Finding the viability of using an automated guided vehicle taxiing system for aircraft

MSc. Thesis

N.J.F.P. Guillaume

Delft University of Technology

TU Delft

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N.J.F.P. Guillaume

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Committee:	Prof. dr. R. Curran,	Delft University of Technology
	Dr. ir. G.H.D.A. Correia,	Delft University of Technology (supervisor)
	Dr. ir. B.F. Santos,	Delft University of Technology (supervisor)
	ir. P.C. Roling,	Delft University of Technology

TU Delft

Preface

This research is done to fulfill the requirements for the degree of Master of Science in Aerospace Engineering at Delft University of Technology. For the project, first literature of the subject has been reviewed after which a clear gap in research was identified; to analyze the use of AGVs for aircraft taxiing. Then a research framework was constructed to fulfill the research objectives. Together, about 9.5 months of full-time work accomplish this research.

During the entire research I have had a great support from people around me. Therefore I would like to give a special word of thanks to the following people:

To my supervisors dr. B.F. Santos and dr. G.H.D.A. Correia. Together they form a great and ambitious team that assisted me during the entire research. With dr. Santos I had many brainstorm sessions regarding the airports operations, while dr. Correia assisted me in the routing and scheduling model. Although both have a fairly busy schedule, they gave me always a warm welcome to ask questions regarding my research.
The fact that both are critical, ambitious and creative, motived me during the entire research. I would also like to thank ir. Roling for giving his input on taxi operations.

To my family who supported me during my entire studies. Especially my parents, who gave me the opportunity to study at the same university as my grandfather did.

To my friends and roommates for giving me a great support during this busy period, but mostly for having a good time during the research. Here also I would like to thank the boys in room 3.15 of the Aerospace Engineering faculty for sharing their thoughts on the research.

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Abstract

The taxi procedure at an airport refers to the surface movement of the aircraft between the parking position and the runway or vice versa. Nowadays, aircraft tend to taxi with the main engines, even if they are not optimized for it. Using an alternative suitable taxiing system that fulfills the requirements of the taxi procedure could be a useful tool to save costs. Automated guided vehicles (AGVs) seem to be a convenient alternative that could potentially be used for aircraft taxiing.

This report focuses on the state-of-the-art concept of using AGVs in the taxi procedure so that the vehicle tows the aircraft to the runway and the main engines of the aircraft are not used during the largest part of the taxi operations, reducing this way the cost of it. The main research objective is "to analyze the effect of using automated guided vehicles for aircraft taxiing at a major airport by creating a routing and scheduling model that is capable of creating trajectories for aircraft and automated guided vehicles while optimizing the cost of aircraft taxiing".

The use of AGVs started in 1955 in different situations and ever since its employment has continuously grown. With the current technologies an AGV system able to cope with the current throughput and reduce the cost of taxi operation could be developed. Indeed, it would be profitable for airlines keeping the throughput and airports.

After an exhaustive literature review of the topic, a routing and scheduling model that improves the current taxiing system has been created. This model takes into account the aircraft taxiing requirements and the optimal way of routing and scheduling with AGVs and is developed by Mixed Integer Linear Programming (MILP) in order to minimize the cost of the airport ground movement problem, including the cost of delay of the aircraft.

The model should be able to find the optimal solution for taxiing using AGVs in any major airport - in this research Amsterdam Airport Schiphol (AAS) has been used as case study. Historical flight data and the taxiing network of AAS are used to model the traffic on the taxi lanes. In this case study it was found that a small fleet of two narrow-body (NB) towing AGV and one wide-body (WB) towing AGV gives the highest cost savings for the analyzed days. The departures at AAS are not evenly distributed over the day, which affects the utilization rate of the vehicles. A roughly year estimation showed that 1.4 million EUR could be saved. Also 11 thousand tons of CO2 could be reduced, which means a plus of 82 thousand EUR to carbon offsetting cost savings in 2020.

By analyzing the effect of changing the input parameters a sensitivity analysis is made on the jet-fuel price, diesel price and the depreciation cost of the AGVs. While diesel price has a relative low effect on the cost savings using AGVs, these cost savings as well as the optimal fleet of vehicles is highly dependent on the jet-fuel price (the higher the jet fuel price is, the more cost savings can be obtained) and the depreciation cost of the vehicles. Since all these costs are an input to the model, it is possible to check whether it is cost-efficient to implement an AGV system based on the expected prices for an airport.

This research can be further improved by analyzing the effect of using AGVs on different airports and by testing more cases for AAS using up-to-date data. Another suggestion would be to decrease the computational time of the model to make it more user friendly to use for further research.

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List of acronyms

AAS	Amsterdam Airport Schiphol
AGV	Automated guided vehicle (often called 'vehicle' in this report)
APU	Auxiliary power unit
ATS	Airplane Transporting System (company)
CFMU	Eurocontrol Central Flow Management Unit
CO	Carbon monoxide
CO2	Carbon dioxide
EGTS	Electric green taxiing system (Safran-Honeywell ETS)
ETS	Electric taxiing system
ECDT	Engine cool down time
ESUT	Engine start up time
FAMS	Flexible automated manufacturing system
FOD	Foreign object damage
FRMHS	Free-ranging flexible material handling systems
GA	Genetic algorithms
GMT	Greenwich Mean Time
GVS	Greedy Vehicle Search
HC	Hydrocarbon
ILS	Iterated Local Search
MBM	Market-based measures
MILP	Mixed integer linear programming
MTOW	Maximum take-off weight
NB	Narrow body
NSA	Network Simplex Algorithm
NOx	Nitrogen oxides
QPPTW	Quickest Path Problem with Time Windows
RH	Receding horizon
TAGV	Tandem automated guided vehicle
WB	Wide body

1 Introduction

Automated guided vehicles (AGVs) could be used for aircraft taxiing. In this concept the aircraft is towed by an external vehicle over the taxi lanes instead of using the main engines to perform taxi operations. According to Morris et al. [2015], this way of taxiing could potentially save costs, due to the lower utilization of the aircraft's main engines.
This thesis analyzes the potential savings that can be obtained by applying such a system in the air transportation industry. What are the potential savings by applying such a system, and what is the effect of extra traffic on the airport by the use of these AGVs?

This report is written for a master thesis project at the Faculty of Aerospace Engineering at the Delft University of Technology. This chapter introduces the problem and the structure of this report.
Air traffic has been growing fast and is about to double in 2020 compared to 2005 in terms of the number of flights. In the overall air traffic management system, major airports often form bottlenecks. Improvement in critical airport operations will be more and more important [Atkin et al., 2010]. In this section the airport operations are reviewed. First a brief history regarding air transportation is given by discussing the typical characteristics of the air transportation industry, followed by the taxiing problem. This chapter ends with a short description of the research objective and the report structure.

Air transportation industry
To describe the air transportation industry the following main characteristics of the industry are shortly discussed:

- **Continuous growth :** The world growth of air travel has averaged approximately 5 % per year over the last 30 years. Even under relatively conservative assumptions concerning economic growth over the next 10-15 years, a continued annual growth of 4-5 % in global air travel will lead to a near-doubling of the total air traffic during this period. [Belobaba et al., 2015]
- **Highly regulated :** Historically airlines have been highly regulated by governments and airworthiness authorities. In 1978 the USA started the economical deregulation of airlines. The reduction of government involvement in the competition of airlines has spread to most of the rest of the world. [Belobaba et al., 2015]
  On the other hand regulations regarding safety, environment and the air traffic management have never been higher. For safety, airlines and airports have strict regulations. Furthermore the industry is increasingly involved in regulations regarding the environment, such as for emissions and noise.
- **Competition:** Airline liberalization has led to a highly competitive international airline industry. Low cost carriers have changed the competitive landscape in most regions with liberalized airline markets affecting structures with their substantial lower fares. Therefore the traditional are forced to match these lower prices to remain competitive. [Belobaba et al., 2015]
- **Fuel costs :** The cost of airlines are highly dependent on the fuel prices (fuel cost was on average 26.5 % of the total cost in 2007). With the high oil price in 2006, fuel emerged as the single largest industry expense.

- **Capital intensive :** The barriers to entry the air transportation industry are high in terms of capital. This also means that technology changes can be expensive to implement.

These airline characteristics also describe the main challenges in the industry the coming years. According to Belobaba et al. [2015] and ICAO [2016] challenges are to sustain profitable, ensure safety and security and focus on a sustainable air transportation infrastructure. Taxiing with AGVs could potentially help the industry to tackle these challenges.

Taxi operations
Due to the continuous growth in air transportation, major airports often form bottleneck in the overall air traffic management system. In the airport operations, ground movements (including aircraft taxiing) form the link between arrival/departure sequencing and gate allocation. As stated by Benlic et al. [2016], an optimal departure sequence is of no use if the aircraft is not able to reach the assigned runway on time. Furthermore the airport ground surface is limited, which can result in congestion during peak hours causing flight delays. According to Morris et al. [2015], in the past, airports used to address congestion through expansion of their airfields. However, the addition of runways and taxiways would increase the complexity of air terminals, which will penalize the efficiency of the system by adding human workload, thus restricting the potential benefits of the surface expansion. The increased complexity will also increase the risk of human error, resulting in potentially hazardous situations.

In addition, the increasing number of taxiing aircraft will contribute significantly to an increase in fuel burn and emissions. During taxiing operations, hydrocarbons and CO are found to be the highest emitted pollutants due to the low engine thrust. Moreover the growth rate of the total taxiing time has been larger than the growth rates of the airborne time, the total time an aircraft is used per flight and the total number of operations. The trend directly results in an increase in fuel consumption and ground emissions. It is therefore becoming increasingly difficult to ignore the importance of optimizing aircraft taxiing operations. [Selderbeek et al., 2013]

Aircraft waste fuel during ground operations, since the aircraft engines are simply not optimized for the task. According to Hospodka [2014b] it is presumed that during taxi the average thrust setting is at 7% of engine performance. For narrow body aircraft, such as an Airbus A320, the fuel burn rate is more than 0.1 kg per second. Fuel flow of an A380 with four engines operating is about 1,2 kg of fuel per second of taxiing. A significant amount of fuel can be saved, 1 to 4% of the overall fuel consumption [IATA, 2013], as the average taxi out time on 20 main European airports is about 17 minutes .

For aircraft taxiing alternatives, there are currently three main developments; electrical taxiing systems (ETS), rail systems and taxiing by towing vehicles. These new devices are designed to decrease costs and environmental impacts of aviation. Advantages of these kind of systems are not only limited to direct fuel savings, but also to fuel savings resulting from smaller quantities of the transported taxi fuel. Furthermore costs can be saved due to engine life and maintenance savings (since working time of the main engines can be saved), wear-out of the brakes and foreign object damage (FOD) savings (reduce the danger of engine damage, since 85% of FOD happens on the stand or during taxiing).[Hospodka, 2014a]
The main advantages and disadvantages of the alternative taxiing systems are explained here:

- In ETS, taxiing is performed by an electric engine in the landing gear. Examples are Wheeltug, where an electric engine is placed in the front wheel of an aircraft powered by the APU and the electric green taxiing system (EGTS) from Safran-Honeywell. In the EGTS system the electrical motor is placed in the main landing gear. According to a case study of Re [2012], ETS could on average save up to 2.6% of the overall fuel consumption (for flight this depends on the flight mission and the duration of the taxi phases). However these systems also have disadvantages, such as a lack of friction or the positioning of the EGTS system in the main landing system. Furthermore these systems are not suitable for wide-body aircraft because the APU performance is not sufficient. Also a lower taxiing speed could be obtained, which can decrease the throughput of an airport as investigated by Sillekens [2015].

- A railway taxiing system is proposed by ATS company. However the main disadvantage of this solution is that a (costly) railway system needs to be constructed on the airport.

- Another option is making use of an aircraft towing vehicle such as TaxiBot from Israeli Aircrafts Industries. Taxibot is a towing car that is controlled from the cockpit. By bar-less towing the aircraft, no main changes for the aircraft are needed. (Bar-less tractors use a pick-up device to accommodate and block the nose gear tire of the aircraft.) TaxiBot is also usable for heavy aircraft, since the towing tractor will not have a lack of power. The disadvantage is that extra vehicles are needed on the already congested airport ground surface. This will also increase the workload of the traffic controllers. An example of TaxiBot operations can be found in Figure 1.1. In this figure it can be seen that main engines of the aircraft will be used in a later stage in the operations for a departing aircraft.

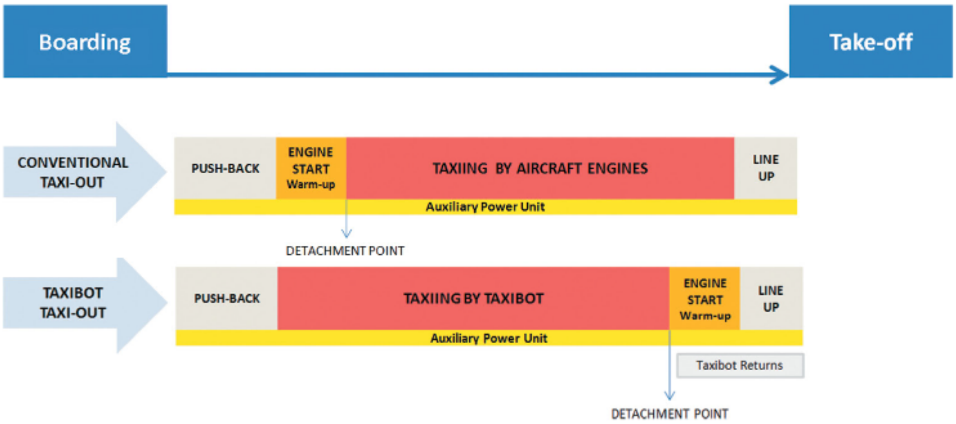


Figure 1.1: Example of TaxiBot operations compared to conventional operations for a departing aircraft. Using TaxiBot the main engines of the aircraft will be used in a later stage, resulting in a lower (total) fuel consumption and lower environmental impact. [Postorino et al., 2017]

As proposed by Morris et al. [2015] an automated guided towing vehicle could be the solution for engine-off taxiing without increasing human workload, however the extra traffic due to these vehicles has to be taken into account. Recent autonomous driving technologies for automobiles make it feasible to apply this technology to airport ground movements. Arguably, deploying self-driving vehicles for this purpose offers fewer technical challenges than deploying them on roadways. Routes between gates to runways and runways to gates are typically predetermined, with little or no possibility for alternatives. In addition, to ensure safety, constraints on taxiing operations are rigid and unambiguous.

Research objective

In order to investigate the operational and economical feasibility of the implementation of automated guided taxiing vehicles, this research looks at the effect of deploying these vehicles at a major airport. Therefore in this research an optimization model is developed to determine the most cost efficient taxi operations using these vehicles. To test the model, Amsterdam Airport Schiphol (AAS) will be used as case study. Different time intervals and days will be analyzed to test the performance of the model and the use of AGVs for aircraft taxiing.

Report structure

Chapter 2 summarizes the state-of-the-art literature regarding airport ground movements and AGV models. Here the gap in literature is defined. This report will scientifically fill this research gap, which is described in Chapter 3. In this chapter also the research objective and scope are described in detail.
Chapter 4 provides the methodology. Each component of the model is described here in detail, from the input data to the assumptions used. In this chapter also the mathematical model is presented. The results of the model are given in Chapter 5. In Chapter 6 the results are validated and sensitivity analysis are done. Finally in Chapter 7 the main conclusions and recommendations are given.

2
Literature review

In order to investigate the operational and economical feasibility of the implementation of automated guided taxiing vehicles, this chapter provides a literature study on this subject. First in Section 2.1 the current airport ground movements and their optimization techniques are discussed. In Section 2.2 research is done on AGV technologies and the different approaches to implement AGVs in the most efficient way. This chapter ends with the state-of-the-art and main conclusions in Section 2.3.

2.1. Airport ground movements

Due to congestion, airports form more often bottlenecks in the overall air traffic management system. Many major airports operate already close to their maximum capacity. With the increase in air traffic over the past years the anticipated future growth highly depends on the available capacity of the airport infrastructure.[Atkin et al., 2010, Morris et al., 2016, Roling and Visser, 2008] Various studies have been done in optimizing the airport ground movements. To get a better understanding in the optimization of the airport surface planning and scheduling, this chapter summarizes the most important studies done on this topic. A similar format as in the literature review on this topic till 2009 by Atkin et al. [2010] is used, however this study will focus on the state-of-the-art literature after 2009.
First in Section 2.1.1 the problem is described, followed by Section 2.1.2 where de integration in airport operations is discussed. In Section2.1.3 different solution approaches are described to solve this problem. In Section 2.1.4, 2.1.5 & 2.1.6 the dynamics, robustness and the balance between execution time and optimality are described respectively.

2.1.1. Problem description

Taxi planning involves managing the aircraft from pushback to take-off (departing aircraft) and from the landing runway to the apron (arriving aircraft). Optimizing the sequencing and flow of airport ground traffic can be seen as a routing and scheduling problem. The goal can be minimizing delays and/or total taxi times, while dealing with amongst others safety constraints and dynamic schedules. For small airports (airports where there is almost no interaction between aircraft), simply the shortest path can be used for the routing of the aircraft. On the other hand for (large) airports, where multiple aircraft taxi at the same time, there is interaction between routes of different aircraft. Here the most optimal route might not be the shortest path for each aircraft, but a conflict free overall optimal solution. This section describes and compares the different ways the taxi planning problem is treated in the literature.

Taxiing objectives

Different objective functions were found in the literature for the airport ground movement problem. Based on the taxiing objective, the problem can be solved to find the most optimal way of taxiing. The most common objectives are:

- **Minimizing taxiing time** : The total taxi time (or delay) is minimized.
- **Minimizing fuel consumption** : The fuel used for taxiing is minimized.

Minimization of the total taxi time/taxiing delay is used by Marín [2006], Rathinam et al. [2008] and Pesic et al. [2001]. In the recent literature Benlic et al. [2016], Bosson et al. [2015] and Gotteland et al. [2014] also used the objective to minimize the total taxi time. A variation of the time minimization is found in García et al. [2005]. Here the minimization of the duration from the first to the last movement (makespan) is used. Roling and Visser [2008] used a weighted combination of the total holding time and the total taxi time.
When more than one variable are used for the objective function, this is considered as a multi-objective function. Often the minimization of the fuel consumption is used in combination with the total taxi time objective, as done by Chen et al. [2016], Ravizza et al. [2014], Weiszer et al. [2015], Yu and Lau [2014].
Another objective is to minimize the costs of the ground movements [Bertsimas and Frankovich, 2015], or to take into account the minimum total distance for taxiing, as presented by Clare and Richards [2011].

Elements of taxiing operations
For the airport ground movement optimization, different constraints were found in the literature based on the elements of taxiing operations. These constraints characterize the airport ground movement problem. The main taxiing operations elements are divided into five categories:

- **Routes**
  In most recent papers, first a set of possible routes for each vehicle is determined. An algorithm will choose between the routes to find an optimum conflict-free path [Roling and Visser, 2008]. This method is also applied by: Bosson et al. [2015], Chen et al. [2016], Gotteland et al. [2014], Weiszer et al. [2015], Yu and Lau [2014].
  Bertsimas and Frankovich [2015], Bosson et al. [2015] and Yu and Lau [2014] do not consider the taxiing management as an independent scheduling problem, but address a model that simultaneously performs the optimization of arrival sequencing, departure sequencing and surface routing. The routes assigned for these problems are part of the optimization of the complete problem (see also Section 2.1.2).

- **Separation distance**
  Separation during taxiing is needed to avoid conflicts. When taxiing with the aircraft engines, it is also important not to be in the jet blast of another aircraft. Different constraints for separation were found. Clare and Richards [2011], Ravizza et al. [2014] use spatial separation that is enforced in the model through temporal separation at the nodes. Separation is ensured by the separation distance of nodes. This approach is also used by Roling and Visser [2008], where aircraft cannot be at the same node or edge at the same time.
  Bosson et al. [2015] use a minimum separation of 200 m while Gotteland et al. [2014], Yu and Lau [2014] use a minimum separation on the taxi ways of 60 m. At the gates, such a separation distance is usually not applied.

- **Movement speeds**
  In the literature the movement speeds of the aircraft can be divided into constant and variable speeds;

  - **Variable speed** : Clare and Richards [2011] used variable speeds for the aircraft, where taxiing speed is determined by the separation between nodes. Ravizza et al. [2014] used variable taxi speeds based on different factors such as total distance traveled, total turning angle and the number of other aircraft of different types which were moving around the airport at the time. Gotteland et al. [2014] used movement speeds based on the procedures of the aircraft with a maximum speed of 10 m/s and included a speed uncertainty. Bosson et al. [2015] used a speed range with a minimum and maximum speed of 8 kts and 16 kts respectively, depending on the aircraft and separation with other aircraft.
  - **Constant speed** : Yu and Lau [2014] assume the speed of the aircraft traveling on the taxiway as constant, independent of aircraft types, weight classes and taxiway passages. Weiszer et al. [2015] use a speed profile optimization problem, where the maximum speed on straight taxiways is restricted to 30 knots (15.43 m/s) and turning speed is set to 10 knots (5.14 m/s). Here stored (fixed) speed profiles in a database have been used. Furthermore, the maximum acceleration and deceleration rate is set to 0.98 m/s^2 for passenger comfort.

- **Time of arrival**
  Arriving flights have to taxi from the runway to the gate. The gate is usually fixed, and therefore the aim

is to reach the gate as soon as possible (preferred by airline and passengers). For the model the time of arrival can be seen as fixed or deviations in the time of arrival are possible. Clare and Richards [2011], Gotteland et al. [2014], Ravizza et al. [2014], Weiszer et al. [2015] used fixed arrival times as input. On the other hand Bosson et al. [2015] used a scheduler for integrated arrival (and departure) operations in the presence of uncertainty, by the integration of air and ground operations. Also Yu and Lau [2014] incorporated a small deviation in the arrival time by taking into account the earliest and latest possible arrival time.

- **Time of departure**
  Aircraft need to be routed from the gate to the runway in order to depart. The push-back time is the earliest time where an aircraft can start taxiing. Different timing constraints were found in the literature and applied to the routing and scheduling for departing aircraft. Some try to reach the runway as soon as possible. This minimum time constraint is used by Bertsimas and Frankovich [2015]. However most papers try to come as close as possible to the predetermined departure time such as in Bosson et al. [2015] or Yu and Lau [2014] where deviations from these target times are penalized. Gotteland et al. [2003] integrated a constraint according to the 15 minutes time slots determined by the Eurocontrol Central Flow Management Unit (CFMU). Here each aircraft should reach the runway in the time window $[t-5; t+10]$, where t is a scheduled slot departure time.

2.1.2. Integration of airport operations

The airport ground movement problem is not an isolated one. Arrival sequencing, departure sequencing and surface routing (to and from gate) are linked to each other as shown in Figure 2.1. Therefore the performance of the ground movement can affect each of these operations and vice versa. Improvement in ground movement optimization can therefore have a significant impact on the total airport operations. Also accurate taxi time predictions are beneficial for improving departure sequencing and re-sequencing.(Atkin et al. [2010], Weiszer et al. [2015])
The optimization arrival/departure sequencing and surface routing can be done simultaneously, however most often these subproblems are not solved simultaneously due to the complexity of their interaction.
This section describes how in research the ground movement is integrated in the overall airport operations, by looking at the interaction with departure/arrival sequences and gate assignment.

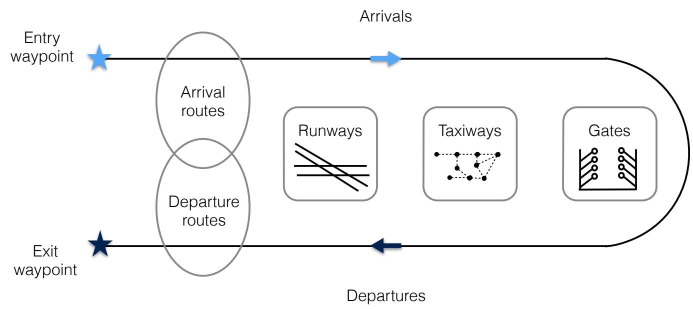


Figure 2.1: Schematic representation of terminal airspace and airport surface components. [Bosson et al., 2015]

Integration of departure sequences

Amongst others, the airport ground movement has an influence on the departure sequence (and vice versa). To maximize the throughput of departing aircraft, wake-vortex separations are of major importance since it determines the time separation between two departing aircraft. Therefore Gotteland et al. [2014] respects aircraft separation and runway capacities, while minimizing the taxi time. Clare and Richards [2011] and Benlic et al. [2016] take into account the departure optimization of aircraft. By optimizing the departure sequence of aircraft instead of simply using the First come–first served rule.
Another approach is presented by Ravizza et al. [2014]. They assume that the runway sequencing and ground movement problems are solved in two distinct stages. In the first stage the integrated (departures and arrivals) runway sequencing problem is solved. From the first stage the landing and take-off times are used in the second stage for the ground movement problem.

Integration of arrival sequences
According to Atkin et al. [2010] the entry time and location of landing aircraft will influence the system. A better prediction of the arrival times can have a positive effect on the ground movement planning. Furthermore for some airport layouts, runway crossings and mixed mode runway usage may be necessary. In this case it is important to integrate arrival (and departure) sequencing into the airport ground movement problem. However the arrival sequence is often an input to the model. Both Clare and Richards [2011] and Gotteland et al. [2014] use fixed inputs for the arriving aircraft.

Integration of gate assignment
Most reviewed papers consider the gate assignment to aircraft as an input (Benlic et al. [2016], Chen et al. [2016], Clare and Richards [2011], Gotteland et al. [2014], Ravizza et al. [2014]). The gate allocation problem has been discussed in the survey of Dorndorf et al. [2007], where a recommendation for the integration with the ground movement problem was given. Simultaneous optimization could reduce the total taxi time. Bosson et al. [2015] includes gate scheduling and Bertsimas and Frankovich [2015], Yu and Lau [2014] determine the gate-holding duration of departures, and the time at which arrivals should reach the gate to optimize the ground movement problem.

2.1.3. Algorithms and solution approaches for airport ground movements
This section describes the models and methods to solve the airport ground movement problem. As stated by Atkin et al. [2010], in the past two main approaches were used; Mixed integer linear programming (MILP) and Genetic Algorithms (GAs). The first solution approach provides an exact solution to the problem by solving the MILP model with a commercial solver.
Since an exact solution can not always be obtained in a reasonable solution time with MILP, in the past often GAs have been used. More recently the quickest path problem with time windows (QPPTW) heuristic are used to solve the taxi-routing and scheduling. The use of MILP, GAs and QPPTW heuristics are reviewed in this section.

Mixed integer linear programming (MILP)
In this section MILP formulations yielding an optimal solution are described. For taxiing optimization, MILP is frequently used. A successful use of MILP for taxiing planning problems can be found in Clare et al. [2009], Keith et al. [2008], Roling and Visser [2008] and Evertse [2014]. In Roling and Visser [2008] a time-space network of AAS is used. A simplified model of the taxiing-lanes consisting of nodes and edges is used. The airport network is often (not only in MILP approaches) simplified to a network with edges that represent taxiways, and nodes that represent stands, junctions and intermediate points. An example of such a simplified network can be found in Figure 2.2.
The MILP can be formulated in the following way:

$$\begin{aligned} &Maximize \quad c^T x \\ &subject \quad to \quad Ax \leq b \\ &and \quad x \geq 0 \end{aligned}$$

In this formulation x represents the decision variables and will be chosen such that $c^T x$ will give the optimal solution. Values of x are restricted to be integer.
The first line is the objective function. The objective function can either be a maximization or minimization function. e.g. if c^T is the fuel cost, the objective is to minimize the cost of fuel. Multiple objectives can be in the objective function. The second line contains the constraints. For example a constraint can be that aircraft cannot be at the same place at the same time to avoid conflicts. To limit the solution to nonzero values, the third line is imposed.
Usually MILP approaches are solved with a commercial solver, such as CPLEX or Xpress. A widely used technique by these solvers is the branch-and-bound (B&B) algorithm. The B&B algorithm is described by Evertse [2014] as follows: first the problem is solved without integrality constraints. Then systematically integrality requirements on the variables are applied. This is done one by one and changes the solution slightly. The solution is saved to the branch of solutions (branching). The best solution during branching is called the bound, which also acts as bound for the other branches to search for the global optimum.

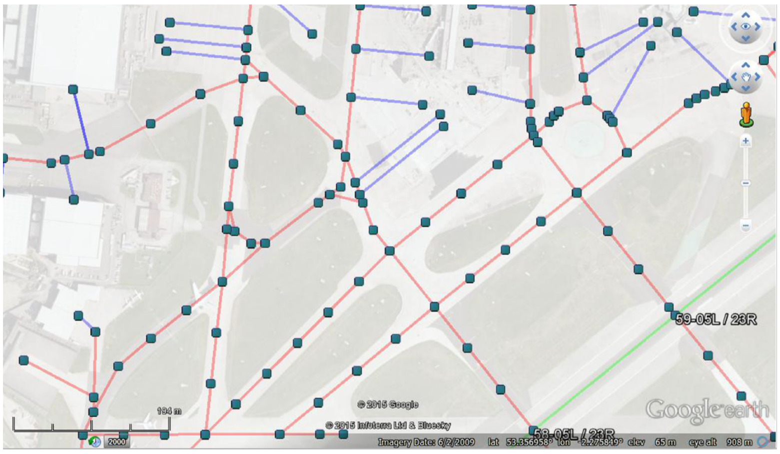


Figure 2.2: Example of a simplified airport network, representing Manchester Airport. Benlic et al. [2016]

The main disadvantages of using MILP are the size of the problem and the computational time. The size of the routing and scheduling problem can consist of millions of variables. This happens because the position of each aircraft at each time, has to be expressed with a binary variable. Furthermore the solving time for MILP grows exponentially with the amount of variables. Especially in on-line applications this can be a disadvantage of using aMILP.
A properly defined MILP ensures optimality. The optimal solution obtained with the MILP shows the best solution regarding the objective function. e.g. if the objective function minimizes the fuel usage for aircraft taxiing, the MILP will give the best solution to use the least amount of fuel.

Atkin et al. [2010] provides a clear overview of the different MILP approaches used till 2009. More recently, Bosson et al. [2015], Clare and Richards [2011] used an extended version of the MILP formulation. Clare and Richards [2011] integrated air and ground operations and Bosson et al. [2015] integrated runway scheduling. Clare and Richards [2011] used the receding horizon formulation (RH), where the minimization of total taxi time takes into account the avoidance constraints. The full problem is not solved at once from the beginning, but all avoidance constraints are initially relaxed. Then for a found solution the avoidance violations are identified, constraints are reapplied to the problem and the MILP is solved again (which is an iterative process). This continues till a solution is found with no constraint violations.
Bosson et al. [2015] used a single optimization model to simultaneously optimize terminal airspace and airport surface operations. A MILP formulation is used for integrated arrival and departure operations in the presence of uncertainty and Gurobi Optimazation is used as solver. This paper extends the previous research of Bosson et al. [2014] by integrating taxiway and runway operations.

Genetic algorithms (GAs)
When exact optimization fails to generate a solution in an acceptable amount of time (or fails to have a solution at all), meta-heuristics can be used. GAs are common used meta-heuristics to solve the airport ground movement problem. GAs are meta-heuristic search methods based on evolutionary biology, with the advantage that they can be used for nonlinear problems. However, the solution does not guarantee optimality. To evaluate the performance of the GA, it can be compared to an algorithm that finds the global optimal solution.

GAs maintain a population of possible solutions and a method for evaluating solutions. A selection of mechanisms guides the algorithm to find good solutions [Atkin et al., 2010]. This means the meta-heuristic solver starts with an initial solution (chosen by the user). After that the algorithm will start exploring the solution space [Evertse, 2014].
The formulation used for GAs is essentially comparable to the MILP formulation. Additionally the GA needs the population size, crossover probability, mutation probability, reproduction factor and number of generations.

GAs were widely used for the optimization of the taxiing problem in the past by, amongst others, García et al. [2005], Pesic et al. [2001] and Gotteland et al. [2003]. Atkin et al. [2010] divide the used GAs in three

main approaches; 1) GA determines for each aircraft initial delay/hold time prior to push-back. 'used by García et al. [2005]' 2) GA determines a delay during movement, which is not restricted to a delay/hold time at the start of taxiing. It determines when and where delay should be applied. 'used by Pesic et al. [2001] and Gotteland et al. [2003]' 3) GA investigates the possibility to prioritize aircraft instead of directly hold the aircraft. Priority determines the sequence of aircraft movement when there are conflicts. 'used by García et al. [2005]'
In recent research, Gotteland et al. [2014] proved th working of a 'Sort GA'. The Sort GA determines an optimal allocation for paths and priority levels for aircraft. It is combined with the (B&B) algorithm, which optimizes the best path and holding position for one aircraft taking into account trajectories of other aircraft.

QPPTW heuristic
In the recent literature (after 2009), also other approaches have been used. The Quickest Path Problem with Time Windows (QPPTW) algorithm could be solved with heuristics for the airport ground movement problem. By using this approach not every solution of the whole problem is checked, only parts of the problem where it is most likely to find an optimum solution. Obviously bad solutions are skipped to speed up the algorithm [Evertse, 2014].
The Quickest Path Problem with Time Windows (QPPTW) algorithm is a generalized vertex-based label-setting algorithm based on Dijkstra's algorithm. It sequentially routes aircraft on the airport surface and no time discretization is needed [Ravizza et al., 2014]. Although it looks like the A* algorithm (a shortest path-finding algorithm, which is also based on Dijkstra's algorithm but uses heuristics to guide its search), QPPTW could give better solutions in similar computation time, which makes it possible to be used for real time decision making. Furthermore information of the aircraft and airport can easily be added in order to realistically model the airport surface. The QPPTW algorithm has been used by Benlic et al. [2016], Ravizza et al. [2014], Weiszer et al. [2015] and Chen et al. [2016].

Ravizza et al. [2014] optimizes in terms of time and fuel spent. In addition to the QPPTW algorithm a swap heuristic for finding better aircraft sequences has been applied, without significantly increasing the execution time of the algorithm (order of milliseconds per aircraft). The algorithm is still fast enough to be used in an on-line environment. The swap-heuristic showed that an overall reduction in taxi time could be obtained. If an aircraft is delayed over the shortest possible path, the algorithm first detects the aircraft that causes the delay. Then the swap-heuristic will allocate routes in reverse order for the aircraft. Using this realistic QPPTW model, it is able to accurately estimate taxi times.

The work of Weiszer et al. [2015] extends the ground movement optimization network of Ravizza et al. [2014]. Where Ravizza et al. [2014] consider whole routes for aircraft, Weiszer et al. [2015] split the original problem into independent taxi-way segment sub-problems. The optimized stored speed profiles from these taxi-way segments are used for the optimization instead of costly on-line optimization.

Benlic et al. [2016] simultaneously optimize runway sequencing and taxiway routing problems in continuous time. The QPPTW algorithm used is a variation from the one used in Ravizza et al. [2014]. It is different in the way that it uses an undirected graph instead of a directed graph for Manchester Airport. Also edges can have different weights depending on predecessor edges, aircraft type and runway crossings. Furthermore a search heuristic is used. The search heuristic can re-order and re-route multiple conflicting aircraft.

Chen et al. [2016] uses an active routing (AR) framework for efficient airport ground operations. The used framework integrates the multi-objective speed profile generation approach into the route and schedule optimization. QPPTW is used to find the most time-efficient, hence most fuel-efficient solutions. Then heuristics and a Population Adaptive Immune Algorithm are used to find the Pareto front. The approach uses an iteration to route all aircraft from the dataset to generate a single solution on the global Pareto front.

2.1.4. Dealing with dynamics

The airport ground movements have a dynamic nature. Predictions such as the arrival time, departure time, push-back time, etc. might not be accurate. Especially the further in the future, predictions become often less accurate. Therefore it is important to update the forecast times, particularly if the model is used for on-line applications. Since some computational methods (for large problems) require a long execution time, often the problem is decomposed in smaller sub problems to reduce the complexity of the problem. Atkin et al.

[2010] describes three methods that have been often used to cope with the dynamic nature of the routing problem:

1. **Shifted windows**: the problem is resolved for a fixed time window. Here every Δ minutes the situation is resolved for a fixed time window. The smaller the time window, the more accurate the prediction.

2. **Rolling horizon**: the planning horizon is split up into equal time intervals. Three variations are used for this method. In the first variant the allocated routes in previous intervals are fixed. In the second variant they are variable. In the third variant the push-back time and landing time is used to sort and a sliding window is applied. This sliding window considers first aircraft 1 to m (m is the total amount of aircraft). Then aircraft 1 is fixed and aircraft 2 to m are considered, and so on. However, this variant requires a higher execution time. A general impression of a rolling horizon can be found in Figure 2.3.

3. **Fix and relax**: the planning period is split into k smaller periods. First the variables within the first period are taken as binary and for all the other variables in the other time windows linear relaxation is applied. Then the variables for the first period are fixed. Subsequently the variables of the second period are made binary and the same process will be repeated. This is done till all variables in the k periods are fixed.

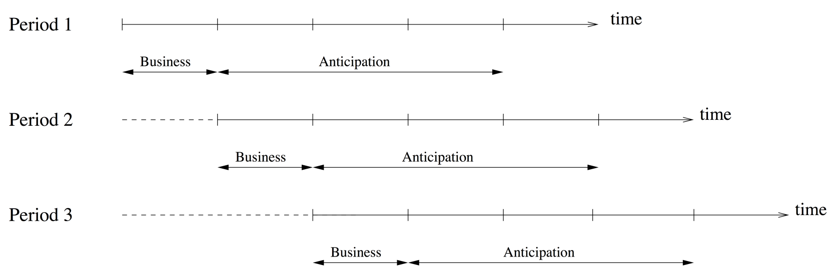


Figure 2.3: In a rolling horizon environment the problem is first solved with period 1 as business period. This solution is then fixed and new information is used to reformulate a new model (with one additional period in the end) where the second period is the business period. This process is repeated on a continuous basis. [Bredström and Rönnqvist, 2008]

2.1.5. Robustness and uncertainty

The papers described in the survey by Atkin et al. [2010] (papers before 2009) mostly used deterministic data sets. However the input data at airport is often uncertain. Therefore in the state-of-the-art literature uncertainty is taken into account in different ways. Gotteland et al. [2014] includes a speed uncertainty for taxiing of ±10 % to cope with uncertainties regarding the predicted taxi times. Bosson et al. [2014] presents an alternative method to solve integrated departures and arrivals in terminal airspace under uncertainty. It is assumed that on the airport surface scheduled runway departure times are impaired by push-back and taxi-out delays and that scheduled gate arrival times are altered by taxi-in delays. Using historical data, an approximation of arrival gate delay distribution is obtained by computing the difference between actual and scheduled arrival time. Error sources drawn from the obtained distributions are respectively added to reference departure release times and reference arrival due dates. This gives realistic schedule scenarios perturbed around the reference schedule. Weiszer et al. [2015] and Chen et al. [2016] used a pre-computed database to shorten the execution time of the model of Ravizza et al. [2014]. This database can incorporate more realistic speed profiles created through a complex and more precise optimization procedure without compromising computational time during the real-time application of the algorithm. In this way a fast algorithm can accommodate for incoming changing data. Benlic et al. [2016] optimized the problem for small time periods in the near future to reduce the influence of inaccurate information and ensures that computational effort is not waisted on future flight plans which are likely to be revisited anyway.

2.1.6. Optimality vs. execution time

The complexity of the problem is an important factor for the execution time, e.g. the amount of aircraft considered simultaneously, amount of possible nodes, degree of integration etc. Exact solutions become often less practical as the load increases. For models with time discretization, the way time discretization is used can affect the execution time, since smaller time intervals might give a better solution but increase the

size of the problem to solve. It must be noted that some papers aim at a fast execution time in order to be applicable for real-time operations.
Exact solutions such as MILP formulations solved by a commercial solver often require longer computation time. In the recent literature, Clare and Richards [2011] used MILP and the rolling window to spread the computation time and to avoid wasting effort on calculating plans for the distant future. All of the horizons of Clare and Richards [2011] are solved within 160 *s*, however the re-planning occurs every 40 *s*. This means that with the used computational power the computation is not fast enough for real-time operation. On the other hand heuristics such as GAs do not guarantee a good solution. But in terms of execution times, heuristics (including GAs) in general outperform exact solutions. Benlic et al. [2016] used the ILS heuristic to solve the coupled runway sequencing and taxiway routing problems in continuous time. Benlic et al. [2016] obtained a maximum computing time per horizon of around 95 *s* for a large problem, due to which real-time operation might be practical with increased computing power. Weiszer et al. [2015] improved the method of Ravizza et al. [2014] in terms of execution time. Their pre-computed database can incorporate more realistic speed profiles created through a complex and more precise optimization procedure without compromising computational time during the real-time application of the algorithm.

2.2. Automated guided vehicles

An automated guided vehicle (AGV) is a non-driver transport system. There is a wide area of applications and types of AGV sytems, such as in manufacturing, distribution and transshipment. AGVs were introduced in 1955 and ever since their use has grown enormous in different applications. Now they are also used in large systems such as completely automated warehouses and container terminals [Carlo et al., 2014]. Another complex application was proposed by Van der Heijden et al. [2002]. They built a simulation of an automated underground transportation system for AAS consisting of 200-400 AGVs.
Morris et al. [2015] introduced an application of self-driving vehicle technology for aircraft taxiing. Here a proposal is made to tow the aircraft from the gate to the runway and vice versa by using AGVs (supervised by human ramp- or ATC controllers). An autonomous engine-off taxiing system could potentially reduce costs, emissions, noise and human workload. At the same time it could increase ground movement efficiency.
This chapter covers the literature that can be used for the application of automated guided vehicles in airport ground operations. As described in Chapter 2.1, the airport ground movement is dynamic, complex and often consist of many aircraft at the same time. The literature surveys of Vis [2006] and Fazlollahtabar et al. [2015] are used to summarize the large field of study of AGVs.

