that were intially unplanned can be found. Using the final number of rescheduled flights (through implementation of the pit stop concept) and the number of added flight, the percentage of rescheduled flights through pit stops is found. This results in the graphical analysis shown in figure 6.3.

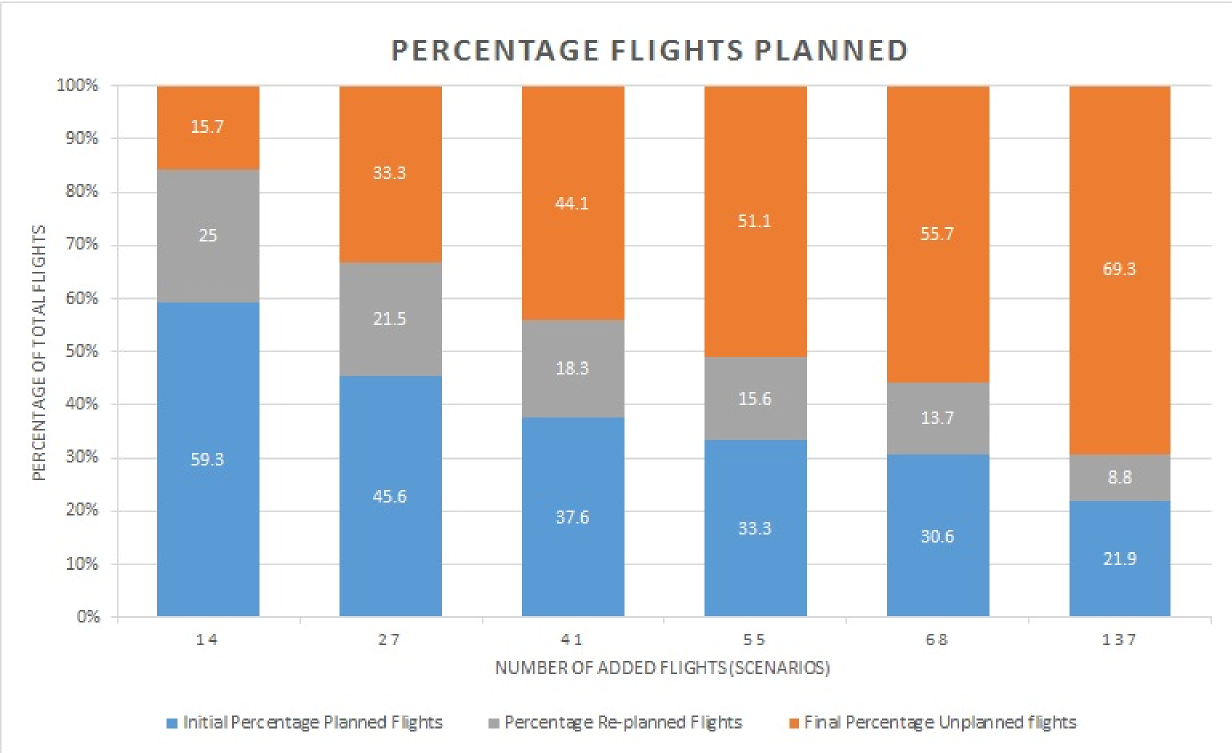



Figure 6.3: Pit stop analysis

From the graph it can be observed that if up to 41 flights are added to the peak hour schedule, more than 50% of those flights can be rescheduled with the use of pit stops. This corresponds to a 30% increase in the number of peak hour flights.

However, it can also be observed that none of the scenarios show a rescheduling of all of the added peak hour flights. At least 15.7% of the added peak hour flights is left unscheduled (corresponding to the 10% added flights scenario).This is due to the fact that the gate at Amsterdam Airport Schiphol are already nearly at their maximum capacity during the peak hours. Randomly adding flights to the peak hour gate schedule therefore already causes problems when only 10% of flight (or 14 flights) are added.

The model results show that a maximum of 25% of added peak hour flights can be rescheduled using the pit stop concept. Even though the number of rescheduled flights increases when more flights are added, the graph in figure 6.3 shows that percentage-wise the number of peak hour flights rescheduled using pit stops decreases when increasing numbers of flights are added. This is due to the fact that as more flights are added, the schedule becomes more and more saturated. It can be seen in table 6.1 that the number of pit stop candidates per scenario does not vary much. This implies that the initially rescheduled added flights often do not qualify as pit stop candidates. With all the restrictions and flight characteristics needed for a pit stop to take place and a new flight to be planned at the gate, it becomes logical that the more flights that are added, the lower the percentage of flights that can be rescheduled is. Thus, even with pit stops there is only very little room in the gate schedule for the additional unplanned flights.

Figure 6.3 also shows the worst case scenario: 100% of the peak hour flights are added to the schedule. In this case 69.3% of the added flights cannot be rescheduled. However, the use of the pit stop concept still allows for an additional 8.8% of flights to be scheduled, corresponding to 12 extra peak hour flights.

Currently, the minimum turnaround time needed for an aircraft to be considered for a pit stop is 170minutes [32]. However, the turn around time needed after off-loading passengers and baggage, and before reloading, is only 22minutes for most narrow body aircraft. Therefore, the turnaround time necessary for a narrow body aircraft to perform a pit stop is actually: 13+10+22+10+20 = 75 minutes. The Pit stop (or extra flights) extended analysis model was run again for each traffic scenario in order to investigate the number of additional peak hour flights that can be handled if pit stops are implemented with an aircraft minimum TAT qualification of 75 minutes. Tables 6.5 and 6.6, provide and overview of the results for pit stop analysis with a candidate minimum TAT of 75minutes instead of 170minutes.

| Scenario | # Added Flights | # Unplanned flights initial | # pit stop candidates |
|---|---|---|---|
| 10 | 14 | 5.7 | 76 |
| 20 | 27 | 14.7 | 76.9 |
| 30 | 41 | 25.6 | 77.4 |
| 40 | 55 | 36.7 | 77.7 |
| 50 | 68 | 47.2 | 78.1 |
| 100 | 137 | 107 | 79 |

Table 6.5: Initial situations per scenario for the pit stop extended analysis model with candidate TAT of 75 minutes.

| Scenario | Final # re-planned flights (due to pit stop implementation) | Final # unplanned flights | Final # of Operations |
|---|---|---|---|
| 10 | 4.3 | 1.4 | 1020.6 |
| 20 | 8.4 | 6.3 | 1056.7 |
| 30 | 12 | 13.6 | 1092.6 |
| 40 | 15 | 21.7 | 1127.5 |
| 50 | 17.2 | 30 | 1158.5 |
| 100 | 23 | 84 | 1310 |

Table 6.6: Final situations per scenario for the pit stop extended analysis model with candidate TAT of 75 minutes.

From the tables it can be observed that there are significantly more pit stop candidates than can be seen with minimum TAT of 170minutes for pit stop candidates. Logically this also leads to a greater number of added flights to be allocated to a gate. A similar analysis graph (see figure 6.4) was created for the pit stop candidate 75 minute TAT for comparison.

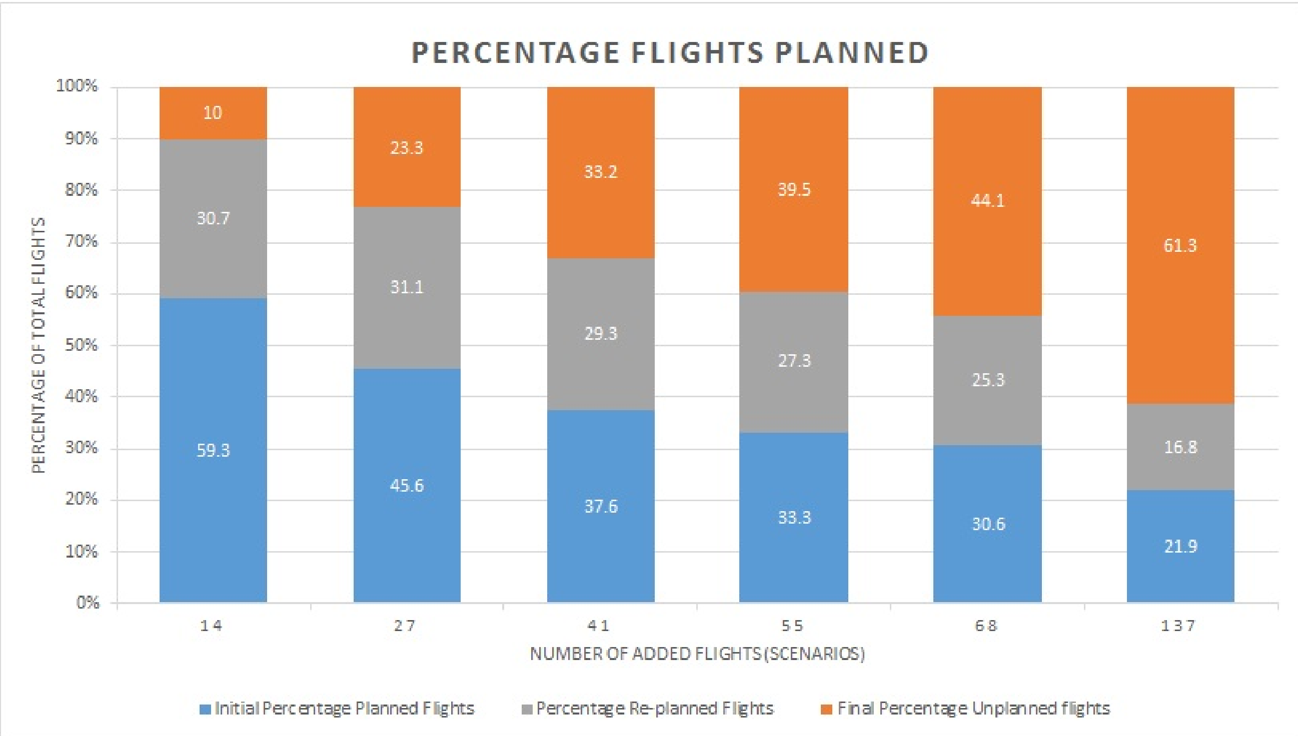



Figure 6.4: Pit stop analysis for a minimum TAT of 75minutes for pit stop candidates

From figure 6.4, it can be seen that, with a minimum TAT of 75minutes for pit stop candidates, up to 30.7%

of added flights can be allocated to a gate through the use of the pit stop concept. This is 5% more than for the case in which a minimum TAT of 170 minutes is necessary. Additionally, where in the initial case 69% of flights could not be rescheduled in the worst case scenario, this is 61% for the 75minute TAT case. Thus, it can be concluded that reducing the minimum TAT required for aircraft to qualify as pit stop candidates, allows for even more flights to be scheduled at the gates. However, it should be noted that even with a minimum TAT of 75minutes, not all aircraft added during the peak hours can be scheduled. This is due to the fact that not all pit stop candidates allow for room in the gate planning schedule where this room is necessary for the additional flight. This is mainly due to the complexity of the flight schedules.

Even though the pit stop procedure is a known procedure at AAS, it is currently not often used and it is also never planned with ahead of time. The ETS will allow for a more widespread application of the concept and may even allow AAS to begin planning gate with pit stops as well.

From the results shown through this simplified model, it can be concluded that the pit stop concept will not be able to alleviate all of the capacity strain on the gate at AAS during peak hours. However, the concept will allow for some congestion relief and if less than 10% of peak hour flights are added, the pit stop concept can help increase capacity at the gates.

### 6.3.2. DISPATCH TOWING EXTENDED MODEL ANALYSIS

The dispatch towing concept also shows some promising results. Table 6.7 provides and overview of the percentages relating to the model results per delay scenario.

| Scenario | % of delayes that cause conflicts | % of conflicts that can be rescheduled | % of delayed flights rescheduled by dispatch towing | Total % of arrival delays that can be avoided |
|---|---|---|---|---|
| 10 | 25.7 | 47.2 | 12.1 | 86.4 |
| 20 | 25.6 | 43.5 | 11.1 | 85.5 |
| 30 | 25.4 | 42.3 | 10.7 | 85.4 |
| 40 | 25.3 | 41.7 | 10.5 | 85.3 |
| 50 | 25.3 | 41.3 | 10.4 | 85.1 |
| 100 | 24.7 | 40.4 | 10 | 85.3 |

Table 6.7: Final situations per scenario for the dispatch towing extended analysis model.

From the table it can be observed that for each scenario approximately 25% of the delayed flights cause conflicts. This does not mean that the same number of conflicts is caused in each scenario but merely that the percentage of delayed flights causing a conflict is nearly the same for each scenario.

Furthermore, it can be seen from the table that most of the percentages are very similar. This implies that the usefulness of the dispatch towing concept does not diminish if more flights are delayed; approximately the same percentage of delay conflicts can still be solved through the use of dispatch towing. Thus, approximately 85-86% of peak hour flights can either be delayed without causing a conflict or dispatch towed to avoid a conflict. 10-12% of the peak hour flights delayed will cause conflicts which can be solved through dispatch towing.

Another interesting thing to note from the results shown in table 6.4 is that the average amount of delay time saved for arriving flights is between 16 and 17 minutes. This means that, on average, with the random delay sequence applied, the next arriving flights would have had to wait 16 to 17 minutes for their planned gates to become available. This time is saved through the application of dispatch towing, allowing the arriving aircraft to taxi to its gate without any delays. This is of particular value to the airlines because of non-performance cost indexing. If a flight has transfer passengers and crew nearing the end of their legal shift hours on board, a delay can be very costly for the airline. Transfer passengers may miss their connecting flights resulting in extra costs for the airline and low customer satisfaction. For the airline it is therefore of vital importance to get their aircraft to a gate on time to avoid these additional costs. The exact extent of these costs differs greatly per flight (as it is dependent on the number and type of transfer passengers, as well as the crew on board). Additionally, KLM does not have the data relating to these costs readily available. Therefore, no estimation of the cost that a 16-17 minute delay would cause (or save in the case of dispatch towing) can be made.

It is important to note that, unlike pit stops, dispatch towing is not a tool that can be used to plan with. The delay that occur at airport are stochastic and dynamic and can therefore not be predicted. Thus, the dispatch towing concept can be applied only on a tactical basis. Should a flight be delayed for unforeseen reasons, the gate planner can then assess whether a dispatch tow is possible in order to prevent further delays to other flights.

From the model results it can be concluded that, even though the not all delay conflicts can be solved using dispatch towing, up to 45% of conflicts can be solved using the dispatch towing concept. Worst case scenario, should all peak hour flights be delayed (137 flights in this case), then on average 33.8 conflicts occur of which 13.7 can be solved by dispatch towing. Thus, not all delay conflicts can be solved through dispatch towing but from the results it can be concluded that the dispatch towing concept offers a good means to absorb some delays by making more efficient use of the buffers.

# 7
# Value Operations Methodology

A performance value model can be established to assist in the development of a design, model, or project. In chapter 2 section 2.2, the theory behind value driven design and decision making is introduced. The value operations methodology (VOM) set-up has been presented and used successfully as a framework in past research performed by Richard Curran et al. [9] in order to evaluate airports and airport systems. Furthermore, Bas Bennebroek [5] used the VOM framework to assess and innovate runway maintenance strategy at AAS while taking the multitude of stakeholders involved into account. Using this literature as a basis, a value model is developed for the ETS impact on apron operations at AAS.

The final value model is presented in chapter 8. However, in order to develop the ETS apron operations value model, the proposed value model set-up is presented and discussed in detail in the following sections (sections 7.1, 7.2, and 7.3).

## 7.1. The Proposed Value Model

The value model proposed for the Msc. thesis work is based on the value operations methodology presented by Richard Curran [26][9]. Inspired by value driven design (VDD), Curran presents a holistic approach to calculating a change in value. Thereby, the impact of a design alternative (or in the case of the ETS: new operational procedures and a new technical system) can be measured as either having a negative effect, no effect, or a positive effect on the system in question (the apron area in this case):

- $\Delta V > 0$ : Value is added/created
- $\Delta V = 0$ : There is no value difference between the base and alternative situations
- $\Delta V < 0$ : Value is decreased/destroyed

Thus, an alternative is compared to a baseline situation according to the following formula [26]:

$$\Delta V = \left\{ \sum_{1}^{n} \lambda_n v_n \right\} - 1 \tag{7.1}$$

with:

$$v_n = \sum_{1}^{p} \omega_p \left( \frac{x_{p,1}}{x_{p,0}} \right) \tag{7.2}$$

and where:

- $\lambda_n$ = The objective group weight
- $v_n$ = The partial $\Delta v$
- $\omega_p$ = The individual attribute weight
- $x_{p,1}$ = Actual attribute score
- $x_{p,0}$ = Baseline attribute score

In order to assess the change in value (added value or deceased value) of design alternatives, the objectives that influence the system are identified. They are subsequently assigned weights according to their importance within the system. Furthermore, the attributes that influence the objective are defined and assigned a reference (base situation) value, a value for the alternative situation, and a weight (according to its importance/influence within the objective group).