2.2.1. Design of an AGV system

This section describes the design aspects for a large AGV system that are capable to handle dynamic operation conditions. According to Vis [2006] the following tactical and operational issues have to be addressed in designing and controlling an AGV system:

- Network layout
- Traffic management: predictions and avoidance of collisions and deadlocks
- Location of pick-up and delivery points
- Vehicle requirements
- Technological aspects (battery/failure)
- Vehicle routing & scheduling (Section 2.2.2)
- Vehicle dispatching
- Positioning of idle vehicles

Layout and control problems are highly interrelated. A well developed layout with an inefficient designing control problem (or vise versa), will influence the overall performance of the AGV system. A good design is therefore required. This section will discuss all the important design aspects and the dispatching and positioning of idle vehicles. The routing and scheduling will be discussed separately in Section 2.2.2. Note that in this chapter the focus lies on the application of AGVs in airport ground operations.

Network layout
According to Vis [2006] the network usually consist of nodes and arcs, where nodes represent the intersections, pick-up and delivery locations and arcs the guide-paths the AGVs can travel on. For an optimal network layout, the design of the network and locations of pick-up and delivery points can be taken into account simultaneously. However, since considering the application for airport ground movements the layout of the facility and the location of pick-up and delivery points are considered as input factors, such as in Morris et al. [2015]. They used a similar network as in Figure 2.2, where the airport surface is represented graphically with nodes, representing locations of gates, runway entrances, spots, or other intersections; and edges, representing traversable surface area.
The travel along arcs can be unidirectional, bidirectional or a mix of both. Furthermore if enough space is available, multiple guide-paths lanes can be introduced (various paths exist between nodes). However since multiple lane guide-paths are not commonly used in airport ground movement systems, these are not considered in this section. More information about the design of these networks can be found in Egbelu and Tanchoco [1986].

Traffic management: predictions and avoidance of collisions and deadlocks
In developing an AGV system it is important to take into account the prevention of collision and deadlocks. A deadlock is for example a situation where two AGVs in opposite direction are stopped in front of each other and no further transport is possible. In designing the system one can choose that during operations, deadlocks and collisions are detected and resolved or deadlocks and collisions are predicted and avoided by pre-planning of routes. The second option gives a better result for the performance of the system [Vis, 2006]. Conflicts and deadlocks can be prevented by the design of the layout of the guide-paths, such as using non-overlapping control zones. Also algorithms can be used for finding conflict-free shortest-time routes for AGVs moving in a bidirectional flow path network as stated by Kim and Tanchoco [1991]. Considering the literature of the use of AGVs for (large) airports, the prevention of collisions and deadlocks could be done with the routing and scheduling algorithm by imposing separation constraints.

Location of pick-up and delivery points
In the design of the AGV system, also the pick-up and delivery points have to be determined. Vis [2006] describes different approaches for the optimal allocation of pick-up and delivery points. However as for the network and traffic management design, the pick-up and delivery point of a an airport are fixed. Morris et al. [2015] describe the pick-up and delivery point of AGVs for departing aircraft as follows: the pick-up position is the designated ready position at a specific gate. The delivery point is the designated location in the takeoff queue near the runway, where the tug autonomously de-attaches from the aircraft and moves to a safe position away from the aircraft. A similar approach can be used for arriving aircraft where the gate is the delivery point.

Vehicle requirements
The amount of vehicles in the fleet of AGVs depends on the system. If the objective is to transport all loads with AGVs on time, the amount of AGV's needs to be sufficient to ensure that all tasks are performed within time. Another objective can be to use a set of vehicles in the most efficient way. Here a set of vehicles is available and the model aims to use the vehicles in the most optimal way.
Too many AGVs in a system can lead to congestion and a low amount of AGVs is preferable for economic reasons. Furthermore the performance an AGV system is often measured in the minimum amount of AGVs needed and the number of loads transported. According to Vis [2006] some important factors that influence the fleet size are:

- Number of units to be transported
- Point of time/time window for transportation
- Capacity of the AGV
- Cost of the system
- Layout of the system and guidepaths
- Traffic congestion and external conditions

- Vehicle dispatching strategies
- Location and number of pick-up and delivery points

The minimum amount of vehicles needed for a system to transport all loads by AGVs, also depends on the solution approach. Egbelu [1987] wrote that analytical techniques underestimate vehicle requirements. There are different ways to cope with underestimation of analytical models. One of them is given by Koo et al. [2005] where number of vehicles in the model is adjusted. Another way is presented by Mantel and Landeweerd [1995]. Here stochastic models are used to incorporate external influences to get more realistic fleet size.

Technological aspects
Battery/fuel management and equipment failure are two important characteristics of AGVs to take into account. Most AGVs use battery changing/charging. McHaney [1995] showed that charging or changing batteries have a significant influence on the amount of AGVs needed. The time required for charging batteries has an impact on congestion, throughput and total costs. A good example is given by Ebben [2001], here battery constraints are taken into account.
Another important aspect to take into account is equipment failure. Failure of equipment is often neglected, while is might cause congestion and deadlocks. Ebben [2001] developed methods to deal with failure for full and empty AGVs.

Vehicle dispatching
Dispatching means that a vehicle will be selected to execute a transportation demand. Vis [2006] discussed two general methods for dispatching vehicles. In the first method there is an available load that needs to be transported. Subsequently an idle vehicle will be assigned to this load (workcenter initiated dispatching). In the second method, when a vehicle will become idle it will be assigned to a new load (vehicle initiated dispatching).
Egbelu and Tanchoco [1984] describe different rules for both workcenter and vehicle initiated dispatching, such as the random vehicle rule, nearest vehicle rule, random workcenter rule and shortest travel time/distance rule. Kızıl et al. [2006] compared different dispatching rules for preventing an unsuccessful load transfer. This because in a cellular manufacturing system an unsuccessful load transfer is critical for operations in the entire system. Different dispatching rules, with as main objective to keep a system functional, were tested and evaluated. Dispatching rules used were defined by Kızıl et al. [2006] as follow:

- First Come First Served: The next job to be processed is the first one in the queue.
- Shortest Processing Time: The next job to be processed has the shortest total processing time.
- Shortest Remaining Processing Time: The next job has the shortest remaining processing time.
- Most Remaining Operations: The next job to be processed has the maximum number of remaining operations.
- Shortest Imminent Operation: The next job has the shortest operation time for the imminent processing.
- Longest Imminent Operation: The next job has the longest operation time for the imminent processing.
- Minimum Number of Processing: The next job to be processed is the first one in the sorted job queue i.e., the first job that has the least number of operations on either the same or different work centers.

Koster et al. [2004] and Van der Meer [2000] looked at the performance of dispatching rules in real time environments such as in container terminals (more literature regarding dispatch in container terminals can be found in Carlo et al. [2014]). They showed that vehicle initiated rules are outperformed by load initiated rules. Furthermore Koster et al. [2004] showed that pre-arrival information of loads leads to a significant improvement in performance. For the optimization a look-ahead heuristic was used.

Positioning of idle vehicles

When an AGV delivered a job at his destination and is not directly assigned to a new job, the vehicle becomes idle. As stated by Vis [2006] the location of the idle vehicle is important to reduce waiting times of loads for transport. Egbelu [1993] describes some criteria for selecting a parking location; Minimization of the response time, minimization of empty travel of AGV and even distribution of idle vehicles over the network. The following three rules are mostly used for positioning idle vehicles;

1. Central zone positioning rule: Empty vehicles are routed to these areas regardless of their destination.
2. Circulatory loop positioning rule: One or more loops are used as loops for positioning idle vehicles. AGVs travel on this loop until a new assignment is requested.
3. Point of release positioning rule: The AGV remain at the point where its load was delivered till a new job is assigned.

2.2.2. AGV routing & scheduling

This section describes the routing and scheduling algorithms of AGVs. The routing and scheduling of AGVs is an extensive field of research. In these sections a strong focus on the state-of-the-art AGV control approaches that are applicable for the potential use of AGVs for aircraft taxiing (AGVs with a unit load). The literature review of Fazlollahtabar and Saidi-mehrabad [2013] discusses recent literature on distribution, transshipment and transportation AGV systems. The paper takes into account large systems in terms of number of AGVs used, number of transportation requests, occupancy degree, distance and the number of pick-up and delivery points. Here the work of Fazlollahtabar and Saidi-mehrabad [2013] is summarized and literature is added for the optimization of the routing and scheduling. Since AGVs could also be used in public transport, relevant literature from this area on the routing and scheduling has been added as well.

Where Fazlollahtabar and Saidi-mehrabad [2013] classifies the routing and scheduling separately, in this literature review they are treated together since they are often interrelated.
The approaches are classified in the following categories: exact mathematical approaches, heuristics mathematical approaches, meta-heuristics, artificial intelligent approaches and simulation. Here the classification is based on de paper presented by Desale et al. [2015]. Exact approaches are used to find the global optimum but fail often to solutions on NP-hard problems. Heuristics are problem-specific approaches which take advantage of the problem properties to get a good (not always the global optimum) solution of the problem. Meta-heuristics are general heuristics schemes that can be applied to many optimization problems. Learning strategies in Meta-heuristics can help to find efficient near-optimal solutions. These approaches has been classified under 'artificial intelligent' approaches.

Exact mathematical approaches

One way to solve the routing and/or scheduling optimization problem is by using an exact mathematical approach. As discussed in Section 2.1.3, exact methods (such as a MILP) have as main disadvantages of size of the problem and the computational time, however an optimal solution can be found.

A bi-level decomposition algorithm for solving the simultaneous scheduling and conflict-free routing problems for AGVs is addressed by Nishi et al. [2011]. The overall objective is to minimize the total weighted tardiness of the set of jobs related to these tasks. In the algorithm, the original problem is decomposed into an aggregated upper level master problem and a lower level subproblem. The upper level master problem consist of decision variables for production scheduling and task assignment. The decision variables for lower level subproblem are used for the routing of the vehicles. The master problem is solved by using Lagrangian relaxation and a lower bound is obtained. Either the solution turns out to be feasible for the lower level or a feasible solution for the problem is constructed, and an upper bound is obtained. If the solution derived at the upper level is not feasible for the lower level, cuts are generated to delete the infeasible region.

Rashidi and Tsang [2011] use the minimum cost flow model is used to schedule AGVs in container terminals. An extended version of the Network Simplex Algorithm (this is special implementation of the Simplex Method) was used to solve the problem, called the NSA+. It provides an optimal solution if it finds one within the time available. With polynomial time complexity, NSA+ can be used to solve very large problems, as verified in experiments. Should the problem be too large for NSA+, or the time available for computation is too short (as it would be in dynamic scheduling), the incomplete algorithm Greedy Vehicle Search (GVS) can complement NSA+. GVS is an incomplete search method.

A decomposition method for the routing and scheduling is used by Corréa et al. [2007]. Using this decomposition method, the master problem (scheduling) is modeled with constraint programming and the subproblem (conflict free routing) with mixed integer programming. Logic cuts are generated by the sub problems and used in the master problem for optimal scheduling solutions whose routing plan exhibits conflicts. The hybrid method presented herein allowed to solve instances with up to six AGVs.

In the field of research of public transport, the effect of the traffic and parking demand due to the replacement of conventional privatively owned vehicles by automated ones is described by Correia and van Arem [2016]. The model solves the User Optimum Privately Owned Automated Vehicles Assignment Problem (UO-POAVAP), which dynamically assigns family trips in their automated vehicles in an urban road network. Xpress is used to solve the cost minimization problem (a MILP) for AGVs.

Heuristic mathematical approaches
Routing and scheduling is a well-known NP-hard problem. Therefore heuristics can be used to find a proper solution in a reasonable execution time. To route the vehicles over the network different approaches en algorithms are used. The state-of-the-art research using heuristics are summarized here.

In public transport, the Dial-a-Ride problem is similar to the pickup and delivery problem with the added constraint of restricting the maximum passenger ride time. Therefore this research might be (partly) useful for the use of AGVs for aircraft taxiing. To solve the Dial-a-Ride problem, Diana and Dessouky [2004] presented a parallel regret insertion heuristic. Here a new route initialization procedure is implemented, that keeps into account both the spatial and the temporal aspects of the problem, and a regret insertion is then performed to serve the remaining requests. It is slower than the classical insertion heuristics. However, the regret insertion heuristic can provide significantly superior solutions in terms of total vehicle miles and fleet size.

Hartmann [2005] proposes a general model for various scheduling problems in container terminals in which the average lateness of a job and the average set up time were minimized. The model can be used for various types of equipment, such as AGVs, cranes and straddle carriers. The performance of the heuristics (a GA and a heuristic for dispatching) in a computational study have been measured. Promising results were obtained that suggest that the genetic algorithm is well suited for application in practice.

By Fazlollahtabar et al. [2015], a scheduling and conflict free routing problem for multiple AGVs in a manufacturing system is proposed and formulated. Considering the due date of AGVs requiring for material handling among shops in a job-shop layout, their earliness and tardiness are significant in satisfying the expected cycle time and from an economic view point. Earliness results in AGVs waiting and tardiness causes temporary part storages in the shop floor. Therefore, a mathematical program to minimize the penalized earliness and tardiness was proposed. Since the mathematical program is difficult to solve with a conventional method, an optimization method in two stages, namely searching the solution space and finding optimal solutions are proposed. Here an integrated heuristic search algorithm was used.

For the use of AGVs for the loading and unloading of ship containers, the complete problem is divided by Zaghdoud [2016] into three subproblems. These subproblems are : the routing problem, assignment problem and scheduling problem. A comparative study was made between three approaches; the first approach consists of applying a GA, the second one presents hybridization between Dijkstra algorithm and the GA and the third approach add to the second one a guide heuristic for the GA. In order to have the best solution the authors request to choose the third approach, however is requires a slightly higher computational time compared to the first and second approach.

Meta-heuristics
Heuristic algorithms are specific and problem dependent. Meta-heuristics, on the other hand, are problem-independent techniques. Like heuristic, meta-heuristics are used widely in different forms for AGV routing and scheduling.

Bozer and Srinivasan [1992] presented an analytical model to evaluate the throughput performance of a single vehicle serving a set of workstations under the First-Encountered-First-Served rule. Now using this analytical model and certain column generation techniques, a heuristic partitioning scheme to configure tandem AGV systems is presented. The partitioning scheme aims for an evenly distributed workload among all the AGVs in the system.

The development of tabu search and GA procedures for designing a AGV system is described by Farahani et al. [2008]. The objective is to minimize the maximum workload of the system. Both algorithms have mechanisms to prevent solutions with intersecting loops and avoid infeasible configurations.

A solution to the problem of controlling operations at an automated container terminal is proposed by Corman et al. [2016]. The work tackles two dynamics of the system, a discrete dynamic, characteristic of the maximization of operations efficiency, by assigning the best AGV and operation time to a set of containers, and a continuous dynamic of the AGV that moves in a geographically limited area. As an assumption, AGVs can follow free range trajectories that minimize the error of the target time and increase the responsiveness of the system. A novel solution framework is proposed in order to tackle the two system dynamics. Various meta heuristic algorithms, including Tabu Search and Branch and bound algorithms, are tested to solve the problem in a near-optimal way.

Artificial intelligent approaches
Due to the complexity of the flexible manufacturing environment, many problems remained unsolved, especially in scheduling dynamic environments. Often traditional optimization techniques are suitable for small problems, but are inefficient in large scale problems. Artificial intelligent approaches are state-of-the-art methods, which are like Meta-heuristics, but with learning strategies. Here related artificial intelligent research is presented.

Jerald et al. [2005] designed different scheduling mechanisms to generate optimum scheduling; these include non-traditional approaches such as a memetic algorithm and particle swarm algorithm. In the paper multiple objectives are considered , i.e., minimizing the idle time of the machine and minimizing the total penalty cost for not meeting the deadline concurrently. The memetic algorithm presented by Jerald et al. [2005] is essentially a genetic algorithm with an element of simulated annealing. The results of the different optimization algorithms (memetic algorithm, genetic algorithm, simulated annealing, and particle swarm algorithm) are compared in this paper. The particle swarm algorithm is found to be superior and gives the minimum combined objective function.

Saravana Sankar et al. [2006] presented a migration model of parallelization is developed for a genetic algorithm based multi-objective evolutionary algorithm (MOEA). The MOEA generates a near-optimal schedule by simultaneously achieving two contradicting objectives of a flexible manufacturing system. The parallel implementation of the migration model showed a speedup in computation time and needed less objective function evaluations compared to a single-population algorithm.
Singh and Tiwari [2010] describe a multi-agent approach to the operational control of AGVs by integration of path generation, enumerating time-windows, searching interruptions, adjusting waiting time and taking decisions on the selection of routes. It presents an efficient algorithm and rules for finding a conflict-free shortest-time path for AGVs. The concept of loop formation in a flow path network is introduced to deal with the parking of idle vehicles, without obstructing the path of movable AGVs. The concept of loop formation at nodes reduces the timing-taking task of finding the dynamic positioning of idle AGVs in the network.

A non-linear multi-objective problem for minimizing the material flow was proposed by Shirazi et al. [2010]. This to optimize the intra and inter-loops material flow and to minimize the maximum amount of inter cell flow. Here the limitation of tandem AGV work-loading is taken into account. For reducing variability of material flow and establishing balanced zone layout, some new constraints have been added to the problem. Due to the complexity of the machine grouping control problem, a modified ant colony optimization algorithm is used for solving this model.

An approach for finding an optimal path in a flexible jobshop manufacturing system (a flexible jobshop system has more than one shop with the same duty) is proposed by Fazlollahtabar and Mahdavi-Amiri [2013b]. Here two criteria of time and cost are considered. The expert system for cost estimation was based on fuzzy rule backpropagation network to configure the rules for estimating the cost under uncertainty. A multiple linear regression model was applied to analyze the rules and find the effective rules for cost estimation. The objective was to find a path minimizing an aggregate weighted unscaled time and cost criteria. A fuzzy dynamic programming approach was presented for computing a shortest path in the network. Then, a comprehensive economic and reliability analysis was worked out on the obtained paths to find the optimal producer's behavior. The results show the effectiveness of the used approach for finding an optimal path in a manufacturing system under uncertainty.

Simulation
Another approach is to simulate the routing and scheduling of AGVs. Mathematical optimization provides not always a realistic solution, therefore one can choose to use a simulation approach. Often simulation is used as validation method. The following studies show how simulation can be used for routing and scheduling of AGVs.

Seifert et al. [1998] introduced a dynamic vehicle routing strategy based on hierarchical simulation. This operates as follow: at the time of each AGV routing decision in the main simulation, subordinate simulations are performed to evaluate a limited set of alternative routes in succession until the current routing decision can be finalized and the main simulation resumed. The results of the case study indicated the superiority of this approach in comparison to the usual static vehicle routing strategy based on the deterministic shortest travel-distance path.

The problem of routing AGVs in the presence of interruptions is considered by Narasimhan [1999]. Via simulation, re-routing of AGVs that encounter interruptions is analyzed. A route database is used to obtain quickly previously generated paths and a flexible re-routing strategy is used when an AGV is interrupted.

A material handling model that rapidly and automatically provides production managers with extensive and significant information is presented by Gamberi et al. [2009]. As a result, integrated layout flow analysis interrelates systematic layout planning with operational research algorithms and visual interactive simulation, using a complete software platform to implement them. This integrated layout flow analysis approach focuses on determining the space requirement for manufacturing department buffers, the transportation system requirements, the performance indices, and the time and cost of material flows spent in the layout and in material handling traffic jams.

Fazlollahtabar and Mahdavi-Amiri [2013a] concerns with applying tandem automated guided vehicle (TAGV) configurations as material handling devices and optimizing the production time considering the effective time parameters in a flexible automated manufacturing system (FAMS) using Monte Carlo simulation. Due to different configurations of TAGVs in FAMS, the material handling activities are performed. With respect to various stochastic time parameters and the TAGV defects during material handling processes, sample data are collected and their corresponding probability distributions are fitted. Using the probability distributions,the TAGV material handling problem is modeled via Monte Carlo simulation.

2.3. Literature conclusions

This chapter has provided an in-depth analysis of the ground movement problem optimization and the modeling of AGV problems. This section will conclude and summarize this research and discuss how the related literature can be used in this research.

2.3.1. Airport ground movements

This review extends the work of Atkin et al. [2010] regarding airport ground movements, with a strong focus on the recent research. Recent research often used a multi-objective function to optimize the ground move-

ment problem in which fuel consumption is often added to the time objective. The different constraints used are discussed in this chapter. It was found that there is also a trend into a high degree of integration of the ground movements, which can include the runway scheduling and gate assignment. Integration makes the problem bigger, however a better overall solution might be found. In other cases runway scheduling has to be taken into account due to runway crossings. To reduce the size of the problem, some papers use the arrival times and/or departures time as given.
If a model is designed for on-line applications, it must bust be fast to deal with the dynamics of the airport ground movement problem. Depending on the application of the model, trade-offs are made between finding an optimal solution and computational time.
Different methods are used to solve the airport ground movement problem. For MILP formulations a commercial solver can be used, such as Xpress or CPLEX. Also heuristics are used to solve the airport ground movement problem. Heuristics can have the advantage to outperform exact solutions in terms of time for complex problems, but do no guarantee a good and optimal solution.

2.3.2. Automated guided vehicles

This survey extends the work of Vis [2006] & Fazlollahtabar and Saidi-mehrabad [2013] on this topic. Here a close look is taken to the design and control aspects for a possible future application of AGVs for aircraft taxiing.
From the literature it can be stated that layout and control problems are highly interrelated. A well developed layout with a inefficient designing control problem (or vise versa), will influence the overall performance of the AGV system. Therefore a good network should be designed and aspects such as the vehicle requirements, traffic management and location of pick-up and delivery should be taken into account. In the case of designing the AGV system for the use of aircraft taxiing at airports, the layout of the airport can be used as starting point.
Dispatching and the positioning of idle vehicles are part of the control problem of an AGV system. One of the main conclusions drawn from the literature for dispatching is that pre-arrival information of loads leads to a significant improvement in performance. It is also important to decide upon the positioning of the idle vehicles. Different rules can be applied and the most suitable for the use of AGVs at airports should be taken.
Based on the survey of Fazlollahtabar and Saidi-mehrabad [2013] an extended literature study has been done into the optimization of routing & scheduling. In detail different solution techniques have been discussed. Exact approaches are used to find the global optimum but fail often to solutions on NP-hard problems. It was found that heuristic, meta-heuristic and artificial intelligent approaches have been used to get a solution in a reasonable computation time. In the state-of-the-art literature often meta-heuristics and artificial intelligent approaches are used. This due to the trend of using large fleets AGVs in complex situations. For these big problems, an exact method is often not suitable. Simulation is most often used for validation of a model.

2.3.3. Gap in literature

Alternative ways of aircraft taxiing could improve the current taxiing performance in throughput, costs, emissions and fuel. Currently the aircraft ground movement problem is an active field of study. Together with the current technology of AGVs, an AGV aircraft taxiing system could be a suitable alternative for the current way of taxiing. In an AGV taxiing system, an AGV will tow the aircraft from the gate to the runway and vice versa. Due to the fact that towing the aircraft is more efficient than using the aircraft main engines for taxiing, a significant amount of fuel can be saved (1 to 4% of the overall fuel consumption [IATA, 2013]). At the same time, the extra traffic due to the AGVs on the taxi-lanes should not deteriorate the airport throughput.
To apply such a system for aircraft taxiing, research should be done on the feasibility and the operations. The main gap identified in from the literature, is that there is no existing scheduling and routing model for aircraft taxiing by AGVs. This literature gap is visualized in Figure 2.4. A routing and scheduling model, based on flight schedules, could demonstrate if such a system is realistic for future airport ground operations.

2.3.4. Optimization method

Concluding from the literature, a routing and scheduling model will be made to research the potential use of AGVs for aircraft taxiing. On one side there is the literature on airport ground movements and on the other side the literature regarding AGV systems. This report will combine both to investigate the routing and scheduling possibilities of AGVs at a major airport.
Considering the algorithms used for routing and scheduling, MILP will be used in this research. Taking into account the scope of this MSc project (see Chapter 3), MILP can demonstrate the maximum potential of using

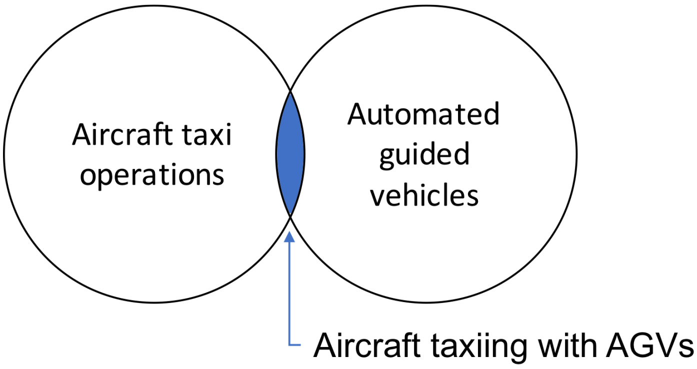


Figure 2.4: Gap in literature between aircraft taxiing and research done on AGVs.

AGVs for aircraft taxing. MILP has proven to be a suitable method for both aircraft taxiing and as algorithm for AGVs. By using MILP an optimal solution can be found. Therefore this research can provide the upper-bound savings of using AGVs, based on the routing and scheduling of these vehicles. Since it is not used in an on-line environment, an optimal solution is preferred over a fast computational time.

3

Research framework

This chapter describes the framework upon the research is build on. Section 3.1 discusses the problem that will be solved. Based on the literature review of Chapter 2, the research objective is defined in Section 3.2. The model design choices and the scope are presented in Section 3.3 and 3.4 respectively. Section 3.5 presents the contribution of this research.

3.1. Problem statement

As described in Chapter 1, the main characteristics of the air transport industry are: continuous growth, high dependence on the fuel prices and capital intensive. For safety, economic and environmental standards the industry is highly regulated. Furthermore, the profit margins for airlines are in general small due to the high amount of competition. In order to reduce costs and to sustain profitable, airlines and airports are forced to increase their efficiency.

Alternative ways of aircraft taxiing could improve the current taxiing performance in costs, emissions and fuel. Currently the aircraft ground movement problem is an active field of study. Together with the current technology of AGVs, an AGV aircraft taxiing system could be a suitable alternative for aircraft taxiing. Costs can be reduced, while meeting the industry's standards.
For an AGV taxiing system, there are two main stakeholders, with particular requirements:

1. **Airlines**
   Taxiing with an AGV taxiing system should not cost more than taxiing with the main engines. As the competition for airlines is high and their profit margins are in general low, taxiing with AGVs should be beneficial for the airline. This includes the delay cost of the aircraft, and the cost of using the vehicle. To measure the potential cost savings of using AGVs, the taxiing cost of using AGVs will be compared to the case where no AGVs are used.

2. **Airports**
   For the airport the following two requirements are important:

   - No large airport layout changes. An efficient routing and scheduling model should not require large changes in the current airport infrastructure. Otherwise airports are not likely to adapt an AGV taxiing system.
   - No capacity deterioration: Since (major) airport often operate close to their maximum capacity, the model should not deteriorate current airport capacity. Airports will most likely not adopt an AGV taxiing system if the throughput of the airport deteriorates. Therefore the actual flight schedule of airports will be used as input to analyze the effect of using AGVs at the airport surface.

3.2. Research objective

In order to fill the research gaps, the following research objective is proposed:

"To analyze the effect of using automated guided vehicles for aircraft taxiing at a major airport by creating a routing and scheduling model that is capable of creating trajectories for aircraft and automated guided vehicles, while optimizing the cost of aircraft taxiing."

By creating a routing and scheduling model for aircraft taxiing, that optimizes the cost for taxiing (with or without AGV), a complete novel approach for aircraft taxiing by a towing vehicle is presented. By analyzing the effect of using AGVs on the taxiing network of a major hub airport, not only effect of towing an individual aircraft is determined, but the effect on all taxi operations. This includes the cost of delay by using an alternative taxiing system, which is novel as well. Throughout the research the following hypothesis will be checked. Each hypothesis is stated with its expected outcome:

- H1 economic feasibility: It is economically profitable to use AGVs for aircraft taxiing at major airports. The cost of using AGVs for aircraft taxiing will be lower compared to taxiing with the main engines.
- H2 throughput: With the use of AGVs the throughput of a major airport will be reduced. The use of AGVs for taxi operations has an influence on the taxi speed and traffic at the surface of the airport. Therefore it is likely the system can only be adopted at the cost of a lower throughput of the airport.

H1 regards the cost of implementing AGVs for aircraft taxiing compared to the cost of the current taxiing operations. If the cost of taxiing with AGVs is higher than the cost of taxiing without AGVs, it is likely that airports and airlines will not adopt such a system for taxiing operations. Therefore the cost of taxiing without AGVs will be used as reference case to test H1. Since the benefits of taxiing with an AGV are not the same for every aircraft and depend on the rest of the network, it is important to determine how AGVs can be used in the best way. This is done by creating a routing and scheduling model for aircraft and vehicles that minimize the cost of taxiing on the current taxiing network.
H2 regards the throughput of the airport. The system could be beneficial in terms of cost savings and environmental impact, however it could increase the taxi-out time. This would cause aircraft delays and reduce the current throughput of the airport. H2 is important since electrical taxi systems currently deal with this problem. Therefore in the test case, real flight-schedule data of the airport will be used. In this way it will be tested if AGVs can deal with the current operations and reduce costs for H1.

3.3. Model design choice

In order to achieve the research objective, a model that gives the optimal routing and scheduling for taxiing by trading will be constructed. It will trade-off the costs for:

1. Normal taxiing operations: the cost of taxiing using the main engines of the aircraft
2. Taxiing with an AGV: the cost related to taxiing with an AGV
3. Delay: the cost associated with the time of taxiing.

In order to meet the requirements of the main stakeholders and to answer the research question, the method should meet the following requirements:

- The used flight schedule should represent the real flight schedule of the airport.
- Network model should be representative of the existing taxiing and service network of the airport
- Method should represent realistic aircraft taxiing operations and corresponding cost of taxiing.
- Output should be presented in graphs and tables.
- Output should present the difference in normal taxiing and taxiing with AGVs in different scenarios.

The functional requirements and computational requirements of the taxiing model as shown in Figure 3.1 will be discussed in Chapter 4.
In order to create such a model, Python version 2.7 has been used as programming language with Spyder as interactive development environment. The advantage of using Python is that it is an open-source programming language, which is free to use. The chosen algorithm is a MILP. To solve the MILP, CPLEX studio 12.7.1 is used. CPLEX use branch-and-cut (variant of the B&B) when solving the MILP models, and it is chosen since it has proven itself in existing research. These design choices can be found in Figure 3.1.

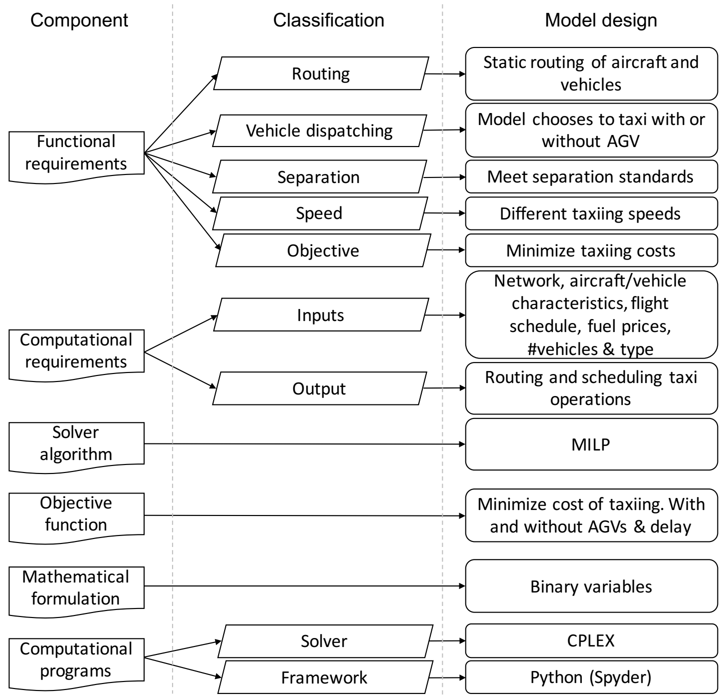


Figure 3.1: Design choices of the research summarized in one figure, where the right side gives the design choice(s) used for each element.

3.4. Research scope

In order to keep realistic research goals in terms of resources and time, the scope provides the boundaries in which the research is performed.

- The scope of this research is to look at the implementation of AGVs for aircraft taxiing. In this research taxi operations is part between the runway and the apron. Taxiing in the apron area is not modeled in detail since different standards are used here; the interaction of the aircraft with the ground vehicles in the apron area is out of scope of this research.
  Runway sequencing and gate assignment will be out of the scope of this research, since this will make the problem too large.

- Geographically it will be applied on AAS. The method could be applied on other airport, but AAS will be used as test case since data from this airport is available. Since AAS is a large airport, a successful future implementation of AGVs at this airport could be a good example for other large airports in Europe.

- For the intended temporal scope, the model should be able to cope with a full day of operations. Different days can be compared to see the effect of using various runway configurations and to validate conclusions made from these results. For the test case of AAS, data from May 2013 is used for the flight-schedule, which will be described in Section 4.2.1.

- Currently there are no existing AGVs for aircraft taxiing. This research will not focus on the design of an AGV and assumes that the current technology will allow to develop AGVs for aircraft taxiing. As a reference for the vehicle characteristics (weight, speed, etc.), TaxiBot is used.

- The use of AGVs is for departures only, since most costs can be saved in taxi-out procedures with AGVs. However, arrivals will be included in the model to ensure no conflicts with the inbound traffic.

3.5. Contribution

An analysis is done on the use of AGVs for aircraft taxiing at a major airport. This research is not limited to calculate the potential fuel or cost savings by using AGVs for individual flights, but also to show the effect on the taxi cost by implementing them in daily operations taking into account the traffic on the taxi-lanes. A routing and scheduling model, based on existing optimization methods for aircraft taxi operations and models used

for AGVs, is designed to see the real effect on the total taxiing cost of the AGVs. The overall impact of using vehicles (in this case AGVs) is demonstrated.
The status quo and the related contribution are summarized as follows:

Status quo:

- Optimization of aircraft taxi operations at major airports.
- Optimization of the routing and scheduling of AGVs.
- Calculating the benefits of alternative taxiing systems based on individual flights.

Contribution:

- Defining the optimal routing and scheduling of AGVs and aircraft for taxi operations at a major airport.
- Optimization of the overall taxiing costs by using AGVs taking into account the traffic at the taxi-lanes.

4 Methodology

This chapter discusses the components that will form the methodology to analyze the effect of using AGVs for aircraft taxiing. To present the used methodology in clear matter, this chapter starts with the functional flow diagram in Section 4.1. The diagram presents all the components of the used method which will be discussed in the subsequent sections, starting with the input data in Section 4.2. Section 4.3 explains the taxi-operations and Section 4.4 describes the method to calculate the fuel usage during taxiing. Section 4.5 provides the designed mathematical model. To test the used method a case study for AAS is done, which is described in Section 4.6.

4.1. Functional flow diagram

Figure 4.1 presents the method in a functional flow diagram. The data inputs described in Section 4.2 are indicated with a parallelogram in Figure 4.1. As it will be explained in Section 4.2, input data is processed to a flight schedule and a node-edge network. When a time interval and the taxi mode (single or dual engine taxiing) are selected (discussed in Section 4.3.1), first the taxi-in time is minimized for arrivals. The taxi-in routing and scheduling, flight schedule, network and selected vehicles are subsequently used to create the MILP formulation as explained in Section 4.5. Here Python is used to create this MILP formulation. Then CPLEX is used to solve the cost minimization problem. After solving the MILP, the output is converted to a time- space dataset. This dataset can be presented in a graph format, or is used to create snapshots of the aircraft and vehicles traveling over the network. This data is saved and is analyzed. Based on the analyzed data, one can choose to change the set of vehicle input, to test different scenarios at the same time interval.

4.2. Data

This section describes the required input data for the model. Section 4.2.1 describes the flight schedule input and the aircraft specifications. Section 4.2.2 refers to the network. Section 4.2.3 and 4.2.4 describe the processed data and the network representation respectively. In Section 4.2.5 the delay costs are explained, followed by the depreciation cost of the AGVs in Section 4.2.6.

4.2.1. Flight schedule

OAG-dataset

As input for the flight schedule, historical data of the ground operations ($the\ OAG-dataset$) is used. OAG is an air travel intelligence company based in the United Kingdom. It provides digital information and applications to the world's airlines, airports, government agencies and travel-related service companies. Extensive historical flight status data is collected by OAG.

The main parameters of the OAG-dataset can be found in Table 4.1.

To be able to use the OAG-dataset, some processing has been done. For the model only commercial passenger aircraft are considered. Therefore small (private) aircraft and freight aircraft have been removed from the dataset base on the IATA aircraft type. For this analysis, these aircraft are not relevant since private and freight aircraft make use of different gates/ loading areas and often use a different runway. Furthermore these aircraft have different characteristics in term of taxiing (cost, speed and full usage) compared to commercial

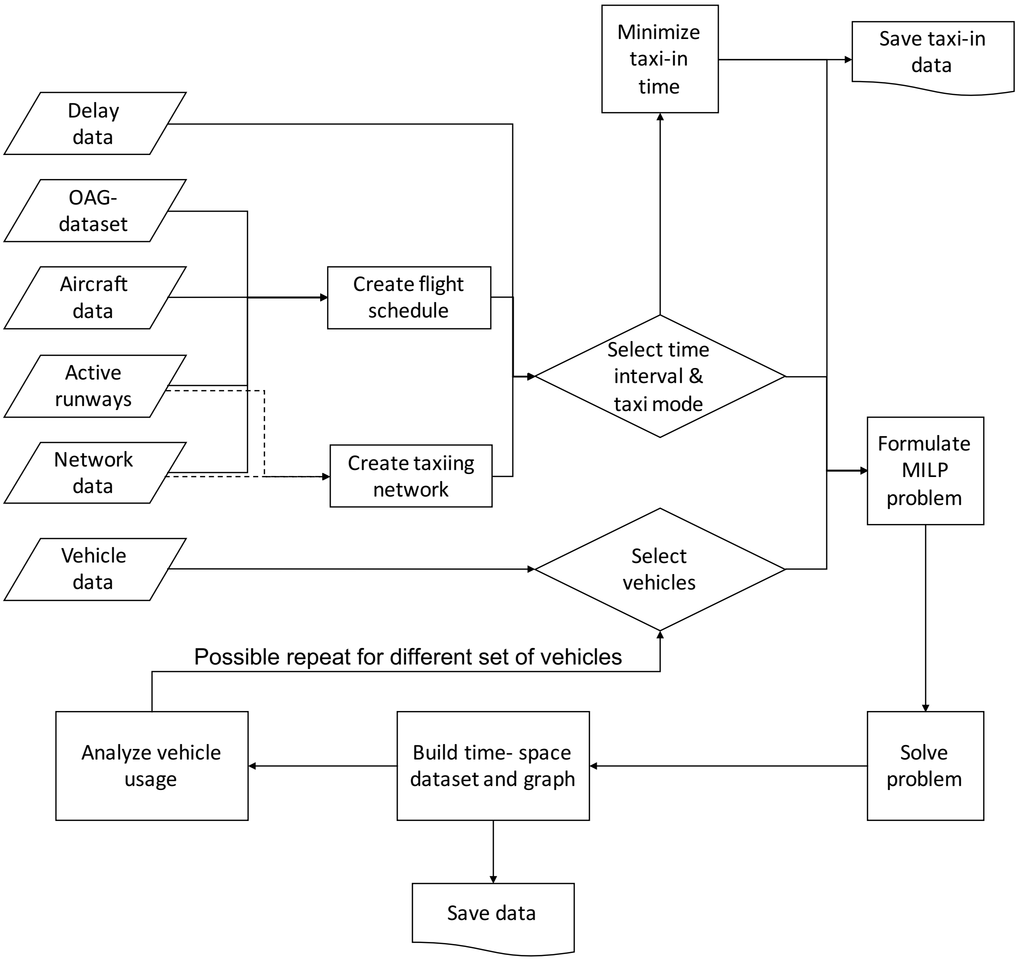


Figure 4.1: Functional flow diagram of the optimization study.

passenger aircraft and are therefore out of the scope of this research.

Since many airlines use code-sharing, the same aircraft could appear multiple times in th OAG-dataset. Based on the aircraft registration code and the scheduled time of departure, all flight numbers that use the same aircraft are filtered out. This results in a dataset where each aircraft with code-sharing only appears once.

Flights with missing important information, such as the block arrival date and time for arriving aircraft, are removed from the dataset. Since flights can be delayed and flight can depart one day and arrive the next day, the block arrival/departure date and time at airport is leading. For example, a flight with original flight date on May 1st that arrives on May 2nd, belongs to the flights arriving on May 2nd. However, a flight with scheduled departure date on May 2nd that due to delays departs on May 3rd is considered to be part of the departures of on May 3rd.

Active runways

In OAG-dataset there is no data given regarding the runway used for an aircraft. Therefore the runway used for an aircraft is based on the block arrival/departure time and the runways active at that time. The runway configuration depends on the wind, departure/arrival peaks and maintenance of the runways. For the case study in Section 4.6 data from the air traffic control of The Netherlands (LVNL) is used for the active runway data.

Based on the active runway configuration and the arrival/departure block time, a runway is assigned for each flight. Here the active runway time is converted to GMT, such as is used in the OAG-dataset. Assigning the runways in use to a flight is done as follows: for a time interval where only one runway is active for arrivals, all

Table 4.1: Data included in the OAG-dataset. In this dataset Greenwich Mean Time (GTM) is used.

Term	Definition
FltNbr	Flight number
OrgFltDateGmt	Original scheduled flight date (DD-MM-YYYY)
SchedDepDateTimeGmt	Scheduled departure date and time (GMT: DD-MM-YYY HH:MM)
BlockDepDateTimeGmt	Block departure date and time (GMT: DD-MM-YYY HH:MM)
SchedArrDateTimeGmt	Scheduled arrival date and time (GMT: DD-MM-YYY HH:MM)
BlockArrDateTimeGmt	Block arrival date and time (GMT: DD-MM-YYY HH:MM)
LegNbr	Leg number
AircraftType	IATA aircraft type
Registration	Aircraft registration code
DepStn	Airport of departure (IATA code)
ArrStn	Airport of arrival (IATA code)
MsgKind	indicates arrival (ARR) or departure (DEP)
MsgDateTimeGmt	Time of message received (GMT: DD-MM-YYY HH:MM)
MsgSelId	Type of message received (EBD - estimated block-time of departure; EBA - estimated block-time of arrival; GAT - gate; Pos - position)
NewMessage	The new information (Gate information can be found here)
OldMessage	The old information
NewDateTimeGmt	New information of EBD/EBA (GMT: DD-MM-YYY HH:MM)
DEP_COUNTRYNAME	Country of departure
ARR_COUNTRYNAME	Country of arrival

flights that have a block arrival time in this time interval are assigned to that runway. In case two runways are active for arrivals, alternately flights will arrive at one runway or the other, based on their block arrival time. The same approach is used for departing flights, using the active departing runways. In real life it might occur that some aircraft are delivered to a different runway, than the runway assigned by this approach. Also since the OAG-dataset is not accurate on the second, it might be that multiple aircraft depart/arrive from the same runway at the same time. In this case it is assumed that one of the aircraft waits near the runway. In general this approach gives a realistic flight schedule, in terms of assigning a departing/arriving aircraft to a runway.

Aircraft specifications
In the OAG-dataset for each flight the IATA aircraft type is given. Taxiing characteristics, such as fuel burn during taxiing, cost of taxiing and speed of taxiing depend on the type of aircraft. Table A.2 in Appendix A provides technical specifications for aircraft in the model. Depending on the airport, this list can be extended. The APU fuel flow and the main engine fuel flow, typical for the aircraft type, is obtained from Watterson et al. [2004]. For the main engines a fuel flow of 7% thrust setting is used for taxiing and during hold. This thrust setting is common used for taxiing operations by the ICAO emission database [Chen et al., 2016, Selderbeek et al., 2013]. Furthermore for each aircraft type the Maximum Take-Off Weight (MTOW) is obtained [1], which is an important parameter for the towing vehicles and the cost of delay.

4.2.2. Airport taxiing network

Aircraft taxi-lanes
The airport taxiing network consist of the aircraft taxi-lanes and the service roads. For the airport in question, the model uses a node-edge network of the airport surface. For each node in the network, the dataset has to provide information if the node is a gate/runway -node and if waiting is allowed at this node. For each active runway the model has one node where aircraft start taxiing (inbound traffic) or where taxi operations end (outbound traffic).
For the gate nodes, not every gate has its own node in the network. Instead, each gate-node represents the apron area near a pier from which aircraft start their taxiing operations after being pushed-back. Since in the OAG-dataset the gates are given, each gate needs to be assigned to one of the nodes in the network.
The length of each edge is the real taxiing distance between two connecting nodes. Furthermore the data

[1] `https://booksite.elsevier.com/9780340741528/appendices/data-a/default.htm`: accessed on October 11th, 2017.

must provide the direction in which an aircraft can travel a taxi-lane. The speed an aircraft can travel at a certain airport has to be known as well.

Service roads
Next to the taxi-lanes there are also service roads that can be used by the vehicles. These service roads are used by vehicles to travel over the airport surface. The model assumes that AGVs can use these service roads when they are not connected to aircraft. For the airport the model will be tested on, these surface roads have to be added to the modeled network.

4.2.3. Processed data

Network
In Table 4.3 a sample of the network data can be found. The explanation of the parameters used in it can be found in Table 4.2. For each node the connecting nodes, including distance and speed are provided by the data (representing the edge). As described in Section 4.2.2, service nodes and edges have been added to the network, indicated with '$service$' in Table 4.3. For the distance between the nodes, the real path distance is used.
For each runway one node has been used. Here aircraft start taxiing (for arrivals), or end their taxi operations (departures).

Table 4.2: Taxiing network dataset description.

Term	Definition
NodeID	Name of the node
posx/posy	Position of the node relative to the other nodes
ConnectNode	Connection with other node (NodeID of the connecting node given)
DistNode	Distance between to the ConnectNode [m]
SpeedNode	Taxiing speed to the ConnectNode [m/s]
Gate	The node is a gate-node
HoldNode	Waiting is allowed at this node
Runway	The node is a runway-node

Table 4.3: Processed network data example.

NodeID	posx	posy	ConnectNode				DistNode [m]				SpeedNode [m/s]				Gate	HoldNode	Runway	Service
			1	2	3	4	1	2	3	4	1	2	3	4				
2	1805	2860	15	0	1	3	100	0	220	300	4	0	8	8	TRUE	FALSE	FALSE	FALSE
20	2809	2625	21	0	0	0	145	0	0	0	7	0	0	0	FALSE	FALSE	FALSE	FALSE
99	-1624	5188	100	0	92	0	500	0	217	0	14	0	10	0	FALSE	FALSE	TRUE	FALSE
113	2720	3250	114	0	0	0	570	0	0	0	10	0	0	0	FALSE	TRUE	FALSE	TRUE

Flight schedule
The OAG-dataset has been processed. Together with the active runway information, aircraft specifications and the airport taxiing network, a flight-schedule that can be used as input to the model has been constructed. An example of the flight-schedule can be found in Table 4.4. StartTime (block) are the block departure times for departures and the block arrival times for arrivals (BlockDepDateTimeGmt and BlockArrDateTimeGmt from the OAG-dataset). StartTime (schedule) are the scheduled departure and arrival times for depatures and arrivals respectively (SchedDepDateTimeGmt and SchedArrDateTimeGmt from the OAG-dataset). For a flight schedule the active runways times are converted to GMT and based on this information a runway-node is assigned to each flight. Also for each gate a node in the network is assigned. Furthermore as described in Section 4.2.1, information regarding the aircraft type is obtained. This information is also added to the flight schedule.

4.2.4. Network representation & input taxiing speeds

The network consists of point (nodes), which are connected with each other (edges). The nodes and edges contain information regarding the taxiing network, which are explained here.

Table 4.4: Processed flight schedule dataset example.

ID	StartTime (block)	StartTime (Scheduled)	Runway	Gate node	Kind	Aircraft type	IATA aircraft code	APU fuel flow [kg/s]	Engine fuel flow 7% [kg/s]	Number of engines	MTOW [kg]
1	5/15/13 8:45	5/15/13 8:40	18R	7	ARR	NB	73H	0.0321	0.1106	2	78220
2	5/15/13 8:46	5/15/13 8:40	24	8	DEP	NB	E70	0.0188	0.0500	2	34000
3	5/15/13 8:46	5/15/13 8:55	24	4	DEP	WB	763	0.0338	0.2542	2	156489
4	5/15/13 8:47	5/15/13 8:55	24	4	DEP	WB	332	0.0675	0.2736	2	230000
5	5/15/13 8:47	5/15/13 9:05	18C	9	ARR	NB	321	0.0278	0.1272	2	89000

Nodes
Nodes are points in the network that contain information and are classified based on the flowing information:

- **Position:** the point on the surface of the airport.
- **Gate:** if $TRUE$ in Table 4.3, the node represents the apron area near its gate from which it starts taxiing (departing flights), or ends the taxiing operations (arriving aircraft).
- **Runway:** if $TRUE$ in Table 4.3, the node represents a point near the runway from where the taxiing operation starts/ends.
- **HoldNode:** next to the gate and runway nodes, there are some nodes in the network where an aircraft or vehicle can wait during taxiing operations. If $TRUE$ in Table 4.3, the node allows waiting.
- **Service:** if $TRUE$ in Table 4.3, the node is a point in the network where towing vehicles can be located (no aircraft can use service roads).

Nodes can be added or removed from the network. Unused points in the network can be removed to make the network smaller. Like Roling [2009] for every active runway one taxiing start or end point is assumed. Therefore the unused nodes at runway from network data can be removed.

Edges
Edges in the network contain the following information:

- **Distance:** the path length between two nodes, which can take corners into account.
- **Speed:** the speed a vehicle or aircraft can travel on the edge.
- **Direction:** the edge can be unidirectional or bi-directional. If the edge is unidirectional, the aircraft or vehicle can only travel from node A to B. For a bi-directional edge, the aircraft or vehicle can travel from A to B and from B to A.
- **Service:** certain edges can only be used by towing vehicles (no aircraft can use service roads).

Taxiing speeds
The speed an aircraft can travel depends on the edge, the aircraft and the towing vehicle (in the case the aircraft is towed by a towing vehicle). Based on Sillekens [2015] and Roling et al. [2015], different taxiing speeds for wide-body (WB) and narrow-body (NB) aircraft have been used. The maximum speed of WB aircraft taxiing was set to 10 m/s and 14 m/s for NB aircraft. For each edge in the network, the data should provide the maximum speeds the aircraft can travel at the taxi lanes. Depending on the airport, these maximum speeds can be different and are therefore an input of the model. The lower value of the maximum allowed taxiing speed and the maximum aircraft speed are used in the model.
Next to the maximum taxiing speeds of WB and NB aircraft, in real life there is also a small deviation in speeds in the 'slow' taxiing areas near the apron. WB aircraft travel on average slightly slower, however this difference is neglected.

For the towing vehicles, the taxiing speeds with aircraft are assumed to be the same as TaxiBot. The NB TaxiBot has a maximum speed of 23 $knots$ (+/- 12 m/s) and the WB Taxibot can obtain a speed of 20 $knots$ when it tows an aircraft (+/- 10 m/s) [ses].
The lower value of the speed restriction and the maximum driving speed is used. The maximum speed of the vehicles without AC is assumed to be 14 m/s at the service roads. In the area near the apron and at taxiway crossings the maximum allowed speed is assumed to be lower. An overview of the maximum speeds of aircraft and vehicles can be found in Table 4.5.

Table 4.5: Maximum taxiing speeds for aircraft, vehicles, and vehicles towing the aircraft. A division is made in WB and NB aircraft en vehicles.

Type	Procedure	Maximum speed [m/s]
NB	Aircraft + vehicle	12
	Aircraft only	14
	vehicle only	14
WB	Aircraft + vehicle	10
	Aircraft only	10
	vehicle only	14

4.2.5. Taxiing delay

One of the main drawbacks of alternative taxiing systems is the potential delay they can cause. A lower taxiing speed of aircraft being towed by a towing vehicle could cause congestion and the extra traffic at the taxi-lanes might cause delay. The delay time is the time between the scheduled and actual time. Since the cost of delay could be substantial (440 EUR for a 15 minutes delayed Boeing 737-800 at the gate and 860 EUR en-route), it is important to take this into account in order to investigate the potential of taxiing system with AGVs. To calculate the cost of delay of an aircraft, the research of Cook [2015] is used.

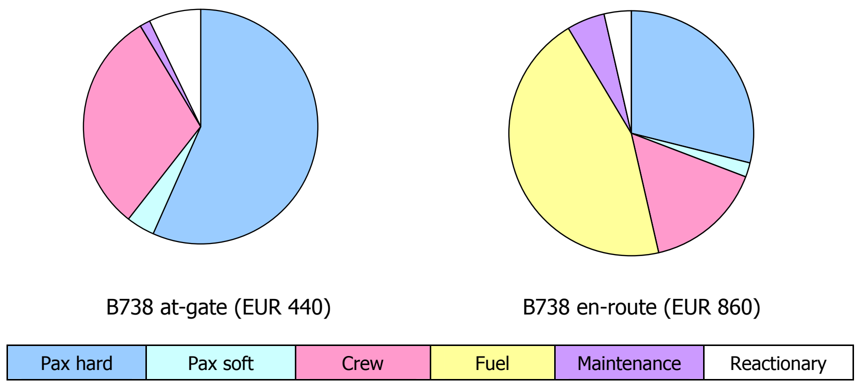


Figure 4.2: Example cost distributions for 15 minute delays for a B738.Cook [2015]

In Figure 4.2 it can be found that according to Cook [2015], the cost of delay consists of six main costs. When an aircraft is delayed extra costs for the crew, fuel and maintenance have to be paid by the airline. There are also extra costs when the passengers are delayed. The passenger delay cost consists of two factors: passenger hard cost and passenger soft cost. 'Hard' costs are due to factors such as passenger re-booking, compensation and care. 'Soft' costs are costs due to revenue loss. For example, when a passenger is not satisfied with an unpunctual airline, and therefore will not book a ticket with them again. Furthermore the effect of delay caused by one aircraft ('primary' delay) on the rest of the network is the 'reactionary' delay cost (or 'secondary' delay cost). This reactionary delay occurs when a flight is delayed due to the fact that another flight is delayed. e.g flight a is one minute delayed, so flight b will be delayed 0.8 minutes.

Figure 4.2 shows that at gate delay cost are mainly due to passengers cost. Since the model itself will take into account the cost of fuel and maintenance (main engines, APU and towing vehicle), the at-gate delay cost will be used in the model.

Cook [2015] showed that there is a relation between the squared root of the maximum take-off weight ($\sqrt{MTOW}$) of the aircraft and the delay costs at given delay durations. An estimation of the cost of delay for an aircraft at time intervals 5, 15, 30, 60, 90 , 120, 180, 240 and 300 minutes can be made based on the $MTOW$ of the aircraft.
Using the aircraft's $MTOW$ in metric tonnes, the cost of delay of each aircraft at the given time intervals can be calculated with Equation 4.1. The values of m and c can be found in Cook [2015].

$$DelayCost = m \cdot \sqrt{MTOW} + c \tag{4.1}$$

A Boeing 737-700 and an Airbus A340-300 with a MTOW of 69.4 and 271.0 *tonnes* respectively are used as an example in Figure 4.3 for the at-gate full tactical delay cost. As it can be seen in the figure, the marginal cost of delay depends on the time of delay. This is due to the fact that the cost of delay consist of multiple factors, which behave different over time. Therefore linear interpolation between two consecutive points is used. In order to calculate the delay cost c at time a, linear interpolation between the data points at 60 and 90 minutes is used. For delayed aircraft over 300 minutes, the gradient and the constant are assumed to be the same as between 240 and 300 minutes. Furthermore the cost of delay for flights, which are delayed less than 5 minutes from the Scheduled Departure Time, are considered to be zero.

Now the cost of delay can be calculated at all time for every aircraft. The model uses the marginal cost of delay, which is the difference in cost of delay of the flight schedule and the cost of delay by the model.
The delay cost of the flight schedule is the delay cost of the Block Departure Time minus the Scheduled Departure Time in the OAG-dataset.
The cost of delay by the model is the delay cost of the difference between the Scheduled Departure Time and the Block Departure time obtained with the model.
For example if Figure 4.3, consider that the delay at a is the delay from the flight schedule. This is the Block Departure Time minus the Scheduled Departure Time. The cost of delay at a is c. Now b is the time of delay, using the taxi-operations of the model (difference between the Scheduled Departure Time and the Block Departure time obtained with the model). This means that $d-c$ is the marginal cost of delay, using the model. This cost of delay will be added as penalty to a flight. In this way, the cost of delay for different scenarios is taken into account, such as for taxiing with towing vehicles and for conventional taxiing operations.

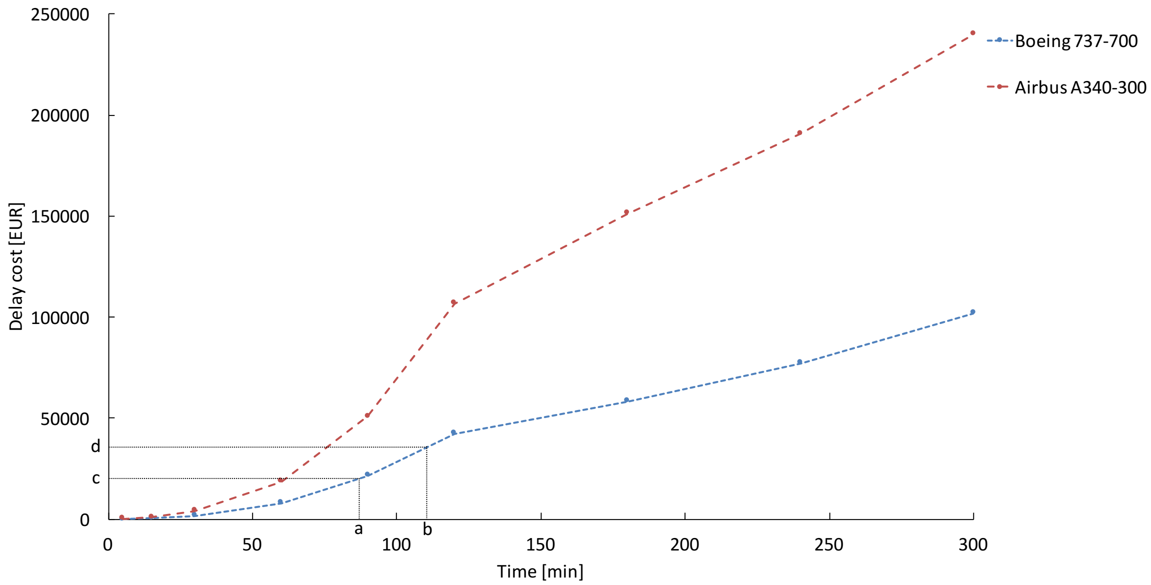


Figure 4.3: At-gate full tactical cost.

4.2.6. Depreciation of a vehicle

Since in this model AGVs will be used for taxiing operations, the cost of these vehicles has to be incorporated to compare it with the cost of taxiing with the main engines. TaxiBot is used as the main reference for the vehicle, since this state-of-the-art towing vehicle is currently used for taxiing operations and can obtain a taxiing speed up to 12 m/s (described in Section 4.2.4). Next to the cost of diesel for these vehicles, as it will be described in Section 4.4, the cost of depreciation and maintenance are included in the following way:

There are two types of TaxiBot vehicles: one vehicle is suitable for wide-body (WB) aircraft, while the other one is suitable and licensed for narrow-body (NB) aircraft. To arrive at an hourly cost depreciation, the vehicles are amortized over 5 years and each vehicle is used for 18 h/day as stated by Vaishnav [2014]. The purchase price of the NB TaxiBot vehicle is considered to be 1.5 million USD and 3.0 million USD for the WB variant [Guo et al., 2014] [2]. In contrast to AGVs, TaxiBot requires a driver, which costs 40 USD/h [Vaishnav, 2014]. Since the AGV operates without driver, it is assumed that 1.0 million USD per vehicle is added to the purchase price of the vehicle. For the exchange rate from USD to EUR the average exchange rate of 2017 has been used, which is 0.894 EUR/USD [3]. A salvage value of 10% is assumed for the vehicle after 5 years. The vehicles require also maintenance, therefore a cost of 7.5% of the new value is added to the depreciation cost of the vehicle [Vaishnav, 2014]. Using straight line depreciation, this results in the following hourly cost for the two vehicle types:

- NB vehicle: 2.5 million USD per vehicle, which correspond to 66.36 EUR per operating hour including the cost of maintenance.
- WB vehicle: 4.0 million USD per vehicle, which correspond to 106.17 EUR per operating hour including the cost of maintenance.

4.3. Taxi-operations

This section explains the taxi-operations that have to be taken into account for the mathematical model that will be developed in Section 4.5. In Section 4.3.1, the taxi procedures are explained. These taxi procedures present the different taxi modes in the functional flow diagram. In Section 4.3.2 the taxi-time assumptions are discussed followed by the inbound traffic assumptions in Section 4.3.3 (minimize taxi-in time in the functional flow diagram).

4.3.1. Taxi procedures

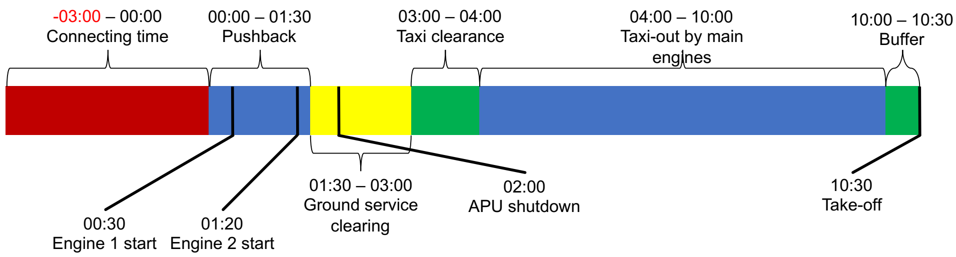
In this research taxiing with towing vehicles is compared with conventional taxiing operations and single engine taxiing. Based on Wijnterp et al. [2014], the taxi-out operations consist of the following procedures and times; the times are assumed to be the same for the different operations and only the order in which they take place changes.

- **Connect tug (3 min):** The AGV or conventional push-back tug drives to the aircraft at the gate and connects to the aircraft. This is considered to be 3 minutes, since the vehicle has to drive from its service node to the gate.
- **Push-back (2 min):** Push-back of the aircraft by conventional push-back vehicle or the AGV.
- **After push-back ground service (1.5 min):** For conventional taxi operations, this takes place in the apron area. For tug taxiing, this takes place near the runway.
- **Taxi clearance/ flaps set (1 min):** It takes place before the taxi-out phase.
- **Taxi-out:** Taxi time from the apron to the runway.
- **ESUT (2-5 min):** This is the Engine start up time or spool-up time. The main engines of the aircraft need this spooling time fore take-off.
- **APU shutdown time (1.5 min):** Time needed for the APU to shut down after one of the main engines has started.
- **Buffer time (0.5 min):** Buffer for unknown take-off time. Here the aircraft will wait for its runway clearance to take-off.

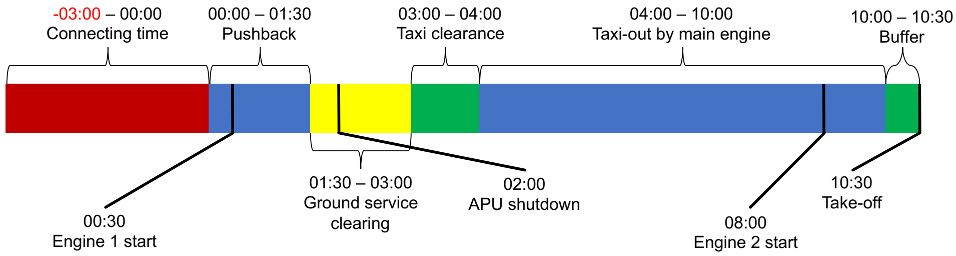
Where in Wijnterp et al. [2014] the taxi procedures from the aircraft perspective are given, here also the driving times of the AGV and pushback vehicles are included. These vehicles have to be taken into account in order to compare AGV taxi operations with conventional taxiing and/or single-engine taxiing. Here the cost of using the AGV will be taken into account.

[2] `https://www.ainonline.com/aviation-news/2012-07-09/electric-taxi-systems-aim-save-airlines-fuel/-money-getting-runway`: accessed on December 11th, 2017.

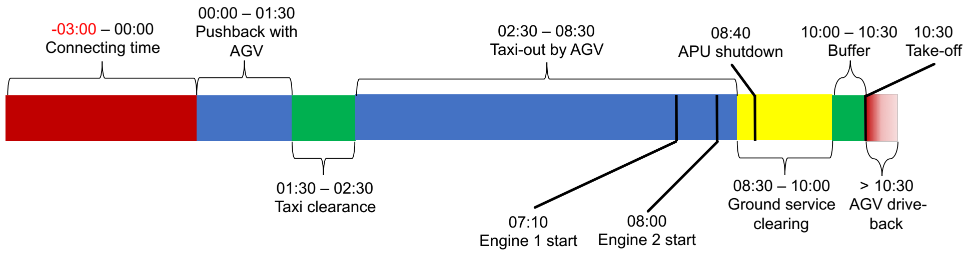
[3] `https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html`: accessed on January 10th, 2018.



(a) Conventional taxiing (with two engines)



(b) Single engine taxiing



(c) AGV taxiing

Figure 4.4: Different taxi procedures example

Conventional taxiing

In conventional taxi-operations the main engines are used for taxiing and are all started before the aircraft starts its taxi operations, as it can be seen in Figure 4.4a.
The taxi-out process starts with driving the pushback car to the aircraft and the vehicle connecting to the aircraft. Then the actual pushback takes place at time 00:00. (From this point the aircraft starts its taxiing operations and is therefore indicated with time 00:00) At this point the APU has already started, and the fuel and maintenance costs are now part of the taxi operation costs. During the pushback, the pilot starts the engines of the aircraft. The thrust of all the main engines is set to 7% during taxiing. According to Khadilkar and Balakrishnan this constant level of thrust during taxiing yields a good estimate of actual fuel burn. After the pushback car is disconnected, and clearance for taxiing is given, the aircraft starts taxiing from the apron to its assigned runway. During the taxi operations the APU is shut down.
According to Sillekens [2015] this way of taxi-out procedure is the most adopted one, mainly due to the fact that the main engines have an ESUT between 2 and 5 minutes [Wijnterp et al., 2014].

Single-engine taxiing

Single-engine taxiing means that the aircraft will not use all the engines. It is a variant of conventional taxiing as shown in Figure 4.4b. According to Vaishnav [2014] single-engine taxiing is not widely adopted, however airlines instruct pilots to use single-engine taxiing as often as possible. It is likely that this approach will become more widely adopted. For this approach the ESUT of Wijnterp et al. [2014] is assumed. During single-engine taxiing for a twin engine aircraft, one engine is shut down. The thrust setting of the operating engine is assumed to be at 7% (i.e. idle thrust) [Airbus, 2004, Dzikus, 2013]. The second engine will start-up

2.5 minutes before the aircraft reach the runway. In normal conditions the minimum start-up time is given by the manufacturers and is 2 minutes for the CFM56 family engines [Sillekens, 2015]. For the model it is assumed that the minimum ESUT for all aircraft is the same and is assumed to be 2.5 minutes. An aircraft with four engines will use two engines during single engine taxiing [Airbus, 2004]. For an aircraft with three engines it is assumed that it will use two of its main engines.

AGV taxiing

Figure 4.4c shows the taxi process with AGVs. The first part is similar to taxiing with the main engines: the AGV drives and connects to the aircraft, followed by the pushback. The APU is already running at this point. Since the AGV will tow the aircraft to the runway, the aircraft main engines are not started yet. The APU keeps running to provide energy to the aircraft. After the taxi clearance, the aircraft will be towed by the AGV to a point near the runway. Just before arriving at the detachment point near the assigned runway, the engines of the aircraft will start up. It is custom to start one engine approximately one minute later than the other [Sillekens, 2015]. At the detachment point, the AGV will disconnect from the aircraft and the APU will shut down. From this point, the AGV will wait until it is assigned to another flight. Since the AGV has to drive back, these costs will be incorporated in the model.

4.3.2. Taxiing time assumptions

The OAG-dataset provides the block and scheduled departure/arrival times of the aircraft as described in Section 4.2. For the model, these times will be used as input. For departures, next to the scheduled and block departure time, the time interval the aircraft can start taxiing is needed. Also a time interval in which the aircraft can depart has to be determined. Here the taxi procedures of Section 4.3.1 have to be taken into account.

- **Earliest taxi start time:** This is the earliest time an aircraft can start with its taxi operations, thus from this time onward, the aircraft can enter in the model.
  For arriving aircraft this is simply the block arrival time of the aircraft from the OAG-dataset. When an aircraft lands at the runway, it can directly start taxiing towards its assigned gate.
  For departing aircraft the block-departure time at the runway is given in the OAG-dataset. However the earliest possible taxi time at the gate is needed. In the model this start time is the block departure time minus the shortest path time from the gate to the runway.

- **Latest taxi start time:** The latest time aircraft can start taxiing is assumed to be 10 minutes after the earliest taxi time. This means that each aircraft in the model can start its taxi operations in the range $[t_{s_{early}}, t_{s_{early}} + 10]$, where $t_{s_{early}}$ is the earliest taxi time for an aircraft. 10 minutes is used since the latest taxi end time is 10 minutes after the block departure time.

- **Latest taxi end time:** In Europe an Air Traffic Flow Management (ATFM) slot is defined as the time period 5 minutes before and 10 minutes after the CTOT (calculated take-off time). If a slot is missed, the Network Operations assigns a new one. Assuming that the block departure time is equal to the CTOT, the latest taxi end time for the aircraft is 10 minutes later. [4]

- **Earliest taxi end time:** The earliest time an aircraft can end its taxi operations is not simply the earliest taxi start time plus the shortest path time the aircraft can travel, since the active taxi network of the airport might change after the earliest taxi start time. As described in Section 4.2.4, the network depends on the active runways. Therefore it is assumed that aircraft can arrive up to 5 minutes at the runway/gate before their block departure/arrival time, which also complies with the ATFM slot. This means that each departing aircraft has to end its taxi operations in range $[t_{d_{block}} - 5min, t_{d_{block}} + 10]$, where $t_{d_{block}}$ is the block departure time. For arriving aircraft the same range in which they have to arrive at their gate is used.

4.3.3. Arriving aircraft

The model will use the AGVs only for taxi-out procedures. AGVs are preferred for taxi-out operations and not for taxi-in operations because of the following factors:

[4] `http://www.eurocontrol.int/articles/atfm-slots:` accessed on November 20th, 2017.

- **Extra handling:** For taxi-out a pushback procedure is required to leave the gate. Arriving aircraft can taxi towards the gate without the use of pushback vehicles, as shown in Figure 4.5. Connecting the AGV near the runway to taxi towards the gate will requires extra time, and will make the taxi-in procedure more complex.
- **Longer taxi out time:** On average, the taxi-in time is lower than the taxi-out time. In the US the average taxi-in time was 7 minutes, while this was 16.5 minutes for taxi-out for major hub airports [Goldberg and Chesser, 2008].
- **Single engine taxiing:** After landing, the engines have a engine cool down time (ECDT), which has a minimum of 3 minutes [Sillekens, 2015] (depending on the type of engine). After this ECDT it is common during taxi-in to use single-engine operations [Goldberg and Chesser, 2008, Hospodka, 2014a].

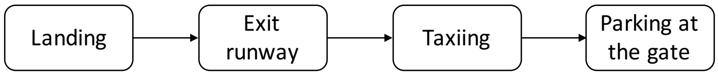


Figure 4.5: Standard taxi-in procedure [Evertse, 2014]

The inbound traffic will be taken into account in the model as input. By simply minimizing the taxi times of the arriving aircraft, the routing of the inbound traffic is determined. This is done by minimizing the total taxi time of the inbound traffic using the model described in Section 4.5. This means that the traveling and waiting costs in the model of Chapter 4.5 are the times of waiting and traveling for the inbound traffic. The cost for delay is not included and either the depreciation cost of the vehicles, since no vehicles are used for the inbound traffic.
The resulting routing of the aircraft forms an input for the outbound traffic model. If a node or edge is occupied by an inbound aircraft, this node/edge cannot be used for outbound traffic. The definition of an occupied node or edge is given in the conflict free nodes/edges constraints in Section 4.5.3.

4.4. Energy usage cost

This section describes the energy usage costs, which are later used in the mathematical model of Section 4.5. The cost of traveling over the network depends on many different factors. Although it is hard to capture all the costs of taxiing at a major airport, it is important to generate a realistic cost function to optimize the taxi operations. The cost of energy for taxiing over the network is part of the total taxiing cost. The cost of energy is dependent on the fuel flows of the AGV and the aircraft. The following fuel flows take place during taxi operations:

- Fuel flow of the main engines of the aircraft (current taxi operations).
- Fuel flow of the APU.
- Fuel flow of the AGV with and without towing an aircraft.

4.4.1. Fuel flow of the main engines

In current taxi operations, ICAO emissions database assumes 7% thrust value for all ground operations. The estimated fuel consumption is calculated by taking the fuel flow of the main engines at 7% thrust setting, multiplied by the taxiing time [Chen et al., 2016]. Figure 4.6 shows a typical fuel flow during taxiing for an Airbus A320 with two engines. Although the increase in velocity is accompanied by the spikes in the fuel flow rate [Khadilkar and Balakrishnan], the fuel flow rate can be modeled as constant over the time during taxi operations. The fuel flow for the engines of an aircraft can be found in Table A.2. Section 4.3.1 describes the operating time of the main engines for different taxi-procedures. The fuel flow of the aircraft's main engines is the operating time of the engines multiplied by the specific fuel flow at 7%.
By using the main engines, the maintenance costs for the operational engines has to be taken into account as well. For the maintenance cost 80 EUR per hour per engine is used during taxi operations [Hospodka, 2014a]. This means 0.022 EUR per second per running engine. According to Hospodka [2014a], this is a conservative assumption for the cost of maintenance.

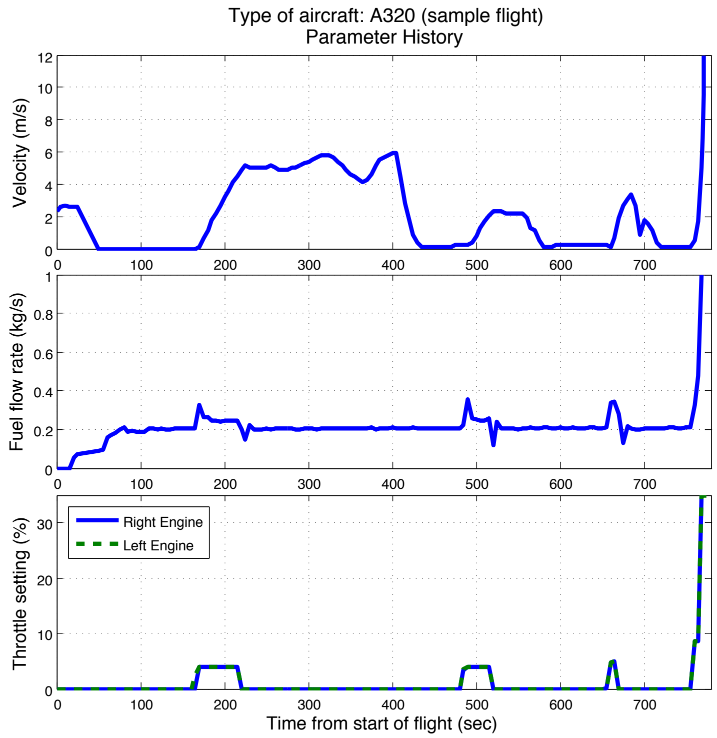


Figure 4.6: Example of an Airbus A320 during taxi operations. Plot of velocity, fuel consumption rate and engine thrust settings. [Khadilkar and Balakrishnan]

4.4.2. Fuel flow of the APU

The APU of the aircraft uses fuel at a constant rate and is therefore depending only on the time. The fuel consumed by the APU (F_i^{APU}) is calculated by Equation 4.2 obtained from Guo et al. [2014].

$$F_i^{APU} = T_i \cdot FF_i^{APU} \tag{4.2}$$

T_i is the time the APU is used. This depends on the taxi procedure as explained in Section 4.3.1. For taxiing with AGVs, the APU is used during almost the entire taxi operation. The APU fuel usage per aircraft is obtained from Watterson et al. [2004] and can be found in Table A.2 of Appendix A.
The maintenance cost of the APU is around 38 EUR per used hour [Theory and Practices]. This means that for every second the APU is running, 0.01 EUR has to be paid for maintenance.

4.4.3. Fuel flow of the AGV

In order to compare the use of AGVs with current taxi operations, the fuel used by AGVs in taxi operations needs to be obtained. For the model, the fuel usage per segment is needed in order to calculate the cost of using this part of the network. Two scenarios are possible: 1) the towing vehicle is connected to an aircraft, 2) the towing vehicle is empty. For each scenario there are different fuel consumptions:

1) The towing vehicle is connected to an aircraft.

- Time stopped: the APU of the aircraft is using fuel at a constant rate, the fuel flow of the vehicle is neglected and assumed to be 0.
- Time taxiing: the APU of the aircraft is using fuel at a constant rate, the fuel flow of the vehicle depends on the segment it is traveling taking into account the aircraft type.

2) The towing vehicle is empty.

- Time stopped: the fuel flow of the vehicle is neglected and assumed to be 0.
- Time taxiing: the fuel flow of the vehicle depends on the segment in which it is traveling.

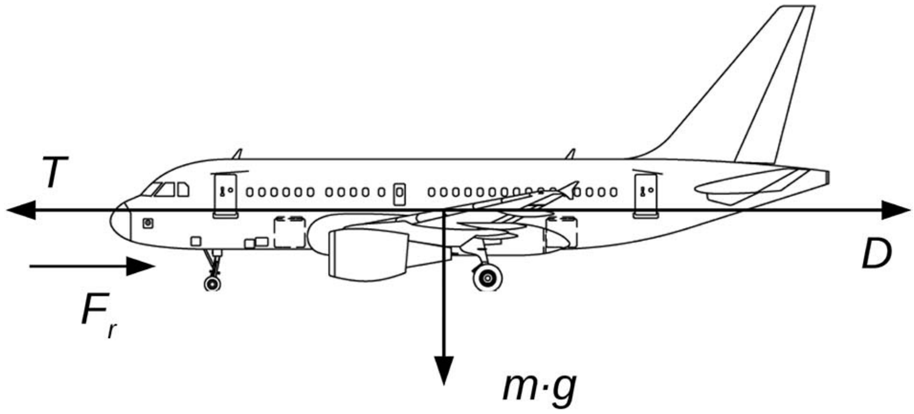


Figure 4.7: Forces acting in the vehicle and aircraft. [Chen et al., 2015]

In order to calculate the fuel usage of the towing vehicle per segment, not simply the time of traveling a certain segment multiplied by a specific fuel flow can be used (such as by the ICAO emission database for conventional taxi operations). This would give as a result that the fuel usage of a segment with a high speed and large distance would require the same amount of fuel as a segment with a low speed and small distance but with an equivalent travel time. As the concept is new and no historical data is available, for each segment the fuel used needs to be calculated. This is based on the characteristics of that segment, the towing vehicle and the aircraft. As can be seen in Equation 4.3, the fuel flow F_i^t depends on the power required and the time that this power is required [Guo et al., 2014].

$$F_i^t = \sum_m (T_{im} \cdot 60) \cdot BHP \cdot LF \cdot FF_{im}^t \tag{4.3}$$

In Equation 4.3 the BHP is the average rated brake horsepower of the towing vehicle engine and LF is the load factor used in the operation. Thus the BHP multiplied by the load factor is the power used for the towing operation. FF_{im}^t is the fuel flow index in $kg/BHP-sec$ for flight i using vehicle type m (WB or NB). The thrust that has to be generated can be calculated using Equation 4.4. This thrust is needed to overcome the forces acting on the aircraft and vehicle during taxiing as can be found in Figure 4.7.

$$\mathrm{T} = \mathrm{m} \cdot \mathrm{a} + \mathrm{F}_r + \mathrm{D} \tag{4.4}$$

Since the taxiways are assumed to meet the international regulations, the maximum taxiway slope is; $\alpha_s < 3\%$ [Sirigu, 2017]. Therefore the taxiway slope is not taken into account. The friction F_r is calculated by Equation 4.5, where g is 9.81 m/s^2 and μ is the rolling resistance coefficient for the concrete surface, which is set to 0.015 [Chen et al., 2015]. The mass m is the total mass of the towing vehicle and the MTOW of the aircraft (if connected to an aircraft).

$$F_r = \mu \cdot m \cdot g \tag{4.5}$$

The drag D can be calculated using Equation 4.6 where C_d is the drag coefficient, ρ (set to $1.225 kg/m^3$) is the density of the air at sea level (depending on the airport), v the speed and S the area of the wing or the vehicle. The ICAO Emission Database further simplifies the thrust equation by not taking into account the drag, since for taxiing the speed v is low and can therefore be neglected. Using the data provided in Table 4.6, for the Airbus A380 taxiing at a constant speed of $10 m/s$ with the WB vehicle, the aerodynamic drag is only 1.86% of the total drag force. For the NB aircraft taxiing with the NB towing vehicle at a speed of $12 m/s$ the aerodynamic drag is 5.63% of the total force.

$$\mathrm{D} = \frac{1}{2} \mathrm{C}_D \cdot \rho \cdot \mathrm{v}^2 \cdot \mathrm{S} \tag{4.6}$$

Neglecting the drag force would change Equation 4.4 into Equation 4.7.

$$\mathrm{T} = \mathrm{m} \cdot \mathrm{a} + \mathrm{F}_r \tag{4.7}$$

Table 4.6: Drag fraction of aircraft based on aircraft specifications and the assumes towing vehicle. [AC, Sirigu et al., 2016]

AC type	Model	MTOW $[kg]$	S aircraft $[m^2]$	C_D aircraft []	m vehicle $[kg]$	S vehicle $[m^2]$	C_D vehicle []
NB	A320	80000	122	0.020	10000	6.9	0.6
WB	A380	540000	858	0.027	50000	6.9	0.6

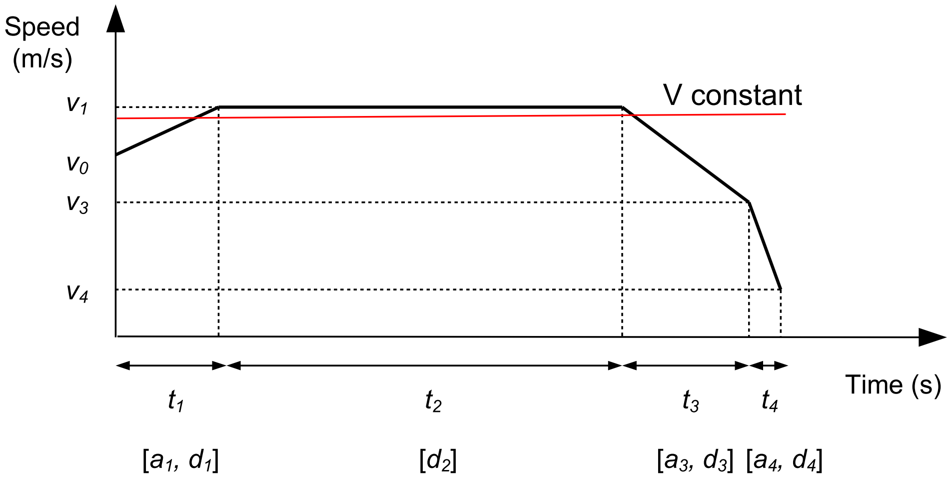


Figure 4.8: Speed profile segment example with four phases [Chen et al., 2015]. The red line represents the constant speed.