The major advantage of using the $\Delta V$ function is that the result is dimensionless which allows the user to combine different units (ex. cost in Euro's and noise in dB) within the same equation to get an overall indication of the value impact of a new design, system, or procedure. However, the accuracy of the model is very dependent on the weight and score definition of objectives and attributes.

The Value model attributes, objectives, and weights are discussed in further detail in sections 7.2 and 7.3.

## 7.2. VALUE MODEL OBJECTIVES AND ATTRIBUTES

The first step to forming the value model for the ETS impact on apron operations, is to determine the values (or objectives) involved. In relation to the airport environment, these objctives are often expressed as key performance indicators (KPIs). For the impact of the ETS on the airport apron environment, four KPIs are identified, namely; safety, capacity/efficiency, costs, and the environment. These KPIs/objectives are further discussed in chapter 8.

In addition to the value model objectives, the attributes that pertain to these objectives are identified. The objectives and attributes can fall into three distinct categories[26]:

- Natural : the objective/attribute is easy to and logical to measure
- Proxy : the objective/attribute is measured indirectly (for example: safety could be indicated by the number of accidents over a period of time)
- Constructed : the objective/attribute cannot be naturally measured and is vaguer. (for example: noise nuisance or situational awareness)

Care should be taken when assigning constructed attribute scores as these attributes are often qualitative and cannot be expressed easily quantitatively. The scores assigned to these attributes need to be well-justified for the value model to remain accurate and valid. Expert consultation should be used in order to determine the appropriate scores for these attributes [26].

As shown in equation 7.3, for each attribute a value of the baseline concept (without ETS) is determined and an attribute value for the new concept (with ETS) is determined.

$$v_n = \sum_{1}^{p} \omega_p \left( \frac{x_{p,1}}{x_{p,0}} \right) \tag{7.3}$$

For a quantitative analysis the values assigned to the attribute scores should be based on existing data and/or calculations performed using data available in order for the value model to be verifiable. However, in some cases, a quantitative analysis is difficult due to a lack of available data or time constraints. A qualitative analysis is more appropriate in those situations. In the qualitative analysis the impact of the new situation (apron operations with ETS) on the attributes and objectives is compared to a reference situation (apron operations without ETS) based on a scoring scale used by Bennebroek [5]:

| | |
|---|---|
| - - - | for a highly negative change to the attribute |
| - - | for a medium negative change to the attribute |
| - | for a low negative change to the attribute |
| 0 | for no change |
| + | for a low positive change to the attribute |
| ++ | for a medium positive change to the attribute |
| +++ | for a highly positive change to the attribute |

The value model, as presented, generally only allows for a quantitative analysis, therefore the quantitative analysis scoring scale needs to somehow be converted to numerical values. This can be done according to the following conversion table 7.1 (see the work of Bennebroek for further reference [5]).

| CONVERSION | +++ | ++ | + | 0 | − | −− | −−− | $x_{min}$ | $x_{max}$ |
|---|---|---|---|---|---|---|---|---|---|
| Constant | 1 | 1 | 1 | 0 | −1 | −1 | −1 | −1 | 1 |
| Linear | 3 | 2 | 1 | 0 | −1 | −2 | −3 | −3 | 3 |
| Polynomial | 9 | 3 | 1 | 0 | −1 | −3 | −9 | −9 | 9 |

Figure 7.1: Qualitative score conversion table for use in the value model. [5]

The qualitative scores assigned to an attribute are sensitive to directional preference. Thus, a negative score does not necessarily imply a negative change in value because the directional preference may be downwards (ex. lower costs). Likewise, a positive change in attribute score may not mean a positive change in overall value (ex. increased emissions).

It is important to note that the attribute score ratio ($\frac{x_{p,1}}{x_{p,0}}$) has a directional preference. In this case, the directional preference is upwards, meaning that if the score of an attribute increases, its contribution to the value is positive (it is increasing value). This can be the case for attributes such as capacity (a higher capacity increases value). However, for many attributes the direction of preference is downwards; value is added when the attribute score decreases. This is case, for example, for costs: a decease in cost increases value. The ratio presented does not work for the downward direction preference (instead of adding value the the attribute decrease, the value is shown to decrease).

A simple solution would be to switch the ratio direction around according to the direction of preference:

$\frac{x_{p,1}}{x_{p,0}}$ for an upwards direction of preference
$\frac{x_{p,0}}{x_{p,1}}$ for a downwards direction of preference.

However, as pointed out by Bennebroek [5], this solution has a big flaw. For the upward directional preference attributes, the value changes linearly:

$$\Delta V = \omega_p \left( \frac{x_{p,1}}{x_{p,0}} \right) = C_1 x_{p,1} \tag{7.4}$$

Whereas for the downward directional preference the value changes hyperbolically [5]:

$$\Delta V = \omega_p \left( \frac{x_{p,0}}{x_{p,1}} \right) = C_2 \frac{1}{x_{p,1}} \tag{7.5}$$

Therefore, it is important to keep the ratio used consistent. For this research the a new score is always divided by the base/reference attribute score ($\frac{x_{p,1}}{x_{p,0}}$).

In order to solve the downward and upward directional preference problem, Bennebroek suggests the use of feasible range equations for the attributes. The feasible range equations, shown in equations 7.6 and 7.7, were originally set up in order to incorporate the fact that the attribute scores are bounded by a maximum and minimum: they cannot change infinitely [5]. Thus, the feasible range equations both allow for the use of a consistent ratio and allow the feasible range of the attribute scores to be included. The feasible range attribute scores for the upward direction preference are calculated using equation 7.6[5]:

$$(x_p)_{0,1}^{FR} = \frac{(x_p)_{0,1} - x_{min}}{x_{max} - x_{min}} \tag{7.6}$$

The feasible range attribute scores for the downward direction preference are calculated using equation 7.7:

$$(x_p)_{0,1}^{FR} = 1 - \frac{(x_p)_{0,1} - x_{min}}{x_{max} - x_{min}} = \frac{x_{max} - (x_p)_{0,1}}{x_{max} - x_{min}} \tag{7.7}$$

The specific objectives and attributes relating to the analysis of the ETS impact on the airport apron area, are discussed in section 8.1.

## 7.3. VALUE MODEL OBJECTIVE AND ATTRIBUTE WEIGHT SCORES

The defined attributes and objectives of the value model are assigned weights according to their importance either within the objective group (attribute weight) or for the overall system (objective weight). Each set of objective group attribute weights needs to add up to a total of 1.

For example: the number of apron personnel accidents and the situational awareness of pilots can be identified as two separate attributes to be measured. They can then be combined under the group attribute: "safety" which is also assigned a weight ($\lambda_n$). The two separate attributes are then assigned weights that add up to 1 according to their importance within the attribute group. In addition, the objective group weights of the value model add up to 1 as well.[5]

Thereby, the objectives and attributes are weighed relatively to other objectives/attributes within the value model or objective group. This is done in a pair-wise comparison between the attributes/objectives; combining the analytical hierarchy process (AHP) with the value operations methodology (presented by Curran et al. [53]).

For example, if an objective X is relatively extremely more important than objective Y, then the pair-wise weight comparison may look like this: $\frac{W_X}{W_Y} = 9$. Whereas, if objective X is only very slightly more important that objective Y, the weight comparison may look like this: $\frac{W_X}{W_Y} = 2$. For this example the fundamental scale (which runs from 1 to 9) was used. However, the comparison scales used to establish the pair-wise comparisons can differ [5]. The most common scales used are shown in figure 7.2.

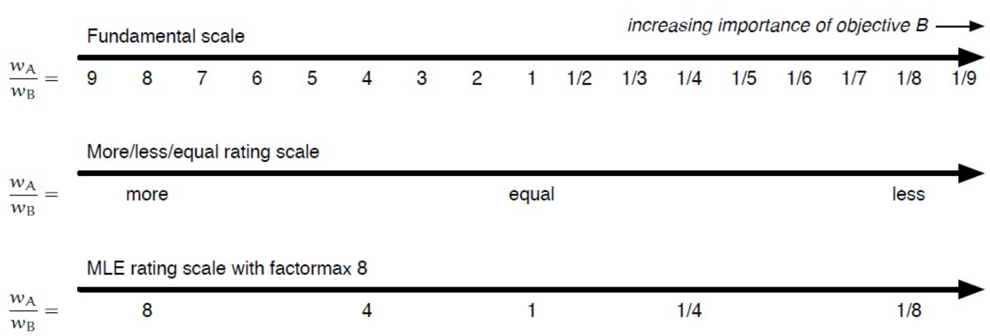



Figure 7.2: Scales used to assign pair-wise comparison weights [5]

Logically, the reciprocal of the weight comparison of objective X to objective Y, is the weight comparison of objective Y to objective X. For example, if $\frac{W_X}{W_Y} = 9$, then $\frac{W_Y}{W_X} = 1/9$, indicating that objective X is much more important than objective Y and objective Y is much less important than objective X.

In his research on the scaling methods for use in the analytical hierarchy process (AHP), Saaty [54][55] proposes two main characteristics the scale should adhere to:

- The rating scale maximum score should be of the same order of magnitude as the number of objectives involved in the pair-wise comparisons [55]. For this research that would imply a maximum scale factor of 4.

- Differences of one unit on the rating scale. (for the more/less/equal rating scale this would mean a maximum factor of only 2 [5])

Furthermore, past research indicates that the rating scale should be expressed as a power series:

$$(\ldots, f^{-3}, f^{-2}, f^{-1}, f^0, f^1, f^2, f^3, \ldots)\ [5]$$

In this rating scale approach, $f^0$=1 and indicates the objectives are equally as important.

Based on this past research on the AHP pair-wise comparison scales, for this research, a scale with a maximum score of 4 is used. This leads to a scale as follows (Imp(A) indicates the importance of objective A):

- $Imp(A) >> Imp(B) \Rightarrow \frac{W_A}{W_B} = 2^2 = 4$
- $Imp(A) > Imp(B) \Rightarrow \frac{W_A}{W_B} = 2^1 = 2$

- $Imp(A) = Imp(B) \Rightarrow \frac{W_A}{W_B} = 2^0 = 1$
- $Imp(A) > Imp(B) \Rightarrow \frac{W_A}{W_B} = 2^{-1} = \frac{1}{2}$
- $Imp(A) >> Imp(B) \Rightarrow \frac{W_A}{W_B} = 2^{-2} = \frac{1}{4}$

To determine the weights to assign to the objectives and their attributes, the pair-wise comparisons can be entered into a comparison matrix (M):

$$M = \begin{pmatrix} 1 & \frac{W_A}{W_B} & \cdots & \frac{W_A}{W_n} \\ \frac{W_B}{W_A} & 1 & \cdots & \frac{W_B}{W_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{W_n}{W_A} & \frac{W_n}{W_B} & \cdots & 1 \end{pmatrix} \tag{7.8}$$

Due to the fact that all of the matrix entries are positive, at least one positive and real eigenvalue ($\lambda$) will exist. The eigenvector ($v$) relating to the largest, positive, real eigenvalue, is used to determine the weights of the objectives or attributes, according to the analytical hierarchy process [9][5]. This is done by normalizing the eigenvector according to equation 7.9.

$$\vec{v}_{normalised} = \frac{\vec{v}}{\sum_{i=1}^{n} v_i} \tag{7.9}$$

The normalized eigenvector values ($\vec{v}_{normalised} = (v_a, v_b, ..., v_n)$) then indicate the objective or attribute weight values [9][5].

Now that the set-up of the value model for this research has been discussed, the value model objectives and attributes related to the ETS impact on the airport apron environment are discussed in the next chapter (chapter 8). Finally, the value model qualitative results are also presented in chapter 8.

# 8
# A Value Model for ETS impact on Apron Operations

As suggested by the value model theory and proposed set-up presented in the previous chapter (chapter 7), the first step in setting up the value model is defining the objectives (or key performance indicators (KPIs)), the objective attributes, and the stakeholders at hand. The objectives and attributes are discussed in section 8.1, followed by the development of the value model pertaining to the ETS impact on the airport apron area.

As indicated by the ETS research and by the companies developing the electric taxi systems (see section 2.1), implementation of an ETS offers the opportunity for many improvements, especially with regards to fuel consumption, emission reductions, and procedural changes (see chapter 2). These improvements influence key performance indicators (KPIs) such as; safety, efficiency, delay, capacity, costs, and environmental factors, defined by the stakeholders involved. In this case, the stakeholders are the airports (specifically AAS in this case), the airlines (specifically KLM in this case), the pilots, ATC, the ground crew, the regulatory authorities, the general public, and the passengers. For the purpose of this research and the development of the value model, the main stakeholders considered are the airport (Amsterdam Airport Schiphol) and KLM Royal Dutch Airlines.

Based on the identified KPIs, the following sections draw light on the predicted improvements and challenges that the ETS can present for apron operation per objective.

## 8.1. ETS & Apron Operations Objectives & Attributes

Due to its characteristics, the ETS offers many advantages for apron operations. As indicated in chapter 2.1, both the EGTS and Wheeltug systems offer overall improvements in fuel and emission savings, especially during the taxi phases of the flight. The taxi-phase presents the most opportunity for fuel saving seeing as this ground phase conventionally requires the use of at least one or two of the aircraft engines to be running. With the use of the ETS the main aircraft engines do not need to be used during the taxi phase except for their required start-up/warm-up time before take-off. The ETS also allows for some small fuel savings during the pushback phase as the aircraft engines are not yet started and the conventional pushback truck, wich is generally powered by fuel, is no longer used. [56][57]

Besides these fuel saving benefits and related environmental benefits, the previous chapters have also shown that the procedures enabled by the ETS may help increase airport gate capacity and reduce arrival delays. Thus, the ETS may also present the opportunity for increased gate planning and capacity efficiency. Furthermore, the ETS provides opportunities regarding safety improvements and cost reduction.

The following sections will discuss the KPIs involved with, or influenced by, the implementation of the ETS in detail. For each KPI the quantitative and qualitative value model attribute scores are summarized at the end of the sections.

### 8.1.1. Safety

The ETS will influence the platform safety by eliminating or reducing the number of operational tow trucks and by allowing for autonomous pushbacks.

#### Reduction in Tow Truck and Pushback Incidents

An important improvement offered by the ETS is the increase in spatial efficiency and, subsequently, the reduction in foreign object damage (FOD) and apron area collisions. The airport apron is a busy area where many activities take place within a relatively small space. Due to the growth in air traffic, airport apron spatial efficiency has become an important aspect in maintaining safe apron operations as well as meeting capacity demands [58]. The elimination of the need for tow trucks would imply less traffic around the aircraft thereby, decreasing the chance of FOD and collisions.

A decrease in the number (or elimination) of operational tow trucks also reduces the amount of traffic on the perimeter roads. The perimeter roads around the terminal buildings are busy with baggage, maintenance, and service trucks. Reducing the number of vehicles on these perimeter roads also decreases the number of incidents that occur on these roads.

Additionally, the tow truck, as well as the pushback process itself, pose risks to the aircraft. Dieke-Meier provides an overview of the recorded number of damages caused by the pushback process using a conventional tow truck. This overview is shown in figure 8.1.

| collision by | caused by | | absolute |
|---|---|---|---|
| tug/towbar | jackknife of the tug because of | | |
| | | poor surface conditions | 7 |
| | | high speed, abrupt stop o. a. | 5 |
| | defect of the tug | | 2 |
| | icy surface – no braking action | | 1 |
| | loss of connection tug to aircraft | | 8 |
| | broken towbar | | 5 |
| | broken shear pin | | 4 |
| aircraft | aircraft defect | | 4 |
| | unintentional moving aircraft | | 6 |
| | mistakes/lack of hand signal "free" | | 8 |
| | parallel engine start (e.g. wrong power setting) | | 3 |
| | released/not released parking break | | 2 |
| | collapsed nose gear | | 4 |
| | | *sum* | *59* ‡ |

Figure 8.1: "Number of occurences of damage to/by a pushed aircraft to/by a tug or towbar at U.S. airports from 1991-2008." (Dieke-Meier, 2012 [4])

From figure 8.1, it can be observed that damage to the aircraft caused by the conventional pushback procedure is not uncommon. This damage not only implies high reparation costs but also a safety breach for ground employees and crew. According to the research performed by Dieke-Meier et al.[4], of the 59 reported damages, 24 were recorded as 'accidents'; implying that the aircraft sustained substantial damage, or a fatality or serious injury occurred. Thus, the use of an ETS, and subsequent elimination of the tow truck, presents the opportunity for reducing the probability of causing damage to or by an aircraft during the pushback procedure.

Besides reducing FOD and pushback damage, the ETS further increases apron safety by reducing the number of employees needed for a successful pushback. Figure 8.2 shows the statistics regarding serious injuries and fatalities of Walk-out assistants or tow truck drivers during the pushback procedure using a conventional tow truck, as presented by Dieke-Meier et al.[4].