In Figure 4.8 a speed profile with four phases for a segment can be found. The first phase corresponds to a constant acceleration rate (a_{max} is set to $0.98 m/s^2$ for passenger comfort) over a distance d_1. In this part the aircraft will accelerate from its initial speed v_0 to v_1. During the second phase the vehicle with the aircraft (or the vehicle only) will taxi at a constant speed. In the third and fourth phase the system will decelerate, being in phase 4 the maximum deceleration in order to reduce the speed quickly. However, most segments will not consist of all the four different phases. To simplify, the average speed of each segment is used, since the acceleration and the deceleration phases depend on the previous path of the vehicle. For the acceleration phase more power will be required than for the constant speed taxiing phase ($m \cdot a$ in Equation 4.7), while for the deceleration part less power is required. Adding the acceleration and deceleration for each segment will add an extra layer of complexity to the model, while according to Nikoleris et al. [2011] the total fuel used for accelerating during taxiing is on average only 4% of the total fuel used during current taxi operations. Furthermore, when an electric or a hybrid taxiing system (such as the TaxiBot) is used, a part of the energy in the deceleration phase can be regenerated. Considering a hybrid/electrical taxiing system with the specifications stated in Table 4.7, almost 70% of the energy used for accelerating the aircraft can potentially be recovered.

Based on the distance between two nodes, the maximum taxiing speed per edge and the maximum speed of the vehicles, the traveling time and speed of an edge can be calculated. Using timesteps of 10 seconds the speed and time traveling an edge are calculated as follows (based on Roling et al. [2015]):

1. Actual taxi time: dividing the length of the edge by the maximum speed allowed at that edge. If the maximum speed of the edge is higher than the maximum speed of the vehicle, or the vehicle with the

Table 4.7: Electrical specifications for regeneration Sirigu et al. [2016].

Electrical data	Description	Value
η_d	energy storage discharging efficiency	0.95
η_c	energy storage recovery efficiency	0.95
η_{out}	discharging efficiency of power electronics	0.98
η_{in}	recovery efficiency of power electronics	0.95
η_{em}	electric motor efficiency	0.9
e_{rec}	energy that can be recovered	0.9

aircraft, then the lowest speed is used.

2. Taxi timestep: since timesteps of 10 seconds are used, the actual taxi time is converted into a timestep. This is done by dividing the actual taxiing time by 10 seconds and rounding-up to the nearest integer.

3. Model taxiing speed: this is the distance of the edge divided by the taxi time step (in seconds). Since the taxi-timestep is rounded up to the nearest integer, the model taxiing speed is lower or equal to the maximum speed.

As an example, consider edge $A-B$ with a distance s of $200m$ and a maximum speed of $14m/s$. For the vehicle, consider a NB towing vehicle with a maximum speed of $14m/s$, towing a NB aircraft with a MTOW of $80tons$. The actual taxiing time is $200/12 = 16.7sec$. Rounding to the nearest timestep of $10sec$. will give a taxi-timestep of 2 ($20sec$.) This means that in the model the time to travel edge $A-B$ is $20sec$. and the average speed v is $200/20 = 10m/s$.
Now the fuel consumption per edge can be calculated using the power P from Equation 4.8 in Equation 4.3.

$$P = \frac{F_r \cdot s}{t} = F_r \cdot v \tag{4.8}$$

For the fuel flow index of NB tugs with diesel engines a value of 5.3879E-05 $kg/BHP - sec$ is used, and 4.68129E-05 $kg/BHP - sec$ for WB tugs [Albee et al., 1995]. Using the fuel flow per second and a constant power per edge in kW, Equation 4.3 can be written as Equation 4.9.

$$F^t_{im} = t \cdot \frac{P \cdot 1.341}{1000} \cdot FF_{im} \tag{4.9}$$

For the example of towing a NB over edge $A-B$, this means that $0.19kg$ of diesel have been used. Using the specifications of the WB towing vehicle with the Airbus A380 from Table 4.6 with a maximum taxiing speed of $10m/s$, the fuel flow of the towing vehicle at edge $A-B$ is $0.054kg/sec$, which corresponds to the fuel flow of $0.06kg/sec$ of TaxiBot towing an A380 [Hospodka, 2014b]. The cost in Euros can be calculated using the local price of diesel and the density of diesel of $840kg/m^3$. For example the average Dutch fuel price from January 1st 2008 to January 1st 2018 CBS was $1.277EUR/L$. For the Jet fuel price the average price between January 1st 2008 to January 1st 2018 was $0.46EUR/L$ with a density of $820kg/m^3$ [Mun]. By testing different fuel price scenarios, the effect of the fuel price and usage on the model can be tested.

4.5. The mathematical model

This section explains in detail how the design choices described earlier in this chapter are implemented in the mathematical program, which is the $'formulate\ MILP\ problem'$ block in the functional flow diagram in Figure 4.1.
The used variables are given and explained in detail in Sections 4.5.1 and 4.5.2 respectively. In Section 4.5.3, the MILP formulation is explained with the objective function and the constraints.

As it was mentioned in Chapter 3, a MILP formulation will be used for the routing and scheduling of AGVs. How this MILP formulation translates into optimal routing and scheduling is explained here.
By minimizing the objective function, the optimal way of using the AGVs can be obtained. The CPLEX output will provide which node/edge will be used by a vehicle/aircraft at a point in time. Since an AGV or an aircraft can visit each node in the network more than once, a time-space network is used. Each node represents a point of the network at each unit of time in the model. The arc represents the edge the vehicle/aircraft can travel between two nodes. By using a time-space network the model keeps track of the position of the vehicles/aircraft in every timestep of the time horizon in order to verify the conflicts.

4.5.1. MILP variables

From the taxiing parameters described in Chapter 4, the parameters those who have been used in the model are:

Sets

- $I = \{0, ...i...I\}$: Set of nodes in the time-space network.

- $R = \{...(i,j)...\}\ i,j \in I, i \neq j$: Set of edges in the network.
- $V = \{0,...v...V\}$: Set of vehicles, where 0^{th} means no vehicle is used. The 'vehicles' are the AGVs proposed in this research.
- $T = \{0,...t...T\}$: Set of all time periods
- $H = \{0,...h...H\}$: Set of all flights, where 0^{th} means no flight is attached to the vehicle.
- $E_I = \{0,...E_i...E_I\}$: Adjacent nodes of node i. An edge exists between i and nodes E_i. i.e. if an edge exists between node i and nodes 4 and 6, $E_i = \{4,6\}$.

Cost variables

- c_{ij}^{hv} : Cost for traveling edge (i,j) in the network with aircraft h and vehicle v.
- q_i^{hv} : Cost for waiting at a node i in the network with aircraft h and vehicle v.
- k^{ht} : For each time t that flight h can arrive at its assigned runway, k^{ht} is the cost of additional delay. If there is no additional delay cost, k^{ht} is equal to zero.
- D^v : Depreciation and maintenance cost of vehicle v, which is time based and only applies if the vehicle is used.

Decision variables

- $x_{i_{t_1} j_{t_2}}^{hv}$: Binary variable equal to 1 if a vehicle v with aircraft h travels on edge (i,j) from time instant t starting at node i to t_2 at node j.
- $w_{i_t}^{hv}$: Binary variable equal to 1 if a vehicle v with aircraft h waits at node i from time instant t.
- p_i^{ht} : Binary variable equal to 1 if flight h is delivered at time t at its assigned runway node i.
- l^v : Binary variable equal to 1 if a vehicle v is ever used in the optimization time.

Time and network parameters

- δ_{ij}^t : Travel time in time steps for edge (i,j) beginning at time instant t. $\forall(i,j) \in R, t \in T$
- t_s : Starting time of the vehicle. From this time vehicle v is active in the network.
- i_s^v : Starting node of vehicle v.
- i_p^h : Starting node of flight h (gate).
- j_d^h : Delivery node of flight h (runway).
- $t_{p_{early}}$: Earliest time for the aircraft to leave the gate.
- $t_{p_{late}}$: Latest time for the aircraft to leave the gate.
- $t_{d_{early}}$: Earliest time for the aircraft to arrive at the runway.
- $t_{p_{late}}$: Latest time for the aircraft to arrive at the runway.
- S_{ij} : The service lane $(i_{service}, j_{service})$ crossing edge (i,j). These are the service edges that cross taxilanes. In order to avoid conflicts of empty vehicles traveling over these service edges, these edges are indicated separately for the conflict free edges constraint.

4.5.2. Variable values and filtering

This section describes in detail how the parameters are used to generate the values of the variables in the model. In order to generate not more variables than needed, the variables should meet certain conditions (filtering), which are described here as well.

Traveling an edge
Decision variables $x^{hv}_{i_{t_1}j_{t_2}}$ have a cost c^{hv}_{ij}. The cost of traveling edge (i, j) depends on the aircraft and vehicle traveling that edge. If $h = 0$, the vehicle is traveling without load and if $v = 0$, the aircraft is taxiing without vehicle, using its main engines. Since there are two types of vehicles, NB and WB, the cost of the vehicle v depends on the aircraft type and the vehicle type. The time it takes to travel an edge (in time steps) was explained in Section 4.4. The configurations and their costs are explained here:

- **Aircraft without vehicle:** The cost of traveling edge (i, j) consists of the fuel cost of the main engines for a specific aircraft and the maintenance cost of the engines. As explained in Section 4.3.1, this cost depends also on the way of taxiing (conventional or single-engine). The cost of jet fuel is the jet fuel used with a 7% thrust setting times the fuel price including the cost of maintenance of the engines as explained in Section 4.4.
- **Vehicle with aircraft:** The cost of traveling edge (i, j) consists of the following costs: fuel cost of the vehicle, fuel of the APU and the maintenance cost of the APU. The cost of fuel for both vehicle and aircraft APU (including maintenance) are explained in Section 4.4.
- **Vehicle without aircraft:** The fuel cost for traveling edge (i, j) for an empty vehicle is calculated in the same way as for a vehicle with aircraft. The associated cost is only the cost of diesel for the vehicle.

Variable $x^{hv}_{i_{t_1}j_{t_2}}$ does not exist for every edge (i, j). In order to exist, it must meet certain conditions. Variable $x^{hv}_{i_{t_1}j_{t_2}}$ is not generated if:

- A runway is active with a possible runway crossing. Variable $x^{hv}_{i_{t_1}j_{t_2}}$ for the edge crossing the runway could not be used at this point in time.
- For flight h, time t is outside the range of the earliest starting time and latest delivery time of the flight.
- Flight h or vehicle v could not reach the edge at time t. For example, flight h can not reach an edge with a minimum driving time of 10 minutes from its gate, in 5 minutes.
- Flight h cannot travel edge (i, j) because this edge is a service-road. Only an empty vehicle is allowed to use service-roads.

Waiting at a node
Decision variables $w^{hv}_{i_t}$ have a cost q^{hv}_i. Like the cost of traveling an edge, the cost of waiting at node i depends on the aircraft and vehicle waiting at the node. Not at every node the aircraft/vehicle is allowed to stop. These hold-nodes are indicated in Tables A.3 and A.4. Furthermore the cost of waiting at a Gate-node and a Runway-node can be different. The cost values and the filtering for the waiting variables are explained here:

- **Vehicle without aircraft:** The cost of waiting without aircraft is considered to be zero, since no fuel is used.
- **Aircraft without vehicle in network:** The cost of waiting without AGV at a node in the network is equal to the cost of jet fuel and maintenance cost for the used main engines of the aircraft (7% thrust setting). The waiting time for each $w^{hv}_{i_t}$ is equal to 1 timestep.
- **Aircraft without vehicle at a gate:** The costs of ground service clearance and taxi clearance from Figure 4.4 are all incorporated in the at-gate waiting time. The cost consists of jet fuel used and maintenance cost for the APU and main engines (depending if dual or single engine taxiing is used), from time 00:00 to 04:00 in Figures 4.4a and 4.4b. It is assumed that the cost of pushback and connecting with a conventional pushback car is similar to the cost of pushback with an AGV. Since the model will compare AGV taxiing with current taxiing, the cost of pushback can be eliminated. Furthermore if the aircraft waits at the gate after taxi clearance, the cost of 'Aircraft without vehicle in network' is used.
- **Aircraft without vehicle at runway:** When the aircraft arrives at the buffer area near the runway, q^{hv}_i is the fuel and maintenance cost for all engines for 30 seconds in conventional taxiing operations. When single engine taxiing is used, the ESUT cost for the engine(s) that is not used for taxi operations is added.

- **Aircraft with vehicle in network:** The cost of waiting at a holdnode for 1 timestep is the fuel and maintenance cost of the APU.
- **Aircraft with vehicle at gate:** Here the cost is just the one from using the APU from 00:00 to 02:30 as indicated in Figure 4.4c. The costs of pushback and connecting time are not included as explained in 'Aircraft without vehicle at gate'. The cost of waiting at the gate after taxi clearance is equal to the cost of using the APU.
- **Aircraft with vehicle at runway:** Disconnecting will take place near the runway. The cost consist of the cost for the ESUT and the cost for using the APU (the time it is still running).
- **Foreign object damage (FOD) saving:** Hospodka [2014a] describes that 85% of foreign object damage happens on the stand or during taxiing. Using AGV taxiing will reduce the danger of damaging the main engines. 11 EUR compared to taxiing with the main engines can be saved on average. According to Hospodka [2014a], this is a conservative estimation. This FOD cost is added to the 'Aircraft without vehicle at gate' cost.

As for the edges, variable $w_{i_t}^{hv}$ is not generated for every h, v, i and t. In order to reduce the amount of variables, $w_{i_t}^{hv}$ does not exist if:

- The vehicle/aircraft is not allowed to stop at node i.
- For flight h, time t is outside the range of the earliest starting time and latest delivery time of the flight.
- Flight h or vehicle v could not reach node i at time t.
- Flight h cannot travel edge i if this edge is a service-roads. Only empty vehicles are allowed to use service-roads.

Delay
k^{ht} are the marginal delay costs and will be added to the cost function if p_i^{ht} is 1. p_i^{ht} is 1 if flight h is delivered at time t at node i. Node i is the assigned runway node for flight h. Cost k^{ht} is the difference in delay costs obtained by the model (the delay cost when aircraft h is delivered at runway node i) and the already existing delay costs (the cost of delay at the block departure time from the OAG-dataset). A detailed description of the delay cost can be found in Section 4.2.5. Since every flight has to be delivered in range $[-5min, 10min]$ from the original block departure time, as described in Section 4.3.2, k^{ht} only exist if t is in this range.

Depreciation
D^v are the depreciation and maintenance costs of the vehicles. The maintenance and depreciation values per hour are used, as described in Section 4.2.6. D^v per vehicle in the model is the amount of used hours times the hourly depreciation and maintenance cost of the AGV.

4.5.3. MILP formulation

This section describes how the variables of Section 4.5.1 can be used in a MILP formulation to find the optimal routing and scheduling of the aircraft and vehicles.

Objective function

Equation 4.10 shows the objective function (C), which is the cost of taxiing that will be minimized. The explanation of the variables is given in Section 4.5.1. The left part of Equation 4.10 is the cost of traveling an edge. The second part adds the cost of waiting at a node. The third and fourth part add the cost of delay and the cost of using a vehicle respectively to the objective function. Using these variables in the cost function, will result in a model that aims to get the aircraft to the runway in the most efficient way, but at the same time takes into account the cost of delay. Optimizing only for the fuel used could result in unrealistic taxi operations, since the cost of delay can exceed the cost of fuel saving by AGVs, which is not preferred by airlines.

$$Min(C) = \sum_{\substack{i,j \in I, v \in V \\ t \in T, h \in H}} (c_{ij}^{hv} x_{i_t j_{t+\delta_{ij}^t}}^{hv} + q_i^h w_{i_t}^{hv} + k^{ht} p_i^{ht} + D^v l^v) \tag{4.10}$$

Constraints

A set of constraints is added to the objective function in order to route the vehicles and aircraft over the network. In this section the used constraints are given and their use is explained.

Starting position of the vehicle

$$\sum_{j\in E_i}(x^{hv}_{i_t j_{t+\delta^t_{ij}}}) + w^{hv}_{i_t} = 1, \quad \forall v \in V, i = i_s, t = t_s, h = 0 \tag{4.11}$$

These constraints introduce the vehicles in the model. Vehicle v will become available to be used for the model at time t_s at its starting position i^v_s. For the starting position an arbitrary node in the network can be used. In the model, all vehicles will start from node 0. This node represent a parking position, where the vehicles can be located near the terminal area. As it can be seen in Equation 4.11, the constraint is equal to 1, which means that at time t_s vehicle v has two options; 1) Staying at the node for the next timestep. In this case $w^{hv}_{i_t}$ is equal to one. 2) The vehicle drives from i^v_s to one of its adjacent nodes E_i. In this case one of the edges, $x^{hv}_{i_t j_{t+\delta^t_{ij}}}$ is equal to one.

Route of flow vehicle constraints

$$\sum_{j\in E_i, h\in H}(x^{hv}_{j_{t-\delta^t_{ji}} i_t} + w^{hv}_{i_{t_0}}) - \sum_{j\in E_i, h\in H}(x^{hv}_{i_t j_{t+\delta^t_{ij}}} + w^{hv}_{i_t}) = 0, \quad \forall i \in I, v \in V, 1 \leq t \leq T \tag{4.12}$$

Constraints 4.12 represent the time continuity constraints of the vehicle. These constraints ensure that each vehicle that enters a node either leaves the node or waits at this node. By implying these constraints, the vehicle will appear in the model till the end of the time window (T).

Constraints 4.12 depend on node i. Since there are different types of nodes, the way constraints 4.12 work at these nodes is explained here:

1. **Service nodes:** If node i is a node that is only connected with service links, $h = 0$ in all cases, since no flights are allowed here. There are two different variants:
   - Node i is a hold-node: The empty vehicle can wait at the service node, where timestep of the waiting variable is 1.
   - Node i is not a hold-node: $w^{hv}_{i_{t_0}}$ and $w^{hv}_{i_t}$ are not part of Equation 4.12 for node i.
2. **Taxi-lanes:** If node i is part of the aircraft taxi-lanes, $h > 0$. In this case the vehicle is towing a flight over the network. Since in the case of AAS it is assumed that vehicles can only travel with aircraft on the taxi-lanes, this part is covered with the time continuity flight constraint. As for the 'service nodes', there are two cases:
   - Node i is a hold-node: The vehicle waits with the aircraft at the node.
   - Node i is not a hold-node: $w^{hv}_{i_{t_0}}$ and $w^{hv}_{i_t}$ are not part of Equation 4.12 for node i.
3. **Gate:** If node i is a gate node, an empty vehicle could pick-up an aircraft here. This means that h on the left side of Equation 4.12 is equal to 0, and $h > 0$ on the right side. If flight h will be picked up, the pick-up time of the aircraft is considered for the waiting time as explained in Section 4.5.2. If the aircraft is picked up at node i, the constraints ensure that the vehicle either waits at this node, or starts traveling over the tax-lanes to one of its adjacent taxi-lanes. The vehicle has also the option to travel, without aircraft, over one of the service roads connected to the gate.
4. **Runway:** If node i is a runway node, the aircraft can disconnect at this node. When disconnecting, h at the left side of Equation 4.12 is larger than zero, while on the left side h is equal to zero. In this case $w^{hv}_{i_t}$ will include the disconnecting time as explained in Section 4.5.2. From this runway node, the empty vehicle can either wait or drive back over one of the service roads.

Pick-up

$$\sum_{\substack{v \in V, i=i_p^h \\ t_{p_{early}} \leq t \leq t_{p_{late}}}} w_{i_t}^{hv} = 1, \quad \forall h > 0 \ \ in \ \ H \tag{4.13}$$

The pick-up constraints ensure that each flight h will be picked-up at its gate i in pickup-range $[t_{p_{early}}, t_{p_{late}}]$. There are two options; 1) The aircraft will taxi with its main engines to the runway. In this case $v = 0$ and the pick-up time for taxiing without AGV is considered. 2) Flight h will be picked-up by an AGV, which means $v > 0$. Each type of aircraft can only be picked-up by a matching vehicle type. The type of vehicle is defined in the input of the vehicle number. e.g. if the set of vehicles consist of two NB and two WB vehicles, vehicle number 1 and 2 are the NB vehicles and vehicle number 3 and 4 are the WB vehicles.

Route of flow aircraft constraints

$$\sum_{j \in E_i} (x_{j_{t-\delta_{ji}^t} i_t}^{hv} + w_{i_{t_0}}^{hv}) - \sum_{j \in E_{i,}} (x_{i_t j_{t+\delta_{ij}^t}}^{hv} + w_{i_t}^{hv}) = 0, \qquad \begin{array}{c} \forall i \in I, h > 0 \ \ in \ \ H, v \in V, \\ t_{p_{early}} \leq t \leq t_{d_{late}} \end{array} \tag{4.14}$$

The route of flow aircraft constraints ensure that each aircraft after being picked up can travel over the taxi-lanes. These constraints works in the same way as the route of flow vehicle constraints. These constraints exist for each aircraft $h > 0$ in time range $[t_{p_{early}}, t_{d_{late}}]$, and are the earliest time the aircraft can leave the gate, and the latest take-off time considered. Aircraft h can be connected to vehicle v from the same type, or can taxi without vehicle ($v = 0$). In constraints 4.14, node i can be either a taxi-lane node, a gate or a runaway:

1. **Taxi-lanes:** If node i is located at one of the taxi-lanes, there are two options:
   - Node i is a hold-node: The aircraft can wait at the service node, where timestep of the waiting variable is 1.
   - Node i is not a hold-node: $w_{i_{t_0}}^{hv}$ and $w_{i_t}^{hv}$ are not part of Equation 4.14 for node i.
2. **Gate:** If i is equal to the gate node i_p^h of flight h, $x_{i_t j_{t+\delta_{ij}^t}}^{hv}$ is eliminated from Equation 4.14. On the right side of the equation, $w_{i_t}^{hv}$ can only be the variable for waiting after being picked-up. $w_{i_t}^{hv}$ with the pick-up time is eliminated. In this way the continuity constraint for flight h starts at its gate node. For example consider that node i is the gate node for flight h. If $w_{i_{t_0}}^{hv}$ is 1 due to the pick-up constraint, flight h has two options; 1) It keeps waiting at the gate. This means it stays at i for at least one more timestep 2) It travels to an adjacent taxi-lane node. In the example, this means that flight h will travel an edge starting from i.
3. **Runway:** If i is equal to the assigned runway node j_d^h of flight h, $w_{i_{t_0}}^{hv}$ and $x_{i_t j_{t+\delta_{ij}^t}}^{hv}$ are eliminated from Equation 4.14. By eliminating these variables from the equation, time continuity for flight h is guaranteed till its runway node, from where it takes-off. e.g. node i is the runway node for flight h. If flight h travels on an edge towards i, $x_{j_{t-\delta_{ji}^t} i_t}^{hv}$ is equal to 1. Since the right hand side of the equation is equal to 0, $w_{i_t}^{hv}$ is equal to 1. $w_{i_t}^{hv}$ is the buffer or buffer and disconnecting time at the runway, which depends if $v = 0$ or $v > 0$, as explained in Section 4.5.2. For each flight at least one $w_{i_t}^{hv}$ at its j_d^h has to be equal to 1, due to the flight delivery constraint. If the flight is delivered, the time route of flow constraints for flight h stops.

Flight delivery

$$\sum_{\substack{v \in V, i=j_d^h \\ t_{d_{early}} \leq t \leq t_{d_{late}}}} w_{i_t}^{hv} = 1, \quad \forall h > 0 \ \ in \ \ H \tag{4.15}$$

The flight delivery constraint is similar to the pick-up constraint. This constraint ensures that for each flight at least one waiting variable at its assigned runway node j_d^h is equal to 1. The time of waiting at the runway for flight h depends on v. Each flight needs to arrive at the runway in time interval $[t_{d_{early}}, t_{d_{late}}]$. There are two options: 1) $v = 0$, which means that te main engine(s) have been used for taxiing. In this case, $w_{i_t}^{hv}$ is the buffer time only as explained in Section 4.5.2. 2) If $v > 0$ an AGV has been used, so $w_{i_t}^{hv}$ also includes the disconnecting time at the runway node.

Delay penalty

$$p_{i_t}^{h} = \sum_{v \in V, i = j_d} w_{i_t}^{hv}, \quad \forall h > 0 \ \ in \ \ H, t_{d_{early}} \leq t \leq t_{d_{late}} \tag{4.16}$$

By adding constraint 4.16, the model takes into account the extra cost of delay. For each flight, the flight delivery constrain ensures that one $w_{i_t}^{hv}$ in Equation 4.16 is equal to 1. Since the right had side is zero, at least one $p_{i_t}^{h}$. In the objective function 4.10, $p_{i_t}^{h}$ is matched to its additional delay cost k^{ht}. The delay cost is obtained for all the possible delivery times for each flight. The magnitude of the additional delay cost depends on the time and aircraft, as explained in Section 4.2.5.

Conflict free edges

$$\sum_{\substack{h \in H, v \in V, \\ t = [t_1, t_2 - 1]}} (x_{i_{t_1} j_{t_2}}^{hv} + x_{j_{t_2} i_{t_1}}^{hv}) + \sum_{\substack{h = 0, v \in V, \\ t = [t_1, t_2 - 1], (i,j) = S_{ij}}} (x_{i_{t_1} j_{t_2}}^{hv}) \leq 1, \quad \forall (i,j) \in R, t \in T \tag{4.17}$$

In order to ensure separation of the aircraft at the taxi-links, constraint 4.17 and 4.18 are added to the model. Constraint 4.17 ensures separation on the edges. Edge separation is guaranteed by the fact that each edge can only be occupied with one aircraft at the time [Roling and Visser, 2008]. In this model the aircraft is either taxiing with or without a towing vehicle. Constraint 4.17 is for separation of the aircraft at the taxi-lanes. For towing vehicles driving over their taxi lanes, it is assumed that these vehicles can drive close to each other and can cross each other, since these vehicles do not have the aircraft separation regulations. With Figure 4.9, the left summation of Equation 4.17 is explained.

e.g. consider edge (a, b). At time t, the constraint sums all the possible flights with or without AGV (with AGV is on the left and without AGV on the right in Figure 4.9a) that are traveling from a to b (variable $x_{i_{t_1} j_{t_2}}^{hv}$ in the equation). It takes into account the different taxiing speeds of aircraft. As the aircraft starts at time t_1 at node i, and arrives at node j at time t_2, for all the timesteps in between the edge is occupied by the aircraft. In this way aircraft do not travel on the same edge in the same direction as shown in Figure 4.9a. Herby overtaking an aircraft is also not possible. Furthermore a long edge can be split-up into smaller segments, so aircraft can taxi closer to each other, however it will increase the size of network.

If an edge is bidirectional, variable $x_{i_{t_1} j_{t_2}}^{hv}$ of constraint 4.17 ensures that also aircraft driving in the opposite direction are taken into account. In the example this means that aircraft cannot travel from a to b and from b to a at the same time. This is shown in Figure 4.9b.

The edges occupied by arriving aircraft have been taken into account by not allowing a flight or vehicle to drive on an edge at time t that is occupied by an arrival.

(a) Two aircraft taxiing in the same direction.

(b) Two aircraft taxiing in the opposite direction.

Figure 4.9: Conflict free edges. Either for aircraft with or without AGV. Taxiing in opposite direction on the same edge is only possible on a bidirectional edge, while taxiing in the same direction can be on bidirectional and unidirectional edges.

As can be seen in Figure 4.13, at some parts of the network a service-lane crosses a taxi-lane. In order to prevent the conflicts of the empty vehicles with aircraft, the right summation in Equation 4.17 is added if edge (i, j) has a service-lane crossing. Figure 4.10 gives an example of such a service-lane crossing. Here service-lane (c, d) crosses taxi-lane (a, b), indicated with S_{ij} in the equation. Constraint 4.17 ensures that edge (a, b) and (c, d) cannot be occupied at the same time.

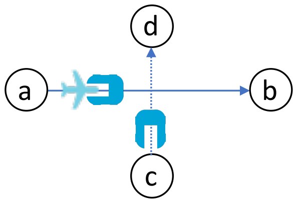


Figure 4.10: Conflict free edges at service crossings. From a to b the vehicle is traveling with aircraft, from c to d the towing vehicle is traveling empty over a service link.

Conflict free nodes

$$\sum_{h\in H, v\in V} w^{hv}_{i_t} + x^{hv}_{i_t j_{t+\delta^t_{ij}}} + x^{hv}_{j_{t-\delta^t_{ji}} i_{t-1}} \leq 1, \quad \forall i \in I, t \in T \tag{4.18}$$

Constraint 4.18 ensures that two flights can not be at the same node at the same time. Figure 4.11 gives an example of the way this constraint works. If node b is the node considered, thus i in Equation 4.18, there can only be one flight that waits at node b, arrives or departs at node b at time t. In Equation 4.18, $w^{hv}_{i_t}$ is the flight waiting at b, $x^{hv}_{i_t j_{t+\delta^t_{ij}}}$ and $x^{hv}_{j_{t-\delta^t_{ji}} i_{t-1}}$ are the flights leaving and arriving at node b respectively. The gray area in Figure 4.11 indicates the area in which only one aircraft can be at time t. e.g. this means that two flight cannot travel from (a,b) and (d,b) and arrive at the same time at b.
The nodes occupied by arriving aircraft have been taken into account by occupying nodes when the arriving aircraft are using them.

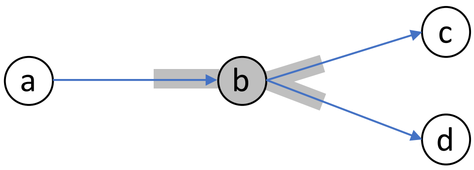


Figure 4.11: Conflict free nodes.

Depreciation vehicle

$$\sum_{h=0, i=i_s} (x^{hv}_{i_t j_{t+\delta^t_{i_s j}}}) - l^v = 0, \quad \forall v \in V, t \in T \tag{4.19}$$

By using constraint 4.19, the cost of depreciation and maintenance of the vehicle is depended whether the vehicle is used or not. If vehicle v has driven from its starting position i^v_s, the summation in Equation 4.19 becomes 1 (in the network a separate node $i^v_s = 0$ is used as staring point for the vehicles). Since the right hand side of the equation is equal to zero, l^v is 1 if the vehicle v is used. By using the depreciation as decision variable, the model will use the minimum amount of vehicles possible to obtain the best result.
For large time periods (such as a full day of operations), the time period can be split-up in time windows. e.g when using a full day of operations the depreciation cost is equivalent to the daily depreciation cost. Thus in each time window not the full day depreciation cost should be considered. Therefore one can choose to relax this constraints and add the full day depreciation cost at a later stage.

4.6. Case study: Amsterdam Airport Schiphol (AAS)

The methodology described in this chapter could be applied for different airports in Europe, since the European delay costs are used. To test the method, AAS will be used as case study due to the availability of data and because it is one of the major airports in Europe. This means that datasets for AAS, which are described in this section, are used as input. First the raw input data for AAS is described in Section 4.6.1 followed by the processed input data in Section 4.6.2.

4.6.1. Raw input data for AAS

OAG-dataset of AAS

For the OAG-dataset, data of AAS is used. The used dataset contains flight status parameters for May 2013 at AAS[5]. With this dataset, different days in May 2013 can be tested.

Active runways at AAS

As input, the active runways at AAS at during the day have to be obtained. For AAS the historical active runway data was found at the website of LVNL. [6] The time is provided in Central European Standard Time (GMT+1) or Central European Summer Time (GMT+2), depending on the date. An example of the active runways of May 2nd can be found in Table 4.8. It might be that the active runway times slightly deviate from the actual active runway times, since there might be a small overlap in runways that are active. This can not be captured from the LVNL website, since the data is not exact on the minute. However it gives a realistic representation of which runways are used at which time.

Table 4.8: Active runway times for May 2nd 2013 (GMT+2).

Runway	Time active (HH:MM)
Aalsmeerbaan (18L)	(05:35-09:00) (10:20-11:20) (12:40-13:20) (14:50-15:50) (17:50-19:35)
Aalsmeerbaan (36R)	
Buitenveldertbaan (09)	
Buitenveldertbaan (27)	
Kaagbaan (06)	
Kaagbaan (24)	(00:00-23:59)
Oostbaan (04)	
Oostbaan (22)	
Polderbaan (18R)	
Polderbaan (36L)	(00:00-11:00) (11:50-23:59)
Zwanenburgbaan (18C)	
Zwanenburgbaan (36C)	(09:00-12:50) (14:10-14:50) (15:50-17:15) (19:35-21:20)

Aircraft taxi-lanes at AAS

The aircraft taxiing network is obtained from Roling et al. [2015], which provides the nodes and edges of the AAS taxi-lanes. Roling et al. [2015] do not model all the gates and runway exit/entrance of AAS. Instead each gate-node represent the apron area near a AAS-pier from which aircraft start their taxiing operations after being pushed-back. Figure 4.13 shows the network, where the gate nodes are the ones in the terminal area connected to both service lanes and taxi-lanes. Runway nodes are located at the start/end position of the runway and are connected to service lanes as shown in Figure 4.13.

Service roads at AAS

The service roads which can be used by the towing vehicles in the terminal area at AAS are shown in Figure 4.12. Since no information is provided regarding the length of the service roads and the available service roads in the runway area, Google Maps[7] is used. The edge length between two gate-nodes of a service edge is the shortest driving distance over the service road between the two gate-nodes. Here the gate-nodes for the

[5]The OAG-data set was provided by the Department of Control and Operations of Delft University of Technology.
[6]`https://www.lvnl.nl/airtraffic:` accessed on October 19th, 2017.
[7]`https://maps.google.nl:` accessed on December 6th, 2017.

service roads are assumed to be near the terminal building as presented in Figure 4.12. From this position the towing vehicle can travel to its designated aircraft. Furthermore Figure 4.12 shows how the terminal service roads are connected to the closest runway service roads with the green dotted lines. These additional service roads are existing service roads.

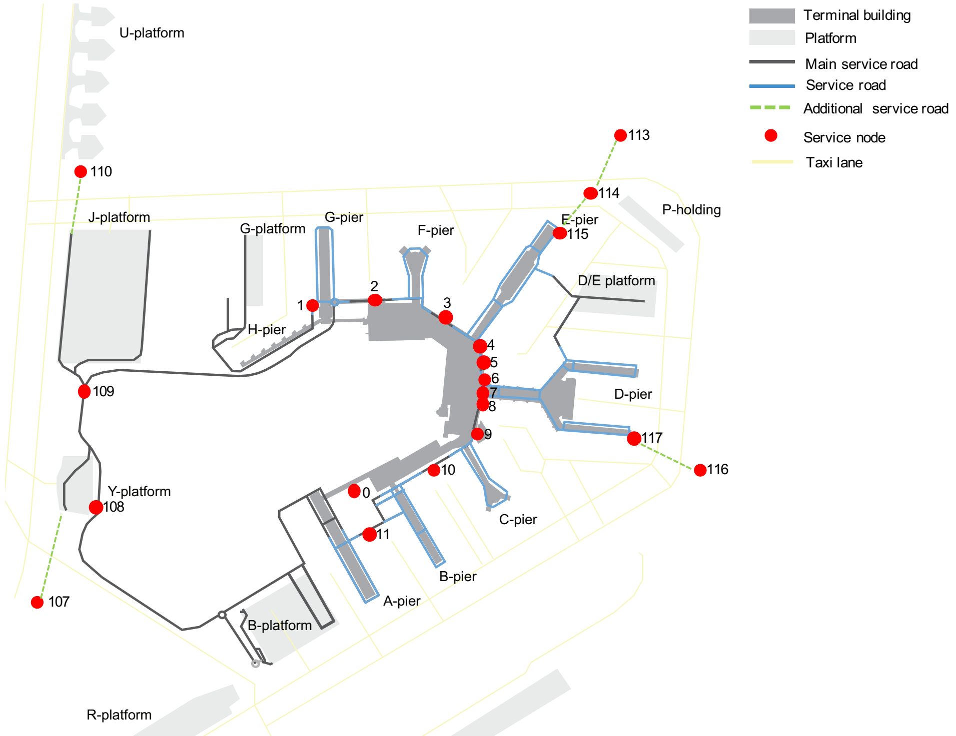


Figure 4.12: Service roads at the terminal area of Amsterdam Schiphol, including the planned A-pier [De Jong, 2016]. Service nodes and additional service roads are also indicated in this figure.

In Table 4.9 for each gate in the OAG-dataset the assigned gate-node is given for AAS. Figure A.1 in Appendix A provides a clear overview of which gate-node corresponds to which apron area at AAS.

Table 4.9: Gates from the OAG-dataset assigned to the gate-node in the network.

NodeID	Gates in OAG-dataset
1	M01,M02,M03,M04,M05,M06,M07,H01,H02,H02,H03,H04,H05,H06, H07,G03,G05,G07,G09,G71,G72,G73,G74,G75,G76,G77,G78,G80,Y71
2	G02,G04,G06,G08,F03,F05,F07,F09
3	F02,F04,F06,F08,E03,E05,E07,E09,E17,E19
4	E02,E04,E06,E08,E18,E20,E22,E24
5	E72,E75,E77
6	D03,D05,D07,D41,D43,D45,D47,D49,D51,D53,D55,D57,D59,D61,D63, D71,D73,D77,D79,D81,D83,D85,D87
7	D21,D23,D25,D27,D29,D31,D44,D46,D48,D50,D52,D54,D56,D72,D74, D76,D78,D82,D84,D86,Z02,Z10,Z07
8	D16,D18,D20,D22,D24,D26,D28
9	D02,D04,D06,D08,D10,D12,D14,C05,C07,C09,C11,C13,D60,D62,D64,D66, D68,C15
10	C04,C06,C08,C10,C12,C14,C16,C18,B13,B15,B17,B23,B27,B31,B35,C21, C22,C23,C24,C25,C26
11	K73,K38,P14,P16,A04,A08,B14,B16,B18,B20,B22,B24,B26,B28,B30,B32,B34, B36,B01,B02,B03,B04,B05,B06,B07,B08

4.6.2. Processed data of AAS

Network & flight schedule

The Processed data explained in Section 4.2 results in network data and flight schedules that form the input to the model. The processed network data can be found in Tables A.3 and A.4 of Appendix A. Processed flight schedules for different time intervals of May 2nd are presented in Appendix B as example for the input.

Network representation of the case study

The data of the taxi-lanes of AAS is used to model the taxiing network of AAS. For the service roads at AAS, nodes have been added. Nodes can also be added in order to divide an edge into two smaller edges. This can be used to get a more detailed network, but it will make the network larger.

Processing all the network data for the aircraft taxiways and service nodes results in the node-edge network of Figure 4.13. In this network, the yellow lines represent the edges aircraft can travel and the green lines are the service roads [8]. As it can be seen in Figure 4.13 not all runways are modeled. These runways are responsible for the majority of the air traffic at AAS, as discussed in Section 4.6.2. In Figure A.2 in Appendix A, the driving direction on the edge and the node numbers are presented for AAS.

Figure 4.13: The aircraft taxiing network (indicated with the yellow lines) and the service roads (indicated with the dotted green lines). The distances between the nodes are the real taxiing distances obtained from Roling [2009]

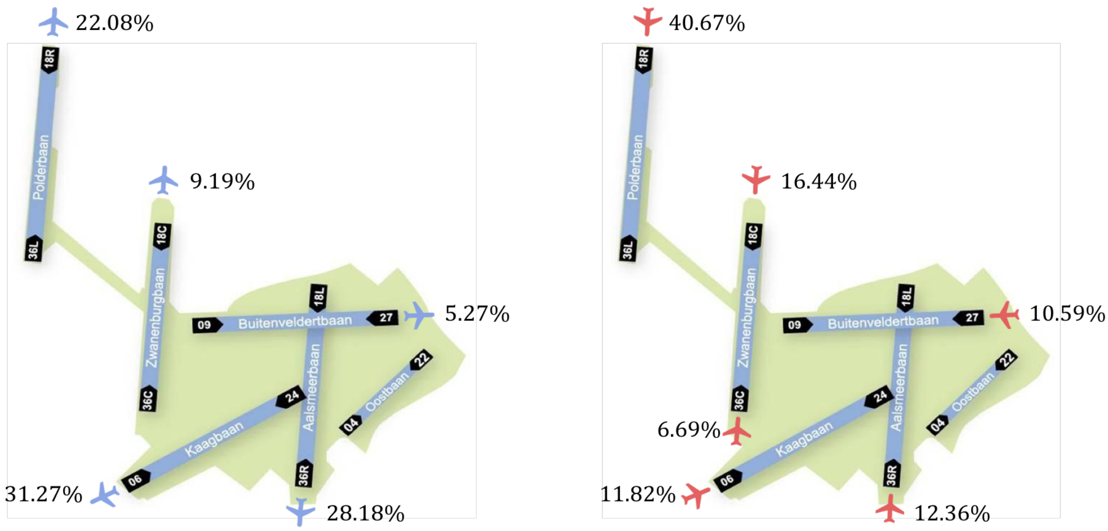
Reduced network due to runway usage at AAS

The used runway configuration at AAS depends highly on the weather and the noise of the aircraft for the surrounding area. Therefore some runways are used more than others. Figures 4.14a and 4.14b show the percentage of departures and arrivals at AAS in 2017. Here it can be found that 59.45% of the departures in 2017 took place from runway 24 and 18*L*. 95.98.% of the departures took place from runway 24, 18*L*, 36*L*, 09 and 36*C*. Runway 18*R* is used for 40.67% of the arrivals. Runway 18*L*, 36*C*, 18*C*, 06, 27 and 36*R* are responsible for 98.56% of the total commercial arrivals in 2017. The usage of all runways can be found in Table A.1 of Appendix A.

Since these runways cover almost all the departures and arrivals, other runways have been taken out of the network to reduce the size of the model.

As it can be found in Table 4.8, the time runways are active varies during the day. Depending on the active runways, some parts of the network of Figure 4.13 can not be used. If runway 36C (Zwanenburgbaan) is active

[8] `https://maps.google.nl`: accessed on September 11th, 2017.



(a) Departures

(b) Arrivals

Figure 4.14: Runway usage at AAS in 2017. For the main runways used in 2017, the percentage of total arrivals/departures is indicated (>5% of the total arrivals or departures).Baa [2017]

for arrivals, no runway crossings at this runway are possible and no aircraft are allowed to travel under the flight path.

Taxiing speeds at AAS

Based on the network data, Figure 4.15 shows the maximum speed-map of AAS. This speed-map shows the maximum taxiing speeds for NB aircraft at AAS during normal operations. For NB aircraft the maximum taxiing speed at AAS is 14 m/s. However due to the restriction of the speed zones, in most parts of the network the maximum allowed speed is lower [Roling et al., 2015]. In areas where the maximum allowed speed is higher than the maximum speed of the AGV or aircraft, the lower bound will be used as explained in Section 4.2.4 (detailed maximum taxi speeds at AAS can be found in Tables A.3 and A.4 of Appendix A.)

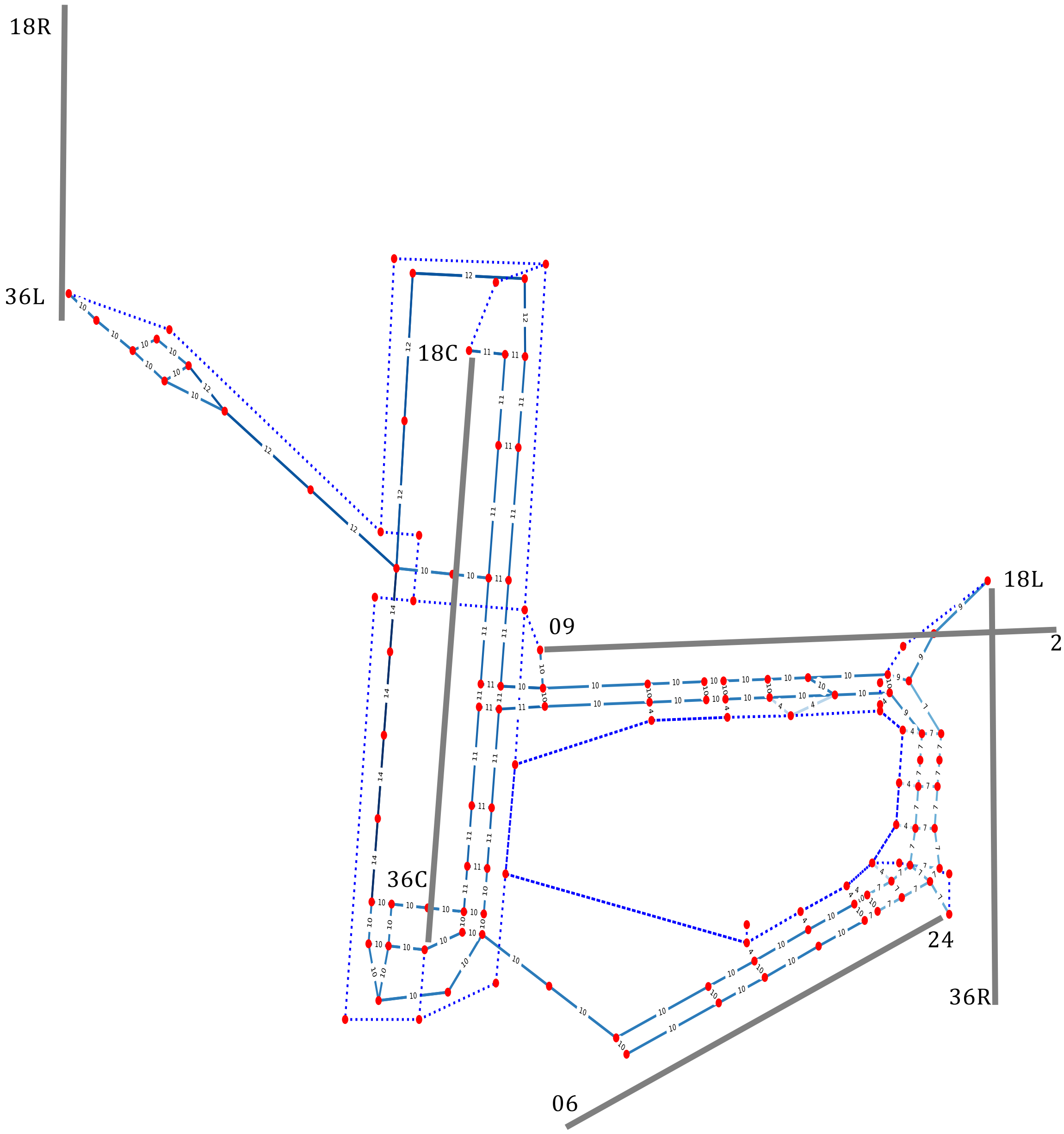


Figure 4.15: Speed restrictions in m/s at the aircraft taxi-lanes of AAS. If the maximum speed of the AGV or aircraft is lower, the lower value is used. Detailed speed and direction information about each node and edge can be found in Tables A.3 and A.4 of Appendix A. The dotted lines are the service roads.

5 Results

In this chapter the results of the model are discussed. First in Section 5.1 the output that the model generates is explained. In Section 5.2 and 5.3 cases for May 15th and May 2nd 2013 have been tested for AAS, which is used as airport for this case study. The amount of cases that can be tested is infinite, however these two days give a realistic representation of the majority of the days at AAS. Different scenarios are tested for these days to analyze the performance of the optimization study. To visualize the output of the model, snapshots and time-space graphs are presented in this chapter. In Section 5.4 the full day analysis for May 2nd and 15th can be found, followed by model performance in Section 5.5. Section 5.6 concludes this chapter.

5.1. Model output

In order to present the results generated by the model a test case is used with the flight-schedule of Table 5.1. This flight schedule is for the departures between 15:50 and 16:00 for May 15th. Furthermore one NB AGV is used for this example.

Table 5.1: Processed flight schedule dataset sample of May 15th 2013, for departures between 15:50-16:00, and arrivals between 15:26 and 16:02

ID	StartTime (block)	StartTime (Scheduled)	Runway	Gate node	Kind	Aircraft type	IATA aircraft code	APU fuel flow [kg/s]	Engine fuel flow 7% [kg/s]	Number of engines	MTOW [kg]
1025	5/15/13 15:26	5/15/13 15:25	99	10	ARR	NB	738	0.0321	0.1106	2	78220
1026	5/15/13 15:26	5/15/13 15:35	99	8	ARR	NB	E70	0.0188	0.05	2	34000
1027	5/15/13 15:32	5/15/13 15:40	99	6	ARR	NB	73H	0.0321	0.1106	2	78220
1028	5/15/13 15:33	5/15/13 15:45	99	9	ARR	NB	73W	0.0321	0.1106	2	69400
1029	5/15/13 15:34	5/15/13 15:15	99	10	ARR	NB	738	0.0321	0.1106	2	78220
1030	5/15/13 15:34	5/15/13 15:40	99	6	ARR	NB	73H	0.0321	0.1106	2	78220
1031	5/15/13 15:42	5/15/13 15:50	99	10	ARR	NB	320	0.0278	0.117	2	73500
1032	5/15/13 15:45	5/15/13 15:05	99	10	ARR	NB	321	0.0278	0.1272	2	89000
1033	5/15/13 15:50	5/15/13 15:45	99	10	ARR	NB	320	0.0278	0.117	2	73500
443	5/15/13 15:51	5/15/13 15:45	94	9	DEP	NB	73H	0.0321	0.1106	2	78220
444	5/15/13 15:51	5/15/13 15:05	94	11	DEP	NB	CR9	0.0231	0.0489	2	38330
445	5/15/13 15:52	5/15/13 15:50	94	4	DEP	WB	77W	0.0675	0.3	2	299370
446	5/15/13 15:55	5/15/13 16:00	94	1	DEP	NB	319	0.0278	0.1164	2	64000
1034	5/15/13 15:55	5/15/13 15:55	99	10	ARR	NB	738	0.0321	0.1106	2	78220
447	5/15/13 15:58	5/15/13 16:00	94	11	DEP	NB	E90	0.0188	0.05	2	47790
448	5/15/13 15:59	5/15/13 16:00	94	9	DEP	NB	73W	0.0321	0.1106	2	69400
1035	5/15/13 15:59	5/15/13 16:20	97	9	ARR	NB	AR8	0.0231	0.0453	4	42184
1036	5/15/13 15:59	5/15/13 15:55	99	10	ARR	NB	321	0.0278	0.1272	2	89000
1037	5/15/13 16:02	5/15/13 16:10	97	9	ARR	NB	73H	0.0321	0.1106	2	78220

The vehicle starts from node zero indicated in Figure 4.12. Single-engine taxiing is considered for both arrivals and departures. Single-engine taxiing is used, since it gives conservative results in terms of potential fuel and cost savings by the use of AGVs for aircraft taxiing. It requires less jet fuel than dual-engine taxiing operations. Using one NB vehicle and the flight-schedule of Table 5.1, the model optimizes the routing and scheduling of the taxiing operations. Since the AGVs will be used for the outbound traffic, the discussed results are for departure aircraft. However the inbound traffic will be shown as well, since the model provides a conflict free solution that takes into account the inbound traffic.
The model creates four different outputs:

1. **General taxi-out information:** The total cost of taxiing, time, delay cost, jet-fuel and diesel usage of the taxiing operations are given.

2. **Time-space graph:** The model will present the obtained optimized routing and scheduling in a time-space graph. Here it can be found how each aircraft and vehicle is traveling over the network. The taxi-in aircraft are also presented to show the conflict free solution.

3. **Time-space table:** By presenting the obtained routing and scheduling in a table, the position of each aircraft and vehicle at a point in time is presented in detail.

4. **Snapshot:** To show how the vehicles and aircraft travel over the surface of AAS, snapshots are created to show their position at a certain time on the taxiing network of AAS.

General taxi-out results

Table 5.2 shows the general taxi-out results. These are the main parameters (total taxi time, total cost, jet-fuel used, diesel used and the cost of delay) obtained from the output of the model. The total taxiing time is the total taxi-out time after taxi clearance till the aircraft arrives at its assigned runway node (as described in Section 4.3.1), which is given in timesteps. Each timestep is equal to 10 seconds. The total cost is the result of minimizing the objective function of Section 4.5.3 and the jet-fuel is the total used jet-fuel by the APU and the main engines for all taxi-out aircraft. The used diesel is the amount of diesel used by the vehicle to tow the aircraft. The value is low due to the fact that the diesel usage in the apron area is not included, since this is assumed to be the same for taxiing with and without AGV as described in Section 4.5.2. Also in case of using runway 24 (Kaagbaan), the taxiing distances are relatively short. The cost of delay in Table 5.2 is equal to zero, which means no extra delay occurs using the model.
The general taxi-out results can be used to compare the overall results of taxiing in different scenarios. e.g. taxi operations with AGVs and taxi operations without AGVs. The scenario gives the amount and type of vehicles available for the model to use.

Table 5.2: General taxi-out results.

Scenario	Taxi time [timestep]	Cost [EUR]	Jet-fuel [kg]	Diesel [kg]	Delay cost [EUR]
1 NB	138	354.41	488.17	1.80	0.00

Time-space graph

To show the position at each time interval of the vehicle and aircraft in the network, a time-space graph is created. Figure 5.1 shows the time-space graph of the example flight schedule with one NB AGV. This graph is plotted in time interval 5630 - 5785 (in time-steps), which corresponds to time interval 15H:38M:20S - 16H:04M:10S). This time interval gives a good presentation of the vehicle starting at node zero till it finishes its operations at runway node 94.
The red lines in Figure 5.1 present the inbound aircraft. In this scenario the inbound traffic starts taxiing from runway 36L (Polderbaan) and 36C (Zwanenburgbaan) to the assigned gates. The model makes sure that there are no conflicts with the taxi-in aircraft.
The green lines are the outbound aircraft that use their main engines for taxi-out. The aircraft appear in the graph at the time the pushback starts, till the time it can take off from the runway (see Section 4.3.1 for the taxi procedures).
The orange and blue lines are from a vehicle point of view; this means the graph shows where the vehicle is at each timestep. Orange indicates that the vehicle is traveling without aircraft, indicating that the vehicle will use service roads to arrive at the gate of the aircraft to pick the aircraft up. Since the graph shows the position of the vehicle at each timestep, the time it takes for the vehicle to drive to the gate and connect to the aircraft is shown as well.
As it can be seen in Figure 5.1, the vehicle drives from node zero to an aircraft at a gate near node nine. There the vehicle will drive, connect and perform the pushback. The time needed to do this is shown with the horizontal blue line at node nine from time-step 5647 to 5680. Then the vehicle with the aircraft starts traveling to runway node 94 where the vehicle subsequently disconnects. After disconnecting, the vehicle drives back over service roads to node nine to pick another aircraft up.

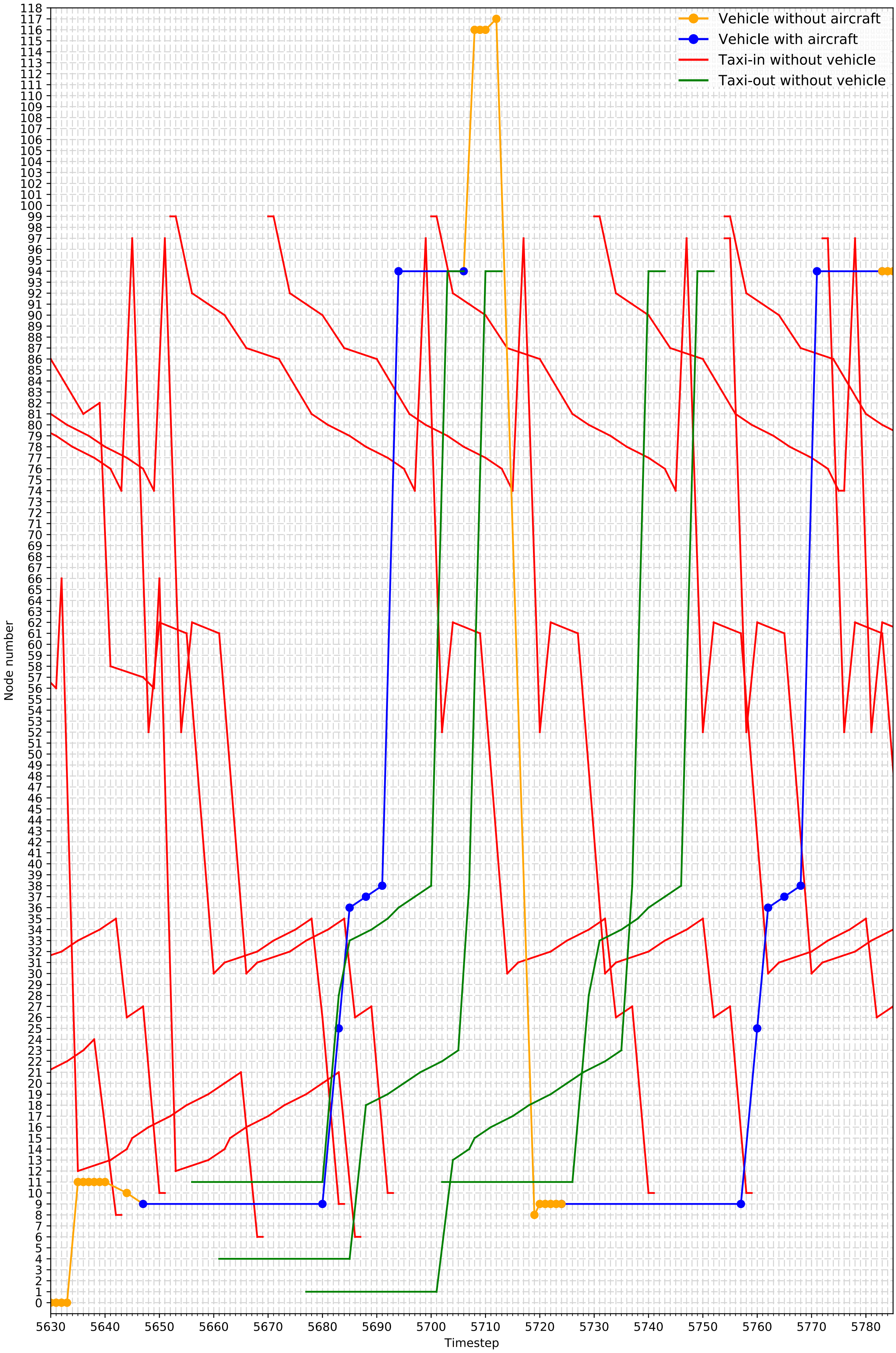


Figure 5.1: Time-space graph of in-bound and out-bound taxiing traffic at the surface of AAS.

Time-space table
To show in more detail which vehicle picks up which aircraft and the related costs and fuel usage, a time-space table is created. Table 5.3 presents the time-space table for the outbound aircraft and the taxiing vehicle. Here for each time interval the position of the vehicle is given. If the aircraft is towed with an AGV, this is indicated, as well as the type of vehicle and aircraft are indicated. In the example, one NB AGV is used (NB 1). In Table 5.3, the aircraft that are towed with this vehicle are indicated with (NB 1), which are in this case aircraft 443 and 448. Other aircraft use their main engines to perform the taxi-out operations.
The model is free to choose aircraft that will be towed with a towing vehicle. Therefore it aims to tow aircraft where most costs can be saved compared to taxiing with main engines. (In this example the towing vehicle is not able to tow aircraft 445 since this is a wide-body aircraft and a NB towing vehicle is used.) In the given timespan, the towing vehicle is able to taxi a maximum of two aircraft to the runway. The model chooses to tow aircraft 443 and 448 to the runway. Although the objective function depends on multiple factors, as described in Chapter 4.5, it looks like in the example the model chooses to tow a Boeing 737 over the Embrear E90. This is due to the fact that in this case the cost savings of towing the 737 are larger is this case compared to the E90.

Snapshot
To visualize the aircraft and vehicles traveling over the surface, snapshots are created. Snapshots are useful to show the behavior of the aircraft and vehicles in the model. It will show the position of aircraft and vehicles at one time-step. From this, it can be seen how the model routes vehicles regarding the other traffic at the taxi lanes.
An example of a snapshot is given in Figure 5.2. Here a snapshot for time-step 5690 is given. In the same way as in Figure 5.1, red indicates the inbound traffic. Blue is the outbound traffic that uses an AGV for taxiing and green are the outbound aircraft that use their main engines for taxiing. If a vehicle is without aircraft at a point in time, this is indicated with orange.

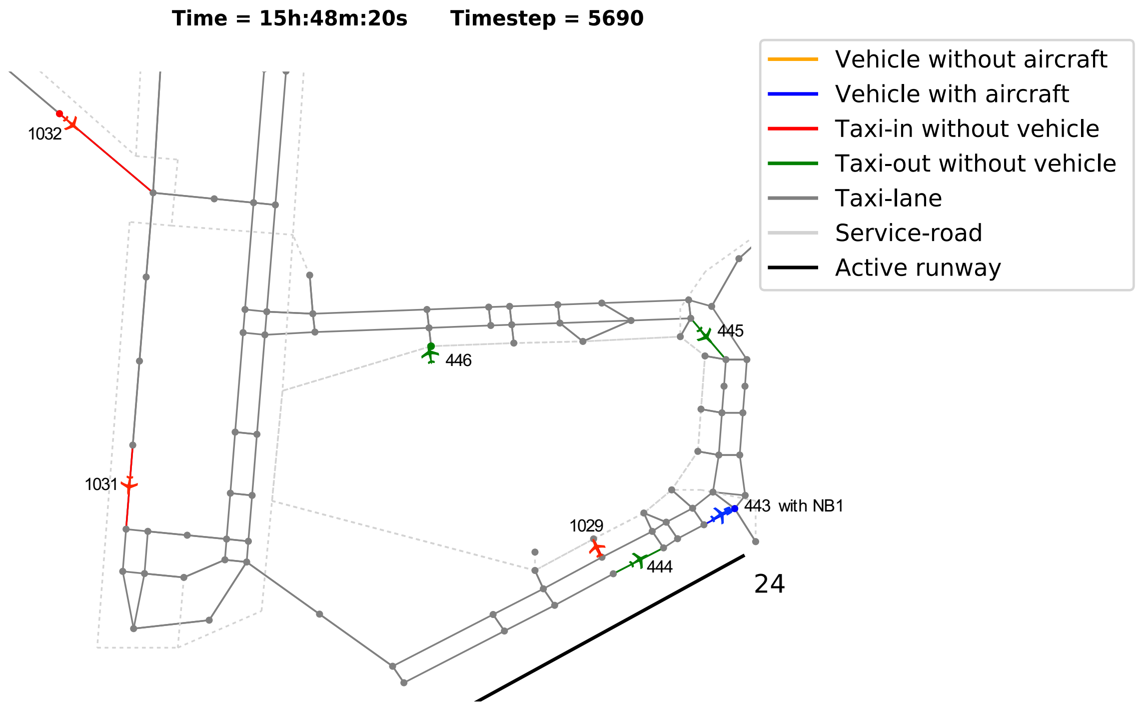


Figure 5.2: Snapshot AAS May 15th 2013 at time-step 5690 (15H:48M:20S). Flights are indicated with their flight ID.

Table 5.3: Time-space table of taxi-out aircraft and vehicles. Flights 443 and 448 are towed by AGV 1, which is a NB towing vehicle (indicated in bold).

Timestep	Vehicle pos	Position flight per aircraft ID						Timestep	Vehicle pos	Position flight per aircraft ID					
	NB 1	443 (NB)	444 (NB)	445 (WB)	446 (NB)	447 (NB)	448 (NB)		NB 1	443 (NB)	444 (NB)	445 (WB)	446 (NB)	447 (NB)	448 (NB)
		NB 1					**NB 1**			**NB 1**					**NB 1**
5630	(0, 0)							5708	(116, 116)			(38, 94)	(15, 16)	(11, 11)	
5631	(0, 0)							5709	(116, 116)			(38, 94)	(15, 16)	(11, 11)	
5632	(0, 0)							5710	(116, 117)			(94, 94)	(15, 16)	(11, 11)	
5633	(0, 11)							5711	(116, 117)			(94, 94)	(16, 17)	(11, 11)	
5634	(0, 11)							5712	(117, 8)			(94, 94)	(16, 17)	(11, 11)	
5635	(11, 11)							5713	(117, 8)				(16, 17)	(11, 11)	
5636	(11, 11)							5714	(117, 8)				(16, 17)	(11, 11)	
5637	(11, 11)							5715	(117, 8)				(17, 18)	(11, 11)	
5638	(11, 11)							5716	(117, 8)				(17, 18)	(11, 11)	
5639	(11, 11)							5717	(117, 8)				(17, 18)	(11, 11)	
5640	(11, 10)							5718	(117, 8)				(18, 19)	(11, 11)	
5641	(11, 10)							5719	(8, 9)				(18, 19)	(11, 11)	
5642	(11, 10)							5720	(9, 9)				(18, 19)	(11, 11)	
5643	(11, 10)							5721	(9, 9)				(18, 19)	(11, 11)	
5644	(10, 9)							5722	(9, 9)				(19, 20)	(11, 11)	
5645	(10, 9)							5723	(9, 9)				(19, 20)	(11, 11)	
5646	(10, 9)							5724	(9, 9)				(19, 20)	(11, 11)	(9, 9)
5647	(9, 9)	(9, 9)						5725	(9, 9)				(20, 21)	(11, 11)	(9, 9)
5648	(9, 9)	(9, 9)						5726	(9, 9)				(20, 21)	(11, 28)	(9, 9)
5649	(9, 9)	(9, 9)						5727	(9, 9)				(20, 21)	(11, 28)	(9, 9)
5650	(9, 9)	(9, 9)						5728	(9, 9)				(21, 22)	(11, 28)	(9, 9)
5651	(9, 9)	(9, 9)						5729	(9, 9)				(21, 22)	(28, 33)	(9, 9)
5652	(9, 9)	(9, 9)						5730	(9, 9)				(21, 22)	(28, 33)	(9, 9)
5653	(9, 9)	(9, 9)						5731	(9, 9)				(21, 22)	(33, 34)	(9, 9)
5654	(9, 9)	(9, 9)						5732	(9, 9)				(22, 23)	(33, 34)	(9, 9)
5655	(9, 9)	(9, 9)						5733	(9, 9)				(22, 23)	(33, 34)	(9, 9)
5656	(9, 9)	(9, 9)	(11, 11)					5734	(9, 9)				(22, 23)	(33, 34)	(9, 9)
5657	(9, 9)	(9, 9)	(11, 11)					5735	(9, 9)				(23, 38)	(34, 35)	(9, 9)
5658	(9, 9)	(9, 9)	(11, 11)					5736	(9, 9)				(23, 38)	(34, 35)	(9, 9)
5659	(9, 9)	(9, 9)	(11, 11)					5737	(9, 9)				(38, 94)	(34, 35)	(9, 9)
5660	(9, 9)	(9, 9)	(11, 11)					5738	(9, 9)				(38, 94)	(35, 36)	(9, 9)
5661	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5739	(9, 9)				(38, 94)	(35, 36)	(9, 9)
5662	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5740	(9, 9)				(94, 94)	(36, 37)	(9, 9)
5663	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5741	(9, 9)				(94, 94)	(36, 37)	(9, 9)
5664	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5742	(9, 9)				(94, 94)	(36, 37)	(9, 9)
5665	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5743	(9, 9)					(37, 38)	(9, 9)
5666	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5744	(9, 9)					(37, 38)	(9, 9)
5667	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5745	(9, 9)					(37, 38)	(9, 9)
5668	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5746	(9, 9)					(38, 94)	(9, 9)
5669	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5747	(9, 9)					(38, 94)	(9, 9)
5670	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5748	(9, 9)					(38, 94)	(9, 9)
5671	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5749	(9, 9)					(94, 94)	(9, 9)
5672	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5750	(9, 9)					(94, 94)	(9, 9)
5673	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5751	(9, 9)					(94, 94)	(9, 9)
5674	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5752	(9, 9)						(9, 9)
5675	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5753	(9, 9)						(9, 9)
5676	(9, 9)	(9, 9)	(11, 11)	(4, 4)				5754	(9, 9)						(9, 9)
5677	(9, 9)	(9, 9)	(11, 11)	(4, 4)	(1, 1)			5755	(9, 9)						(9, 9)
5678	(9, 9)	(9, 9)	(11, 11)	(4, 4)	(1, 1)			5756	(9, 9)						(9, 9)
5679	(9, 9)	(9, 9)	(11, 11)	(4, 4)	(1, 1)			5757	(9, 25)						(9, 25)
5680	(9, 25)	(9, 25)	(11, 28)	(4, 4)	(1, 1)			5758	(9, 25)						(9, 25)
5681	(9, 25)	(9, 25)	(11, 28)	(4, 4)	(1, 1)			5759	(9, 25)						(9, 25)
5682	(9, 25)	(9, 25)	(11, 28)	(4, 4)	(1, 1)			5760	(25, 36)						(25, 36)
5683	(25, 36)	(25, 36)	(28, 33)	(4, 4)	(1, 1)			5761	(25, 36)						(25, 36)
5684	(25, 36)	(25, 36)	(28, 33)	(4, 4)	(1, 1)			5762	(36, 37)						(36, 37)
5685	(36, 37)	(36, 37)	(33, 34)	(4, 18)	(1, 1)			5763	(36, 37)						(36, 37)
5686	(36, 37)	(36, 37)	(33, 34)	(4, 18)	(1, 1)			5764	(36, 37)						(36, 37)
5687	(36, 37)	(36, 37)	(33, 34)	(4, 18)	(1, 1)			5765	(37, 38)						(37, 38)
5688	(37, 38)	(37, 38)	(33, 34)	(18, 19)	(1, 1)			5766	(37, 38)						(37, 38)
5689	(37, 38)	(37, 38)	(34, 35)	(18, 19)	(1, 1)			5767	(37, 38)						(37, 38)
5690	(37, 38)	(37, 38)	(34, 35)	(18, 19)	(1, 1)			5768	(38, 94)						(38, 94)
5691	(38, 94)	(38, 94)	(34, 35)	(18, 19)	(1, 1)			5769	(38, 94)						(38, 94)
5692	(38, 94)	(38, 94)	(35, 36)	(19, 20)	(1, 1)			5770	(38, 94)						(38, 94)
5693	(38, 94)	(38, 94)	(35, 36)	(19, 20)	(1, 1)			5771	(94, 94)						(94, 94)
5694	(94, 94)	(94, 94)	(36, 37)	(19, 20)	(1, 1)			5772	(94, 94)						(94, 94)
5695	(94, 94)	(94, 94)	(36, 37)	(20, 21)	(1, 1)			5773	(94, 94)						(94, 94)
5696	(94, 94)	(94, 94)	(36, 37)	(20, 21)	(1, 1)			5774	(94, 94)						(94, 94)
5697	(94, 94)	(94, 94)	(37, 38)	(20, 21)	(1, 1)			5775	(94, 94)						(94, 94)
5698	(94, 94)	(94, 94)	(37, 38)	(21, 22)	(1, 1)			5776	(94, 94)						(94, 94)
5699	(94, 94)	(94, 94)	(37, 38)	(21, 22)	(1, 1)			5777	(94, 94)						(94, 94)
5700	(94, 94)	(94, 94)	(38, 94)	(21, 22)	(1, 1)			5778	(94, 94)						(94, 94)
5701	(94, 94)	(94, 94)	(38, 94)	(21, 22)	(1, 13)			5779	(94, 94)						(94, 94)
5702	(94, 94)	(94, 94)	(38, 94)	(22, 23)	(1, 13)	(11, 11)		5780	(94, 94)						(94, 94)
5703	(94, 94)	(94, 94)	(94, 94)	(22, 23)	(1, 13)	(11, 11)		5781	(94, 94)						(94, 94)
5704	(94, 94)	(94, 94)	(94, 94)	(22, 23)	(13, 14)	(11, 11)		5782	(94, 94)						(94, 94)
5705	(94, 94)	(94, 94)	(94, 94)	(23, 38)	(13, 14)	(11, 11)		5783	(94, 94)						
5706	(94, 116)			(23, 38)	(13, 14)	(11, 11)		5784	(94, 94)						
5707	(94, 116)			(38, 94)	(14, 15)	(11, 11)		5785	(94, 94)						

5.2. Time interval results of May 15th 2013

In this section the results for different time intervals for May 15th are presented. The full day analysis of this day can be found in Section 5.4. This date is chosen since the runway configuration used at this day is responsible for most of the departures and arrivals during the year (preferred runway configuration). The active runways of AAS during this day are presented in Table 4.8.

Figure 5.3 shows the departures at AAS during the day. As it can be seen in this figure, the amount of departures varies considerably during the day. At the departure peaks, the traffic on the taxi-lanes due to out-bound traffic will be the highest. The routing and scheduling of the vehicles at these peaks will be the most complex, due to the high amount of flights. These peaks are therefore good to test the model for using AGVs at AAS. Between 07:15 and 08:45, a departure peak at AAS was found. The amount of departures in this departure peak is one of the highest during the day as can be seen in figure 5.3 and is therefore used as test case.

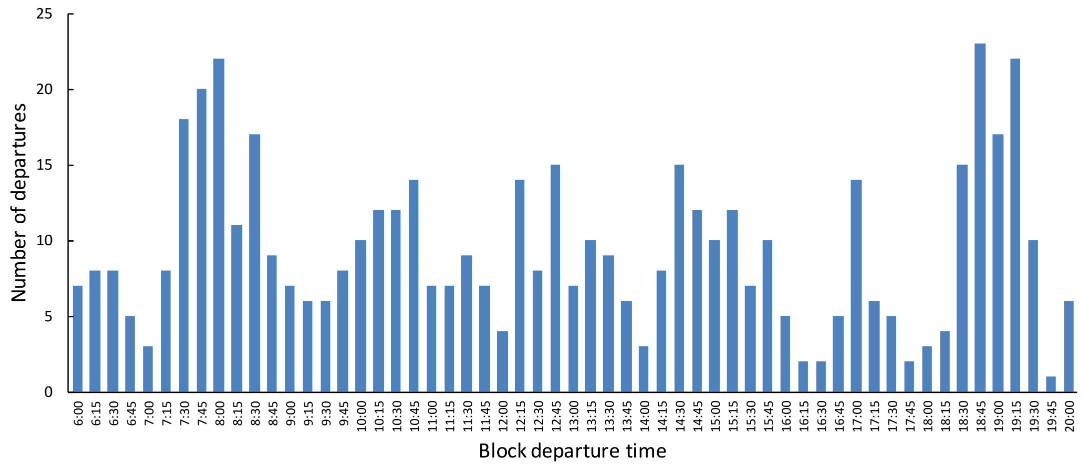


Figure 5.3: Departures at AAS on May 15th 2013 per 15 minutes (time in GMT).

Figure 5.4 shows the narrow body (NB) and wide body (WB) departures during the day. As it can be seen in this figure, the ratio of WB aircraft with NB aircraft differs during the day. On May 15th, most WB aircraft depart between 08:00 and 13:00, due to the fact that these aircraft are mostly used for intercontinental flights. The amount of WB vehicles needed to save the maximum amount of costs, depends highly on the time of the day. For NB aircraft, departure peaks all over the day can be found.

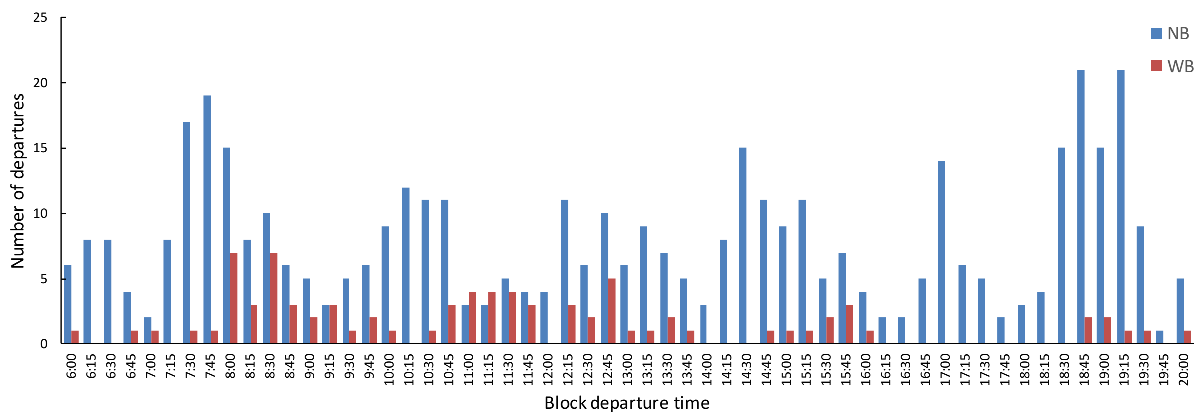


Figure 5.4: Departures at AAS on May 15th 2013 per 15 minutes divided in NB and WB aircraft (time in GMT).

As shown in Figure 5.4, the departure peak for WB aircraft is different from NB aircraft. The departure peak of 07:15-08:45 is tested for different sets of vehicles, where 07:15-08:15 is considered to be the departure peak for NB aircraft and between 07:45-08:45 is considered to be the departure peak for WB aircraft. As it can be seen in Figure 5.4, the ratio of WB to NB aircraft in this peak varies highly. Between 07:15 and 08:00 this ratio is 3/50, while tis ratio is 17/27 between 08:00 and 08:45. Table B.2 and B.3 in Appendix B show the full processed flight-schedule between 07:15-08:45. The active runway time can be found in Table B.1.
The effect of using AGVs has been tested for WB and NB departure peak separately, to obtain the maximum cost savings that can be achieved using a set of vehicles of one type.

5.2.1. NB peak 07:15-08:15

Since the amount of NB aircraft per minute that depart is one of the highest in time interval 07:15-08:15 during the day, this time interval is analyzed to show the full potential of using NB AGVs. In this time interval 61 NB departures were found. The general results are summarized in Table 5.4, where scenario 0 vehicles (0 veh.) is the case where no AGVs are used (the base scenario).

Table 5.4: General taxi-out results for NB peak 07:15-08:15 May 15th.

Scenario	Taxi time [timestep]	Cost [EUR]	Jet-fuel [kg]	Diesel [kg]	Delay cost [EUR]
0 veh.	2284	5441.75	7497.90	0.00	474.65
1 NB	2272	5325.97	7367.86	6.20	404.14
2 NB	2268	5240.59	7240.64	11.63	364.17
3 NB	2268	5195.48	7102.37	18.95	364.17
4 NB	2268	5153.18	6967.72	27.72	364.17

In Table 5.4, it is shown that the use of AGVs results in a decrease of the taxiing costs. This is mainly due to the reduction of the use of the main engines of the aircraft. However looking at the cost of delay between the scenario with 1 NB and 0 veh., a reduction of about 70 EUR when 1 NB AGV is used can be found. This means that in case of using AGVs for aircraft taxiing, one or more aircraft arrive earlier at the runway compared to when no AGV is used. Due to the fact that at some parts of the network AGVs with aircraft have a lower taxi speed compared to taxiing with the main engines, it is expected that more delay will occur by using AGVs.

Looking in more detail to the data output of the model it was found that a large part of the cost savings was due to the change in delay cost of flight 127. Flight 127 starts taxiing at node 11 and has to be delivered at node 94 (runway 24). Both in the scenario without AGV and with one AGV flight 127 uses the same path to travel from the gate to the runway: $\{11-28-33-34-35-36-37-38-94\}$ (nodes numbers are presented in Figure A.2 of Appendix A). On this path, the speed of taxiing is the same for NB aircraft with AGV and without AGV.

In the scenario without AGV, flight 127 is ready to take-off at time-step 2839. Figure 5.5 shows the case for taxiing without AGV. As it can be seen, flight 127 waits until flights 136, 125, 126 and 757 have passed by, before it travels to the runway.
In the scenario with 1 NB AGV, flight is 127 towed by the AGV to the runway and is ready to take-off at time-step 2825. The fact that flight 127 arrives earlier at the runway when it is traveling with AGV is due to the different taxi procedure as explained in Section 4.3.1. When taxiing with the AGV, the disconnecting time from the push-back vehicle does not take place at the apron, but the aircraft will be disconnected from the AGV near the runway. Because of this shift in the procedure, flight 127 can start earlier taxiing over the taxi-lanes. In this specific case, the shift in operations moves flight 127 preventing conflicts with other aircraft. When flight 127 starts its taxiing operations earlier, it can taxi in front of departing aircraft 136, 125 & 126 and arriving aircraft 757. Figure 5.6 shows this for the case of taxiing with AGV where disconnecting takes place at the runway.

Also in the scenario where 2 NB AGVs are available some delay cost can be saved due to another sequence compared to when no AGVs are used. However the main cost savings are due to the reduction of the main engines use. With 3 NB vehicles or more, no extra delay savings are obtained by scheduling the aircraft in a different way.
This specific case shows how the model deals with the effect of the different taxiing procedure and shows how the model can use this to obtain the best result. Due to the different procedures, the optimal sequence of taxiing over the network is depends on whether AGVs are used or the main engines are used.
As shown in Table 5.4 a significant amount of jet-fuel can be saved compared to the base scenario without AGVs. In the scenario where 3 NB AGVs are used, the total amount of saved jet-fuel is almost 400 kg. Using Table 5.5, the amount of emissions saved can be calculated, taking into account the diesel consumption of the AGVs. Although the emissions are specific for each aircraft engine, as indicated in the ICAO emission database, an estimation of the emission savings can be done using the values of Table 5.5. Here the average emission values for taxiing aircraft are used [Selderbeek et al., 2013].