With fewer ground crew in the proximity of the aircraft, a reduction in the probability of serious injuries or

| accident/incidents | | fatalities | serious injuries |
|---|---|---|---|
| walk out assistance | contact with nose gear | 1 | 4 |
| | contact with tug | 1 | 1 |
| | other causes (towbar …) | 0 | 3 |
| tug operator | contact with aircraft | 1 | 5 |
| aircraft cabin crew | abrupt pushback stop | 0 | 3 |

Figure 8.2: "Ground/Aircraft crew injuries and fatalities during pushback at U.S. airports, 1991-2008" (Dieke-Meier, 2012 [4])

fatalities of ground personnel can be realized. Thus, the ETS with autonomous pushback capabilities presents an additional safety advantage compared to conventional taxi procedures.

At AAS tow truck incidents are not uncommon. To shed light on the impact of removing tow trucks from operation through the use of ETS, data regarding the incidents involving tow trucks was collected. The data, provided by AAS, indicates that between the period of 13-01-2013 and 23-09-2015 (983 days), a total of 551 tow truck incidents took place at the airport. This implies that approximately 1 incident takes place every two days. Table 8.1 provides an overview of the number of tow truck incidents recorded and the processes and process phases during which the incident occurred. The incidents recorded are those which were either caused by or simply involved tow trucks.

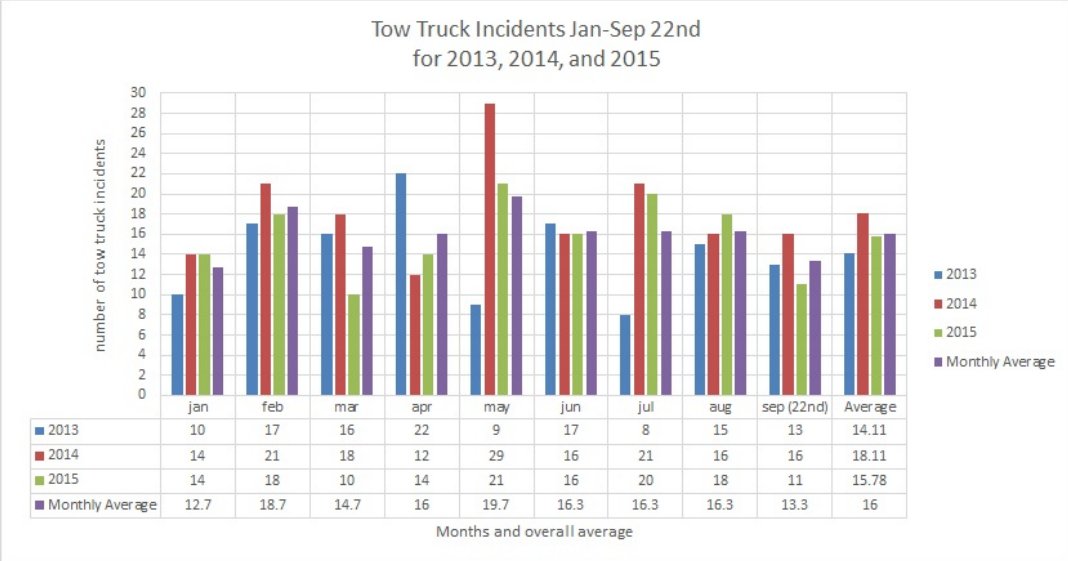
As Amsterdam Airport Schiphol is nearing its capacity, the platform and perimeter roads are becoming busier. The Tow trucks take up a large amount of space, especially on the perimeter roads, and also require to be parked somewhere safely during off-peak hours. From table 8.1 it can be seen that the parking and moving of tow trucks results in nearly 260 of the overall 551 incidents. The actual maneuvering of the aircraft (towing and pushback processes) resulted in 250 incidents. From this it can be concluded that the elimination of the use of tow trucks would significantly reduce the number of platform, perimeter road, towing, and pushback incidents. Thereby, the ETS offers a means to improving apron safety at AAS.

| Process | Process phase | Number of Incidents |
|---|---|---|
| Pushback/Start-up | Total | **181** |
| | At-/detachment of pushback-truck | 75 |
| | During Aircraft Pushback | 102 |
| | Aircraft Engine Start-up 1 | 4 |
| Towing | Total | **69** |
| | At-/detachment of tow truck | 9 |
| | placement/removal blocks | 1 |
| | During towing maneuver | 59 |
| Relocation of vehicle | Total | **160** |
| | Relocation on platform | 77 |
| | Relocation on perimeter road | 53 |
| | Relocation in aircraft maneuvering area | 21 |
| | Relocation on public roads | 1 |
| | Relocation on road | 8 |
| Taxi-out | Taxi to runway | 2 |
| Take-off | Acceleration | 1 |
| AAS activity | Snow and ice prevention | 1 |
| Parked Vehicle | | 100 |
| Parked Aircraft | | 11 |
| Docking | Enter Aircraft Stand Area | 5 |
| Landing | | 1 |
| Loading/offloading | Opening and closing of freight doors | 1 |
| At-/detachment of ground systems | At-/detachment of GPU | 1 |
| Not Applicable | | 8 |
| To be determined | | 10 |
| | **Total** | **551** |

Table 8.1: Tow truck incidents Jan 2013 until Sep 2015

From the incident data gathered over 2013, 2014, and 2015, a monthly analysis was performed. This analysis is shown in figure 8.3. It should be noted that the incidents with processes recorded as "Not applicable", "To be determined", or "Airport Activity" related to snow, are not included in the analysis. These incidents cannot be verified as avoidable through the use of ETS and reduction in the use of tow trucks. From the graph and data table shown in figure 8.3, it can be observed that the average number of incidents that occurs per month ranges between 12.7 and 19.7 with an overall average of 16 incidents per month.

It should be noted that no distinction is made between incidents involving narrow body aircraft or wide body aircraft in this instance. Furthermore, the cause of the tow truck incidents is not investigated in this research. For example, the high number of incidents in may 2014 may be attributed to new communication procedures. The relatively high number of average monthly incidents in the month of February may be due




| | jan | feb | mar | apr | may | jun | jul | aug | sep (22nd) | Average |
|---|---|---|---|---|---|---|---|---|---|---|
| 2013 | 10 | 17 | 16 | 22 | 9 | 17 | 8 | 15 | 13 | 14.11 |
| 2014 | 14 | 21 | 18 | 12 | 29 | 16 | 21 | 16 | 16 | 18.11 |
| 2015 | 14 | 18 | 10 | 14 | 21 | 16 | 20 | 18 | 11 | 15.78 |
| Monthly Average | 12.7 | 18.7 | 14.7 | 16 | 19.7 | 16.3 | 16.3 | 16.3 | 13.3 | 16 |

Figure 8.3: Analysis of the monthly tow truck incidents over the first nine months (until september 22nd) of 2013, 2014, and 2015. The analysis included a monthly average over the three years.

to snow/ice/foggy weather circumstances in this month. However, no clear monthly trends can be distinguished.

The extent, seriousness or result of the incidents recorded is not assessed in this research. However, it is safe to say that any incident that can be avoided is beneficial in the long run and increases airport platform safety.

The implementation of the ETS and ETS maneuvers would allow for a significant reduction in the use of tow trucks. KLM currently has 21 operational tow trucks for narrow body aircraft, and 33 operational tow trucks in total. Initially, not all narrow body aircraft will be equipped with an ETS, therefore a reduction of 7 tow trucks initially is suggested [7]. This a reduction of 1/3 of the narrow body operational tow trucks and a 21% overall reduction in the number of tow trucks operational at the airport. Logically, it would follow that reducing the number of operational tow trucks by 21%, would also reduce the number of incidents by 21%. This would result in a reduction of 3 tow truck incidents per month. The implementation of the ETS and the development of the system for wide body aircraft may even result in the overall elimination of the use of tow trucks in the long run. Saving 16 incidents per month increases safety and reduces potential costs resulting from incidents and FOD.

### COMMUNICATION EFFICIENCY

Besides tow truck incidents, another potential benefit related to operational safety offered by the implementation of ETS and autonomous pushbacks pertains to communication efficiency.

The ETS allows for the elimination of third party communication between the ATCo, the pilot, and the tow truck operator. As explained in section 2.3.2, the pilot communicates with the tow truck driver (and vice versa) and with the ATCo. However, the tow truck driver and ATCo cannot communicate directly. Additionally, the communication system between the pilot and the tow truck driver/marshaller is often inefficient voice or hand-signal communication [4][23]. This third-party communication system is not only inefficient and time consuming [23], but also presents a dilemma for the pilot in charge. Essentially the pilot (or captain) of an aircraft remains responsible for the safety of the aircraft in all situations. However, this essential responsibility is difficult for the pilot to maintain when the aircraft is being moved by a third party with whom the pilot has limited/inefficient communication possibilities[4].

Autonomous pushback using the ETS would transfer the control of the aircraft back to the pilot, thereby allowing the pilot to comply with his/her primary responsibility for the safety of the aircraft[4]. Additionally, the communication chain is shortened due to the elimination of the tow truck. A shorter communication chain implies a more efficient and safer communication system.

According to research performed be EUROCONTROL on data from the NASA Aviation Safety Reporting System (ASRS) [6], 37% of ramp incidents attributed to human factors, are caused by a communication breakdown. The main causes for human factor related incidents on the apron area are shown in figure 8.4.

| ASRS SEARCH "Parked" + "HF" + Category below | | |
|---|---|---|
| Troubleshooting | 4269 | 78% |
| Time Pressure | 3530 | 64% |
| Communication Breakdown | 2030 | 37% |
| Situational Awareness | 1258 | 23% |
| Confusion | 858 | 16% |
| Training & Qualification | 523 | 9.5% |
| Distraction | 396 | 7% |
| Workload | 276 | 5% |
| Human-Machine Interface | 190 | 3.5% |
| Fatigue | 134 | 2.5% |
| Physiological | 86 | 1.6% |

Figure 8.4: The main causes for human factor related incidents on the ramp area based on data obtained from NASA ASRS [6]

However, it should be noted that not all of the communication breakdowns happen between the pilot and the tow truck driver. Many of the pushback communication incidents are caused by language barriers and misunderstandings between the Pilot and the ATCo. This part of the communication chain remains intact during autonomous pushback procedures and more pushback responsibility is put in the pilot. Therefore, the communication mishaps between the pilot and the ATCo may result in faulty pushback procedures more often. Further research needs to be done to assess the increase or decrease in pushback communication errors during autonomous pushbacks at AAS, as no data is available on the subject yet.

Unfortunately, even though the concept of autonomous pushbacks has been researched in the past (refer to the works of Dieke et al. and Gomez et al. [4][23]), no sufficient system or procedure is in place yet to allow for the elimination of third party communication. An aircraft is a large object to maneuver and the pilot has little situational awareness in the cockpit when maneuvering backwards (in some cases the pilot cannot even see the wing tips of the aircraft from the cockpit) [4]. This increases the risk for incidents and accidents significantly.

One solution might be to employ the help of a marshaller on the ground who can provide guidance to the pilot during the pushback maneuver. However, this would imply the same safety and communication issues as with the current procedure; thrid party communication would not be eliminated. Additionally, new procedures for the communication between the pilot and the marshaller need to be implemented. This communication is currently made possible by the connection between the tow truck and the aircraft. The connection between the tow truck and aircraft does not exist anymore if tow trucks are eliminated and autonomous pushbacks are implemented. Thus, new safety and communication procedures will need to be extensively investigated in order for the autonomous pushbacks to be performed.

A better solution, as presented by Dieke-Meier [4], would be to provide video technology and other support systems to the pilot to provide for the necessary situational awareness. Unfortunately, no such system is currently available. Further development in this area is necessary to allow for the optimal use of the ETS for autonomous pushback. Up until now most research performed on autonomous pushbacks has been done either via simulation or through the use of a marshaller on the ground to guide the pilot backwards. Even though the marshaller on the ground would not help eliminate third party communication, it would still allow for the pilot to remain in control of the aircraft, increase efficiency of the pushback procedure itself, and reduce the number of tow truck incidents around or involving aircraft.

Thus, even though the implementation of autonomous pushbacks through the use of ETS might be able to enhance pushback communication efficiency in the long run, currently not much safety can be gained in this aspect due to the decreasing situational awareness of the pilot.

#### Safety Objective Overview

Table 8.2 provides a qualitative and, where possible, quantitative overview of the influence of the ETS and autonomous pushbacks on the apron area safety value. It should be noted that the 'initial' category refers to the situation where only narrow body aircraft can use the ETS. The potential situation shows the attribute scores when the ETS is used on all aircraft.

| **Objective: Safety** | **Qualitative Analysis Attribute Score** | | **Quantitative Analysis Attribute Score** | |
|---|---|---|---|---|
| | Initial | Potential (long term) | Initial | Potential (long term) |
| Elimination Tow Truck incidents | - | - - - | -3 incidents/month | -16 incidents/month |
| Communication Efficiency | 0 | ++ | N/A | N/A |
| Situational Awareness | - - | 0 | N/A | N/A |

Table 8.2: Value model objective: safety. Overview of objective attribute scores.

As mentioned in section 7.2, a negative score does not mean a negative influence on value, but rather a reduction in the attribute (ex. a reduction in the number of incidents). The direction of preference for the tow truck incident attribute is downwards. The direction of preference for the communication efficiency and situational awareness attributes is upwards.

### 8.1.2. Gate Capacity, Efficiency, Delay Reduction

As presented in the first chapters of this report, through the implementation of pit stops and dispatch towing, the ETS offer the opportunity for increased gate capacity, more flexible gate use and improved holding area utilization. Additionally, the pushback time for aircraft is reduced through the use of the ETS.

#### ETS enabled Pit stops and Dispatch Towing Procedures

As shown by the results of the gate planning models and extended analysis models (see sections 5 and 6.2) and indicated by the analysis of the extended model results (see section 6.3), the use of pit stops allows for more optimal gate use, increased capacity, and more efficient buffer usage. On the day of July $21^{st}$ 2014, the pit stop concept would have been able to create 6 additional slots at gates for aircraft handling. Additionally, with an increase of 10% in peak hour flights, on average 11 pit stop candidates exist resulting in 3 extra flights to be planned.

Furthermore, the implementation of dispatch towing could allow for better delay absorption and more efficient buffer usage. On July $21^{st}$, 6 dispatch towing procedures may have been able to be performed resulting in 6 fewer arrival delays. The delay codes show that eventually 3 of these dispatch tows could have been performed based on the reason for the delays. If an increase of 10% in peak hour delays would occur, on average 3.5 conflicts would occur and 1.7 flights (45.7% of the conflicts) would be solvable through the use of dispatch towing.

Thus, one of the major advantages of the ETS is the increase in gate capacity and reduction in delays due to the possibility of implementing pit stop and dispatch towing concepts.

Furthermore, as no pushback tow truck is needed, the aircraft is more flexible to maneuver when it is ready. Where otherwise the pushback process cannot start until a tow truck is available, with the ETS the pilot can start the pushback process when the aircraft (and ATC) is ready. This extra flexibility offers the opportunity for pushback rates to be more easily controlled. Improved pushback rate control has been shown to reduce airport ground congestion (Simaiakis, 2011 [59]). During peak hours, the pushback (or tow trucks) are in high demand. According to information from Schiphol, aircraft are rarely delayed due to a late arrival of a tow truck. However, the pilot cannot request a pushback until the truck has arrived and the aircraft is fully ready to depart. If the pushback truck is no longer needed for the pushback to take place, the pilot can request a pushback as soon as the aircraft is ready for departure. The link with the tow truck (the actual physical connection process) is no longer necessary. Thereby, the pushback/departure procedure becomes slightly more efficient.

The flexible maneuverability of the aircraft also implies that the pit stop procedure can be more freely applied. Currently, the procedure is often not used mainly due to the extra pushback and towing operations required to complete it. Instead of the aircraft remaining at the gate for its full turnaround time, during the pit stop procedure the aircraft requires two additional pushbacks and tows to get it to and from the buffer. Not to mention the additional aircraft being handled at the original gate requires a pushback as well. Thus, during peak hours, when the tow/pushback trucks are already in high demand, performing extra towing and pushback operations is often avoided and, therefore, the pit stop procedure is avoided. With the implementation of the ETS, however, no extra tow/pushback truck is needed to perform the pit stop maneuver. The aircraft itself is more autonomous and flexible in maneuvering, thus the pit stop procedure can be more easily applied.

### PUSHBACK TIME SAVING

In addition, research has shown that the ETS allows for better on-time performance (Dieke-Meier et al. 2012[4], Wijnterp 2014 [7]) and a shorter aircraft turn around time (Gomez 2009[23]). As indicated in chapter 2.1 and table 2.1, the EGTS and WheelTug ETS both provide the opportunity for pushback time saving. Even though the time reductions presented are quite marginal (in the order of 1 minute for the EGTS system), Dieke-Meier et al. (2012) argue that, considering the pushback phase constitutes a significant time portion of the overall taxi-out time, for an overall taxi-out time of 10-20 minutes, a conservative 1min pushback time saving will amount to a 10% overall taxi-out time saving [4]. Considering the number of taxi-out (and pushback) procedures performed each day (especially by short-haul narrow-body flights), this will amount to significant overall time savings. In his research Chris Wijterp created a graphical overview of the pushback and taxi-out process, illustrating the time that can be won through pushback with ETS. This graphic if shown in figure 8.5.

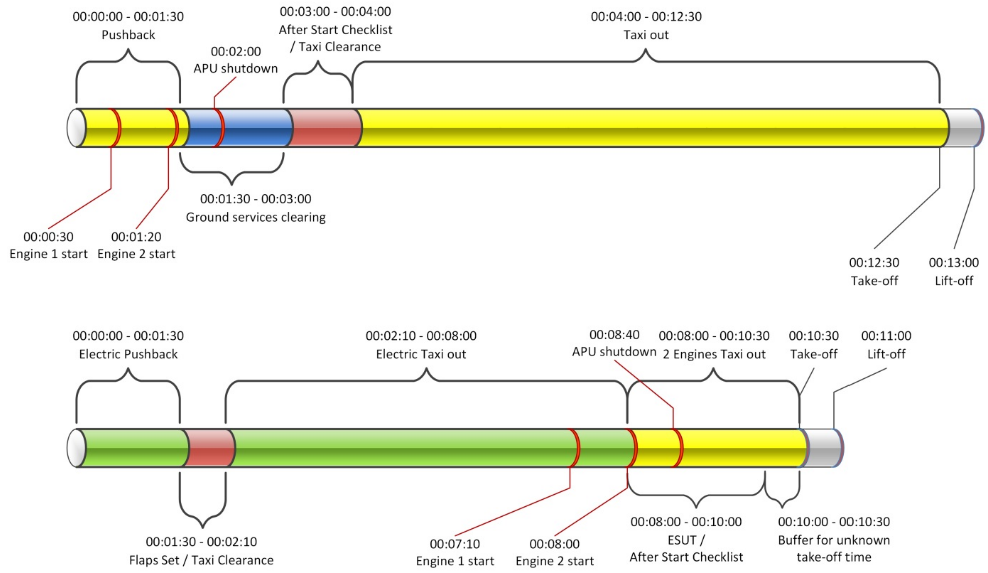



Figure 8.5: Pushback and Taxi-out time-line comparison between conventional tug-pushback dual engine taxi-out and ETS-pushback and taxi-out [7]

From the graphic in figure 8.5 it can be seen that conventionally from the start of the pushback until the taxi clearance is gained, takes approximately 4 minutes. With the ETS the start of the pushback until the taxi clearance only takes 2minutes and 10 seconds. Thus on average, the ETS reduces the pushback phase time by 1 minute and 50 seconds (where the pushback phase refers to the time from the start of the pushback until the taxi clearance is gained). This time saving is mainly caused by the elimination of ground service clearing in the ETS case. With the conventional pushback the aircraft has to wait for the pushback truck to be disconnected before taxi clearance can be granted. In the ETS case, no pushback truck is needed, thus no time for tug disconnection is needed either. The aircraft can pushback from the gate and immediately ask for taxi clearance to continue taxiing towards the runway. The EGTS [8] estimation of the amount of time saved during pushback is very similar and supports Wijnterp's graphic. The EGTS pushback time estimation provided by EGTS is shown in figure 8.6.

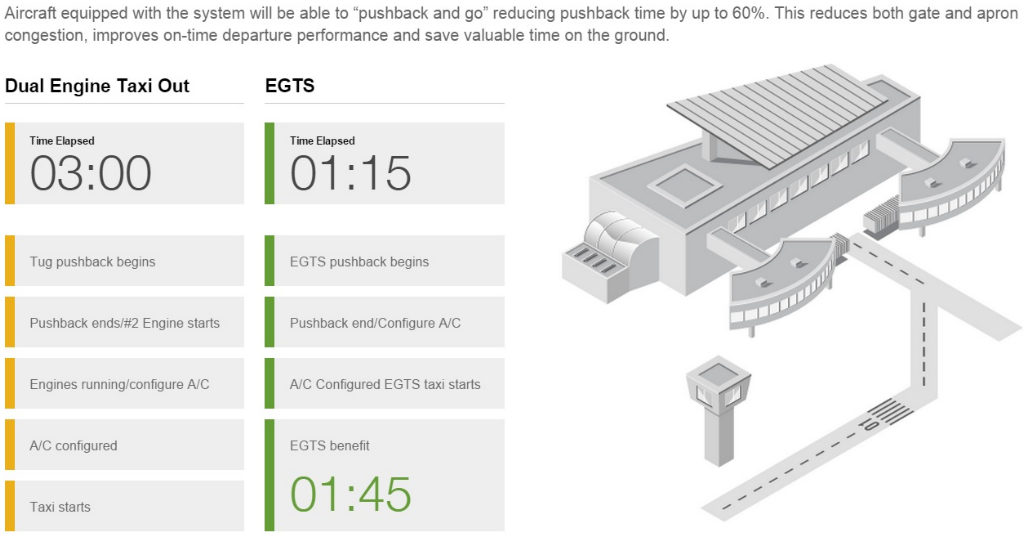



Figure 8.6: Pushback time-line comparison between conventional tug-pushback and EGTS-pushback as provided by EGTS [8]

Thus, the ETS may allow for up to 01:50 minutes of pushback time saving, thereby allowing for better overall on-time performance and efficiency.

For airlines, a faster turnaround time implies a higher aircraft utilization, which increases the revenue earned by the aircraft for the airline. Additionally, a higher aircraft utilization also results in a higher ETS utilization, which implies a larger benefit from the system. As indicated by Wijterp [7], the value of the ETS increases significantly with higher utilization. Thus, as indicated by Wollenheit et al. (2013 [17]), aircraft flying shorter routes (and thereby spending more time on the ground and taxing) will benefit more from the ETS than aircraft flying longer routes, simply because of the higher system utilization.

### Capacity, Efficiency, and Delay Reduction Objective Overview

Table 8.3 provides and qualitative and, where possible, quantitative overview of the influence of the ETS and autonomous pushbacks on the apron area capacity, efficiency, and delay reduction value. It should be noted that the 'initial' category refers to the situation where only narrow body aircraft can use the ETS. The potential situation shows the attribute scores when the ETS is used on all aircraft.

As mentioned in section 7.2, a negative score does not mean a negative influence on value, but rather a reduction in the attribute. The direction of preference is upwards for the pit stops and dispatch towing additional capacity and efficiency attributes. The direction of preference for the pushback time attribute is downwards.

| **Objective: Capacity, Efficiency** | **Qualitative Analysis Attribute Score** | | **Quantitative Analysis Attribute Score** | |
|---|---|---|---|---|
| | Initial | Potential (long term) | Initial | Potential (long term) |
| Pit Stops | + + + | + + + | 6 gate slots/day<br><br>Peak hour traffic increase of 10%:<br>3 additional peak hour flights | See initial impact |
| Dispatch Towing | + + + | + + + | Avg 17.2min time saved per delayed AC<br><br>10.8% peak hour flight delay conflicts solved | see initial impact |
| Pushback Time reduction | - - | - - | -1:50 min/pushback | see initial impact |

Table 8.3: Value model objective: Capacity, efficiency, and delay reduction. Overview of objective attribute scores.

### 8.1.3. Cost Reduction

With the reduction in aircraft main engine and tow truck use, the ETS can cause a decrease in maintenance costs, as well as ground service costs.

Aircraft engine maintenance is related to the utilization of the engine. Thus, with the ETS presenting the opportunity to reduce the engine utilization, the engine maintenance costs can also be reduced [19][7]. However, for this research the taxi-in and taxi-out phases are not considered. For further information on these phases and the use of ETS please refer to the works of Sillekens [16] and Wijnterp [7].

#### Tow Truck Maintenance and Personnel Costs

With the introduction of the ETS, towing and pushback of aircraft will no longer be performed using tow trucks. Thus, the tow truck maintenance costs and ground services costs will be reduced significantly.

Gomez presents a reduction in ground handling cost of approximately 190 USD [23](this amount depends on the ground operator charges per airport). This incorporates a decrease in the number of ground crew as well as a reduction in the amount of equipment needed (autonomous pushback using the ETS would eliminate the need for tow trucks as well as tow truck drivers).

With data obtained from KLM ground services, some estimations can be made regarding the reduced cost related to a reduction in the number of operational tow trucks. KLM currently has a total of 33 operational tow trucks. Of these 33 tow trucks, 21 are narrow body tow trucks. It would be advisable to maintain a number of tow trucks in case an ETS fails or weather conditions limit the availability of the ETS [7]. KLM estimates that initially, 7 of these narrow body tow trucks can be eliminated with the implementation of the ETS (and an ETS utilization of 99.65%) [7]. The reduction of 7 tow trucks will reduce operating and maintenance costs by 807,333.00$/Year [60].

Reducing the number of operational tow trucks and number of pushbacks performed by tow trucks, also reduces the amount of fuel used by the tow trucks. Provided the average fuel price over the past 10 year is 763.68$/ton ([7]), and the average tow truck uses 2.4kg/fuel per pushback ([14]), a tow truck costs 1.83$ of fuel per pushback. With an average of 40258 KLM pushbacks at AAS per year, this results in a conventional cost of 73,786.36$ per year on tow truck fuel for pushbacks. Should the ETS be implemented, 40117 pushbacks per year will be performed without the use of tow trucks. This results in a fuel cost reduction of 73,527.93$ per year for KLM pushbacks at AAS.

Thus, in total, a reduction of 7 tow trucks and a 99.65% ETS utilization for pushback, results in a saving of 978,548.60$ per year on tow truck maintenance and fuel costs. An overview of the calculations made is provided in appendix C.

The reduction in the number of employees needed for the pushback process not only increases operational safety, but also reduces operating cost. Again, based on data provided by KLM ground services [60], an average tow truck driver costs 61,639.34$/year. Usually one tow truck driver is needed per pushback. Eliminating all tow trucks and all tow truck driver personnel would result in a cost saving of 9,860,854$/year.

However, The elimination of the tow trucks does not necessarily imply the reduction of all tow truck personnel. In order to help the pilot navigate the aircraft backwards safely, at least one guiding marshaller will still be necessary in most cases (see section 8.1.5). The cost of a guiding marshaller is slightly less than that of a tow truck driver. Therefore, a slight reduction in personnel costs is still possible. Additionally, the marshaller may be able to combine multiple tasks in order to increase the efficiency of his function around the apron area.

In total the difference in cost between a tow truck driver and a marshaller is 3066$/year. Initially, 7 out of 21 narrow body tow trucks are eliminated, this a 33% reduction. A reduction of 33% of tow truck drivers replaced by marshallers, results in a 163,520.-$/year personnel cost reduction. Should all tow trucks be eliminated and only marshallers be used, as cost saving of 490,560.-$/year is possible.

Thus, a reduction in the number (or elimination in the long run) of tow trucks results in decreased tow truck maintenance costs, possible decrease in tow truck personnel costs, and a reduction in tow truck fuel usage (and, thereby, fuel costs). The cost of tow truck operations for KLM at AAS, as discussed in the previous paragraphs, is summarized in table 8.4 [7][60]. The costs presented have been calculated according to the current USD and EUR exchange rate (1EUR = 1.121USD).

| | Initial savings (reduction of 7 tow trucks) | Maximum savings (elimination of all tow trucks) |
|---|---|---|
| Reduction in truck costs | 807,333.-$/Yr | 4,522,000.-$/Yr |
| Reduction in truck Fuel costs | 73,527.93$/yr | 73,786.36$/yr |
| Reduction in truck and fuel costs | 978,548.60$/yr | 4,595,786.36$/yr |
| Reduction in personnel costs | 163,520.-$/yr | 490,560.-$/yr |
| **Total reduction** | **1,142,068.60$/yr** | **5,086,346.36$/yr** |

Table 8.4: Costs reduction of tow trucks and personnel per year in the initial ETS situation and the maximum usage ETS situation

The maintenance costs for the ETS itself are relatively very small. The electric systems are known for their robustness and generally require relatively little maintenance [61]. Furthermore, the increased use of the APU by the ETS results in the need for more APU maintenance. However, as indicated by Raes, the APU and ETS maintenance costs are lower than the maintenance costs for the engines and tow trucks [61]. EGTS estimates an increase in APU and ETS maintenance costs of 15,000$/year [7].

### FOREIGN OBJECT DAMAGE (FOD) AND APRON AREA COLLISION COSTS

As mentioned in section 8.1.1, FOD to aircraft may decrease due to the elimination of tow truck. The platform and ramp area are busy areas, therefore, fewer tow trucks on the platform and ramp will decrease the likelihood of FOD and collision occurrences.

In his research, Mcreary [62] provides insight into the cost of FOD and the likelihood of occurence of FOD per location at the airport (runway, taxiway, and ramp area). Based on this research, table 8.5 shows the FOD costs for the apron ramp area, caused by tools and vehicles.

| | **FOD near AC stand (ramp)** | **FOD due to Ground vehicles and tools** |
|---|---|---|
| Engine FOD maintenance costs | 2.1$/Flight Cycle (FC) | 0.315$/Flight Cycle (FC) |
| Tire replacement costs | 0.6$/FC | 0.09$/FC |
| AC Body damage | 0.01$/FC | 0.0015$/FC |
| KLM average FC/year | 80,516 FC/year | |
| | **Total FOD costs/year** | **32,730.-$/year** |

Table 8.5: FOD costs per year at the aircraft stand area due to ground vehicles and tools

The data shown in table 8.5 provides an estimation of the FOD costs at the airport stands. With the elimination of th use of tow trucks the number of FOD occurences can be reduced significantly. Thereby, the FOD costs around the stand area could be reduced by a maximum of approximately 32,730.-$/year.

#### Arrival Ground Delay Costs

In addition to Maintenance costs, through the implementation of the dispatch towing concept with ETSs, delay costs to the airline may also be reduced. When an aircraft is delayed, transfer passengers may miss their connecting flights, airline crew may exceed their permitted working times, emissions and fuel usage increase, and airline scheduling may be influenced [63]. These implications caused by delays imply extra costs for the airline. Therefore, during flight, the airline often makes a trade-off between the cost of the increased fuel needed to fly faster in order to reach the destination on time (no delay), and the costs per 5 minutes of delay. This is known as cost indexing [63].

However, on the ground delays upon arrival (after the aircraft's landing but before the aircraft reaches its gate) are often not taken into account even though these delays essentially have the same effect as in-air delays. This is due to the fact that the airline has little or no control over the amount of ground delay an aircraft will experience after landing; its mainly down to the availability of a gate at the airport. As shown in chapters 5 and 6, with the implementation of the dispatch towing concept many of the ground delays upon arrival can be eliminated. As long as the aircraft occupying the assigned gate has an ETS and can be moved from the gate to a buffer, the arriving flight no longer has a ground delay. This delay reduction then results in a cost reduction as well.

From the extended analysis results, it can be concluded that an average of 17.2 minutes of ground delay time can be saved through the use of dispatch towing when possible. No data on the costs of delay per minute for KLM aircraft was available during the time of this research. However, research on indirect costs for the taxi-in phase (ground delay costs) provided by Mcreary [62], indicates that, on average, a taxi-in delay costs 30$ per minute. With an average time saving of 17.2 minutes during peak hours, this leads to an average cost saving of 516$ per peak hour dispatch tow/ground delay avoidance.

#### Costs Objective Overview

Table 8.6 provides and qualitative and, where possible, quantitative overview of the influence of the ETS and autonomous pushbacks on the apron area capacity, efficiency, and delay reduction value. It should be noted that the 'initial' category refers to the situation where only narrow body aircraft can use the ETS. The potential situation shows the attribute scores when the ETS is used on all aircraft.

| Costs | **Qualitative Analysis Attribute Score** | | **Quantitative Analysis Attribute Score** | |
|---|---|---|---|---|
| | Initial | Potential (long term) | Initial | Potential (long term) |
| Tow Truck Maintenance and fuel costs | - - | - - - | -978,549.-$/yr | -4,595,786.-$/yr |
| Personnel Costs | - - | - - | -163,520.-$/yr | -490,560.-$/yr |
| FOD costs | - | - | Unknown | -32,730.-$/yr |
| Ground delay costs | - | - - | -516$ per peak hour dispatch tow | see initial impact. More dispatch tows possible if more aircraft have an ETS |
| ETS and APU maintenance costs | + | + | 15,000.-$/year | see initial impact |

Table 8.6: Value model objective: Costs. Overview of objective attribute scores.

As mentioned in section 7.2, a negative score does not mean a negative influence on value, but rather a reduction in the attribute. As expected, the direction of preference for costs is downwards.

### 8.1.4. Emissions

An ETS obviously offers opportunities in emission savings. For the most part this reduction can be experienced during the taxi-in and taxi-out times because during these phases, the aircraft engines would conventionally be used. Using the APU during these phases then results in a reduction in emissions and fuel costs. However, the focus of this investigation lies on the apron area. Therefore, a focus is put on the APU emissions and the fuel cost and emission reduction of the pushback trucks and apron area.