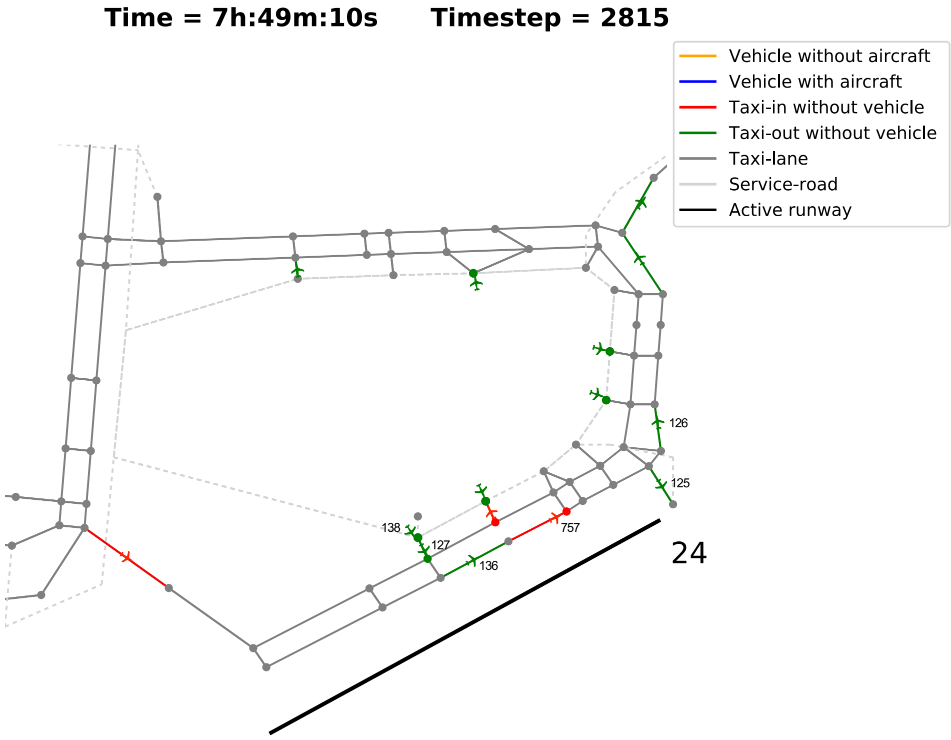


Figure 5.5: Snapshot scenario without AGV. At AAS on May 15th 2013 at time-step 2815 (07H:49M:20S). Flight 127 just started taxiing and is still near the apron area.

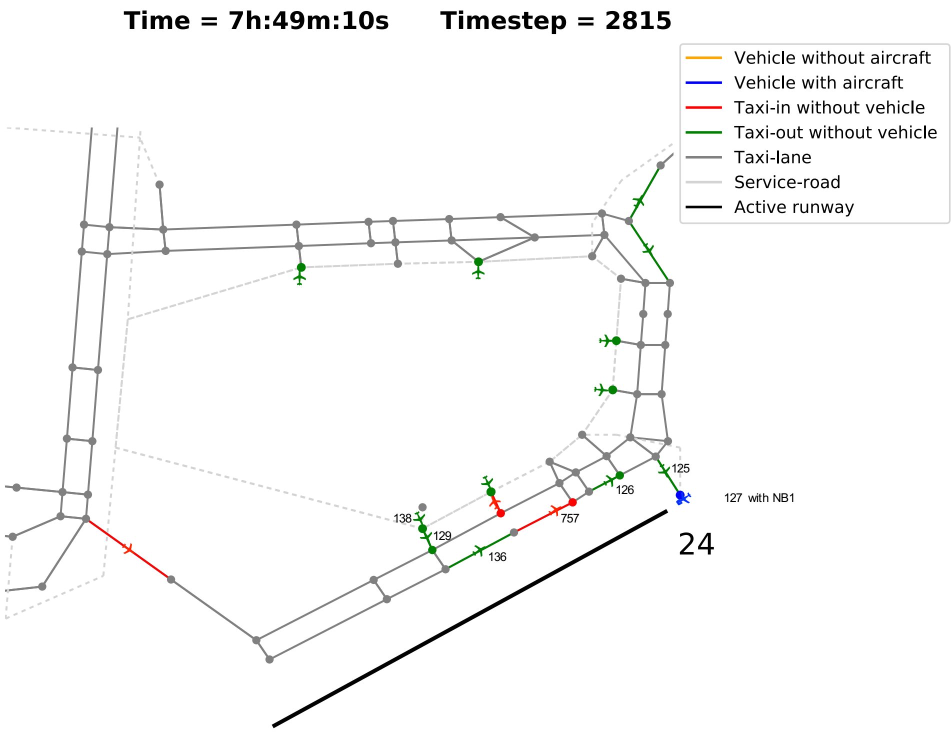


Figure 5.6: Snapshot scenario with 1 NB AGV. At AAS on May 15th 2013 at time-step 2815 (07H:49M:20S). Flight 127 avoids congestion by using an AGV and is disconnected near the runway.

Table 5.5: Emission in $gram/kg$ of the fuel used [Albee et al., 1995, Khammash and Mantecchini, 2017, Selderbeek et al., 2013].

Emission	Jet-fuel	Diesel
CO2	3390.00	3178.57
HC	2.59	6.19
CO	23.25	20.62
NOx	4.69	56.72

Using the values of Table 5.5 on the tested scenarios, the results in the emission savings of Table 5.6 are obtained. The savings in terms of CO2 are worth mentioning. A single vehicle can save more than 400 kg of CO2 per hour. Since the emission per kg of NOx is significantly higher for a diesel powered engine, even if the fuel savings are large, the NOx reduction is minimal.

Table 5.6: Emission savings for NB peak 07:15-08:15 May 15th compared to the scenario without AGVs.

Scenario	Jet-fuel saved [kg]	Diesel used [kg]	CO2 reduction [kg]	HC reduction [kg]	CO reduction [kg]	Nox reduction [kg]
1 NB	130.05	6.20	421.16	0.30	2.90	0.26
2 NB	257.26	11.63	835.17	0.59	5.74	0.55
3 NB	395.53	18.95	1280.63	0.91	8.81	0.78
4 NB	530.18	27.72	1709.23	1.20	11.76	0.91

Since different amount of vehicles are tested on the same departure peak, the effect per vehicle can be analyzed and compared to the different scenarios. Table 5.7 shows the marginal cost savings per vehicle. As it can be seen in the table, the cost savings per vehicle decreases when more vehicles are used. This is due to the fact that the model optimizes the use of the vehicles. It will use the vehicles for flights where the most cost savings can be obtained. In case 1 vehicle is used, this vehicle will choose to pick the aircraft with the most cost savings. When 2 vehicles are used, the model also chooses flights that give smaller cost savings. Therefore the cost savings per vehicle decreases with the amount of vehicles.

Next to the saving per vehicle, the effect of using AGVs can also be seen from the airline perspective. Table 5.7 shows also the cost savings per flight. When 1 vehicle is used, around 29 EUR per towed flight can be saved in this peak. The main reason why these absolute cost savings are small is due to the short taxi distances at this peak and the cost of using the vehicle.

The average taxi cost per flight in the scenario without vehicles is approximately 78 EUR. This includes NB and WB aircraft. Obtaining an average cost saving per towed flights of 29 EUR means that 37% of the average taxi cost can be saved per towed flight.

Table 5.7: Savings per vehicle and flight for NB peak 07:15-08:15 May 15th compared to the scenario without AGVs.

Scenario	Cost [EUR]	Cost savings [EUR]	Cost savings per used vehicle [EUR]	Flights towed per vehicle	Cost savings per towed flight [EUR]
0 veh.	5441.75	-	-	-	-
1 NB	5325.97	115.78	115.78	4	28.94
2 NB	5240.59	201.16	100.58	4	25.15
3 NB	5195.48	246.28	82.09	4	20.52
4 NB	5153.18	288.57	72.14	4	18.04

5.2.2. WB departure peak 07:45-08:45

A similar analysis as for the NB departure peak is done for the WB departure peak. In this case the WB departure peak is from 07:45 to 08:45. Different scenarios have been tested, starting with the scenario where no AGVs are used for taxiing. Table 5.8 shows the general taxi-out results of using WB AGVs in this WB departure peak.

Also for WB aircraft the use of AGVs results in a decrease in the total taxi costs for departures. As shown in Table 5.8, using one WB vehicle could potentially save 369 EUR for one hour of departures. As shown in

Table 5.8: General taxi-out results for WB peak 07:45-08:45 May 15th.

Scenario	Taxi time [timestep]	Cost [EUR]	Jet-fuel [kg]	Diesel [kg]	Delay cost [EUR]
0 veh.	2114	6053.17	8271.41	0.00	878.27
1 WB	2114	5683.84	7823.88	33.94	614.38
2 WB	2121	5653.80	7454.38	60.57	667.08
3 WB	2121	5637.74	7255.99	78.75	638.69
4 WB	2121	5630.46	7027.69	94.86	638.69
5 WB	2121	5630.46	7027.69	94.86	638.69

the table, the delay cost without AGVs is higher than in the scenario with 1 WB AGV. This is mainly due to the difference in delay cost for flight 162. Flight 162 is a Boeing 744 with a delay of already 30 minutes. As discussed in Section 4.2.5, the cost of delay depends on the MTOW and the already obtained delay compared with the scheduled block time of departure. The marginal cost of delay for this aircraft is estimated to be 609 EUR per minute. By using an AGV for this aircraft, the procedure of taxiing is different. In this case the model the different procedure to avoid congestion on the taxi-lanes (similar to flight 127 in the NB peak). Therefore it is able to arrive earlier at the runway and 203 EUR of delay cost can be saved.
This shows the ability of the model to sequence the aircraft and the AGVs in the most optimal way.
With more than one vehicle, the model balances the cost of delay and the cost savings of not using the main engines. In the scenario with 2 WB AGVs, the model chooses to incur a bit of delay cost in order to save more costs by using the AGVs. Where with one AGV flights 136, 154, 170 had no extra delay cost, they had some extra delay cost when 2 WB AGVs were used.
Another example worth mentioning is flight 184. As shown in Table 5.9, this flight arrives 23 time-steps later at the runway in the case it is towed with an AGV in the scenario with 2 WB AGVs. Figures C.1 and C.2 in Appendix C show clearly the differences between using one and two vehicles respectively. As it can be seen in these figures, is that in the scenario with 2 WB AGVs (C.2) flight 184 waits for AGV WB1 to be picked-up. Instead of using its main engines to start taxiing at time-step 3112, as shown in Figure C.1, it will be towed with an AGV and the taxi-out phase starts at time 3126, to minimize the overall cost of taxiing.

Table 5.9: Delivery time flights, where bold indicates a towed flight by an AGV.

Flight/scenario	141	162	177	152	133	172	184
0 veh.	2880	3002	3102	2923	2850	3072	3142
1 WB	**2880**	**3000**	**3111**	2913	2850	3072	3138
2 WB	**2880**	**3000**	**3100**	**2933**	**2850**	**3072**	**3161**

In Table 5.8 it can be seen that at this peak the model uses a maximum of 4 AGVs towing a maximum of 11 flights. Although in this timespan 19 flights depart, the model chooses not to use all AGVs since the fuel cost savings will not overcome the depreciation cost of using an extra vehicle.
As for the fleet of NB AGVs, also here a closer look is taken to the potential environmental benefits. Table 5.10 shows the fuel usage and the potential emission savings. As shown, a significant amount of jet-fuel can be saved. Using four WB vehicles for one hour of departures can reduce for tons of C02 emissions during taxiing.

Table 5.10: Emission savings for WB peak 07:45-08:45 May 15th compared to the scenario without AGVs.

Scenario	Jet-fuel saved [kg]	Diesel used [kg]	CO2 reduction [kg]	HC reduction [kg]	CO reduction [kg]	NOx reduction [kg]
1 WB	447.53	33.94	1409.27	0.95	9.71	0.17
2 WB	817.03	60.57	2577.19	1.74	17.75	0.40
3 WB	1015.43	78.75	3191.99	2.14	21.98	0.30
4 WB	1243.72	94.86	3914.70	2.63	26.96	0.45
5 WB	1243.72	94.86	3914.70	2.63	26.96	0.45

The cost savings per flight and per vehicle can be found in Table 5.11. Using more vehicles results in lower savings per vehicle and per flight. The large savings with using one vehicle is due to the fact that the model was able to reduce the delay of flight 162, as explained earlier in this section. Table 5.11 shows that from a cost perspective the two extra vehicles of the scenario with four AGVs will result only in 5.8% extra cost savings compared to the scenario with two AGVs. From an emission point of view, these extra two vehicles can save 52% more C02 compared to the scenario with two AGVs.

Table 5.11: Savings per vehicle and flight for WB peak 07:45-08:45 May 15th compared to the scenario without AGVs.

Scenario	Cost [EUR]	Cost savings [EUR]	Cost savings per used vehicle [EUR]	Flights towed per vehicle	Cost savings per towed flight [EUR]
0 veh.	6053.17	-	-	-	-
1 WB	5683.84	369.34	369.34	3	123.11
2 WB	5653.80	399.37	199.68	3 to 4	57.05
3 WB	5637.74	415.43	138.48	3	46.16
4 WB	5630.46	422.71	105.68	2 to 4	38.43
5 WB	5630.46	422.71	105.68	2 to 4	38.43

5.2.3. NB & WB departures 10:45-11:45

The input flight schedule for this time interval can be found in Tables B.4 and B.5 in Appendix B. In this time interval WB and NB AGVs will be used independent and simultaneously to show the capability of the model using different types of vehicles at the same time. As shown in 5.12 a fleet of three WB and three NB vehicles will result in the largest cost savings for this time interval. If more than three vehicles of each type would be available, the model would not use them. Therefore the results of scenarios three and four are the same. The same holds for scenarios six and seven.

Table 5.12: General taxi-out results for departures 10:45-11:45 May 15th.

Scenario	Taxi time [timestep]	Cost [EUR]	Jet-fuel [kg]	Diesel [kg]	Delay cost [EUR]
0 veh.	695	3856.35	3818.43	0	1554.98
1 WB	695	2801.14	3548.83	16.97	524.25
2 WB	695	2761.76	3272.02	41.72	524.25
3 WB	695	2737.36	3015.65	59.70	524.25
4 WB	695	2737.36	3015.65	59.70	524.25
3 WB 3 NB	683	2396.40	2735.49	72.65	249.72
3 WB 4 NB	683	2396.40	2735.49	72.65	249.72

Table 5.13 shows the potential emission and fuel savings. Using a set of six vehicles in this time interval can save up to 3440 kg of CO2 emission.

Table 5.13: Emission savings for departures 10:45-11:45 May 15th compared to the scenario without AGVs.

Scenario	Jet-fuel saved [kg]	Diesel used [kg]	CO2 reduction [kg]	HC reduction [kg]	CO reduction [kg]	NOx reduction [kg]
1 WB	269.60	16.97	859.99	0.59	5.92	0.30
2 WB	546.41	41.72	1719.74	1.16	11.84	0.20
3 WB	802.78	59.70	2531.65	1.71	17.43	0.38
4 WB	802.78	59.70	2531.65	1.71	17.43	0.38
3 WB 3 NB	1082.94	72.65	3440.25	2.36	23.68	0.96
3 WB 4 NB	1082.94	72.65	3440.25	2.36	23.68	0.96

Table 5.14 shows that the cost savings are substantial. A fleet of six vehicles could save 38 % of the taxiing cost. However large part of these savings (1305.26 EUR) comes from avoiding delays by using the de-attaching time of the vehicle at the runway.

Table 5.14: Savings per vehicle and flight for departures 10:45-11:45 May 15th compared to the scenario without AGVs.

Scenario	Cost [EUR]	Cost savings [EUR]	Cost savings per used vehicle [EUR]	Flights towed per vehicle	Cost savings per towed flight [EUR]
0 veh.	3856.35	-	-	-	-
1 WB	2801.14	1055.20	1055.20	2	527.60
2 WB	2761.76	1094.59	547.30	2 to 3	218.92
3 WB	2737.36	1118.98	372.99	2 to 3	139.87
4 WB	2737.36	1118.98	372.99	2 to 3	139.87
3 WB 3 NB	2396.40	1459.95	243.33	2 to 4	76.84
3 WB 4 NB	2396.40	1459.95	243.33	2 to 4	76.84

5.3. Time interval results of May 2nd 2013

On May 2nd the departure runways used were runway 36L and 36C (Polderbaan and Zwanenburgbaan respectively). As shown in Figure 4.15, these runways are much further away from the apron area compared to runway 24 and 18L used for departures on May 15th. Where the taxi-distance on May 15th was between one and three kilometers, the taxi distance to runway 36L can be larger than eight kilometers.
May 2nd has been chosen as day to test cases with a long taxi distance/time.

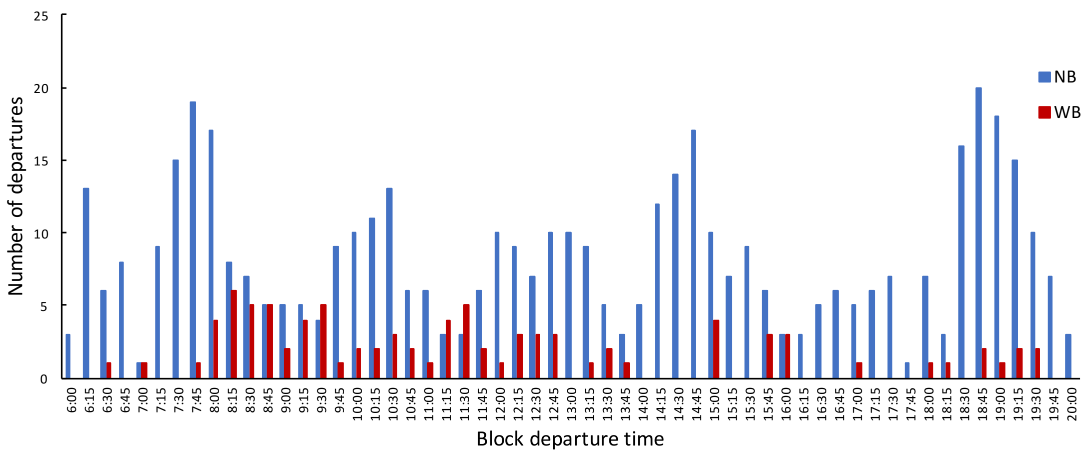


Figure 5.7: Departures at AAS on May 2nd 2013 per 15 minutes divided in NB and WB aircraft (time in GMT).

Figure 5.7 shows the departure peaks for NB and WB aircraft. Also for May 2nd different parts of the day will be tested. Here the most worth noting results are presented. The WB departure peak of 07:45 - 08:45 is described in detail, and subsequently for time interval 10:45 - 11:45, where a mixed fleet of vehicles is used to show the maximum savings in this time interval without the extra cost of delay.

5.3.1. WB departure peak 07:45-08:45

In this WB departure peak, 18 WB aircraft depart from AAS. Different scenarios for the fleet have been tested and the general results are presented in Table 5.15. Using three WB vehicles, 13% of jet fuel on this part of the taxi operations can be saved. Negative delay means that some aircraft arrive earlier than their expected earliest time at the runway, which will give a negative contribution to the objective function. This can be due to the fact that the layout of the network can change during the taxi operations or the aircraft can travel faster avoiding congestion or not using an AGV. It is important to observe the change in delay between the scenario without AGVs and the scenarios with the AGVs.
In the specified time window the model tries to use the vehicles as much as possible. Since runway 36L is located far away from the terminals, especially when runway 36C is active, in most cases the vehicle can not drive twice to runway 36L (runway node 99). e.g. in the scenario with three vehicles, vehicle three drives flight 322 from gate node four to runway node 99. The taxi time takes almost 12 minutes. Including the time for the

Table 5.15: General taxi-out results for WB peak 07:45-08:45 May 2nd.

Scenario	Taxi time [timestep]	Cost [EUR]	Jet-fuel [kg]	Diesel [kg]	Delay cost [EUR]
0 veh.	3872	6456.79	11122.85	0.00	-54.50
1 WB	3873	6266.82	10428.76	62.29	-54.50
2 WB	3875	6176.63	10000.11	107.60	-74.32
3 WB	3897	6135.23	9630.48	151.93	-80.04

Table 5.16: Flight numbers taken to runway 36L or 36C by vehicles 1-3 in the scenario with 3 vehicles.

WB vehicle	1	2	3
Runway 36L	351	298	322
Runway 36C	301	348	360

vehicle to connect, pushback and disconnect, over 19 minutes are required by the vehicle to take the aircraft to the runway. After disconnecting the flight, vehicle two has to drive back to the terminal area to pick-up a new flight. Taking another flight to runway node 99 would delay the aircraft, so the model often prefers to tow a second flight to runway 36C, instead of towing an extra flight to runway node 99 (although the fuel savings to 99 are higher). Table 5.16 shows which flights are towed by which AGV to their assigned runway.
Table 5.17 shows the emission and fuel savings. The NOx emission is higher in the scenario in which AGVs are used. This is because the specific NOx emission of diesel by the vehicle is higher than the NOx produced by the jet engines.

Table 5.17: Emission savings for WB peak 07:45-08:45 May 2nd compared to the scenario without AGVs.

Scenario	Jet-fuel saved [kg]	Diesel used [kg]	CO2 reduction [kg]	HC reduction [kg]	CO reduction [kg]	NOx reduction [kg]
1 WB	694.09	62.29	2154.97	1.41	14.85	-0.28
2 WB	1122.75	107.60	3464.08	2.24	23.88	-0.84
3 WB	1492.38	151.93	4576.24	2.93	31.56	-1.62

Since in these scenarios the difference in delay costs are small, the effect of using vehicles instead of the main engines can be clearly seen in Table 5.18. By using more vehicles the marginal contribution to the cost saving decreases. Also the marginal cost savings per towed flight decreases.
In this time interval a clear demonstration is found how the model finds a free solution with the vehicles and the aircraft as shown in Figure 5.8. Vehicle WB 2 is waiting at its node for flight 666 to cross the edge.

5.3.2. WB & NB departures 10:45-11:45 without extra delay costs

For this time interval fleets scenarios with only WB or NB vehicles are tested, as well as a mix of vehicles. The general results are presented in Table 5.19. From previous results, it has been found that the model is highly dependent on the delay costs of. Therefore often the model uses the vehicles to avoid high delay costs. This analysis shows how the algorithm performs without having the marginal delay costs. In Table 5.19 it is shown that the cost of delay is fixed and is in all cases 340.49 EUR. This is the initial cost of delay in the model which occurs if no AGVs are used.

In this time interval the model will use a maximum of two WB vehicles. When three WB vehicles are available, the model chooses to use only two. Furthermore it can be seen that the more vehicles the model used, the longer the total taxi time is. The total taxi time increases due to the fact that taxiing without aircraft is faster at some parts of the network for NB aircraft (see Section 4.2.4 for different taxiing speeds).
Since there is no marginal cost of delay, the model will not penalize late delivery at the runway. Table 5.20 shows the scheduled and block delivery time, together with the time delivered in the model by the AGV. In case the cost of delay was taken into account, for flights 563, 602, 604 and 608 a delay penalty would be applied. These flight depart later than five minutes from their scheduled take-off time and arrive later than their block departure time in the flight schedule.

Table 5.18: Savings per vehicle and flight for WB peak 07:45-08:45 May 15th compared to the scenario without AGVs.

Scenario	Cost [EUR]	Cost savings [EUR]	Cost savings per used vehicle [EUR]	Flights towed per vehicle	Cost savings per towed flight [EUR]
0 veh.	6456.79	-	-	-	-
1 WB	6266.82	189.97	189.97	2	94.99
2 WB	6176.63	280.16	140.08	2	70.04
3 WB	6135.23	321.56	107.19	2	53.59

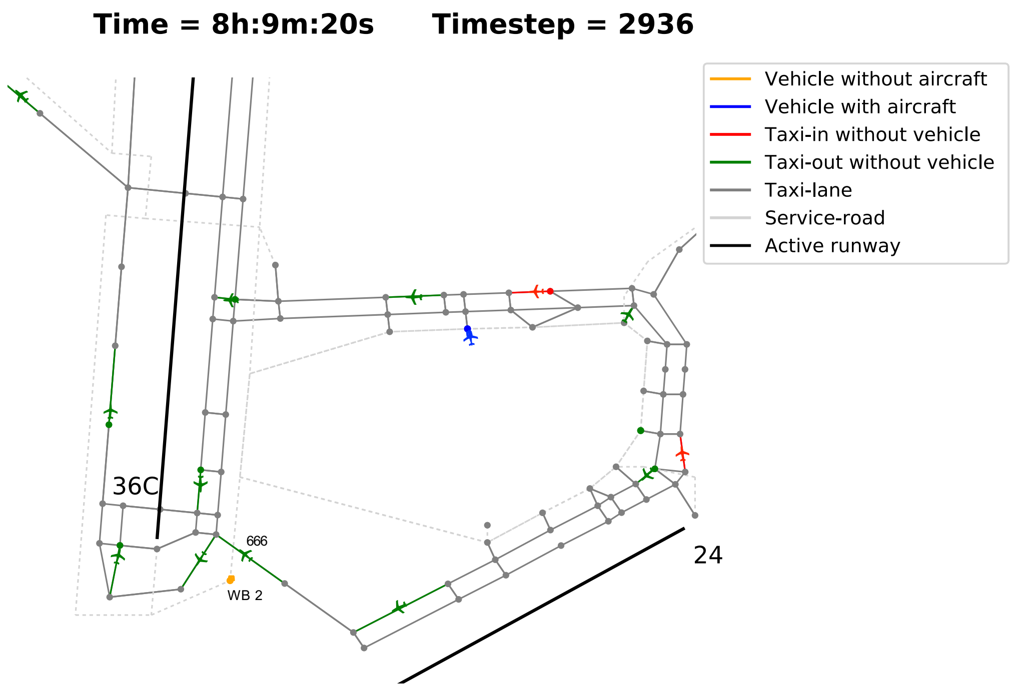


Figure 5.8: Snapshot scenario 4: AAS May 15th 2013 at time-step 2936 (08H:09M:20S).

Table 5.19: General taxi-out results for 10:45-11:45 May 2nd.

Scenario	Taxi time [timestep]	Cost [EUR]	Jet-fuel [kg]	Diesel [kg]	Delay cost [EUR]
0 veh.	1975	3671.50	5859.18	0.00	340.49
1 WB	1974	3551.60	5321.20	49.51	340.49
2 WB	1980	3525.95	5008.13	80.30	340.49
3 WB	1980	3525.95	5008.13	80.30	340.49
1 NB	1993	3606.31	5638.83	15.20	340.49
2 NB	2010	3574.61	5594.14	25.26	340.49
3 NB	2024	3546.84	5311.37	34.53	340.49
2 WB 2NB	2015	3432.02	4625.70	105.19	340.49
2 WB 4NB	2037	3377.27	4309.54	126.27	340.49

Table 5.20: Delivery time of aircraft towed by an AGV. Bold indicates delayed delivery times.

ID	StartTime (block)	StartTime (Scheduled)	Time delivered
528	10:45:00	10:45:00	10:48:10
533	10:49:00	11:00:00	10:51:00
538	10:55:00	10:55:00	10:56:10
555	11:07:00	11:05:00	11:09:10
556	11:07:00	11:05:00	11:07:00
563	11:12:00	11:05:00	**11:14:00**
570	11:18:00	11:20:00	11:18:00
584	11:25:00	11:25:00	11:25:30
585	11:25:00	11:30:00	11:27:40
602	11:35:00	11:20:00	**11:37:50**
604	11:36:00	11:25:00	**11:39:00**
607	11:41:00	11:45:00	11:41:20
608	11:41:00	11:20:00	**11:44:00**

The emission savings and cost savings per vehicle can be found in Tables 5.21 and 5.22 respectively. Due to the fact that the delay cost is fixed, these results present clearly the cost savings obtain from using the main engines a lower amount of time. Table 5.22 shows that the marginal savings per additional vehicle decreases when more vehicles are used. In this time window the maximum savings for one WB vehicle is 119.90 EUR and 65.19 EUR for a NB vehicle.

Table 5.21: Emission savings 10:45-11:45 May 2nd compared to the scenario without AGVs.

Scenario	Jet-fuel saved [kg]	Diesel used [kg]	CO2 reduction [kg]	HC reduction [kg]	CO reduction [kg]	NOx reduction [kg]
1 WB	537.98	49.51	1666.35	1.09	11.49	-0.29
2 WB	851.05	80.30	2629.83	1.71	18.13	-0.56
3 WB	851.05	80.30	2629.83	1.71	18.13	-0.56
1 NB	220.35	15.20	698.68	0.48	4.81	0.17
2 NB	265.04	25.26	818.19	0.53	5.64	-0.19
3 NB	547.81	34.53	1747.33	1.21	12.02	0.61
2 WB 2 NB	1233.48	105.19	3847.15	2.54	26.51	-0.18
2 WB 4 NB	1549.64	126.27	4851.94	3.23	33.42	0.11

5.3.3. Changing runway

Runway 36C is open for departures till 10:50. Before that time no runway crossings are possible, while after this time aircraft and vehicles can cross the runway. To show how the model takes into account the active runways, the path of vehicle NB4 of the scenario with 2 WB and 2 NB AGVs is presented in table C.1 of Appendix C. This vehicle travels in time interval 10:45-11:45 three times to runway 36L with a flight, using three different paths. The path of this vehicle demonstrates how the model takes into account the changing runways.

Figure C.3 in Appendix C visualizes the data of Table C.1. Flights 528, 570 and 608 are successively towed by vehicle NB 4 to runway 36L. Figure C.3a shows the path of the vehicle to tow flight 528 to runway 36L. Since runway 36C is active at this time, it goes around it. Figure C.3b shows how vehicle NB 4 drives from runway 36L to the apron area to pick flight 570 up. The vehicle crosses runway 36C, since it is not active anymore. Also with flight 608 NB 4 uses the runway crossing as demonstrated in Figure C.3c.

5.3.4. Secondary emission savings

Aviation is estimated to be responsible for approximately 2% of the global CO2 emissions. Significant improvement in air transport operations and technological progress have been made in the aviation sector, resulting in less fuel per passenger per kilometer than in the 1960s. However the next decades the total avia-

Table 5.22: Savings per vehicle and flight 10:45-11:45 May 2nd compared to the scenario without AGVs.

Scenario	Cost [EUR]	Cost savings [EUR]	Cost savings per used vehicle [EUR]	Flights towed per vehicle	Cost savings per towed flight [EUR]
0 veh.	3671.50	-	-	-	-
1 WB	3551.60	119.90	119.90	2	59.95
2 WB	3525.95	145.55	72.77	2	36.39
3 WB	3525.95	145.55	48.52	2	36.39
1 NB	3606.31	65.19	65.19	3	21.73
2 NB	3574.61	96.89	48.44	2 to 3	19.38
3 NB	3546.84	124.66	41.55	2 to 3	17.81
2 WB 2 NB	3432.02	239.48	59.87	2 to 3	26.61
2 WB 4 NB	3377.27	294.23	49.04	2 to 3	22.63

tion emissions are forecasted to grow. Especially Technological benefits ans more efficient operations will be insufficient for the sector to grow carbon neutral [ICAO, 2016].
In order to achieve this, ICAO developed a global MBM (Market-based measures) scheme for international aviation. Different scenarios for the cost of carbon offsetting have been analyzed by the ICAO. Table 5.23 gives these cost scenarios for carbon offsetting in the airline industry as presented by ICAO [2016].

Table 5.23: Cost of CO2 offsetting with different price scenarios. [ICAO, 2016]

Carbon price assumption	2020 USD/ton	2030 USD/ton	2035 USD/ton
Low	20	33	40
Base	8	15	20
Additional low	6	10	12

As described by ICAO [2016], the implementation of a global MBM scheme is expected to have a lower impact on international aviation than the one caused by fuel price volatility. Putting the offsetting prices in perspective, the estimated offsetting price for 2030 is equivalent to an increase of 2.6 USD per barrel in the fuel price. In high cost scenario for carbon offsetting, this an extra of 10 USD per barrel in 2030. Compared to the jet fuel price, the standard deviation of jet fuel has been almost 40 USD per barrel. This means that airlines managed to cope with the price volatility of more than 15 times the size of the estimated offsetting cost in 2030 [ICAO, 2016].

In order to show the effect of the carbon offsetting cost on the total savings, Table 5.24 shows the carbon offsetting cost savings for the scenarios of Section 5.3.2. Adding the assumed carbon offsetting costs savings will increase the cost savings of using AGVs for aircraft taxiing. The higher the offsetting costs, the higher the savings by using AGVs. The percentage of cost savings that is due to carbon offsetting savings, varies from 4.33% to 24.42% depending on the scenario. Figure 5.9 shows clearly which part of the cost savings are due to carbon offsetting for the different scenarios in 2020.

Table 5.24: Additional cost savings due to carbon offsetting. Three different scenarios for carbon offsetting costs in 2020 are applied for WB & NB departures 10:45-11:45 with no extra delay.

		Low		Base		High	
Scenario	CO2 reduction [kg]	Offset savings [EUR]	% offset saving of total savings	Offset savings [EUR]	% offset saving of total savings	Offset savings [EUR]	% offset saving of total savings
1 WB	1666	8.94	6.94%	11.92	9.04%	29.79	19.90%
2 WB	2630	14.11	8.84%	18.81	11.44%	47.02	24.42%
3 WB	2630	14.11	8.84%	18.81	11.44%	47.02	24.42%
1 NB	699	3.75	5.44%	5.00	7.12%	12.49	16.08%
2 NB	818	4.39	4.33%	5.85	5.70%	14.63	13.12%
3 NB	1747	9.37	6.99%	12.50	9.11%	31.24	20.04%
2 WB 2NB	3847	20.64	7.93%	27.51	10.31%	68.79	22.31%
2 WB 4NB	4852	26.03	8.13%	34.70	10.55%	86.75	22.77%

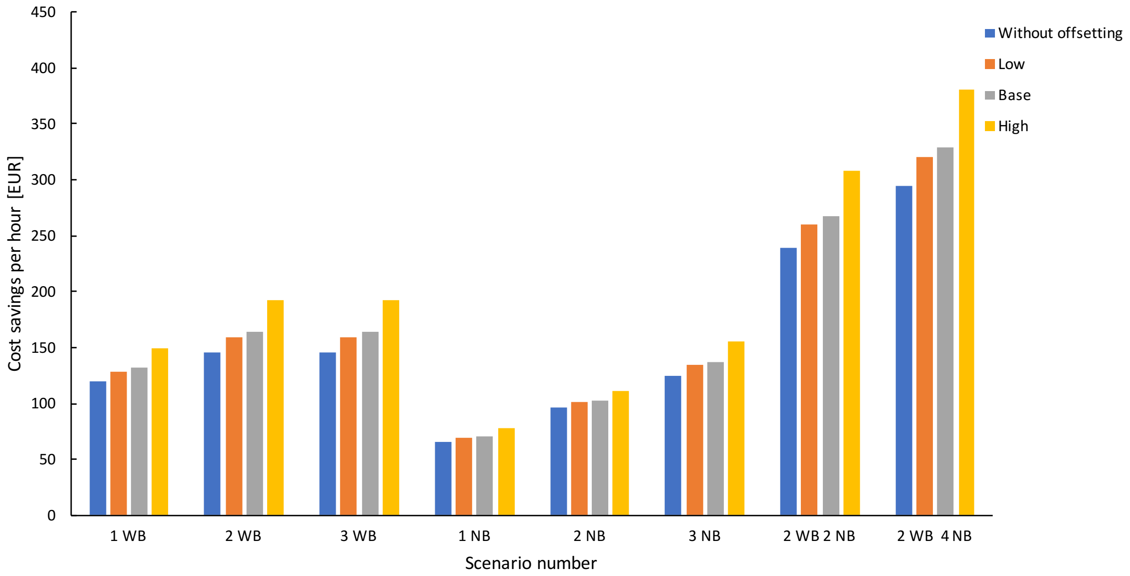


Figure 5.9: Additional cost savings due to carbon offsetting. Three different scenarios for carbon offsetting costs in 2020 are applied for WB & NB departures 10:45-11:45 with no extra delay.

5.4. Full day analysis

To show the effect of using the AGVs on a full day, the potential benefits for the entire day of May 2nd and May 15th are analyzed in this section.

In order to calculate the routing and scheduling for one day, the day is split-up in time windows. The amount of variables for a full day of operations is too large to calculate the optimum by CPLEX in an acceptable amount of time (maximum of a few hours). In a peak hour with two AGVs the amount of variables can already exceed the 2 million. Splitting up the day in time windows will give subproblems with lower complexity compared to the complete problem. The downside of using time windows is that it will provide a sub-optimal solution, compared to solving the problem at once. Furthermore the position of the AGV at the end of a time window and the beginning of the subsequent time window can deviate. The largest difference in cost between the actual position of the AGV at the end of the time window compared to the beginning of the subsequent one was found to be 2.46 EUR AAS. This cost is neglected since for May 15th and May 2nd this means for a typical hour of operation during the day less than 0.1% of the total taxiing cost.

Depending on the amount of departing flights, the length of the time interval is chosen. e.g. between 00:00 and 06:00 on May 15th 58 flights depart from AAS while in one hour, between 07:00 and 08:00, 59 flights depart. Therefore the smallest time window used is one hour (during peaks) and the largest time window used is six hours (during the night).

The depreciation cost for the AGV for a full day is considered. This cost is added to the total cost after solving the time windows for the full day. In this way the depreciation cost is not a decision variable and the model will aims to use the vehicles as much as possible during a time window.

Using this approach at AAS for a full day of operations will provide a realistic insight of the effect using these vehicles. This can be useful for the airport and airline to decide whether to implement such a system.

5.4.1. May 2nd

Table 5.25 shows the effect of using the vehicles on May 2nd. Using one NB AGV, the cost savings found compared to the scenario without AGVs are 3455 EUR. From the cost savings 2904 EUR are due to avoiding delay. The amount of flights where the model can avoid delay costs is limited, therefore when two NB AGVs are used, most of the additional savings are due to not using the main engines of the aircraft. The additional cost savings of using two NB AGVs instead of one NB AGV is 859 EUR. When three NB vehicles are used the total cost savings are slightly lower compared to when two NB are used, due to the depreciation costs of the three vehicles. The used depreciation cost per NB AGV for a full day of operations is 1193 EUR.

Table 5.25: Full day result for May 2nd.

Scenario	Total cost [EUR]	Cost savings [EUR]	Savings delay [EUR]	Jet-fuel [kg]	Diesel [kg]	Flights towed	CO2 reduction [kg]
0 veh.	57594	-	-	92608	0	-	-
1NB	54139	3455	2904	89823	196	39	8819
2NB	53280	4314	3301	87442	395	76	16258
3NB	53291	4303	3421	85611	606	107	21793
1WB	56217	1377	408	85407	597	22	22514
2WB	56688	906	350	81944	918	40	33233

From Table 5.25 it can be found that in all scenarios a significant amount of jet-fuel can be saved (up to 12 % using two WB vehicles). Using the carbon offsetting cost of the base scenario of Section 5.3.4, Figure 5.10 shows the total cost savings for the scenarios with and without carbon offsetting. As shown in Figure 5.10 even when the carbon offsetting costs are included, the cost savings of using one WB AGV are higher compared to when two WB AGVs are used. This is due to the depreciation cost of the WB vehicle of 1911 EUR and the relative low utilization rate of the vehicles during the day (13 minutes per hour on average when two WB AGVs are used). An AGV is considered as utilized when it starts connecting to the aircraft, till it disconnects from the aircraft near the runway.
The main reason for this is due to the fact there are less WB departures compared to NB departures and because they not even distributed over the day as shown in Figure 5.7.

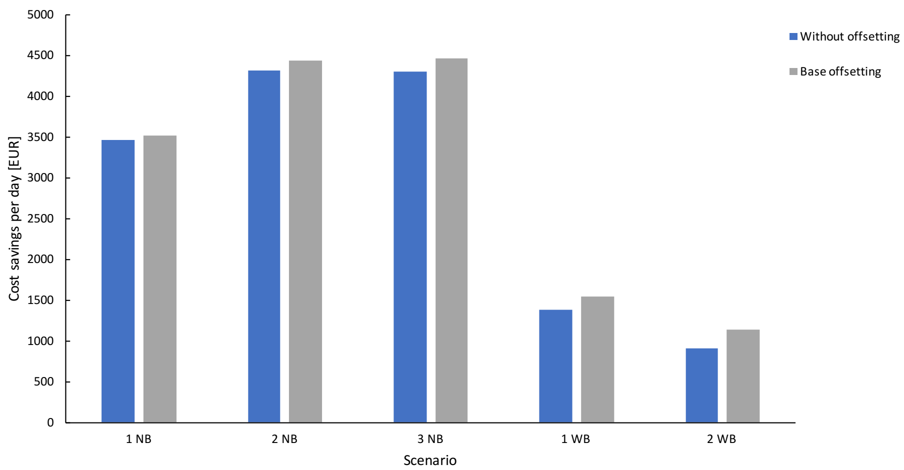
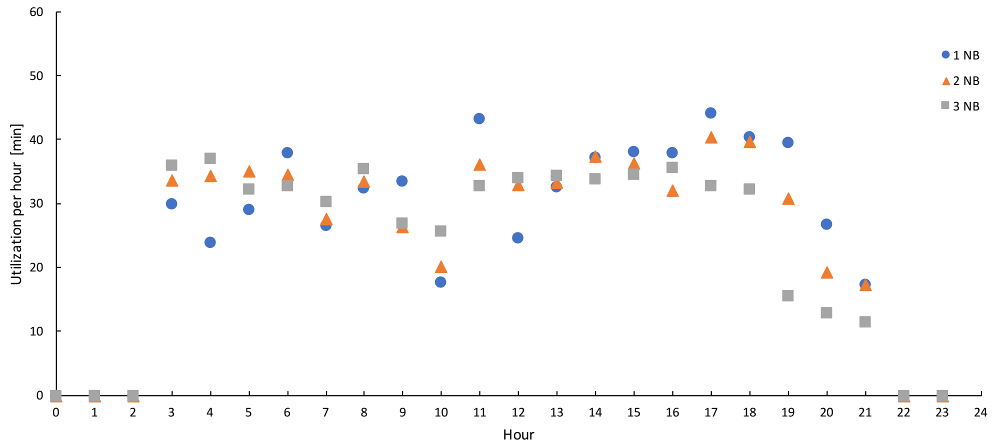


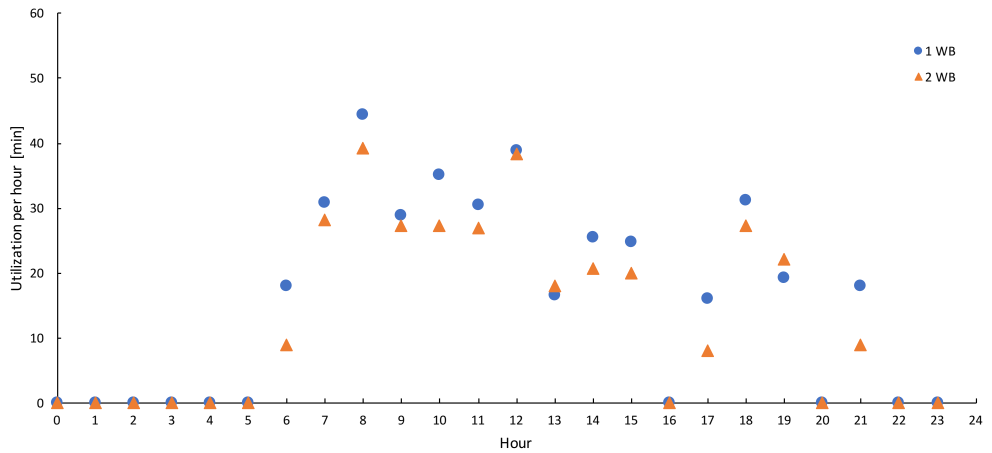
Figure 5.10: Additional cost savings due to carbon offsetting. Three different scenarios for carbon offsetting costs in 2020 are applied for WB & NB departures on May 2nd.