### FUEL USAGE PIT STOPS AND DISPATCH TOWING

Through the use of the ETS for pushbacks, pit stops and dispatch tows, the APU usage increases. The pit stop and dispatch towing procedures also imply an additional taxi(or tow) time and pushback. In order to be able to assess the added fuel usage and emissions through the use of pit stops and dispatch towing, the following figure (figure 8.7) provides and overview of the emission specifications of two common narrow body aircraft (for comparison) and the average APU. Figure 8.8 then provides insight into the fuel flow (or fuel consumption) of the APU. For reference and comparison, data of two common narrow body aircraft engines is also provided. [7].

| *Engine* | CFM56 | | V2500 | | APU |
|---|---|---|---|---|---|
| *Emission type* | Idle | Flight | Idle | Flight | average |
| HC | 0,105 | 0,041 | 2,3 | 0,03 | 0,375 |
| CO | 12,43 | 0,62 | 34,71 | 0,15 | 3,875 |
| NOx | 4,7 | 22,3 | 4,09 | 15,6 | 8,75 |
| CO2 | 3160 | 3160 | 3160 | 3160 | 3160 |

Figure 8.7: Emission specifications (g/kg of fuel) [7]

| Main engines | | APU | |
|---|---|---|---|
| Fuel flow 1 engine idle | 6,36 [kg/min] | Fuel flow full ETS load | 2,17 [kg/min] |
| Fuel flow 1 engine taxi | 8,62 [kg/min] | Fuel flow normal load | 1,58 [kg/min] |
| Fuel flow 2 engines taxi | 11,97 [kg/min] | Fuel flow idle | 1,25 [kg/min] |

Figure 8.8: APU and engine fuel flow table [7]

Assuming that the taxi time between a gate and a buffer is a maximum of 10 minutes during the pit stop and dispatch tow procedures, and during these 10 minutes the APU is functioning at full load because the ETS is used, this would result in 21.7kg of fuel used. Thereby, approximately 8.1375g HC, 84.0875g CO, 189.875g $NO_x$, and 68572g CO2 are emitted during each extra tow/movement maneuver caused by the implementation of the pit stop and dispatch towing procedures.

Even though this is an increase in emissions, the capacity and efficiency benefits weigh against this. Additionally, conventionally a tow truck would need to be used to perform these procedures. A fuel operated tow truck uses approximately 2.4kg of fuel per minute. Thus, the conventional tow truck uses more fuel to tow an aircraft than the ETS does. The ETS thereby, allows the pit stop and dispatch towing procedures to be used in a more environmentally friendly way than conventional.

The dispatch towing concept also allows for an additional potential fuel and emission saving. This is due to the decrease in arrival delays. An aircraft that has to wait before being able to reach its gate has its engines on idle power (unless the aircraft also has an ETS in which case it would be operating on its APU). This means that the waiting aircraft is producing noise and emissions, and is burning costly fuel. Through the implementation of the dispatch towing concept, on average 16 minutes of waiting time/ delay can be avoided (see section 6.3). This corresponds to 101.8kg of fuel saved, or if the aircraft waiting is equipped with an ETS, 34.7kg of fuel saved. This fuel saving can then be translated to a reduction in emissions according to table 8.7.

As mentioned earlier, the dispatch towing concept does imply an extra aircraft movement on behalf of the delayed aircraft (from the gate to the buffer). This movement with the ETS 'costs' 21.7kg of fuel approximately. Thus, overall 80kg of fuel can be saved with the dispatch towing concept, if the arriving flight would have used idle engines during its waiting time otherwise. If the arriving aircraft has an ETS, on average, 13kg of fuel can be saved through the implementation of the dispatch towing maneuver. It is also worth noting that should the arriving aircraft have an ETS and only need to wait 10 minutes for its gate, the dispatch towing maneuver becomes less fuel efficient: the aircraft towed to the buffer also uses 10 minutes worth of fuel get there thus, the fuel savings decrease accordingly. However, on average it can be said that the fewer aircraft have to wait for a gate though the implementation of dispatch towing, the more fuel can be saved and the more emissions and noise can be reduced.

### PUSHBACK FUEL SAVING

Most tow trucks at AAS use fuel to perform pushbacks and maneuver. The reduction of the number of tow trucks (approximately 7 trucks initially) thereby, also saves fuel. If the number of conventional pushbacks is reduced to 141 pushbacks per year at AAS(as suggested in the research of Wijnterp [7]), and a pushback truck uses 2.4kg of fuel per pushback, only 338.4kg of fuel per year is used for conventional pushbacks. Compared to 40258 conventional tows (96,619.3kg of fuel), this is a significant reduction. However, it should be noted that the ETS load on the APU also requires a fuel consumption during pushback. Assuming a fuel load of 2.17kg/pushback, 0.23kg of fuel can be saved per pushback. Thus, with 141 conventional pushbacks and 40117 ETS pushbacks at AAS, 9,227kg of fuel can be saved per year.

Table 8.7 shows the translation of the ETS pushback fuel savings to emissions and fuel cost.

| | |
|---|---|
| Fuel saved | 9,227kg |
| HC saving | 3460g |
| CO saving | 35,755g |
| $NO_x$ saving | 80,736g |
| CO2 saving | 29157320g |
| Fuel cost savings | 7,046.50$/year (based on fuel price of 763.70$/ton) |

Table 8.7: Pushback fuel saving translated to emission savings and cost savings

### APRON NOISE REDUCTION

Fuel and emissions around the platform operations can be reduced through the use of ETS but platform noise is also reduced. The engines of the aircraft (even when on idle) cause a lot of noise. Conventionally, during the pushback maneuver, the pilots are already starting up the aircrafts main engines in order to taxi with the engines on idle. If an aircraft taxis-in, maneuvers, is pushed back, and taxis-out using the ETS, only the APU noise remains around the apron area.

The average APU noise level (dB at 152m) for the common narrow body aircraft types; A319, BAe146, and the B737, is 64dB [64]. During maneuvering, the average engine noise for these aircraft types is 75dB[64]. With the elimination of engine noise from the airport apron, a 69% noise level reduction is achieved.

### COSTS OBJECTIVE OVERVIEW

Table 8.8 provides and qualitative and, where possible, quantitative overview of the influence of the ETS and autonomous pushbacks on the apron area capacity, efficiency, and delay reduction value. It should be noted that the 'initial' category refers to the situation where only narrow body aircraft can use the ETS. The potential situation shows the attribute scores when the ETS is used on all aircraft.

As mentioned in section 7.2, a negative score does not mean a negative influence on value, but rather a reduction in the attribute. As expected, the direction of preference for emissions and fuel used is downwards.

For the pit stop fuel reduction an average of 6 pit stops performed during the day is assumed. This result in 12 extra movements for the aircraft involved, leading to an extra 120minutes of taxiing using the APU and ETS. It should also be noted that the additional fuel costs are calculated using the average fuel price over the past 10 years: 0.764$/kg of fuel [7].

| Emissions | **Qualitative Analysis Attribute Score** | | **Quantitative Analysis Attribute Score** | |
|---|---|---|---|---|
| | Initial | Potential (long term) | Initial | Potential (long term) |
| Pit Stop Extra Fuel usage | ++ | ++ | Extra Fuel used: 260.4kg<br>HC: 97.7g<br>CO: 1009.1g<br>$NO_x$: 2278.5g<br>CO2: 822864g<br>Fuel costs: 198.9$<br>per 6 pit stops: 12 extra taxi movements | See initial impact |
| Dispatch Towing Fuel saving | - - | - | Fuel saved: 80kg<br>HC: 30g<br>CO: 310g<br>$NO_x$: 700g<br>CO2: 252800g<br>Fuel costs: 61.10$<br>per dispatch tow | Fuel saved: 13kg<br>HC: 4.88g<br>CO: 46.5g<br>$NO_x$: 105g<br>CO2: 37920g<br>Fuel costs: 9.93$<br>per dispatch tow |
| Pushback Fuel Saving | - - | - - | Fuel saved: 9,227kg<br>HC: 3460g<br>CO: 35,755g<br>$NO_x$: 80,736g<br>CO2: 29157320g<br>Fuel costs: 7,046.50$<br>per year | See initial impact |
| Apron Noise Reduction | - - | - - | -69% | see initial impact |

Table 8.8: Value model objective: Emissions. Overview of objective attribute scores.

furthermore, the initial dispatch towing savings are calculated based on the arriving aircraft not being equipped with an ETS. The potential dispatch towing savings are based on savings when all narrow body aircraft (including the arriving aircraft) have and ETS.

### 8.1.5. GENERAL CHALLENGES AND CONSIDERATIONS PRESENTED BY THE ETS

The previous sections have pointed out the main ETS challenges for apron operations. However, the system also face some other challenges that are important to mention. The introduction of a new system, such as the ETS, presents opportunities for improvements as well as new challenges.

One of the main drawbacks of the ETS is the additional weight of the system [7]. The ETS is attached to the landing gear of the aircraft (in case of the EGTS to the main landing gear, See chapter 2.1) and is not removed before take-off. This means the aircraft is carrying an additional weight throughout the flight which consequently, results in a fuel penalty. However, as indicated by Wijnterp [7], the value of the ETS is still significant. Even though the system adds weight to the aircraft, the fuel and emissions saved due to the electric taxiing and the time savings, counteract the fuel penalty. Further investigation into this area is outside of the scope of this research.

With the implementation of the ETS for autonomous pushback, some standard operating procedures (SOP) will need to be changed. Some of the new operating procedures may cause an increase in the pilot workload. Currently, the pilot can focus his attention on the engine start and after engine start procedures and checklists during most of the pushback process [4]. The pilot workload for the pushback process is, therefore, quite low. This will change dramatically with the implementation of the ETS for autonomous pushback procedures. During an autonomous pushback procedure the pilot will need to be fully focused on the pushback task, leaving no room for other checks and start-up procedures. Pilot workload is an important factor for safe and efficient apron operation thus, the impact of the ETS for autonomous pushback on pilot workload needs to be fully investigated before implementation.

### 8.1.6. KEY PERFORMANCE INDICATOR SUMMARY

Key performance indicators (KPIs) provide a means to assess a system or process based on values held by the stakeholders involved. The KPIs presented in table 8.9, have been identified during the research presented in the sections above. In the table, the stakeholders and ETS properties pertaining to each KPI are listed.

| KPI | ETS property | Stakeholders |
| --- | --- | --- |
| Safety | Number of incidents caused by tow trucks<br>Situational awareness of pilots<br>Communication efficiency | Airport<br>ATC<br>Airlines<br>pilots<br>passengers<br>ground crew<br>regulatory authority |
| Capacity<br>Efficiency<br>Delays | Pit Stops<br>Dispatch Towing<br>pushback time saving | Airport<br>ATC<br>Airlines<br>pilots<br>passengers |
| Costs | Tow truck maintenance and fuel costs<br>APU and ETS maintenance costs<br>Ground operation costs<br>Non-performance costs (cost indexing) | Airlines<br>Airports |
| Environment | Dispatch towing emission reduction<br>Extra maneuvering pit stop concept<br>pushback fuel saving<br>Noise Reduction on platform | Airport<br>Airlines<br>pilots<br>passengers<br>ground crew<br>regulatory authority |

Table 8.9: Airport apron KPIs, ETS characteristics influencing those KPIs, and Stakeholders

## 8.2. THE RESULTING VALUE MODEL: PUTTING IT ALL TOGETHER

From the information and data presented in the previous section (section 8.1), the value model attribute scores can be determined. Subsequently the attribute and objective weights are determined and, finally, the qualitative value model is provided.

### 8.2.1. VALUE MODEL ATTRIBUTE SCORES

Based on the data provided in the previous sections of this chapter (sections 8.1, 8.1.6, and 8.1.5), a qualitative value model overview is created and shown in table 8.10. At this stage in the research a qualitative analysis is chosen over a quantitative analysis due to the fact that some of the quantitative data is still incomplete. However, for the missing data, a qualitative assessment can be made because the impact of the attribute is already known. Further research regarding the quantitative missing quantitative data (such as the impact of autonomous pushback on pilot situation awareness) needs to be further investigated.

| KPI | ETS property/attribute | Initial Value Score | Potential Value Score | Direction of Preference |
|---|---|---|---|---|
| Safety | Number of incidents caused by tow trucks | - | - - - | Downwards |
| | Pilot Situational Awareness | - - | 0 | Upwards |
| | Communication efficiency | 0 | ++ | Upwards |
| Capacity Efficiency Delays | Pit Stops capacity enhancement | + + + | + + + | Upwards |
| | Dispatch Towing efficiency enhancement | + + + | + + + | Upwards |
| | pushback time saving | - - | - - | Downwards |
| Costs | Tow truck maintenance and fuel | - - | - - - | Downwards |
| | APU and ETS maintenance costs | + | + | Downwards |
| | Ground operation costs | - - | - - | Downwards |
| | Delay costs | - | - - | Downwards |
| | FOD costs | - | - | Downwards |
| Environment | Pit Stop Fuel Usage | + + | + + | Downwards |
| | Dispatch Towing Fuel saving | - - | - | Downwards |
| | Pushback Fuel Saving | - - | - - | Downwards |
| | Noise Reduction on platform | - - | - - | Downwards |

Table 8.10: KPI attibute qualitative scores for the for ETS platform operations

The qualitative scores are now translated to quantitative scores in order to be able to use them in the value model. In this case a linear scale is used, as presented in figure 7.1 in section 7.2. The conversion is presented in table 8.11.

Next the feasible range scores are calculated. Recall the feasible range equations presented in section 7.2.

| Qualitative Score | Conversion Value |
|---|---|
| + + + | +3 |
| + + | +2 |
| + | +1 |
| 0/no change | 0 |
| - | -1 |
| - - | -2 |
| - - - | -3 |
| $x_{max}$ | 3 |
| $x_{min}$ | -3 |

Table 8.11: Qualitative score conversion

The feasible range equation for the attributes with an upward direction of preference is given by:

$$\left(x_p\right)_{0,1}^{FR} = \frac{\left(x_p\right)_{0,1} - x_{min}}{x_{max} - x_{min}} \tag{8.1}$$

The feasible range attribute scores for the downward direction preference are calculated using equation 7.7:

$$\left(x_p\right)_{0,1}^{FR} = 1 - \frac{\left(x_p\right)_{0,1} - x_{min}}{x_{max} - x_{min}} = \frac{x_{max} - \left(x_p\right)_{0,1}}{x_{max} - x_{min}} \tag{8.2}$$

In this case, the base attribute score $x_1^{FR}$, is equal to zero. Therefore, the base situation scores for both upward and downward direction of preference is: $x_1^{FR} = 1/2$. The qualitative attribute scores are given relative to the base/reference situation with score 0. The resulting feasible range scores are presented in table 8.12.

| KPI | ETS property/attribute | Initial Score $x_1^{FR}$ | Potential Score $x_1^{FR}$ | Initial $\frac{x_{p,1}}{x_{p,0}}$ | Potential $\frac{x_{p,1}}{x_{p,0}}$ |
|---|---|---|---|---|---|
| Safety | Number of incidents caused by tow trucks | 2/3 | 1 | 4/3 | 2 |
| | Pilot Situational Awareness | 1/6 | 1/2 | 1/3 | 1 |
| | Communication efficiency | 1/2 | 5/6 | 1 | 5/3 |
| Capacity Efficiency Delays | Pit Stops capacity enhancement | 1 | 1 | 2 | 2 |
| | Dispatch Towing efficiency enhancement | 1 | 1 | 2 | 2 |
| | pushback time saving | 5/6 | 5/6 | 5/3 | 5/3 |
| Costs | Tow truck maintenance and fuel | 5/6 | 1 | 5/3 | 2 |
| | APU and ETS maintenance costs | 1/3 | 1/3 | 2/3 | 2/3 |
| | Ground operation costs | 5/6 | 5/6 | 5/3 | 5/3 |
| | Delay costs | 2/3 | 5/6 | 4/3 | 5/3 |
| | FOD costs | 2/3 | 2/3 | 4/3 | 4/3 |
| Environment | Pit Stop Fuel Usage | 1/6 | 1/6 | 1/3 | 1/3 |
| | Dispatch Towing Fuel saving | 5/6 | 2/3 | 5/3 | 4/3 |
| | Pushback Fuel Saving | 5/6 | 5/6 | 5/3 | 5/3 |
| | Noise Reduction on platform | 5/6 | 5/6 | 5/3 | 5/3 |

Table 8.12: Attribute feasible range scores

### 8.2.2. ETS VALUE MODEL OBJECTIVE AND ATTRIBUTE WEIGHT ASSIGNMENT

The coefficient (or weight) values of the KPIs (objectives) and the ETS objective attributes can be determined in multiple ways as they are dependent on the main stakeholders involved and the extent of the influence of each attribute on the overall system. Based on a combination of past research performed by Bennebroek [5], Curran[9], Wijnterp [7], and Sillekens [16], a suggestion for the KPI coefficients is made.