Figure 5.11 shows the utilization rate of the vehicles during the day. From Figure 5.11b it can be found the the utilization in case when two WB AGVs are used is in general lower than the case when one WB AGV is used. The hours where the utilization is high highest for the WB vehicles, correspond with the WB departure peaks at AAS (demonstrated in Figure 5.7). During 10 hours of the day, the WB vehicles are not utilized.

For NB vehicles, the utilization is on average higher than for the WB vehicles, due to the higher amount of NB departures during the whole day (average utilization 13 minutes per hour using one WB AGV, while this is 26 minutes for using two NB vehicles). Only during the night, for 5 hours, the vehicles are not utilized. As shown in Figure 5.11a, the utilization rate when two NB vehicles are used is often higher compared to when one NB AGV is used. Using one AGV, the model chooses to pick up aircraft where high cost savings can be obtained (often due to avoiding delay as can be found in Table 5.25). When using two NB AGVs, the vehicles are often utilized more, since the aircraft where relatively high cost saving (due to delay) can be obtained are limited.



(a) Utilization rate NB vehicles



(b) Utilization rate WB vehicles

Figure 5.11: Average AGV utilization rate in [min/hour] May 2nd. Utilization is considered to be the time an AGV is connected to an aircraft.

Instead of using the AGV to pick up a specific aircraft with high cost savings, the model aims to use the AGV as much as possible to save costs by not using the main engines of the aircraft.

5.4.2. May 15th

As can be found in Table 5.26, the results for May 15th are similar to the ones obtained for May 2nd. Also here one WB towing vehicle gives optimal cost savings for the WB aircraft. A fleet of maximum two NB AGVs is used since the additional cost savings of the second vehicle is only for 45 % due to savings of not using the main engines (55 % is due to delay avoidance). Using two NB AGVs 8 % of the taxi cost can be saved compared to current operations. Using one WB AGV, 4 % on the taxi operations can be saved.

Figure 5.12 shows th cost savings including the expected carbon offsetting costs in 2020. The effect of the additional cost savings due to carbon offsetting varies between the 2 % for one NB AGV and 12 % for two WB AGVs.
Figure 5.13 shows the utilization of the vehicles per hour during the day. Also for this day the utilization of the NB aircraft is higher compared to the WB aircraft. For the same reason as for May 2nd this is because of the lower amount of WB departures and their uneven distribution over the day. When one NB vehicle is used the average utilization is 29 minutes per hour while this is 16 minutes for one WB vehicle.

Table 5.26: Full day result for May 15th.

Scenario	Total cost [EUR]	Cost savings [EUR]	Savings delay [EUR]	Jet-fuel [kg]	Diesel [kg]	Flights towed	CO2 reduction [kg]
0 veh.	46320	-	-	59171	0	-	-
1NB	43767	2553	1839	56871	127	58	7395
2NB	42763	3557	2398	54854	245	114	13855
1WB	44633	1687	1519	54955	300	34	13340
2WB	45409	911	1572	52794	444	53	20205

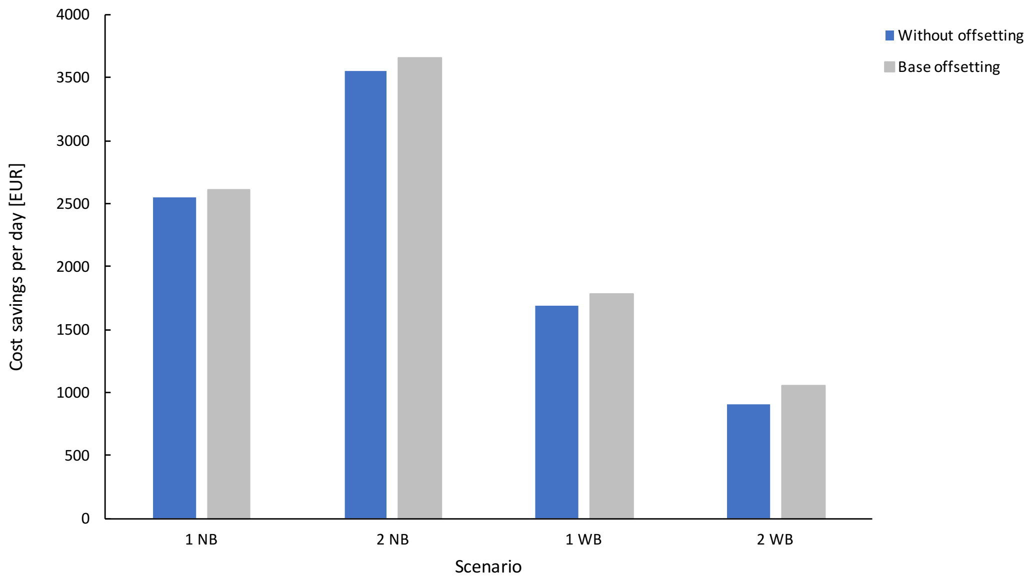


Figure 5.12: Additional cost savings due to carbon offsetting. Three different scenarios for carbon offsetting costs in 2020 are applied for WB & NB departures on May 15th.

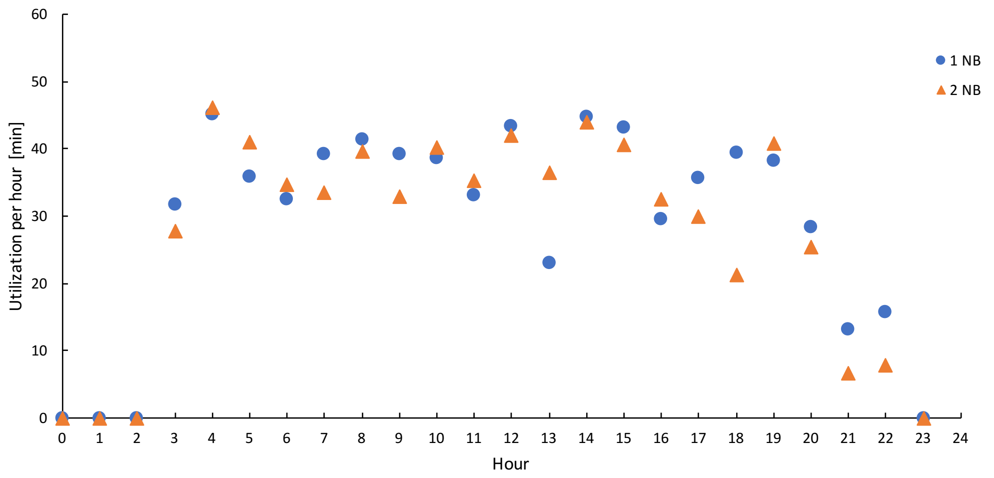
5.4.3. Expected yearly savings

May 2nd and May 15th are chosen as case study since the runways used for May 15nd are responsible for 59.45 % of the departures in 2017. 31.27 % took place from the runways used on May 2nd. Table 5.27 shows the amount of flights towed using two NB and one WB vehicle during these days.

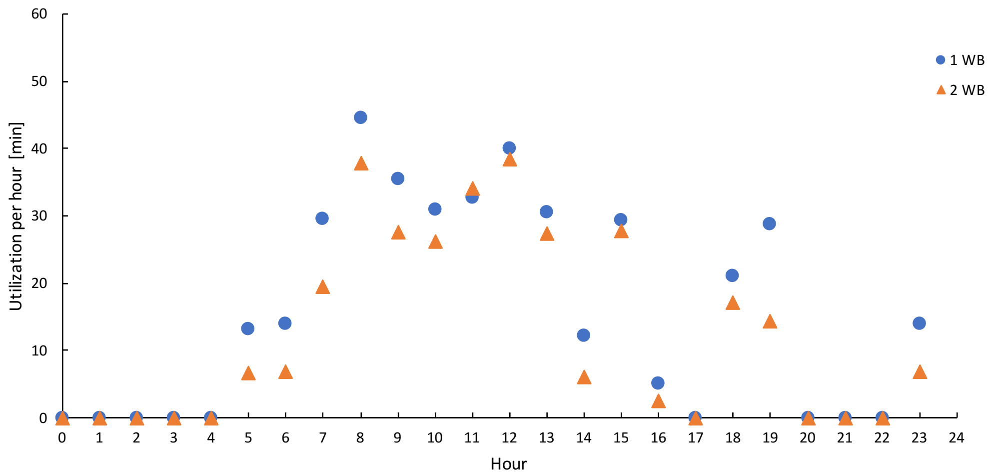
Table 5.27: Scheduled and towed flights using 2 NB and 1 WB AGVs

Day	May 2nd	May 15th
Total flights	617	600
Scheduled WB	91	86
1 WB AGV	22	34
Scheduled NB	526	514
2 NB AGVs	76	114

By assuming that all departures use the runways of May 2nd and May 15th, a rough estimate of using AGVs during a year can be made. It is assumed that the ratio is equal to the departures from these runways in 2017. This means that for the estimation 66 % of the departures will use the configuration of May 15th and 34 % use the configuration as in May 2nd. Table 5.28 shows an estimation of the yearly savings using two NB and one WB aircraft. As shown 1.40 million EUR can be saved on taxi operations. Not taken into account the cost of delay 566 thousand EUR can be saved on a yearly bases by towing approximately 48 thousand flights (this is almost 10 % of the total movements of AAS). These results show that the implementation of an AGV system is profitable for AAS. Next to that, 11 thousand tons of CO2 could be saved on a yearly basis (this could add 82 thousand EUR to the savings for carbon offsetting).



(a) Utilization rate NB vehicles



(b) Utilization rate WB vehicles

Figure 5.13: Average AGV utilization rate in [min/hour] May 15th. Utilization is considered to be the time an AGV is connected to an aircraft.

Table 5.28: Rough estimation of yearly savings.

	Cost savings [EUR]	Savings delay [EUR]	Savings no delay [EUR]	Jet-fuel [kg]	Diesel [kg]	Flights towed	CO2 reduction [kg]
Total (x1000)	1970	1404	566	47903	254	48	11363

This is a rough estimate, since it is only based on two days of operation in May 2013. Because the amount of movements between 2013 and 2017 has increased at AAS [Baa, 2017] it is expected that the savings using AGVs could be even higher for 2017.

5.5. Model performance

This section describes shortly the computational time to solve the problems and how this model is different from a model with human drivers.

5.5.1. Computational time

As solver CPLEX version 12.7.1 is used, accessed from the Python (version 2.7) API. A 2.4 GHz processor performs the calculations. The solve time highly depends on the complexity of the problem. Table 5.29 shows the solve time for different scenarios. The solve time is not only dependent on the amount of variables, but also the ability of the solver to differentiate the costs to find the optimum.

Table 5.29: Solve time for different random scenarios.

Scenario	Variables [x1000]	Solve time [seconds]
0 veh	1630	2400
3 NB	1910	5593
2 WB	840	508
2 WB	1032	755

5.5.2. Comparison of AGVs and human drivers

One of the effects of using AGVs instead of drivers can be seen in Figures C.1 and C.2. As shown in these figures the vehicle is not restricted to human constraints. The model could decide that the AGV will stay unused for a long time near the runway, which is not labor friendly in case drivers are used. This means that extra constraints need to be added in order to cope with human schedules.
One of the disadvantages of using human drivers is that the model is also restricted to the amount of drivers in a certain time interval. e.g. by using AGVs, the model can decide to use an AGV for only two aircraft in a certain day. When a human driver is used, this means that the driver will only be used for these two aircraft. A work-shift for a driver that will only drive two aircraft to the runway is considered to be unrealistic.

Furthermore, drivers need a salary. Fixed monthly loan payments for these drivers would add a fixed cost to the objective function (will be discussed in Section 6.3). This means that independent on the use of the vehicles, the loans for the drivers have to be paid.

5.6. Conclusion of results

In this chapter the results obtained by the model for the case study of AAS have been discussed. First the outputs that program generates haven been demonstrated in Section 5.1. To demonstrate in detail the performance of the model in Section 5.2 and Section 5.3, different scenarios have been tested for time intervals on May 15th and May 2nd. Here is was found that the model is highly dependent on the delay costs of the aircraft. Often the model uses the change in procedures by using AGVs to avoid delay, this is possible due to the freedom the model to choose its own route and schedule. Since the costs of delay can be large, this can be a substantial part of the costs/savings.

It was also found that using a large fleet of AGVs could even in the peak hours result in low cost savings per aircraft (<20 EUR). Often the model choses not to use all the vehicles since it is not profitable to use all of them. Higher cost savings per flight were obtained when a small fleet of vehicles was used. Furthermore

when the delay cost is not incorporated, the model will choose to deliver the aircraft later at the runway. This is not favorable for the throughput of the airport.
By considering a full day of operations, it was found that the utilization rate for WB vehicles is in general lower compared to the NB AGVs. This is because the majority of the WB departures take place concentrated at certain time intervals during the day.

The yearly savings have been roughly estimated. Optimally a fleet of two NB vehicles and one WB vehicle could save up to 1.40 million EUR. Not considering delay, the savings will be around 566 thousand EUR. Also 11 thousand tons of CO2 could be saved, which could add 82 thousand EUR to the cost savings for the expected carbon offsetting costs in 2020.

6

Validation and sensitivity analysis

The results of Chapter 5 are only useful if they are realistic. Therefore in this chapter the fuel usage by the towing vehicles is validated and a sensitivity analysis is done on the diesel prices in Section 6.1. In Sections 6.2 and 6.3 a sensitivity analysis is done on the price of jet fuel and depreciation cost of the vehicle respectively. Section 6.4 describes the effect of the taxi distance and Section 6.5 shows the elasticity of the costs relative to each other (in a case with and without delay).

6.1. Fuel validation and sensitivity analysis

This section verifies the calculated fuel consumption of the vehicles and a sensitivity analyses of the effect of the fuel price on the model.

6.1.1. Diesel usage

Since the objective function is dependent on the diesel usage it is important to verify the used assumptions for the diesel usage. The use of towing vehicles for aircraft taxiing is only recently applied by TaxiBot, therefore little data regarding the fuel usage of such vehicles is available. As discussed in Section 4.4, assumptions were made to have a realistic estimation of the diesel usage, but without adding extra complexity to the model. Furthermore the fuel usage for the pushback by either a conventional pushback car or an AGV is assumed to be equivalent and therefore not included in the model.
Here the obtained fuel consumption will be compared to fuel consumption data found in recent literature regarding taxiing with towing vehicles. Four different scenarios have been used to verify the fuel usage of the vehicle:

1. **09:45-10:45 May 15th** : Fuel usage of the NB vehicles data from scenario 6 of NB departure peak 09:45-10:45 May 15th. In this scenario, all vehicles together are traveling on a taxi-lane with aircraft for 522 timesteps (5220 seconds). Therefore 28.34 kg of diesel is used. This is equivalent to a diesel fuel flow of 0.00543 kg/sec. Where Selderbeek et al. [2013] neglects the fuel usage of driving back, this model takes into account the diesel usage from the runway to the gate. Additionally 2.7 kg is used for the driving of the empty vehicles.

2. **10:45-11:45 May 15th** : Fuel usage of the WB vehicles data from scenario 4 of departures between 10:45-11:45 May 15th. The three WB vehicles use 53.64 kg of diesel during the 262 timesteps towing the aircraft. This means that when towing on average 0.02047 kg/sec of diesel is used. Additional 6.06 kg of diesel is used for the vehicle to drive without aircraft.

3. **07:45-08:45 May 2nd** : Fuel usage of the WB vehicles data from scenario 4 of WB departure peak 07:45-08:45 May 2nd. The three WB vehicles use 138.52 kg of diesel during the 461 timesteps towing the aircraft. This means that when towing on average 0.03005 kg/sec of diesel is used. Additional 13.41 kg of diesel is used for the vehicle to drive without aircraft.

4. **10:45-11:45 May 2nd** : Fuel usage of the NB vehicles data from scenario 3 of 10:45-11:45 May 2nd. During towing operations 22.88 kg of fuel is used during the 406 timesteps. This is equivalent to a diesel fuel flow of 0.00564 kg/sec. 2.38 kg of diesel is added for driving the empty vehicles.

Table 6.1 shows the fuel usage of the vehicles in the model compared to the ones obtained from literature. Here the fuel usage from Hospodka [2014a] is for towing a fully load Airbus A380 and is therefore higher to the average found in the literature and in the model. Comparing the obtained fuel flows of the vehicles in this research to the ones found in Khammash and Mantecchini [2017] and Postorino et al. [2017], the values are within 4.0 % of the values found in this literature and are therefore considered to be realistic.

Table 6.1: Fuel verification of different scenarios compared to vehicle fuel flow (FF) found in the literature.

Source	Hospodka	Khammash and Mantecchini	Postorino et al.	Model May 2nd		Model May 15th	
				07:45-08:45	10:45-11:45	09:45-10:45	10:45-11:45
NB vehicle FF [kg/s]	-	0.0054	0.0054	-	0.00564	0.00543	-
WB vehicle FF [kg/s]	0.06	0.0197	-	0.03215	-	-	0.02047

6.1.2. Diesel usage and price sensitivity analysis

The model takes into account the cost of using diesel. This means that the increase of the diesel price has the same effect to an equivalent increase in the diesel usage. e.g. if the price of diesel becomes twice as high, the effect is the same as if the fuel flow of the vehicle is twice as high. Therefore testing the effect of a higher diesel usage is the same as testing the effect of a higher diesel price. This sensitivity analysis can thus be seen from a price and usage perspective:

- **Diesel price :** The price for diesel is not constant as shown in Figure 6.1. In the model the price of diesel is an input and for the results in Chapter 5 the average diesel price between January 2008 and January 2018 is used. Varying the price of diesel as input to the model will show the effect on the output.
- **Diesel usage :** As explained in Section 6.1.1, the diesel usage is based on different assumptions. Furthermore the actual diesel usage might be different from the one used in the model due to weather conditions, hills, vehicle engine type, etc. Varying the fuel price gives the same effect as varying the diesel usage.

Figure 6.1: Price of diesel including taxes in the Netherlands between January 2008 and January 2018.[CBS]

In order to see the effect of a different diesel usage/price, time interval 10:45-11:45 on May 2nd is used. In this time interval runway 36C and 36L are used for departure, therefore the taxi distance is relatively long and the effect of the diesel price is the largest. In this time interval both WB and NB aircraft are departing and therefore it is chosen to use two WB and two NB vehicles for this sensitivity analysis. Although the optimal amount of vehicles is dependent on the fuel price, it is chosen to keep the fleet of vehicles constant, because from an airport perspective it is not realistic that the fleet of vehicles changes constantly. While the fuel prices changes constantly, a vehicle is bought for the use of multiple years. Therefore this sensitivity analysis show what the cost savings are with a fixed fleet and changing diesel prices.

Table 6.2: Savings on total taxi cost for different diesel prices. Cost of taxiing without vehicles is 3671.50 EUR.

Fuel price index	Diesel price [EUR/L]	Total taxiing cost [EUR]	Savings [EUR]	Percentage saved
80%	1.02	3414.20	257.30	7.54%
100%	1.28	3432.02	239.48	6.98%
120%	1.53	3449.78	221.72	6.43%
140%	1.79	3467.68	203.82	5.88%

From the results of Chapter 5 it was found that the model is highly dependent on the cost of delay. In order to demonstrate the effect of a changing diesel price the delay cost is fixed. In this analysis the cost of delay in all scenarios is equal to the cost of initial delay (taxiing without vehicles). By keeping the delay cost constant, the effect of the changing fuel price can be demonstrated clearly. Here the cost of delay is equal to the scenario where no vehicles are used (340.49 EUR).

Table 6.2 shows the effect of the different diesel price on the total taxi costs compared to the base scenario of 100%. The percentage of total taxiing costs saved, in case the diesel price is 0.8 times the base price (average of 10 years), is 7.54% of the total taxiing costs if no vehicles were used (3671.50 EUR). When the diesel price is 1.4 times the base price, the percentage of total savings is 5.88%. However compared to the savings in the base scenario, a diesel price of 1.4 times the base price will save 203.82 EUR instead of 239.48 EUR.
As explained in this section, a diesel price of 1.2 times the base-price is equivalent fo the model to a scenario where 1.2 times the amount of diesel is used. Table 6.2 shows that the effect of using 20 % more or less diesel does not has a large effect on total taxiing costs. Taking into account the exact fuel usage in corners, during acceleration/deceleration, wind, small slopes and other factors that have an influence on the fuel usage, will make the model more detailed, but will add complexity. However it is shown here that a more complex model that calculates the diesel usage in detail will not have a large effect on the results.
Figure 6.2 shows the cost savings for different diesel prices compared to the cost of taxiing without AGVs. In this case the cost savings decrease with a higher diesel price. The line in Figure 6.2 visualizes the negative relationship between the diesel price and the cost savings. The linear relationship is because in this case the only factor that has changed in the output is the price of diesel (no differences in routing and scheduling). A similar relation was found in case with the cost of delay as shown in Figure 6.8. Higher diesel prices could result for the model to choose not to use the vehicles.

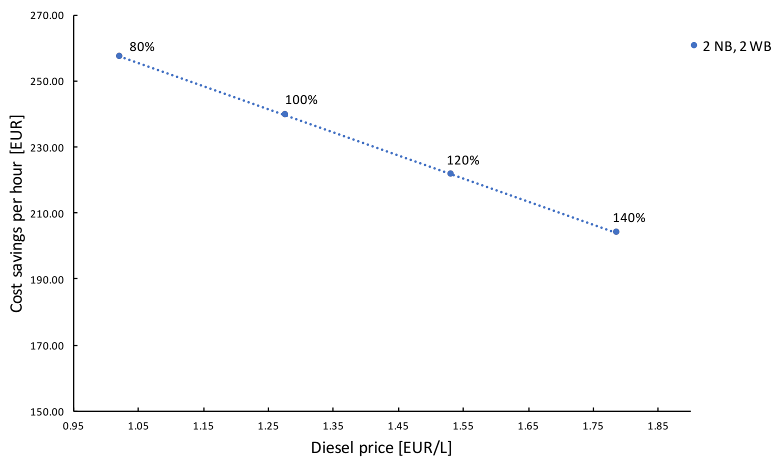


Figure 6.2: Price of diesel change of -20%, +20% and +40% for 10:45-11:45 May 2nd compared to the base scenario of 100%. The x-axis shows the diesel fuel price per liter for the scenarios. Two NB and two WB vehicles are available.

6.2. Jet fuel price

Figure 6.3 shows the jet fuel prices between January 2008 and January 2018. As a base scenario the average jet fuel price of this period is used. As shown in the figure, the jet fuel prices are volatile. To analyze the effect of the different fuel prices on the model, a sensitivity analysis on the jet fuel price is done. Here the same fleet

Table 6.3: Savings on total taxi cost for different jet fuel prices compared to the base scenario of 100%.

Fuel price index	Jet fuel price [EUR/US GAL]	Total taxiing cost no veh. [EUR]	Total taxiing cost with veh [EUR]	Savings [EUR]	Percentage saved
60%	1.05	2786.31	2709.68	76.63	2.75%
80%	1.40	3231.89	3084.78	147.11	4.55%
100%	1.75	3671.50	3432.02	239.48	6.52%
120%	2.09	4116.44	3783.23	333.21	8.09%
140%	2.44	4556.47	4130.56	425.91	9.35%
160%	2.79	5001.51	4481.90	519.61	10.39%

of vehicles is used as for the sensitivity analysis of the diesel price.

Figure 6.3: Price of jet fuel in EUR per US gallon in time interval January 2008 to January 2018. [Mun]

Table 6.3 shows the results of the different fuel prices used. For each fuel price the scenario with and without AGVs is compared. As discussed for the diesel prices, the optimal fleet is dependent on the jet fuel price, however from the stakeholder perspective it is not realistic to change the available fleet constantly. Also here the delay cost is kept constant to show purely the effect of the jet fuel price. Since the price of jet fuel is more volatile compared to the price of diesel, price variations of -40 % till +60 % with respect to the base price of 100% are used in this analysis. These prices will mostly cover the jet fuel prices found in Figure 6.3.

Found in Table 6.3, the change in jet fuel price has a large effect on the potential cost savings of using AGVs. When a cost index of 0.8 times the base jet fuel price is used, the model will use three instead of four vehicles to taxi to the runway. WB 2 is not used when the fuel price is either 0.6 or 0.8 times the base scenario of fuel price. In this case this means that is more profitable for two aircraft to taxi with their main engines to the runway instead of using AGVs.
The line in Figure 6.4 visualizes qualitatively the positive relationship between the jet fuel price and the cost savings. A higher jet fuel price clearly gives higher total cost savings. The linear relationship her is not expected, since in the scenario of 60 % and 80 % of the fuel price, less AGVs are used. Figure 6.8 shows that incorporating the cost of delay would result in non linear cost savings due to the change in AGVs used. This is because the model will pick the aircraft first that will generate the highest cost savings.

Dual engine taxiing
With dual engine taxiing more fuel is used during taxiing operations. The objective function considers the cost of used jet fuel. Therefore the results of dual engine taxiing can be seen as taxiing with a high fuel price. However, the fuel usage is dependent on the types of engines (APU and main engines). Therefore the preferences of the model to taxi certain aircraft can change in dual-engine operations compared to single-engine operations. Table 6.4 shows the general results for using dual engine taxiing with two NB and two WB vehicles for 10:45-11:45 on May 2nd. Clearly the fuel and cost savings are larger for the dual-engine case.

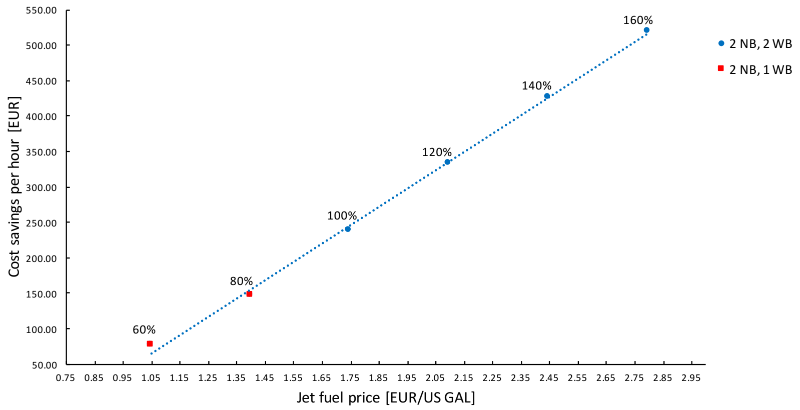


Figure 6.4: Price of jet fuel change of -40%, -20%, +20%, +40% and +60% for 10:45-11:45 May 2nd compared to the base scenario of 100%. The x-axis shows the jet fuel price per gallon for the scenarios. Two NB and two WB vehicles are available.

Table 6.4: Dual-engine vs. single-engine

Scenario	WB vehicles	NB vehicles	Cost [EUR]	Jet-fuel [kg]	Diesel [kg]
Single-engine	2	2	3432.02	4625.70	105.19
Dual-engine	2	2	4520.80	6718.77	107.73

Since the implementation of AGVs for aircraft taxiing is not operational yet, it takes a larger challenge to implement such a system than to use always single engine taxiing. Therefore the case of dual-engine taxiing is not further considered in this research.

6.3. Depreciation cost

Another large cost factor in the objective function is the depreciation cost of the vehicle. This cost is only applied if the vehicle is used. For the depreciation cost it is assumed that the purchase value will depreciate over five years. Since AGVs have never been implemented before, the cost of these vehicles are based on the purchase cost of TaxiBot as described in Section 4.2.6, together with an assumed amortization time. By changing the hourly depreciation value of the vehicles the following can be analyzed:

1. **Purchase value :** The actual purchase (and maintenance) cost might be higher or lower than the ones used in the model. When AGVs for taxiing will be adopted by different airports it is likely that the price of the vehicles will decrease. On the other hand the purchase cost can be higher than the assumed ones.

2. **Depreciation rate :** The hourly depreciation rate could be different due to another way of depreciating the vehicles. e.g. a longer/shorter amortization time, interest on the value of money and non-linear depreciation change the hourly depreciation value.

By changing the hourly depreciation value, the effect of a different purchase value and the depreciation rate can be obtained. Relative to the base purchase cost (as used in the model) of the vehicles, the following scenarios are tested for the hourly depreciation value compared to the base scenario depreciation cost; -40 %, -20 % , +20 % and +40 %. As for the sensitivity analysis for the jet fuel and diesel, the savings are calculated with respect to the case if no vehicles are used. The cost of taxiing without vehicles, is 3671.50 EUR (the reference case).
Table 6.5 shows the effect of different hourly depreciation values on the potential savings of using AGVs. In the scenario where the depreciation value is 40 % higher than the used base scenario in the model, only three vehicles will be used. In the model an unused vehicle will not ad its depreciation value to the objective function. Therefore when the depreciation value is high, this cost does not outweigh the cost of using the main engines of the aircraft. Also for the case with delay in Figure 6.8, the relationship is not linear. When the depreciation cost becomes high, less vehicles are used. The vehicles that are used generate relative high cost savings, since the model optimizes the use of them (model will pick the aircraft first that will generate the highest cost savings).

Table 6.5: Hourly depreciation value sensitivity analysis. Cost of taxiing without vehicles is 3671.50 EUR, which is the reference case.

Depreciation price index	NB hourly depreciation [EUR]	WB hourly depreciation [EUR]	Total taxiing cost [EUR]	Savings [EUR]	Percentage saved w.r.t. reference case
60%	39.82	63.70	3294.04	377.46	10.28%
80%	53.09	84.94	3363.03	308.47	8.40%
100%	66.36	106.17	3432.02	239.48	6.52%
120%	79.63	127.40	3501.00	170.50	4.64%
140%	92.90	148.64	3550.23	121.27	3.30%

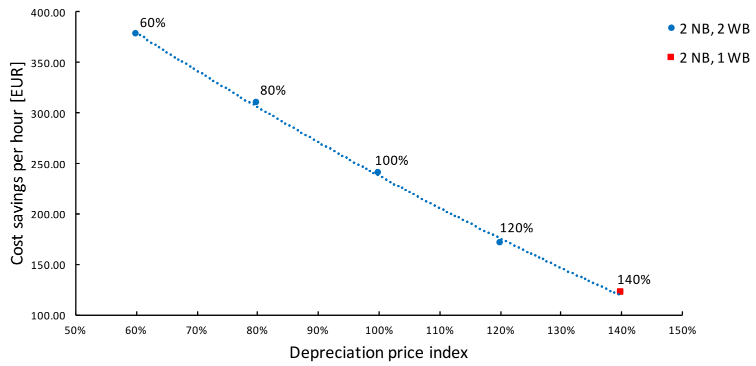


Figure 6.5: Price of hourly depreciation change of -40%, -20%, +20% and +40% for 10:45-11:45 May 2nd where two NB and two WB vehicles are available.

Human drivers

This research is focused on the futuristic approach to use AGVs for aircraft taxiing. However the optimizer could also be used be used for towing vehicles with human drivers, such as TaxiBot. The main difference for the model is that using human drivers require extra constraints. For example for human drivers their scheduling has to be taken into account. Assuming that human drivers behave roughly the same and the influence of the scheduling is minimal, the method in this research could give a realistic analysis of using towing vehicles with drivers. Using the purchase cost of TaxiBot, 40 USD per hour for the tug driver [Dzikus, 2013] and the depreciation method of Section 4.2.6, the costs of the vehicles is as follows:

- NB vehicle: 1.5 million USD per vehicle, which correspond to 75.56 EUR per operating hour including the cost op maintenance and the driver.
- WB vehicle: 3.0 million USD per vehicle, which correspond to 115.36 EUR per operating hour including the cost op maintenance and the driver.

Comparing these values to the hourly values of Table 6.5, it can be found that the cost of using a driver is equivalent for the model as using a depreciation value between 100 and 120%. This example shows that since the hourly depreciation value is an input to the model, the model can also be used for analysis of vehicles with drivers, such as TaxiBot.

6.4. Distance

The savings of the vehicles also depend on the distance between the apron and the runway. The longer the distance the more fuel can be saved, however the vehicle can be used for less flights. Especially since it has also a longer driving distance on the way back to the terminal area.
By changing the distances of the edges a sensitivity analysis is performed. This means that if the edge is 100 m in the model, the same edge of +10% is now 110 m. Although this method could have an effect on the conflict free requirements, is gives qualitatively the effect of a loner or shorter taxiing distance. For the cost savings taxiing with and without vehicles per distance index are compared to each other.
As can be found in Table 6.6, in general the larger the distance the larger the absolute savings. However in a timespan of one hour, a larger distance could mean that the vehicle can be used for less aircraft, which could explain the non-continuous behavior of the savings for the different scenarios (the scenario of +130 %

is added since the differences between +20 and +40% were creatively large).

Table 6.6: Distance sensitivity analysis.

Distance index	Total taxiing cost without veh. [EUR]	Total taxiing cost with veh. [EUR]	Savings [EUR]	Percentage saved w.r.t. no veh.
60%	2701.61	2554.58	147.03	5.44%
80%	3236.42	3024.27	212.15	6.56%
100%	3671.50	3432.02	239.48	6.52%
120%	4065.66	3863.68	201.98	4.97%
130%	4303.48	4092.89	210.59	4.89%
140%	4636.39	4394.13	242.26	5.23%

Figure 6.6 shows qualitatively the effect of the taxiing distance on the total cost savings. A positive relationship is found, however not as clear is in the other cases. This is because changing the edge length influences the conflict free constrain for the edges (2 aircraft can not be on the same edge at the same time) and the amount of aircraft that can be towed in a time interval. For these reasons it is not included in the sensitivity comparison. The reference case where the jet fuel price, diesel price and depreciation costs are 100% shows a cost saving of 239.46 Eur compared to not using AGVs.

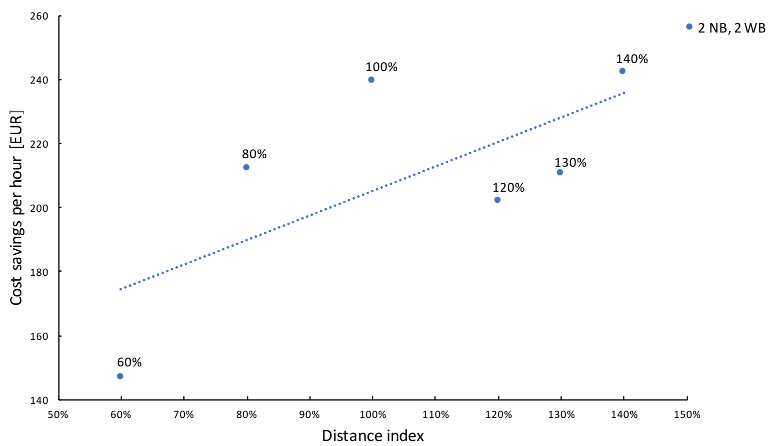


Figure 6.6: Distance change of -40%, -20%, +20%, +30% and +40% for 10:45-11:45 May 2nd where two NB and two WB vehicles are available.

6.5. Sensitivity comparison

In this section the sensitivity analysis are qualitatively compared to each other. First in Section 6.5.1 the comparison without the cost of delay is demonstrated. Section 6.5.2 shows the sensitivity analysis as done in this chapter for the same time interval and vehicles, but with delay.

6.5.1. Without delay

Figure 6.7 shows the effect of varying different variables on the cost savings. Qualitatively this shows the effect of changing the parameters compared to each other. Like the sensitivity analysis of Vaishnav [2014] the effect of changing the jet fuel price is relatively high compared to the depreciation and diesel cost. This means that the price of diesel has relatively a higher elasticity than the price of jet fuel and the depreciation cost. The effect of the changing diesel price is relatively the lowest on the total cost savings.

6.5.2. With delay

Here the same case is tested including the cost of delay. As shown in Figure 6.8 the cost savings in this time interval are lower than in the case when delay is included. It must also be noted that when the delay cost is included on average less vehicles will be used by the model. In case when not all the vehicles are used, the

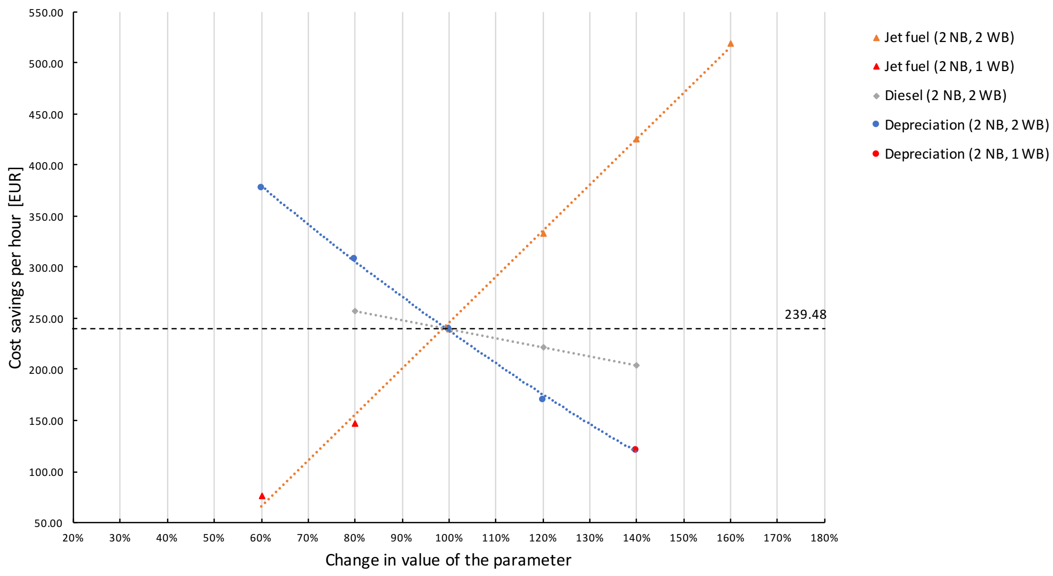


Figure 6.7: Sensitivity analysis of different parameters showing effect on cost savings. The reference case has 239.48 EUR cost savings. The points in red show where less AGVs than available are used.

potential cost savings of the AGVs do not out-weight the depreciation cost of the vehicles and the extra delay costs.

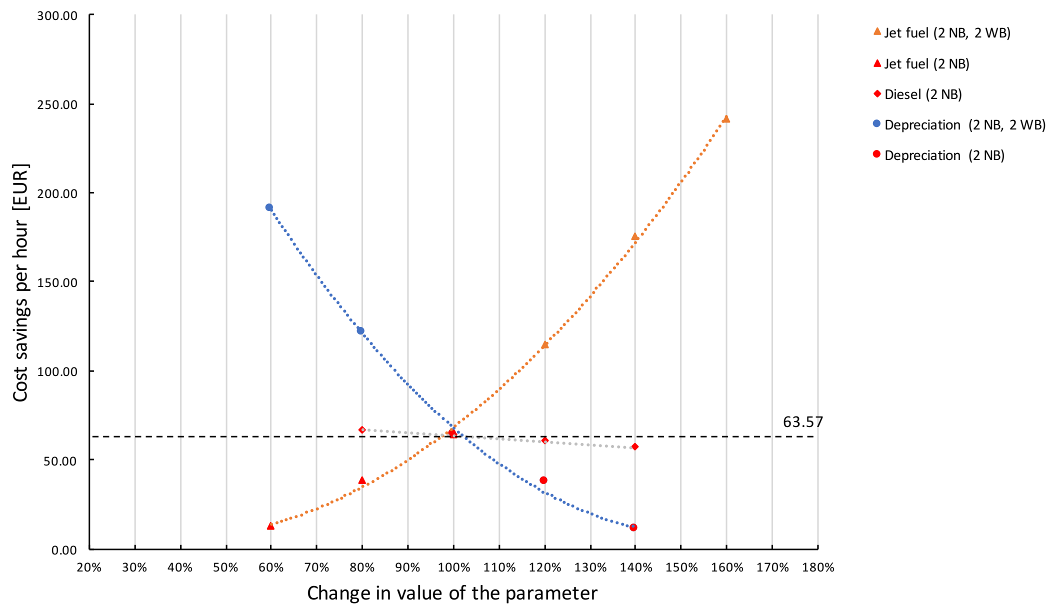


Figure 6.8: Sensitivity analysis of different parameters showing effect on cost savings. The reference case has 63.57 EUR cost savings. The points in red show where less AGVs than available are used.