In the past ETS research ([7][16]), the same stakeholders can be recognized; the two main stakeholders are Amsterdam Airport Schiphol and KLM. Based on interviews and questionnaires, the safety KPI was the most highly valued KPI. On the apron area, the ETS also has a large impact on safety. Therefore, the safety KPI is given the highest coefficient (level of impartance in the value model).

Wijnterp also suggests that the KPI most effected by the ETS should have a high coeffcient [7]. The apron KPI at the center of this investigation and the one most influenced by the implementation of the ETS and the ETS concepts (pit stops and dispatch towing), is the capacity and efficiency KPI. Therefore, this KPI is rated as the second most important ETS apron attribute.

Obviously, for any airport, costs play a large role in decision making. The implementation of the ETS suggest many changes in the tow truck and pushback operations. These operational changes result in significant operational cost changes as well. Though many of these costs need to be further investigated and evaluated ni more detail when the means arise. The cost KPI is therefore the third most important value/KPI.

In today's world, the environment is becoming a larger factor in decision-making at airports and for airlines. Airports and airlines have an increasing awareness of the aviation industry's impact on global emissions and the environment. At AAS and KLM many restrictions, regulations, and sustainability projects have already been put in place. The idea of an ETS is one of the most promising projects that will hopefully be able to make a difference in the fights for a more sustainable airport and airline industry. The apron area is a highly congested area due to the parked aircraft, the moving aircraft and all of the ground operations taking place around these aircraft. Therefore, emissions and noise around the apron area are of concern. The ETS will have an impact on the apron environment, however, most of the environmental profit from the ETS takes place during the taxi phases of the flight due to the high utilization of the ETS. The environmental profit around the gates and the apron is limited due to the short ETS usage times. Therefore, the environmental KPI is rated as the fourth important KPI.

In his research Curran indicates that based on profile or scenario priority, weights can be assigned to values at airports [9]. Figure 8.9 provides an overview of a suggested weight assignment to four distinct values for different airport scenarios (different priorities). In this case the Operations value includes the safety aspect at airports. The figure demonstrates how the importance of objectives and attributes can shift according to the stakeholder's main focus.

| | | Fundamental objective weighing factors | | | |
|---|---|---|---|---|---|
| Airport scenario | | Capacity [C] | Operations [O] | Economics [Ec] | Environment [E] |
| Customer-oriented airport | | 0.20 | 0.50 | 0.15 | 0.15 |
| Time-efficient airport | | 0.20 | 0.60 | 0.10 | 0.10 |
| Cost-efficient airport | | 0.10 | 0.20 | 0.60 | 0.10 |
| Ultra-green airport | | 0.10 | 0.10 | 0.10 | 0.70 |
| Ultra-secure airport | | 0.10 | 0.40 | 0.40 | 0.10 |

Figure 8.9: weights for value functions for different airport scenarios [9]

Furthermore, the pair-wise comparison matrix approach presented by Bennebroek [5] and introduced in section 7.3 can be used. Recall the comparison matrix (M):

$$M = \begin{array}{c} \\ A \\ B \\ \vdots \\ n \end{array} \begin{array}{c} \begin{array}{cccc} A & B & \cdots & n \end{array} \\ \begin{pmatrix} 1 & \frac{W_A}{W_B} & \cdots & \frac{W_A}{W_n} \\ \frac{W_B}{W_A} & 1 & \cdots & \frac{W_B}{W_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{W_n}{W_A} & \frac{W_n}{W_B} & \cdots & 1 \end{pmatrix} \end{array} \tag{8.3}$$

and the pair-wise objective importance scoring:

- $Imp(A) >> Imp(B) \Rightarrow \frac{W_A}{W_B} = 2^2 = 4$
- $Imp(A) > Imp(B) \Rightarrow \frac{W_A}{W_B} = 2^1 = 2$
- $Imp(A) = Imp(B) \Rightarrow \frac{W_A}{W_B} = 2^0 = 1$
- $Imp(A) > Imp(B) \Rightarrow \frac{W_A}{W_B} = 2^{-1} = \frac{1}{2}$
- $Imp(A) >> Imp(B) \Rightarrow \frac{W_A}{W_B} = 2^{-2} = \frac{1}{4}$

Using the importance scoring and the comparison matrix, the comparison matrix shown by equation 8.4 is established for the ETS apron environment case. The objective annotations S, Ca, Co, and E stand for: Safety, Capacity, Costs, and Environment, respectively.

$$M = \begin{array}{c} \\ S \\ Ca \\ Co \\ E \end{array} \begin{array}{c} \begin{array}{cccc} S & Ca & Co & E \end{array} \\ \begin{pmatrix} 1 & 1 & 2 & 4 \\ 1 & 1 & 1 & 2 \\ 1/2 & 1 & 1 & 1 \\ 1/4 & 1/2 & 1 & 1 \end{pmatrix} \end{array} \tag{8.4}$$

The matrix above has four eigenvalues; two real and two imaginary. We are interested in the eigenvector belonging to the largest positive eigenvalue. In this case, the eigenvector is v=(2.82843, 2, 1.41421, 1). Normalizing the eigenvector according to 7.9 shown in section 7.3 provides the suggested weights of the objectives. The weights are shown in table 8.13

| KPI/Attribute | Suggested attribute weight |
|---|---|
| Safety | 0.39 |
| Capacity/efficiency | 0.28 |
| Costs | 0.19 |
| Environment | 0.14 |

Table 8.13: Objective Weights based on the comparison matrix

The higher level objectives have also been broken down into various lower level attributes, as discussed on the previous sections of this chapter. The attributes can also be assigned weights in a similar fashion as done for the higher level suggested weights. The comparison matrices are shown in appendix D. The suggested weight assignment for the lower level attributes is shown in table 8.14. It should be noted that the assigned weights are estimates.

| KPI | ETS property/attribute | Attribute Weight |
|---|---|---|
| Safety | Number of incidents caused by tow trucks | 0.50 |
| | Pilot Situational Awareness | 0.25 |
| | Communication efficiency | 0.25 |
| Capacity Efficiency Delays | Pit Stops capacity enhancement | 0.40 |
| | Dispatch Towing efficiency enhancement | 0.40 |
| | pushback time saving | 0.20 |
| Costs | Tow truck maintenance and fuel | 0.25 |
| | APU and ETS maintenance costs | 0.25 |
| | Ground operation costs | 0.25 |
| | Delay costs | 0.13 |
| | FOD costs | 0.12 |
| Environment | Pit Stop Fuel Usage | 0.25 |
| | Dispatch Towing Fuel saving | 0.25 |
| | Pushback Fuel Saving | 0.25 |
| | Noise Reduction on platform | 0.25 |

Table 8.14: Attribute Weights

Now that the weights have been suggested the complete value model can be proposed. The model will be presented in section 8.2.4. First, the following section discusses the assumptions and limitations of the value model.

### 8.2.3. VALUE MODEL ASSUMPTIONS AND LIMITATIONS

In order to set up the value model some assumptions have to made and limitations of the model set-up and data need to be noted for validity.

As discussed in section 8.1, some of the values cannot yet be determined. The situational awareness of pilots, communication efficiency, and non-performance costs need to be assessed at a later stage of research as no data regarding these attributes was available for AAS. The non-performance costs were researched during this investigation, but given that the data is very volatile and very little data could be found, no valuable and solid conclusions could be made. KLM has indicated that they are working on producing a database with these non-performance costs. Therefore, once this data becomes available, more light can be shed on the extent of the non-performance costs that can be saved through the reduction of delays and the implementation of the dispatch towing concept.

The situational awareness and communication efficiency concepts are constructed attributes. This implies that they can only be qualitatively described and there is no easy way quantitatively express them. Therefore, finding data pertaining to these attributes is extremely difficult. Often the best solution lies in running pilots (or test runs), in this case for autonomous pushback situations, during which pilots rate their situational awareness via a questionnaire or scale rating system. It is assumed that currently the only way for pilots to perform autonomous pushbacks is with the help of a marshaller: thus, no communication efficiency increase or decrease can be measured yet.

Furthermore, it is assumed that the ETS has a pushback utilization 99,65%. This is done in order to keep the results consistent and comparable with earlier research performed on the value of the ETS [7][16]. Additionally, it is assumed that even though tow trucks may disappear from use completely in the long run, at the start of the ETS implementation, at least 14 out of 21 KLM narrow body aircraft tow trucks are still needed (resulting in a reduction of 7 tow trucks).

It should be noted that given the scope and time limit set for this investigation, not all data was assessed in detail. The pit stop and dispatch concepts were investigated in detail, as well as the pushback time saving and the number of tow truck incidents occurring at the airport. As no additional data was available, the maintenance and ground operation costs are based on data provided by KLM in 2014[60]. For the research scope and time frame, a qualitative value analysis was, therefore, chosen.

The weights assigned to the value model objectives and attributes are based on qualitative assessments of the attribute's importance or impact within a certain group. Given that the focus of this investigation lies on the impact of the ETS on the capacity at AAS, this KPI was assumed to be of higher importance (along with the safety KPI). Additionally, AAS and KLM were considered as the main stakeholders for this thesis research work.

### 8.2.4. ANALYSIS OF THE VALUE MODEL RESULTS

Now that the model data, set-up, assumptions, and limitations have been discussed, the suggested model is presented.

$$\Delta V = \{0.39 * \text{Safety} + 0.28 * \text{Capacity/efficiency} + 0.19 * \text{Costs} + 0.14 * \text{Environment}\} - 1 \tag{8.5}$$

The partial delta V equation (shown below) is used to calculate the objective scores (based on the objective's attribute scores). The calculations are shown in appendix E.

$$v_n = \sum_{1}^{p} \omega_p \left( \frac{x_{p,1}}{x_{p,0}} \right) \tag{8.6}$$

| **KPI** | **Initial Partial Value** | **Potential Partial Value** |
|---|---|---|
| Safety | 1 | 1.67 |
| Capacity and efficiency | 1.93 | 1.93 |
| Costs | 1.33 | 1.46 |
| Emissions | 1.33 | 1.25 |
| | **Initial Objective Value** | **Potential Objective Value** |
| | 0.39 | 0.65 |
| | 0.54 | 0.54 |
| | 0.25 | 0.28 |
| | 0.19 | 0.18 |
| | **Total Initial Value** | **Total Potential Value** |
| **Value created** | 0.37 | 0.64 |
| (Maximum value created is 1) | | |

Table 8.15: Value calculation results

Thus, from the quantitative value analysis it can be concluded that the implementation of the ETS, and enabling the pit stop and dispatch towing concepts, will produce value for the airport apron environment. The potential value, or maximum value predicted in the long run, is 0.64 with a maximum value that can be created equal to 1. Even initially, with not all the tow trucks eliminated yet, the ETS will be a valuable asset to the apron environment.

It is important to note that the value functions presented here are qualitative and, therefore, sensitive to stakeholder 'opinions'. Additionally, a quantitative analysis will improve the accuracy of the value model in a later stage of the research. The completeness of the quantitative value function depends on the level of detail and data available. This level of detail can be increased further with the development of the implementation project for the ETS. However, as shown by the outcome of this value function and based on the extent of the research thus far, the implementation of the ETS shows to have promisingly positive effects on the operation and capacity of the apron area at AAS.

# 9
# Conclusions and Recommendations

Based on the research presented in this thesis work, some conclusions can be made about the impact of the ETS on airport gate capacity and apron operations. As presented in the introduction chapter, the research of this thesis work and the conclusions drawn from the research aim to answer the following main research question:

> ***What opportunities does the ETS offer for gate and buffer utilization optimization, and what is the value of the impact of the ETS on apron operations at Amsterdam Airport Schiphol?***

The following sections will present the main conclusions drawn from the gate planning model and the value model developed, thereby drawing light on the impact of the ETS for gate planning and capacity, and airport apron operations. Additionally, section 9.2 presents the recommendations that follow from the research and research conclusions.

## 9.1. Conclusions

The ETS not only influences the taxi-phase of a flight, but it also has an influence on the apron and pushback procedures. The ETS will allow autonomous pushbacks to be performed. Additionally, as no tow truck is need to maneuver the aircraft, a (fully loaded) narrow body aircraft has more maneuverability. In order to make use of these features and to explore any other apron operation opportunities presented by the ETS, a gate planning simulation model and a value model are designed. Conclusions can be drawn from the gate planning models and the value model presented.

### 9.1.1. Conclusions on the Gate Planning Models

The ETS presents the opportunity for more extensive use of the dispatch towing and pit stop concepts. These concepts aim to improve the efficiency of the apron operations, reduce delays, and enhance gate capacity. Even though both are existing concepts, neither is commonly used at AAS. The ETS may offer the opportunity to implement the concepts more widely.

From the gate capacity analysis for the busiest day at AAS in 2014, it can be concluded that the narrow body gates are at or near their peak capacities during the airport's peak operating hours. The buffers are not used to their full capacity yet. Therefore, AAS is looking to enhance their gate capacity in order to accommodate the increasing air traffic demand. The pit stop and dispatch towing concepts may offer good solutions for reducing arrival ground delays and enhancing capacity at the airport.

The gate planning models are designed to investigate the impact of the pit stop and dispatch towing concepts on the gate capacity, efficiency, and arrival delays at AAS.
The initial gate planning model developed, aims to provide insight into the impact and potential value of the dispatch towing and pit stop concepts enabled by the ETS. The initial gate planning model uses gate scheduling data from AAS to graphically show the current gate and buffer occupancy and the change in the gate planning caused by the potential implementation of the dispatch towing and pit stop concepts. From the model it can be concluded that, on the busiest day at AAS in 2014, the pit stop concept would have allowed for 6 extra flights to be planned during the day. Additionally, the dispatch towing concept would have prevented 6 arriving flights from being delayed, resulting in an average of 16 minutes less delay per dispatch tow. Thereby, the model shows that the concepts, enabled by the use of ETSs, are of good use for airport capacity enhancement and arrival ground delay reduction.

The extended analysis models further investigates and explores the usefulness of the pit stop and dispatch towing concepts. In total the models explore 12 different scenarios.

Six of the scenarios involve a certain percentage of flights to be added to the existing peak hour schedule. The model attempts to accommodate the added flights in the existing schedule. Subsequently, the model determines the pit stop candidates and implements pit stops, in an attempt to create more room within the gate schedule for the remaining added flights to be scheduled. From the pit stop extended analysis model it can be concluded that, with a pit stop candidate TAT of 170 minutes, a maximum of 25% of the added flights can be scheduled. The more flights that are added to the schedule, the lower the percentage of flights that can be allocated with pit stops becomes. This is due to the saturation of the gate schedule. If 100% (173 flights) of the peak hour flights are added, approximately 12 flights (8.8%) can be added to the peak hour schedule due to pit stop implementation.

The other six scenarios created delay certain percentages of peak hour flights. The delays may cause schedule conflicts. The model attempts to solve these conflicts by implementing dispatch tows. Approximately 10-12% of the delay conflicts caused, can be resolved through the use of dispatch towing. If all of the peak hour flights were to be delayed, an average of 13-14 conflicts would be resolved through the use of dispatch towing. An average of 17.2minutes is saved on arriving aircraft ground delay per dispatch tow. Therefore, if all of the peak hour flights were to be delayed, an average of 236 minutes of delay can have been saved in total through dispatch towing.

The dispatch towing and Pit stop concepts are known concepts at AAS. However, they are often not implemented for various reasons that relate to the towing operations.

The pit stop concept requires two extra towing and pushback movements. At a congested airport such as AAS, the tow trucks are often busy or, during peak hours, in short supply. Therefore, the pit stop concept is conventionally not used very often. The ETS can change this by eliminating the need for a tow truck. The pit stop with the ETS would, therefore, not put any extra demands on the tow truck resources at the airport. Thus the procedure can be implemented more widely.

The dispatch towing concept is currently not used often because of towing restrictions implemented by the designers of the aircraft. Heavy, fully-loaded aircraft cannot to towed long distances with the use of a tow truck for the risk of damaging the nose landing gear of the aircraft. During the dispatch towing maneuver, the delayed aircraft at the gate is often already fully loaded. The ETS does allow for a fully-loaded aircraft to pushback and taxi to a buffer without any harm on the structure of the aircraft.

Thus, the ETS provides the opportunity for the pit stop and dispatch towing concepts to be implemented more widely at AAS. Thereby, the benefits of the concepts can be reaped. The initial models have shown that on a busy day, approximately 6 dispatch tows and 6 pit stops can be performed. The extended models have shown that with increasing air traffic demand every year, the pit stop concept can offer a way to accommodate more flights at the airport: increasing much needed capacity. Increasing air traffic demand also implies more delays (whether caused by ATC or just statistically speaking). The models have shown that some delay conflicts can be solved through dispatch towing, saving, on average, 17 minutes of arrival ground delays per dispatch tow.

### 9.1.2. Conclusions on the Value Model

A value model can be used to assess the impact of the implementation of a new system or procedure in an environment. This research focused on the airport apron environment and gate capacity influenced by the implementation of the ETS.

Two main stakeholders and four main objectives (or KPIs), involved with the implementation of the ETS and its impact on the airport apron area, were identified. The two main stakeholders considered in this research are KLM Royal Dutch Airlines and Amsterdam Airport Schiphol (AAS). Both companies will be highly involved with, and affected by, the implementation of the ETS. The four main apron operation KPIs identified are safety, capacity and efficiency, costs, and emissions.

The value model measures the influence of the implementation of ETSs on the identified objectives/KPIs. Attributes pertaining to the identified objectives are investigated in detail in order to assess the impact of the ETS per attribute and objective.

The objective 'safety' is influenced by the ETS on the basis of three attributes. One of these attributes is the reduction in the number of tow truck incidents due to a reduction in the number of operational tow trucks at the airport when the ETS is implemented. A total of 16 incidents per month can be avoided should all tow trucks disappear in the long run. The two other attributes pertaining to safety are the pilot situational awareness during autonomous pushbacks and the pushback communication efficiency. Very little data is available regarding these attributes due to the fact that autonomous pushbacks are currently rarely used at AAS. In order to maintain sufficient situational awareness the pilot will need to be guided backwards during his pushback by a marshaller on the ground. Therefore, the pushback communication chain efficiency benefits are not immediately applicable.

The attributes of the objective 'capacity, efficiency, and delay reduction' are closely linked to the gate planning and analysis models created during the research. The pit stop concept is able to increase capacity (by approximately 6 extra flights per day) and the dispatch towing concept can increase efficiency and reduce arrival ground delays (by approximately 17.2 minutes per dispatch tow). The ETS further enhances the apron operational efficiency by reducing pushback time by a maximum of 1:50minute per pushback.

The ETS also influences the cost objective by impacting five cost-related attributes. Tow truck maintenance and fuel costs are reduced due to the elimination or reduction in the number of tow trucks. If all tow trucks are eventually eliminated, approximately 4,6 Million$ can be saved on fuel and maintenance. Additionally, with the elimination of tow trucks, personnel costs are also reduced. Even though a guiding marshaller is still needed during the autonomous pushback, the tow truck driver is relatively more expensive, so a cost reduction is still achieved. The tow trucks also cause FOD and pose a collision risk in the aircraft stand area. Again, the elimination or reduction in the number of tow trucks will reduce this collision cost. As stated before, the dispatch towing concept reduces arrival ground delay time. This also reduces the cost associated with the arriving aircraft not reaching their gate on time. The ETS is thereby able to save costs. However, the ETS also requires maintenance. Additionally, the APU is used more frequently, resulting in additional maintenance costs as well. EGTS estimates that these costs will amount to approximately 15,000$/year.

The main reason for the development of the ETS is the reduction in taxi fuel and subsequent reduction in aircraft ground emissions. Most ETS fuel and emission savings are achieved during the taxi phase of the flight because conventionally the aircraft main engines would be used during this phase. However, some emission savings around the apron area caused by the use use of the ETS are also worth noting. Tow trucks largely operate on fuel. Therefore, the elimination of tow trucks during pushbacks also reduces the fuel usage during pushbacks. Furthermore, the time saved by implementing dispatch towing also results in a fuel usage reduction for the arriving aircraft. Due to the extra towing/taxiing maneuvers, resulting in a higher APU usage, the pit stop concept slightly increases the fuel and emissions. Besides, emissions and fuel, however, the ETS also reduces apron noise by eliminating the need for aircraft engines to be started during the pushback phase. Therefore, only the aircraft APU noise remains.

Based on the data available, a quantitative analysis of each of the attributes was performed. Subsequently, by converting the quantitative analysis scores, the value model attributes are quantified. The weights assigned to the attributes and objectives are based on the past research, the stakeholder values, and the extent of the impact of the ETS on the attribute or objective (pair-wise comparisons).

From the qualitative value analysis performed, it can be concluded that the ETS can create value in the apron environment, initially and even more so in the long run. The value added by the ETS in the apron environment is dependent on the number of operational ETSs and the utilization of the ETS. More aircraft operating with ETSs results in a larger reduction in the number of operational tow trucks, and more widespread ability to use the pit stop and dispatch towing concepts, which eventually results in larger benefits.

The research performed provides insight into the impact of the implementation of ETSs in the airport apron environment. Even though the introduction of ETSs implies new challenges and procedural/operational changes, the system offers many benefits for the airport apron environment as well. It can be concluded that, through the use of ETSs and the operational concepts it enables, gate capacity and airport apron operational efficiency can be enhanced, safety can be increased, costs can be mitigated, and the environmental impact of apron operations is reduced.

## 9.2. RECOMMENDATIONS

As discussed throughout the thesis, some limitations adhere to the research. To reduce these limitations further research can be conducted. The following recommendations for further research and development can be made based on this thesis work:

- Extend the models to include year round data. Currently, the models and the analysis are based on data from July $21^{st}$ 2014. Implementation of more extensive data can result in more accurate results that can be used in the value model.
- Analyze the impact of the ETS enabled pit stop and dispatch towing concepts for planning strategies. Currently, AAS only uses the concepts as a last resort. The gate planners do not plan with the concepts. Efficiency can potentially be enhanced when the concepts are used to plan with ahead of time.
- Investigate how the ETS and ETS enabled concepts can be used optimally when not all narrow body aircraft have an ETS yet.
- Further investigation into autonomous pushbacks is necessary to fully scope the impact of the ETS. Currently, little is known about the effects on safety and pilot situational awareness during autonomous pushbacks at AAS. Additionally, autonomous pushback procedures need to be investigated and established for pilots and AAS personnel.
- Procedural and operational changes need to be determined, documented, and implemented in order for pilots and ground crew to work with the ETS.
- Pilot workload changes during pushback and taxiing with the ETS procedures and implications needs to be investigated.
- The value model used and developed is based on a qualitative analysis of the objective attributes. Once more data becomes available (regarding situational awareness, communication efficiency, delay costs, and noise reduction) a quantitative value model can be established in a similar fashion to provide a more accurate value indication.
- This research focuses on the apron environment. Previous research has focused on the taxi phase with ETS [16]. The two value indications need to be taking into account together in order to gain a good overview of benefits and challenges the ETS offers for KLM and AAS.
- Finally, the focus of the research work can be extended to include wide body aircraft as well. The ETS currently available are designed for use on narrow body aircraft. This has two main reasons; narrow body aircraft have a higher ETS utilization (due to the shorter-haul flights and more frequent landings and take-offs), and the APU of the narrow body aircraft can deliver enough power to enable the ETS and move the weight of the aircraft. Wide body aircraft are heavier, thus more power is required from the APU to move the aircraft through the use of an ETS. Currently many of the wide body APUs cannot provide sufficient power for an ETS. In combination with the lower ETS utilization realized by wide body aircraft (long-haul flights), the ETS is not yet feasible or valuable. However, the ETS can eventually be implemented on wide body aircraft as well. Especially with the design on more electrically advanced aircraft, such as the B787 Dreamliner, the ETS has a future for wide body aircraft as well.

# Bibliography


[1] Safran, *EGTS,* (2014).

[2] AIS-Netherlands, *Aeronautical Information Package: EHAM — AMSTERDAM / Schiphol,* .

[3] *AMS - Amsterdam Schiphol - Airport Terminal Map,* (2015).

[4] F. Dieke-meier and H. Fricke, *Expectations from a Steering Control Transfer to Cockpit Crews for Aircraft Pushback,* in *International Conference on Application and Theory of Automation in Command and Control Systems*, ATACCS (IRIT PRESS, London, 2012) pp. 62–70.

[5] B. Bennebroek, *Innovation of the runway system maintenance strategy at Amsterdam Airport Schiphol using the Value Operations Methodology*, Msc. thesis, Delft University of Technology (2012).

[6] *Verbal Communication - SKYbrary Aviation Safety,* (2015).

[7] C. Wijnterp, *Electric Taxi Devices: A value model and operations estimation*, Msc. thesis, Delft University of Technology (2014).

[8] Honeywell and Safran, *EGTS - electric taxiing system. Introducing the future of aircraft taxiing,* (2014).

[9] R. T. delft) Curran, F. Smulders, and F. Van der Zwan, *Evaluation of Airport System of Systems from a Human Stakeholder Perspective using a Value Operations Methodology ( VOM ) Assessment Framework,* in *11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, September (American Institute of Aeronautics and Astronautics, Virginia Beach, 2011) pp. 1–12.

[10] AAS, *Verkeer en Vervoer 2014-11-Ned,* (2014).

[11] *IATA - New IATA Passenger Forecast Reveals Fast-Growing Markets of the Future,* (2014).

[12] Amsterdam Airport Schiphol Group, *Schiphol Group - Corporate Responsibility,* (2015).

[13] KLM Royal Dutch Airlines, *KLM Takes Care,* (2015).

[14] WheelTugPLC, *WheelTug: Driving Aerospace,* (2014).

[15] TaxiBot, *TaxiBot-International,* (2013).

[16] P. Sillekens, *Effect of EGTS on airport taxi movements at AAS*, Msc. thesis report, Technical University of Delft (2015).

[17] R. Wollenheit and T. Mühlhausen, *Operational and Environmental Assessment of Electric Taxi Based on Fast-Time Simulation,* Transportation Research Record: Journal of the Transportation Research Board **2336**, 36 (2013).

[18] T. Dubois, *WheelTug, Safran-Honeywell and IAI Offer Three Rival Solutions for Airline Engine-off Taxiing,* (2014).

[19] P. Sillekens, *Effect of ETS on airport taxiway congestion*, Msc. thesis literature study, Delft University of Technology (2014).

[20] Honeywell and Safran, *News Release: HONEYWELL AND SAFRAN TO CREATE JOINT VENTURE TO LAUNCH NEW GREEN AIRCRAFT TAXIING SYSTEM,* (2011).

[21] Honeywell, Safran, and Airbus, *Press Release: Airbus Signs MoU with Honeywell and Safran to Develop Electric Taxiing Solution for the A320 Family,* (2013).

[22] G. Norris, *Electric Taxi Puts On A Show At Paris,* (2013).

[23] F. Gomez, D. Scholz, and B. Tor, *IMPROVEMENTS TO GROUND HANDLING OPERATIONS AND THEIR BENEFITS TO DIRECT OPERATING COSTS,* in *Deutscher Luft- und Raumfahrtkongress 2009* (Hamburg, 2009) pp. 1–11.

[24] B. Jerew, *Taxiing Green With Airbus A320's Fuel-Efficient eTaxi System,* (2013).

[25] *ElAl launches WheelTug,* (2011).

[26] R. Curran, *Introduction to Value Engineering and Operations Optimization (TU Delft AE4425),* (2014).

[27] R. L. Keeney, *Building models of values,* European Journal of Operational Research **37**, 149 (1988).

[28] R. L. Keeney, *Value-focused thinking : Identifying decision opportunities and creating alternatives,* Elsevier: European Journal of Operational Research **92**, 537 (1996).

[29] FAA, *Surface Movement Guidance and Control System: Advisory Circular,* (1996).

[30] Amsterdam Airport Schiphol Group, *Amsterdam Airport Schiphol: Traffic Analysis & Forecasts,* (2014).

[31] R. de Neufville and A. Odoni, *Airport Systems. Planning, Design, and Management*, second edi ed., edited by L. S. Hager and D. E. Fogarty (McGraw-Hill Education LLC., 2013).

[32] Amsterdam Airport Schiphol, *RASAS: Regulation Aircraft Stand Allocation Schiphol*, Tech. Rep. July (Amsterdam Airport Schiphol, Amsterdam, 2013).

[33] AAS, *Airport Facts: Airport Capacity,* (2015).

[34] F. A. Duivenvoorde, A. L. Jongen, and F. L. Olislagers, *Amsterdam Airport Schiphol- Airport Collaborative Decision Making Operations Manual: Draft*, Tech. Rep. (Amsterdam Ariport Schiphol, Amsterdam, 2013).

[35] R. Horonjeff, F. X. Mckelvey, W. J. Sproule, and S. B. Young, *Planning and Design of Airports*, fifth edit ed. (McGraw-Hill, 2010).

[36] AAS, *About Collaborative Decision Making,* (2015).

[37] Amsterdam Airport Schiphol Group, *Schiphol Jaarverslag 2014*, Tech. Rep. (Schiphol Group, Schiphol).

[38] Airbus, *ICAO ARC, FAA ADG, Aircraft Approach Category for Airbus Aircraft. origin: EIJA. reference: X00ME1306541.*, Tech. Rep. (Airbus, 2013).

[39] G. Diepen, J. M. V. D. Akker, J. A. Hoogeveen, and J. W. Smeltink, *Using column generation for gate planning at Amsterdam Airport Schiphol*, Tech. Rep. (Utrecht University, Utrecht, 2007).

[40] S. D. Man, *A proposal for improvement of mid-term capacity planning for gates and remote stand at Amsterdam Airport Schiphol (AAS)*, Msc. thesis, Technical university of Delft (2011).

[41] S. G. Hamzawi, *Management and planning of airport gate capacity: a microcomputer-based gate assignment simulation model,* Journal of Transportation Planning and Technology **11**, 189 (1986).

[42] B. Mirkovic, *Airport Apron Capacity Estimation – Model Enhancement,* Elsevier Journal: Procedia - Social and Behavioral Sciences **20**, 1108 (2011).

[43] R. Mangoubi and D. F. Mathaisel, *Optimizing Gate Assignments at Airport Terminals,* Journal of Transportation Science **19**, 173 (1985).

[44] A. Haghani and M.-C. Chen, *Optimizing gate assignments at airport terminals,* Elsevier Science Journal: Transportation Research Part A **32**, 437 (1998).

[45] J. Xu and G. Bailey, *The Airport Gate Assignment Problem : Mathematical Model and a Tabu Search Algorithm,* in *Proceedings of the 34th Hawaii International Conference on System Sciences* (Delta Technology Inc., Atlanta Georgia, 2001) pp. 1–10.

[46] U. Dorndorf, A. Drexl, Y. Nikulin, and E. Pesch, *Flight gate scheduling: State-of-the-art and recent developments,* Omega Elsevier **35**, 326 (2007).

[47] S. Yan, C.-Y. Shieh, and M. Chen, *A simulation framework for evaluating airport gate assignments,* Elsevier Science Journal: Transportation Research Part A: Policy and Practice **36**, 885 (2002).

[48] Y. Cheng, *A rule-based reactive model for the simulation of aircraft on airport gates,* Elsevier: Knowledge-Based Systems **10**, 225 (1998).

[49] Y. Cheng, *Solving push-out conflicts in apron taxiways of airports by a network-based simulation,* Computers and Industrial Engineering **34**, 351 (1998).

[50] FAA, *Simmod Manual: How SIMMOD Works,* .

[51] Jeppesen, *TOTAL AIRSPACE AND AIRPORT MODELLER (TAAM): Product Profile,* (2011).

[52] N. J. Ashford, S. Mumayiz, and P. H. Wright, *Airport Engineering: Planning, Design and Development of 21st Century Airports*, 4th ed. (John Wiley & Sons Ltd, 2011).

[53] R. T. delft) Curran, K. Dinh, P. T. D. Roling, and E. S. G. van Calck, *Simulation of taxiway system maintenance to optimize airport operational value,* in *Third International Air Transport and Operations Symposium 2012*, edited by R. Curran, L. Fischer, D. Pérez, K. Klein, J. Hoekstra, P. Roling, and W. Verhagen (IOS Press, 2012) pp. 130–148.

[54] T. L. Saaty, *A scaling method for priorities in hierarchical structures,* Journal of Mathematical Psychology **15**, 234 (1977).

[55] T. L. Saaty, *Deriving the AHP 1-9 scale from first principles,* in *Sixth International Symposium on Analytical Hierarchy Process*, August (Berne, 2001) p. pg. 245.

[56] N. M. Dzikus, R. Wollenheit, M. Schaefer, and V. Gollnick, *The Benefit of Innovative Taxi Concepts: The Impact of Airport Size, Fleet Mix and Traffic Growth,* in *2013 Aviation Technology, Integration, and Operations Conference* (American Institute of Aeronautics and Astronautics, Reston, Virginia, 2013) pp. 1–16.

[57] N. Dzikus, J. Fuchte, A. Lau, and V. Gollnick, *Potential for Fuel Reduction through Electric Taxiing,* in *11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, September (American Institute of Aeronautics and Astronautics, Hamburg, 2011) pp. 1–9.

[58] R. Caves, *A search for more airport apron capacity,* Journal of Air Transport Management **1**, 109 (1994).

[59] I. Simaiakis, H. Khadilkar, H. Balakrishnan, T. G. Reynolds, R. J. Hansman, B. Reilly, and S. Urlass, *DEMONSTRATION OF REDUCED AIRPORT CONGESTION THROUGH PUSHBACK RATE CONTROL*, Tech. Rep. January (MIT Internation Center for Air Transportation (ICAT), Cambridge, MA, USA, 2011).

[60] KLM Royal Dutch Airlines, *KLM ground services and fleet management data,* (2013).

[61] D. Raes, *Efficient autonomous pushback and taxiing- a step forward to reducing costs and pollution*, Msc. thesis, Katholieke Hogeschool Brugge-Oostende and Hochschue fur Angewandte Wissenschaften Hamburg (2008).

[62] I. Mccreary, *The economic cost of FOD to airlines,* Insight SRI (2008).

[63] A. Cook, G. Tanner, V. Williams, and G. Meise, *Dynamic cost indexing - Managing airline delay costs,* Journal of Air Transport Management **15**, 26 (2009).

[64] Bickerdike Allen Partners, *Noise Impact Assessment of Proposed Curium Development: Appendix N(6)-Ground Noise Elementary Assessments*, Tech. Rep. (London Luton Airport Operations Limited, London).

# A

# APPENDIX A: SCHIPHOL AIRPORT LAY-OUT


Figure A.1: The runway lay-out of AAS (schiphol.nl)

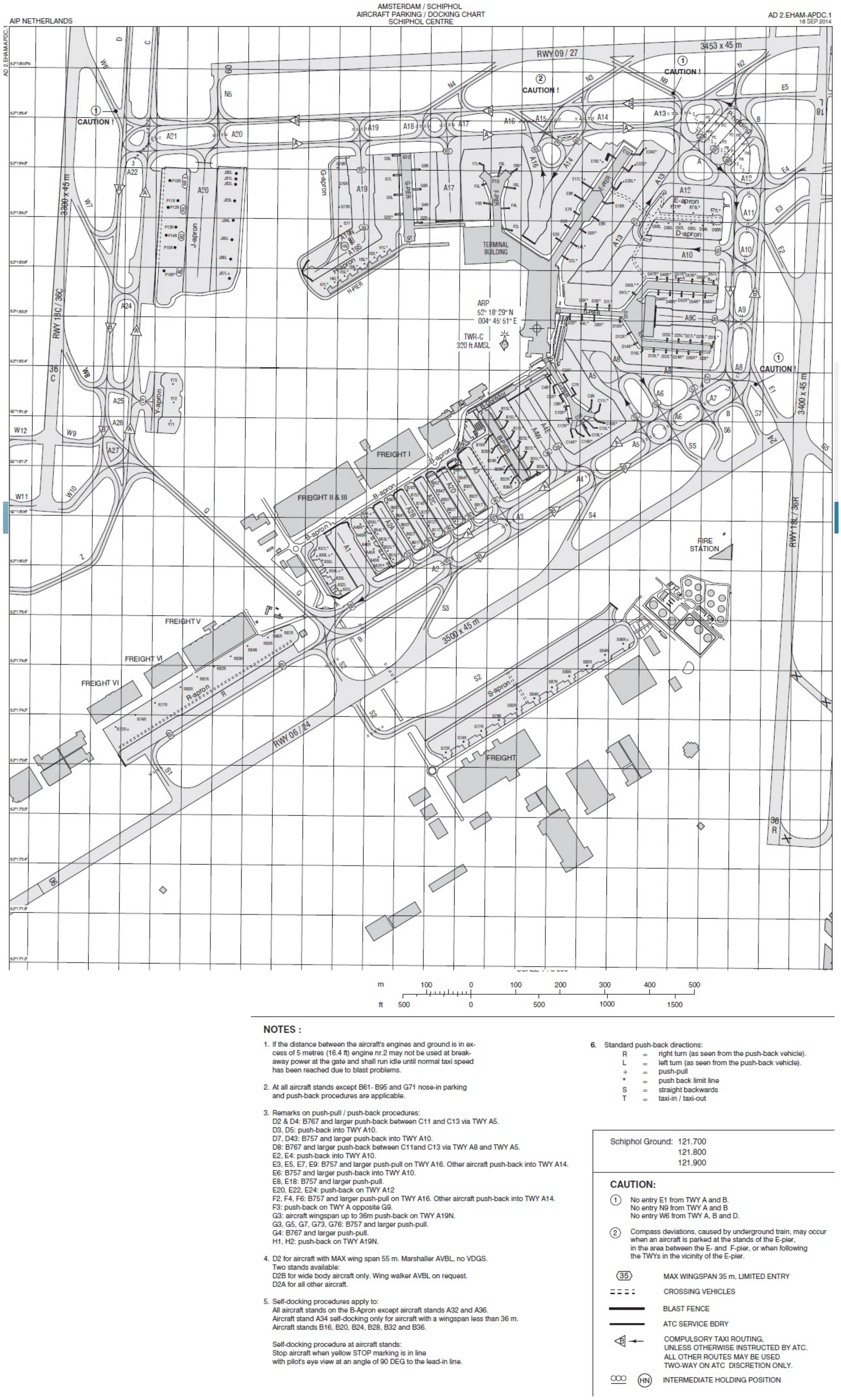



Figure A.2: The light gray areas represent the apron, taxiways, and runways. The terminal buildings are represented in a slightly darker shade of gray [2]

# B

# Appendix B: Dispatch Towing Gate Planning Results

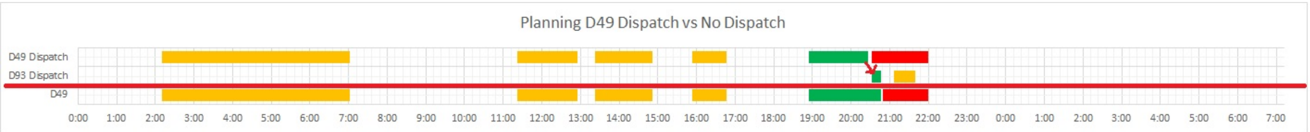



Figure B.1: Gate planning D49 with and without dispatch towing

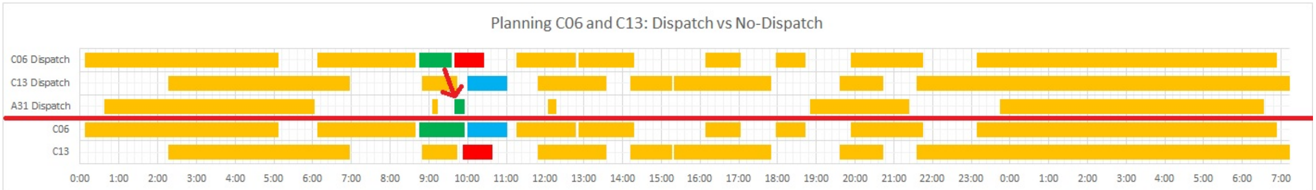



Figure B.2: Gate planning C06 and C13 with and without dispatch towing

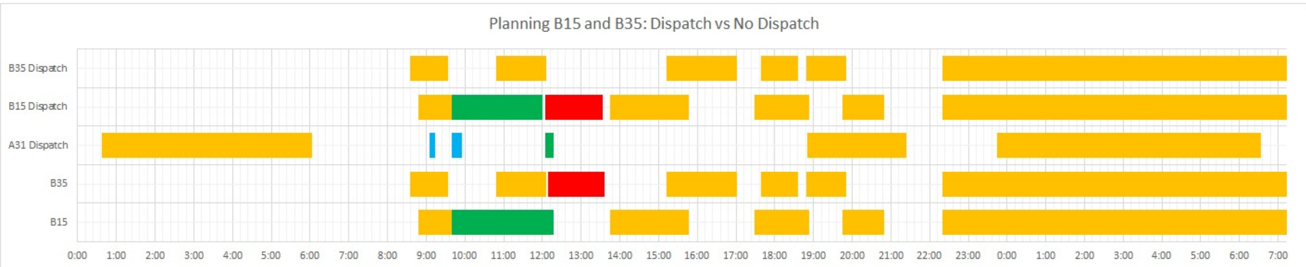



Figure B.3: Gate planning B15 and B35 with and without dispatch towing

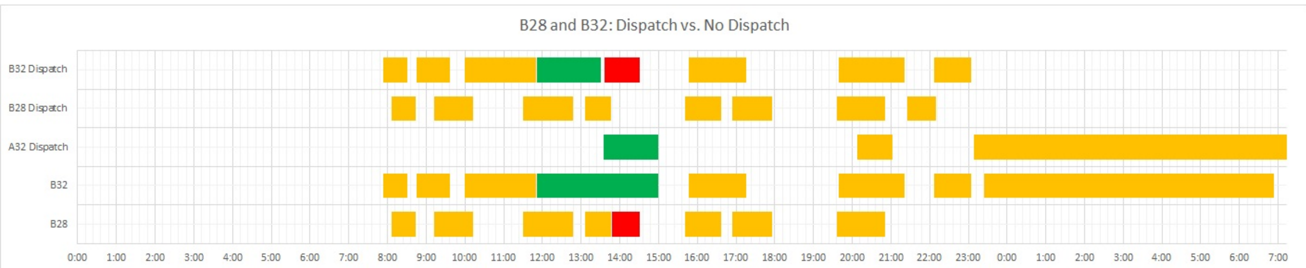



Figure B.4: Gate planning B28 and B32 with and without dispatch towing

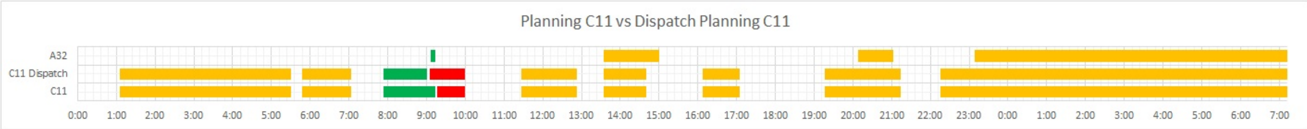



Figure B.5: Gate planning C11 with and without dispatch towing

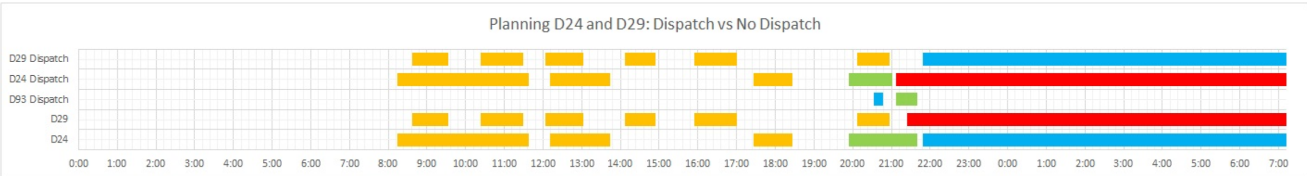



Figure B.6: Gate planning D24 and D29 with and without dispatch towing

# C

# APPENDIX C: TOW TRUCK COST CALCULATION

| Type | Total costs/year | number of tow trucks | costs per tow truck per year | total number of operational hours | costs per operational hour |
|---|---|---|---|---|---|
| | | | | | |
| AM110 | € 950,000 | 12 | € 79,167 | 25600 | € 37 |
| | | | | | |
| AM210 | € 1,472,000 | 9 | € 163,556 | 21600 | € 68 |
| | | | | | |
| AM500 | € 2,100,000 | 12 | € 175,000 | 20400 | € 103 |

| | | total cost |
|---|---|---|
| NB tow trucks | 21 | 2422000 euro |
| total tow trucks | 33 | 4522000 euro |

| | | |
|---|---|---|
| **Average # flights/year** | 80516 | (reference Wijnterp) |
| **Average KLM AMS pushbacks** | 40258 | (reference Wijnterp) |
| **99.65% utilization** | | (reference Wijnterp) |
| **ETS pushbacks AMS** | 40117 | |
| **conventional pushbacks AMS** | 141 | |

| | | | |
|---|---|---|---|
| **Average Fuel Price (last 10 years)** | 763.6822 $/ton | 0.7636822 $/kg | |
| **Tow truck fuel usage** | 2.4 kg/pushback | (reference WheelTug) | |

| | conventional | ETS | savings | |
|---|---|---|---|---|
| **Tow truck fuel cost/pushback** | 1.83283728 | 1.83283728 | | $/PB |
| **Total tow truck fuel cost/year** | 73786.36322 | 258.430056 | 73527.93316 | $/year |
| | 65821.91188 | 230.535287 | 65591.37659 | Euro/year |

| | |
|---|---|
| 1 Euro | 1.121 $ |
| 1$ | 0.89206066 euro |

| **Total tow tuck costs (incl fuel)/year** | | |
|---|---|---|
| all tow trucks+fuel | 4587821.912 euro/year | 5142948.363 $/year |
| NB tow trucks +fuel | 2487821.912 euro/year | 2788848.363 $/year |

| reduce by 7 NB tow trucks | | costs/year | (Reference KLM ground services) |
|---|---|---|---|
| AM110 | 4 | 316,667 | |
| AM210 | 3 | 490,667 | |
| Total | 7 | 807,333 | |
| **ETS savings** | | | |
| **872,925** | **$/year saved** | | |
| **978,548.60** | **$/year saved** | | |

# D

# Appendix D: ETS Value Model Attribute Comparison Matrices

Comparison matrix for the safety attributes. I=Incidents, SA=Situational Awareness, and Com=Communication

$$M = \begin{array}{c} \\ I \\ SA \\ Com \end{array} \begin{array}{c} \begin{array}{ccc} I & SA & Com \end{array} \\ \begin{pmatrix} 1 & 2 & 2 \\ 1/2 & 1 & 1 \\ 1/2 & 1 & 1 \end{pmatrix} \end{array} \tag{D.1}$$

Comparison matrix for the capacity, efficiency, and delays objective attributes. P=Pit stop capacity enhancement, D=Dispatch towing efficiency, and T=Time saving during pushback

$$M = \begin{array}{c} \\ P \\ D \\ T \end{array} \begin{array}{c} \begin{array}{ccc} P & D & T \end{array} \\ \begin{pmatrix} 1 & 1 & 2 \\ 1 & 1 & 2 \\ 1/2 & 1/2 & 1 \end{pmatrix} \end{array} \tag{D.2}$$

Comparison matrix for the costs objective attributes. TMF=Tow Truck Maintenance and Fuel costs, M=APU and ETS maintenance, P=personnel costs, D=Delay costs,F=FOD costs

$$M = \begin{array}{c} \\ TMF \\ M \\ P \\ D \\ F \end{array} \begin{array}{c} \begin{array}{ccccc} TMF & M & P & D & F \end{array} \\ \begin{pmatrix} 1 & 1 & 1 & 2 & 2 \\ 1 & 1 & 1 & 2 & 2 \\ 1 & 1 & 1 & 2 & 2 \\ 1/2 & 1/2 & 1/2 & 1 & 1 \\ 1/2 & 1/2 & 1/2 & 1 & 1 \end{pmatrix} \end{array} \tag{D.3}$$

Comparison matrix for the emissions objective attributes. PF=Pit Stop Fuel Usage, DF=Dispatch towing fuel saving, PB=Pushback fuel saving, N=Noise reduction on the platform.

$$M = \begin{array}{c} \\ PF \\ DF \\ PB \\ N \end{array} \begin{array}{c} \begin{array}{cccc} PF & DF & PB & N \end{array} \\ \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{pmatrix} \end{array} \tag{D.4}$$

# E

# Appendix E: ETS Value Model Calculations

| Attribute Weight | Initial score | potential score | attribute initial value | attribute potential value |
|---|---|---|---|---|
| 0.5 | 1 1/3 | 2 | 0.67 | 1.00 |
| 0.25 | 1/3 | 1 | 0.08 | 0.25 |
| 0.25 | 1 | 1 2/3 | 0.25 | 0.42 |
| | | | **1.00** | **1.67** |
| | | | | |
| 0.4 | 2 | 2 | 0.80 | 0.80 |
| 0.4 | 2 | 2 | 0.80 | 0.80 |
| 0.2 | 1 2/3 | 1 2/3 | 0.33 | 0.33 |
| | | | **1.93** | **1.93** |
| | | | | |
| 0.25 | 1 2/3 | 2 | 0.42 | 0.50 |
| 0.25 | 2/3 | 2/3 | 0.17 | 0.17 |
| 0.25 | 1 2/3 | 1 2/3 | 0.42 | 0.42 |
| 0.13 | 1 1/3 | 1 2/3 | 0.17 | 0.22 |
| 0.12 | 1 1/3 | 1 1/3 | 0.16 | 0.16 |
| | | | **1.33** | **1.46** |
| | | | | |
| 0.25 | 1/3 | 1/3 | 0.08 | 0.08 |
| 0.25 | 1 2/3 | 1 1/3 | 0.42 | 0.33 |
| 0.25 | 1 2/3 | 1 2/3 | 0.42 | 0.42 |
| 0.25 | 1 2/3 | 1 2/3 | 0.42 | 0.42 |
| | | | **1.33** | **1.25** |

| initial value | objective weight | intial objective value | potential objective value |
|---|---|---|---|
| Safety | 0.39 | 0.39 | 0.65 |
| capacity/ efficiency | 0.28 | 0.54 | 0.54 |
| Costs | 0.19 | 0.25 | 0.28 |
| Emissions | 0.14 | 0.19 | 0.18 |
| | | 1.37 | 1.64 |
| | **Value created** | **0.37** | **0.64** |
| | max value created=1 | | |