7 Conclusion and recommendations

This chapter will present the main conclusions and recommendations obtained from this research. First Section 7.1 will cover the conclusions, followed by the recommendations in Chapter 7.2.

7.1. Conclusion

This research answers the main research goals drawn in Chapter 3. By checking the stated hypothesis the research objective will be answered, starting with the first hypothesis regarding the economic feasibility of using an AGV taxiing system.

H1 economic feasibility: it is economically profitable to use AGVs for aircraft taxiing at major airports.

This research has proven that the use of AGVs could be profitable for aircraft taxiing operations. Optimizing the routing and scheduling of the AGVs and aircraft during taxi operations has shown that using AGVs could reduce cost compared to current taxiing operations. Therefore the cost of the vehicle, cost of the aircraft and the cost of delay have been taken into account. Taxi procedures and the aircraft/AGV specifications have been used to calculate in detail the cost of using them at each part of the network.

To test the model, AAS is used as test case. Using historical flight-schedule data of AAS, it has been shown that two AGVs, that can tow NB aircraft, could reduce the total taxiing cost with 7 % compared to the scenario where no AGVs are used. This means that on a typical day between 3500-4300 EUR can be saved by towing NB aircraft. For this analysis May 2nd and May 15th 2013 have been used as test cases, due to the available data and the used runway configurations on these days. The used runways were responsible for 95.98 % of the commercial departures at AAS in 2017.

For WB aircraft the optimal savings are found when one vehicle is used. This is mainly due to the fact that most WB aircraft at AAS depart within a relative small time interval and the total amount of WB aircraft is lower compared to the NB aircraft (15% WB aircraft at AAS). The utilization rate of using two WB vehicles at May 2nd was found to be 13 minutes per hour, while this is 26 minutes for the two NB vehicles. Although the utilization rate is low, the depreciation cost of the vehicle has to be paid for the full day. Therefore from an economic point of view one WB taxiing vehicle gives the optimal amount of cost savings.

One of the state-of-the-art aspect in the model is the incorporation of the delay costs of the aircraft. It has been found that the cost of delay has a large influence on the optimal routing and scheduling of the vehicles. By looking in detail at the routing and scheduling in time intervals of an hour, the effect of the delay cost has been analyzed. The model finds the optimal solution between the cost of delay when an AGV is used and the cost savings. It was found that delay costs can also be avoided using AGVs. This because the sequence in operations is different when AGVs are used compared to normal taxi operations. The model uses this to avoid congestion and detours for active runways.

From the sensitivity analysis in Chapter 6 it was found that the diesel usage/price (used for the AGVs) has a

relative low influence on the potential savings. On the other hand the jet-fuel price and the purchase price of the vehicles have a relative high effect on the potential savings. It is shown that with a low jet-fuel price the savings are minimal (<50 EUR per hour with and without AGV in the used case study). Here the model does not use the entire available AGV fleet to optimize the cost savings (depreciation cost is a decision variable in this case and is only applied when the AGV is used).
For the sensitivity analysis of the depreciation cost the opposite can be found. The lower the depreciation cost of the vehicle the more available AGVs will be used and the higher the potential cost savings.

H2 throughput: with the use of AGVs the throughput of a major airport will be reduced.

No, using a small fleet of AGVs will not necessarily reduce the throughput of a major airport. In some cases it can even reduce the total taxi out time by avoiding congestion and active runway detours. This is possible due to the fact that the model is free to choose its optimal path.
The throughput is important to be taken into account since it is not likely that a major airport will implement such a system if it will reduce the capacity of the airport.

The use of AGVs could lead to extra congestion at taxiways due to the extra traffic and in some cases lower maximum taxiing speeds. The method described in this paper allows AGVs to use the existing service roads of the airport. Using historical flight data of AAS, a conflict-free optimal routing and scheduling was obtained, showing that AGVs can be used in combination with normal taxi operations keeping the current throughput. To fix the current throughput, all aircraft have to take-off in range $[t_{d_{block}} - 5min, t_{d_{block}} + 10]$, where $t_{d_{block}}$ is the block departure time from the flight schedule. The flight schedules used for AAS show clearly the WB and NB departure peaks. Since departures are not evenly distributed over the day, the model looks at the benefits of an AGV system based on realist airport operations.

If the flight is not able to arrive in the time interval using an AGV, or if the benefits of using the AGV do not outweigh the cost savings, the aircraft will taxi towards the runway using its main engines.

Overall it can be concluded that the designed model provides a realistic insight in the possible benefits of using AGVs for aircraft taxiing. This research goes further than looking at the benefits for an individual flight. By taking into account the traffic at the airport and the cost of the vehicle and the aircraft it was found that a small fleet of AGVs (3 in case of AAS), will give the highest cost benefits.
A roughly yearly estimation on the cost savings has been made which shows that 2 NB vehicles and 1 WB vehicle could save up to 1.40 million EUR at AAS. Not considering delay the savings will be around 566 thousand EUR. Also 11 thousand tons of CO2 could be saved, which could add 82 thousand EUR to the cost savings for carbon offsetting.

7.2. Recommendations

In this section recommendations for further research are made. These recommendations could provide a wider scope on the implementation of AGVs for aircraft taxiing.

- Widen geographical scope. The method described in this research could be used for other European airport. For other areas in the world the cost of delay in those regions should be used. AAS is used as test case due to the available data. Testing the model on other airport could give an insight of the potential benefits of using AGVs for the specific airport.

- Broaden temporal scope. For the case study of AAS, data of May 2013 was available. Current data of AAS of different months could improve the quality of the research.

- Decrease the computational time. The computational time to find the optimal solution can be long for a large problem (few hours for one hour of operations at AAS). A faster algorithm could reduce the solution time which will make the method more user friendly.
  Another way to decrease the solving time is to decrease the amount of variables. In this research the model is free to choose its own routes, however a set of fixed taxiing routes could reduce the amount of variables, but could lead to lower cost savings.
  A rolling horizon or smaller time windows can be used to decrease the complexity of the problem and the solving time. Here it should be taken into account that it could lead to a sub-optimal solution.

- Detailed vehicle data. Since AGVs are not used for aircraft taxiing (yet) their fuel and costs are based on TaxiBot and other related aircraft towing vehicles. A more detailed analysis and calculation of the fuel usage could give a better insight of the exact diesel usage.
  Since the effect of the deprecation value is high on the total cost savings (as showed in the sensitivity analysis), a more detailed analysis could be done on the purchase and maintenance price of the AGVs.

- Human drivers. The model is designed for the use of AGVs for aircraft taxiing, however it could give also insight of the benefits of using towing vehicles without drivers. This can be done by adding constraints to the model for human drivers.

- Other airport operation. This research is limited to taxi-out operations. Inbound traffic is taken as input to the model, but in further research this could be part of the optimization problem. Also runway sequencing and gate sequencing could be taken into account to improve the quality of the research.

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A
Appendix

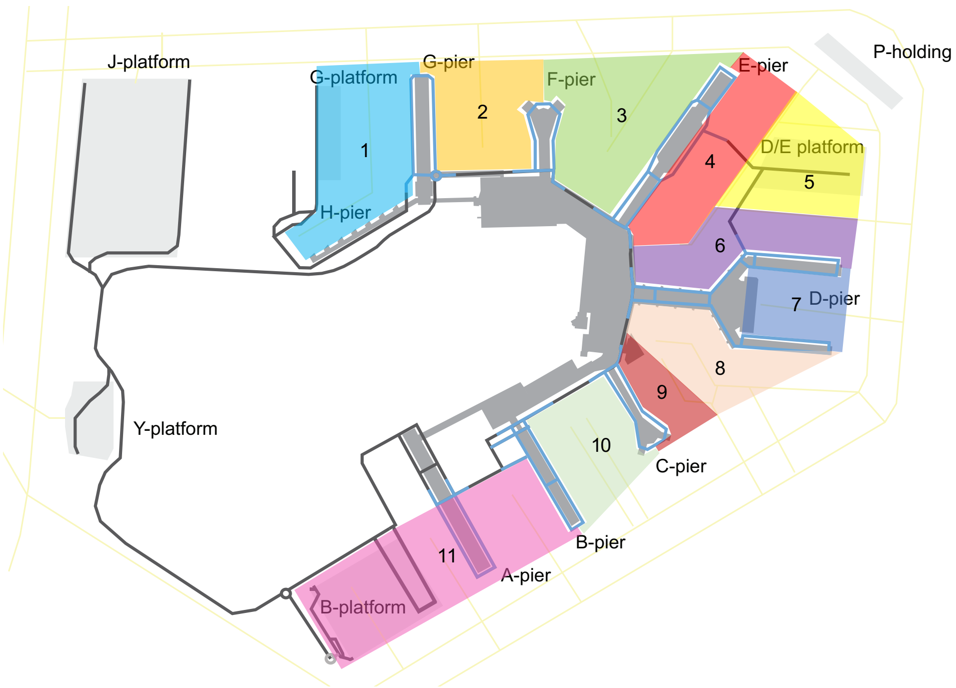


Figure A.1: Service area per service node. The number in each area represents the service node that covers that area.

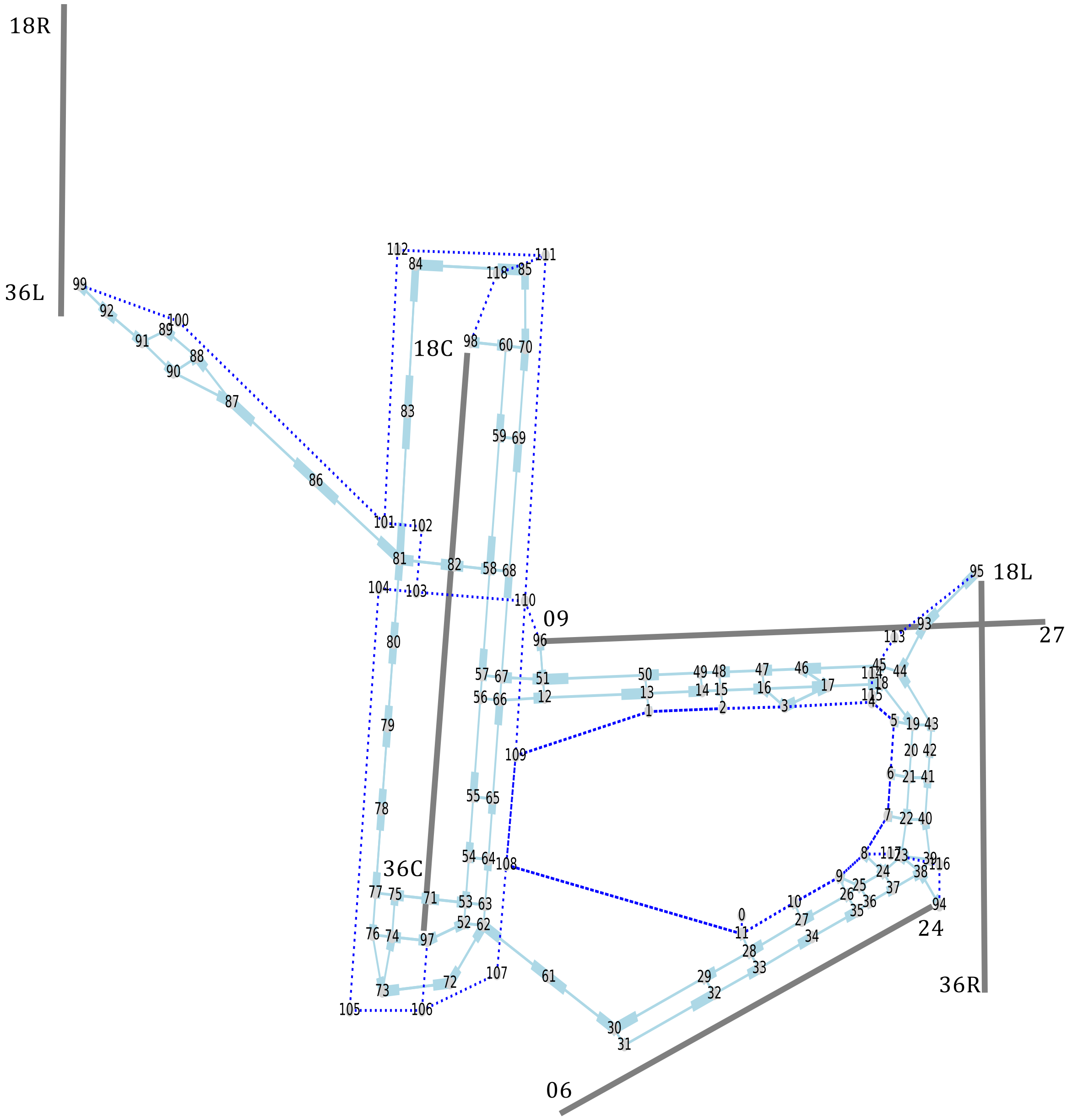


Figure A.2: Node numbers and taxiing direction at the aircraft taxi-lanes of AAS. The direction an aircraft can travel is indicated with a wider line. Detailed direction information about each node and edge can be found in tables A.3 and A.4 of Appendix A. The dotted lines are the service roads.

Table A.1: Number of flights per runway and the percentage of the total commercial arrivals and departures. Small business aircraft are not part included in the data. [Baa, 2017]

Runway	Arrivals	Departures	Total	Arrivals [%]	Departures [%]
Aalsmeerbaan (18L)		69732	69732	0.00%	28.18%
Aalsmeerbaan (36R)	30577		30577	12.36%	0.00%
Buitenveldertbaan (09)	20	13032	13052	0.01%	5.27%
Buitenveldertbaan (27)	26210	609	26819	10.59%	0.25%
Kaagbaan (06)	29260	188	29448	11.82%	0.08%
Kaagbaan (24)	631	77380	78011	0.25%	31.27%
Oostbaan (04)	1	4	5	0.00%	0.00%
Oostbaan (22)	2914	39	2953	1.18%	0.02%
Polderbaan (18R)	100645		100645	40.67%	0.00%
Polderbaan (36L)		54635	54635	0.00%	22.08%
Zwanenburgbaan (18C)	40680	9115	49795	16.44%	3.68%
Zwanenburgbaan (36C)	16546	22755	39301	6.69%	9.19%
Total	247484	247489	494973	100.00%	100.00%

Table A.2: Aircraft specifications, where WB stands for wide-body aircraft en NB for narrow-body aircraft. The engine fuel flow and the APU fuel flow are typical fuel flows for the type of aircraft. The engine fuel flow is given per engine at a thrust setting of 7%.[Watterson et al., 2004]

Aircraft name	IATA aircraft code	MTOW [kg]	WB/ NB	APU fuel flow [kg/s]	Engine fuel flow 7% [kg/s]	Number of engines
AIRBUS A300-600	AB6	170500	WB	0.0338	0.2055	2
AIRBUS A310-300	313	150000	NB	0.0338	0.1959	2
AIRBUS A319	319	64000	NB	0.0278	0.1164	2
AIRBUS A320-100/200	320	73500	NB	0.0278	0.1170	2
AIRBUS A321	321	89000	NB	0.0278	0.1272	2
AIRBUS A330-200	332	230000	WB	0.0675	0.2736	2
AIRBUS A330-300	333	217000	WB	0.0675	0.2797	2
AIRBUS A340-300	343	271000	WB	0.0675	0.1204	4
AIRBUS A380-800	388	540000	WB	0.1305	0.4000	4
ATR42-500	AT4	18600	NB	0.0188	0.0517	2
AVROLINER RJ85/QT	AR8	42184	NB	0.0231	0.0453	4
BOEING 717-200	717	51710	NB	0.0296	0.0960	2
BOEING 737-300	733	56700	NB	0.0296	0.1181	2
BOEING 737-400	734	62820	NB	0.0296	0.1238	2
BOEING 737-500	735	52390	NB	0.0296	0.1148	2
BOEING 737-600	736	65090	NB	0.0321	0.1006	2
BOEING 737-700	737/73G/73W	69400	NB	0.0321	0.1065	2
BOEING 737-800	738/73H	78220	NB	0.0321	0.1106	2
BOEING 737-900	73J	85130	NB	0.0321	0.1106	2
BOEING 747-400	744/74E	396830	WB	0.1087	0.2410	4
BOEING 757-200	752/75W/75C	115900	WB	0.0338	0.1900	2
BOEING 757-300	753	122470	WB	0.0338	0.1900	2
BOEING 767-200	762	136078	WB	0.0338	0.2055	2
BOEING 767-200	76W	136078	WB	0.0338	0.2044	2
BOEING 767-300	763	156489	WB	0.0338	0.2542	2
BOEING 777-200	772	242670	WB	0.0675	0.2750	2
BOEING 777-300	777/77W	299370	WB	0.0675	0.3000	2
BOMBARDIER DASH 8 Q100/200	DH4	16465	NB	0.0087	0.0510	2
BOMBARDIER DASH 8 Q400	DH8	29574	NB	0.0087	0.0510	2
BOMBARDIER REGIONAL JET 100/200	CR2	23133	NB	0.0231	0.0489	2
BOMBARDIER REGIONAL JET RJ900	CR9	38330	NB	0.0231	0.0489	2
BRITISH AEROSPACE BAe-146-200	142	42184	NB	0.0184	0.0408	4
Embraer EMB 135	ER3	19000	NB	0.0188	0.0500	2
Embraer EMB 145	ER4	19200	NB	0.0188	0.0500	2
Embraer EMB 170	E70	34000	NB	0.0188	0.0500	2
Embraer EMB 175	E75	38790	NB	0.0188	0.0500	2
Embraer EMB 190	E90	47790	NB	0.0188	0.0500	2
Embraer EMB 195	E95	48790	NB	0.0188	0.0500	2
Fokker 100	100	43090	NB	0.0231	0.1200	2
Fokker 70	F70	36740	NB	0.0169	0.1100	2
MCDONNELL-DOUGLAS MD11	M11	283720	WB	0.0583	0.2105	3
MCDONNELL-DOUGLAS MD81	M81	63500	NB	0.0296	0.1363	2
MCDONNELL-DOUGLAS MD83	M81	72600	NB	0.0296	0.1363	2

Table A.3: Network data Part A.

NodeID	posx	posy	ConnectNode				DistNode [m]				SpeedNode [m/s]				Gate	HoldNode	Runway	Service
			1	2	3	4	1	2	3	4	1	2	3	4				
0	1906	1721	11	0	0	0	100	0	0	0	8	0	0	0	TRUE	TRUE	FALSE	FALSE
1	1410	2843	13	0	109	2	100	0	1000	220	4	0	14	8	TRUE	FALSE	FALSE	FALSE
2	1805	2860	15	0	1	3	100	0	220	300	4	0	8	8	TRUE	FALSE	FALSE	FALSE
3	2135	2869	16	17	2	4	149	220	300	180	4	4	8	8	TRUE	FALSE	FALSE	FALSE
4	2600	2895	18	0	3	5	112	0	180	50	4	0	8	8	TRUE	FALSE	FALSE	FALSE
5	2718	2790	19	0	4	6	102	0	50	70	4	0	8	8	TRUE	FALSE	FALSE	FALSE
6	2699	2500	21	0	5	7	102	0	70	50	4	0	8	8	TRUE	FALSE	FALSE	FALSE
7	2684	2270	22	0	6	8	102	0	50	50	4	0	8	8	TRUE	FALSE	FALSE	FALSE
8	2559	2060	24	0	7	9	141	0	50	70	4	0	8	8	TRUE	FALSE	FALSE	FALSE
9	2426	1934	26	25	8	10	108	118	70	200	4	4	8	8	TRUE	FALSE	FALSE	FALSE
10	2186	1793	27	0	9	11	108	0	200	320	4	0	8	8	TRUE	FALSE	FALSE	FALSE
11	1906	1621	28	0	10	108	108	0	320	1500	4	0	8	14	TRUE	FALSE	FALSE	FALSE
12	855	2920	0	51	13	0	0	100	545	0	0	10	10	0	FALSE	TRUE	FALSE	FALSE
13	1400	2943	0	50	14	1	0	100	295	100	0	10	10	4	FALSE	FALSE	FALSE	FALSE
14	1695	2956	0	49	15	0	0	100	100	0	0	10	10	0	FALSE	FALSE	FALSE	FALSE
15	1795	2960	0	48	16	2	0	100	230	100	0	10	10	4	FALSE	FALSE	FALSE	FALSE
16	2025	2969	0	47	17	3	0	100	340	149	0	10	10	4	FALSE	FALSE	FALSE	FALSE
17	2365	2983	0	46	18	3	0	169	285	220	0	10	10	4	FALSE	FALSE	FALSE	FALSE
18	2650	2995	0	45	19	4	0	100	281	112	0	9	9	4	FALSE	FALSE	FALSE	FALSE
19	2818	2770	20	43	0	5	145	100	0	102	7	7	0	4	FALSE	TRUE	FALSE	FALSE
20	2809	2625	21	0	0	0	145	0	0	0	7	0	0	0	FALSE	FALSE	FALSE	FALSE
21	2799	2480	22	41	0	6	230	100	0	102	7	7	0	4	FALSE	FALSE	FALSE	FALSE
22	2784	2250	23	40	0	7	204	100	0	102	7	7	0	4	FALSE	FALSE	FALSE	FALSE
23	2756	2048	24	38	0	0	131	138	0	0	7	7	0	0	FALSE	TRUE	FALSE	FALSE
24	2659	1960	25	37	0	8	147	105	0	141	7	7	0	4	FALSE	FALSE	FALSE	FALSE
25	2533	1884	26	36	0	9	84	105	0	118	10	10	0	4	FALSE	FALSE	FALSE	FALSE
26	2466	1834	27	35	0	9	278	105	0	108	10	10	0	4	FALSE	FALSE	FALSE	FALSE
27	2226	1693	28	0	0	10	329	0	0	108	10	0	0	4	FALSE	FALSE	FALSE	FALSE
28	1946	1521	29	33	0	11	278	105	0	108	10	10	0	4	FALSE	FALSE	FALSE	FALSE
29	1706	1381	30	32	0	0	557	105	0	0	10	10	0	0	FALSE	TRUE	FALSE	FALSE
30	1226	1099	31	61	0	0	105	450	0	0	10	10	0	0	FALSE	TRUE	FALSE	FALSE
31	1280	1009	0	30	32	0	758	105	557	206	0	10	10	0	FALSE	FALSE	FALSE	FALSE
32	1760	1291	0	29	33	0	0	105	278	320	0	10	10	0	FALSE	FALSE	FALSE	FALSE
33	2000	1431	0	28	34	0	0	105	329	0	0	10	10	0	FALSE	FALSE	FALSE	FALSE
34	2280	1603	0	35	0	0	0	278	320	0	0	10	0	0	FALSE	FALSE	FALSE	FALSE
35	2520	1744	0	26	36	0	0	105	84	0	0	10	7	0	FALSE	TRUE	FALSE	FALSE
36	2587	1794	0	25	37	0	0	105	147	216	0	10	7	0	FALSE	FALSE	FALSE	FALSE
37	2713	1870	0	24	38	0	0	105	171	221	0	7	7	0	FALSE	FALSE	FALSE	FALSE
38	2860	1958	0	23	39	94	0	138	88	206	0	7	7	7	FALSE	FALSE	FALSE	FALSE
39	2910	2030	0	23	40	0	0	155	221	242	0	7	7	0	FALSE	FALSE	FALSE	FALSE
40	2884	2250	0	22	41	0	0	100	230	0	0	7	7	0	FALSE	FALSE	FALSE	FALSE
41	2899	2480	0	21	42	0	0	100	145	0	0	7	7	0	FALSE	FALSE	FALSE	FALSE
42	2909	2625	0	0	43	0	349	0	145	232	0	0	7	0	FALSE	FALSE	FALSE	FALSE
43	2918	2770	19	0	44	0	100	0	335	0	7	0	7	0	FALSE	TRUE	FALSE	FALSE
44	2750	3060	45	0	93	0	115	0	347	403	9	0	9	0	FALSE	FALSE	FALSE	FALSE
45	2640	3095	46	18	0	0	415	100	0	360	10	10	0	0	FALSE	FALSE	FALSE	FALSE
46	2225	3078	47	17	0	0	210	169	0	244	10	10	0	0	FALSE	FALSE	FALSE	FALSE
47	2015	3069	48	16	0	0	230	100	0	0	10	10	0	0	FALSE	TRUE	FALSE	FALSE
48	1785	3060	49	15	0	0	100	100	0	279	10	10	0	0	FALSE	FALSE	FALSE	FALSE
49	1685	3056	50	14	0	0	295	100	0	0	10	10	0	0	FALSE	FALSE	FALSE	FALSE
50	1390	3043	51	13	0	0	545	100	0	0	10	10	0	0	FALSE	FALSE	FALSE	FALSE
51	845	3020	67	96	0	12	220	211	0	100	10	10	0	10	FALSE	TRUE	FALSE	FALSE
52	425	1679	97	0	62	0	218	0	105	0	10	0	10	0	FALSE	FALSE	FALSE	FALSE
53	433	1792	52	71	0	63	113	189	0	105	10	10	0	10	FALSE	TRUE	FALSE	FALSE
54	451	2042	53	0	0	64	251	220	0	105	11	0	0	11	FALSE	FALSE	FALSE	FALSE
55	474	2375	54	0	65	0	334	409	105	0	11	0	11	0	FALSE	FALSE	FALSE	FALSE
56	512	2917	55	0	66	0	543	0	105	0	11	0	11	0	FALSE	FALSE	FALSE	FALSE
57	521	3043	56	0	0	0	126	0	336	0	11	0	0	0	FALSE	FALSE	FALSE	FALSE
58	562	3625	57	82	0	68	583	189	0	105	11	10	0	11	FALSE	FALSE	FALSE	FALSE
59	613	4354	58	0	0	69	731	0	247	105	11	0	0	11	FALSE	FALSE	FALSE	FALSE
60	648	4854	59	98	70	0	502	189	105	0	11	11	11	0	FALSE	FALSE	FALSE	FALSE
61	877.5	1383	62	30	0	0	449.5	450	0	0	10	10	0	10	FALSE	FALSE	FALSE	FALSE
62	529	1667	52	72	63	61	105	364	113	449.5	10	10	10	10	FALSE	FALSE	FALSE	FALSE

Table A.4: Network data Part B.

NodeID	posx	posy	ConnectNode				DistNode [m]				SpeedNode [m/s]				Gate	HoldNode	Runway	Service
			1	2	3	4	1	2	3	4	1	2	3	4				
63	537	1780	0	64	53	0	0	251	105	0	0	10	10	0	FALSE	FALSE	FALSE	FALSE
64	555	2030	0	65	54	0	0	334	105	0	0	11	11	0	FALSE	FALSE	FALSE	FALSE
65	578	2363	0	66	55	0	0	543	105	0	0	11	11	0	FALSE	FALSE	FALSE	FALSE
66	616	2905	0	67	0	12	0	126	0	239	0	11	0	11	FALSE	FALSE	FALSE	FALSE
67	625	3031	0	68	57	51	0	583	105	220	0	11	11	11	FALSE	FALSE	FALSE	FALSE
68	666	3613	0	69	58	0	0	731	105	0	0	11	11	0	FALSE	TRUE	FALSE	FALSE
69	717	4342	0	70	59	0	0	501	105	0	0	11	11	0	FALSE	FALSE	FALSE	FALSE
70	752	4842	0	85	60	0	0	428	105	0	0	12	12	0	FALSE	TRUE	FALSE	FALSE
71	245	1813	0	75	0	53	0	189	0	189	0	10	0	10	FALSE	FALSE	FALSE	FALSE
72	350	1350	62	73	0	0	364	364	0	0	10	10	0	0	FALSE	FALSE	FALSE	FALSE
73	-11	1304	72	74	0	0	364	304	0	0	10	10	0	0	FALSE	FALSE	FALSE	FALSE
74	41	1604	0	0	97	75	71	0	189	231	0	0	10	10	FALSE	TRUE	FALSE	FALSE
75	57	1834	0	77	71	0	0	105	189	0	0	10	10	0	FALSE	FALSE	FALSE	FALSE
76	-63	1616	73	74	0	0	316	105	0	0	10	10	0	0	FALSE	FALSE	FALSE	FALSE
77	-47	1846	76	0	78	0	231	0	500	0	10	0	14	0	FALSE	FALSE	FALSE	FALSE
78	-15	2304	79	77	0	0	410	500	0	0	14	14	0	0	FALSE	FALSE	FALSE	FALSE
79	17	2762	78	80	0	0	410	500	0	0	14	14	0	0	FALSE	FALSE	FALSE	FALSE
80	49.5	3220.5	81	79	0	0	410	500	0	0	14	14	14	0	FALSE	FALSE	FALSE	FALSE
81	82	3679	80	82	86	83	410	294	621	812	14	10	12	12	FALSE	TRUE	FALSE	FALSE
82	374	3646	0	0	81	58	0	0	294	189	0	0	10	10	FALSE	FALSE	FALSE	FALSE
83	124	4489	81	84	0	0	812	812	0	0	12	12	0	0	FALSE	FALSE	FALSE	FALSE
84	167	5300	83	85	0	0	812	584	0	0	12	12	0	0	FALSE	FALSE	FALSE	FALSE
85	750	5270	70	84	0	0	428	584	0	0	12	12	0	0	FALSE	FALSE	FALSE	FALSE
86	-365	4110	81	87	0	0	621	621	0	0	12	12	0	0	FALSE	FALSE	FALSE	FALSE
87	-812	4542	88	0	86	0	313	0	621	0	12	0	12	0	FALSE	FALSE	FALSE	FALSE
88	-1000	4792	89	90	0	0	221	151	0	0	10	10	0	0	FALSE	FALSE	FALSE	FALSE
89	-1166	4938	91	0	0	0	140	0	0	0	10	0	0	0	FALSE	TRUE	FALSE	FALSE
90	-1125	4708	0	88	87	0	0	151	354	0	0	10	10	0	FALSE	TRUE	FALSE	FALSE
91	-1291	4875	0	92	0	90	486	278	0	235	0	10	0	10	FALSE	FALSE	FALSE	FALSE
92	-1480	5041	99	91	0	0	217	278	460	0	10	10	0	0	FALSE	TRUE	FALSE	FALSE
93	2880	3320	0	44	0	95	0	347	0	443	0	9	0	9	FALSE	FALSE	FALSE	FALSE
94	2960	1778	0	38	0	116	0	206	0	200	0	7	0	10	FALSE	FALSE	TRUE	FALSE
95	3160	3610	93	113	0	0	443	670	0	0	9	14	0	0	FALSE	FALSE	TRUE	FALSE
96	830	3230	51	110	0	0	211	150	0	0	10	10	0	0	FALSE	FALSE	TRUE	FALSE
97	229	1583	74	0	52	106	189	0	218	380	10	0	10	10	FALSE	TRUE	TRUE	FALSE
98	460	4875	118	60	0	0	400	189	0	0	10	11	0	0	FALSE	FALSE	TRUE	FALSE
99	-1624	5188	100	0	92	0	500	0	217	0	14	0	10	0	FALSE	FALSE	TRUE	FALSE
100	-1100	4990	101	0	0	0	1500	0	0	0	14	0	0	0	FALSE	FALSE	FALSE	TRUE
101	0	3879	102	112	0	0	250	1470	0	0	10	14	0	0	FALSE	TRUE	FALSE	TRUE
102	200	3860	103	0	0	0	250	0	0	0	10	0	0	0	FALSE	TRUE	FALSE	TRUE
103	170	3500	104	110	0	0	250	580	0	0	10	10	0	0	FALSE	TRUE	FALSE	TRUE
104	-30	3520	105	0	0	0	2300	0	0	0	14	0	0	0	FALSE	FALSE	FALSE	TRUE
105	-185	1200	106	0	0	0	350	0	0	0	10	0	0	0	FALSE	FALSE	FALSE	TRUE
106	200	1200	107	0	0	0	700	0	0	0	14	0	0	0	FALSE	FALSE	FALSE	TRUE
107	600	1400	108	0	0	0	460	0	0	0	10	0	0	0	FALSE	TRUE	FALSE	TRUE
108	650	2000	109	11	0	0	380	1500	0	0	10	14	0	0	FALSE	FALSE	FALSE	TRUE
109	700	2600	108	1	0	0	380	1000	0	0	10	14	0	0	FALSE	FALSE	FALSE	TRUE
110	750	3450	109	0	0	0	1100	0	0	0	14	0	0	0	FALSE	TRUE	FALSE	TRUE
111	860	5350	110	0	0	0	1870	0	0	0	14	0	0	0	FALSE	FALSE	FALSE	TRUE
112	70	5380	111	0	0	0	650	0	0	0	14	0	0	0	FALSE	FALSE	FALSE	TRUE
113	2720	3250	114	0	0	0	570	0	0	0	10	0	0	0	FALSE	TRUE	FALSE	TRUE
114	2600	3050	115	0	0	0	85	0	0	0	10	0	0	0	FALSE	TRUE	FALSE	TRUE
115	2600	2930	4	0	0	0	500	0	0	0	8	0	0	0	FALSE	FALSE	FALSE	TRUE
116	2960	2000	117	0	0	0	200	0	0	0	10	0	0	0	FALSE	TRUE	FALSE	TRUE
117	2700	2060	8	0	0	0	500	0	0	0	8	0	0	0	FALSE	FALSE	FALSE	TRUE
118	600	5250	111	0	0	0	160	0	0	0	10	0	0	0	FALSE	TRUE	FALSE	TRUE

B
Appendix

Table B.1: Active runway times for May 15th 2013 (GMT+2).

Runway	Time active (HH:MM)
Aalsmeerbaan (18L)	(09:08-11:00) (11:58-12:38) (14:18-14:50) (16:18-17:00) (20:18-21:48)
Aalsmeerbaan (36R)	
Buitenveldertbaan (09)	
Buitenveldertbaan (27)	
Kaagbaan (06)	
Kaagbaan (24)	(00:00-23:59)
Oostbaan (04)	
Oostbaan (22)	
Polderbaan (18R)	
Polderbaan (36L)	(00:00-23:59)
Zwanenburgbaan (18C)	
Zwanenburgbaan (36C)	(06:43-09:08) (10:23-11:27) (12:38-14:28) (14:50-15:43) (17:58-19:43)

Table B.2: Processed flight schedule dataset sample of May 15th 2013, 06:55-08:45 for arrivals & 07:15-08:45 for departures. Part A

ID	StartTime (block)	StartTime (Scheduled)	Runway	Gate node	Kind	Aircraft type	IATA aircraft code	APU fuel flow [kg/s]	Engine fuel flow 7% [kg/s]	Number of engines	MTOW [kg]
723	5/15/13 6:56	5/15/13 6:50	99	10	ARR	NB	73H	0.0321	0.1106	2	78220
724	5/15/13 6:56	5/15/13 6:45	97	7	ARR	NB	320	0.0278	0.117	2	73500
725	5/15/13 6:56	5/15/13 6:40	99	1	ARR	NB	320	0.0278	0.117	2	73500
726	5/15/13 6:58	5/15/13 6:55	97	9	ARR	NB	319	0.0278	0.1164	2	64000
727	5/15/13 6:59	5/15/13 6:45	99	11	ARR	NB	F70	0.0169	0.11	2	36740
728	5/15/13 7:00	5/15/13 6:30	97	9	ARR	NB	321	0.0278	0.1272	2	89000
729	5/15/13 7:00	5/15/13 6:45	99	11	ARR	NB	F70	0.0169	0.11	2	36740
730	5/15/13 7:01	5/15/13 7:00	97	6	ARR	NB	73J	0.0321	0.1106	2	85130
731	5/15/13 7:01	5/15/13 7:00	99	7	ARR	NB	73H	0.0321	0.1106	2	78220
732	5/15/13 7:02	5/15/13 7:00	97	10	ARR	NB	320	0.0278	0.117	2	73500
733	5/15/13 7:03	5/15/13 7:05	99	2	ARR	WB	74E	0.1087	0.241	4	396830
734	5/15/13 7:03	5/15/13 6:45	97	11	ARR	NB	F70	0.0169	0.11	2	36740
735	5/15/13 7:03	5/15/13 7:05	99	1	ARR	NB	320	0.0278	0.117	2	73500
736	5/15/13 7:04	5/15/13 7:00	97	10	ARR	NB	319	0.0278	0.1164	2	64000
737	5/15/13 7:06	5/15/13 7:15	99	11	ARR	NB	F70	0.0169	0.11	2	36740
738	5/15/13 7:08	5/15/13 7:00	97	10	ARR	NB	DH4	0.0087	0.051	2	16465
739	5/15/13 7:10	5/15/13 7:25	99	1	ARR	NB	319	0.0278	0.1164	2	64000
740	5/15/13 7:10	5/15/13 7:05	99	1	ARR	NB	73H	0.0321	0.1106	2	78220
741	5/15/13 7:13	5/15/13 7:10	99	11	ARR	NB	F70	0.0169	0.11	2	36740
742	5/15/13 7:13	5/15/13 7:00	99	8	ARR	NB	320	0.0278	0.117	2	73500
743	5/15/13 7:13	5/15/13 7:10	99	10	ARR	NB	733	0.0296	0.1181	2	56700
744	5/15/13 7:16	5/15/13 7:30	99	4	ARR	WB	763	0.0338	0.2542	2	156489
89	5/15/13 7:17	5/15/13 7:15	94	11	DEP	NB	F70	0.0169	0.11	2	36740
745	5/15/13 7:17	5/15/13 7:15	99	10	ARR	NB	319	0.0278	0.1164	2	64000
746	5/15/13 7:18	5/15/13 7:40	99	3	ARR	WB	333	0.0675	0.2797	2	217000
747	5/15/13 7:18	5/15/13 7:10	99	11	ARR	NB	DH4	0.0087	0.051	2	16465
748	5/15/13 7:19	5/15/13 7:05	99	1	ARR	NB	320	0.0278	0.117	2	73500
90	5/15/13 7:20	5/15/13 7:20	95	11	DEP	NB	F70	0.0169	0.11	2	36740
91	5/15/13 7:20	5/15/13 7:20	94	10	DEP	NB	73W	0.0321	0.1106	2	69400
749	5/15/13 7:20	5/15/13 7:30	99	1	ARR	NB	319	0.0278	0.1164	2	64000
92	5/15/13 7:21	5/15/13 7:25	95	11	DEP	NB	E90	0.0188	0.05	2	47790
93	5/15/13 7:21	5/15/13 7:15	94	1	DEP	NB	319	0.0278	0.1164	2	64000
750	5/15/13 7:22	5/15/13 7:10	99	9	ARR	NB	320	0.0278	0.117	2	73500
94	5/15/13 7:24	5/15/13 7:25	95	9	DEP	NB	F70	0.0169	0.11	2	36740
95	5/15/13 7:24	5/15/13 7:35	94	10	DEP	NB	73W	0.0321	0.1106	2	69400
751	5/15/13 7:24	5/15/13 7:25	99	10	ARR	NB	320	0.0278	0.117	2	73500
96	5/15/13 7:26	5/15/13 7:00	95	4	DEP	WB	333	0.0675	0.2797	2	217000
97	5/15/13 7:27	5/15/13 7:30	94	11	DEP	NB	E90	0.0188	0.05	2	47790
98	5/15/13 7:27	5/15/13 7:20	95	9	DEP	NB	E90	0.0188	0.05	2	47790
99	5/15/13 7:27	5/15/13 7:15	94	9	DEP	NB	F70	0.0169	0.11	2	36740
100	5/15/13 7:28	5/15/13 7:05	95	1	DEP	NB	320	0.0278	0.117	2	73500
752	5/15/13 7:28	5/15/13 7:15	99	11	ARR	WB	343	0.0675	0.1204	4	271000
101	5/15/13 7:30	5/15/13 7:25	94	11	DEP	NB	F70	0.0169	0.11	2	36740
753	5/15/13 7:30	5/15/13 7:45	99	6	ARR	WB	332	0.0675	0.2736	2	230000
754	5/15/13 7:30	5/15/13 7:40	99	10	ARR	NB	73G	0.0321	0.1106	2	69400
102	5/15/13 7:31	5/15/13 7:10	95	9	DEP	NB	F70	0.0169	0.11	2	36740
103	5/15/13 7:31	5/15/13 7:30	94	9	DEP	NB	73W	0.0321	0.1106	2	69400
104	5/15/13 7:31	5/15/13 7:35	95	1	DEP	NB	320	0.0278	0.117	2	73500
755	5/15/13 7:31	5/15/13 7:30	99	11	ARR	NB	DH4	0.0087	0.051	2	16465
105	5/15/13 7:32	5/15/13 7:20	94	6	DEP	NB	73H	0.0321	0.1106	2	78220
106	5/15/13 7:33	5/15/13 7:25	95	10	DEP	NB	319	0.0278	0.1164	2	64000
107	5/15/13 7:34	5/15/13 7:20	94	9	DEP	NB	F70	0.0169	0.11	2	36740
108	5/15/13 7:34	5/15/13 7:30	95	9	DEP	NB	73H	0.0321	0.1106	2	78220
756	5/15/13 7:35	5/15/13 7:45	99	10	ARR	NB	M81	0.0296	0.1363	2	63500
757	5/15/13 7:36	5/15/13 7:40	99	10	ARR	NB	736	0.0321	0.1006	2	65090
109	5/15/13 7:36	5/15/13 7:15	94	11	DEP	NB	CR9	0.0231	0.0489	2	38330
110	5/15/13 7:37	5/15/13 7:35	95	9	DEP	NB	73H	0.0321	0.1106	2	78220
111	5/15/13 7:37	5/15/13 7:35	94	7	DEP	NB	73W	0.0321	0.1106	2	69400
112	5/15/13 7:38	5/15/13 7:20	95	8	DEP	NB	73H	0.0321	0.1106	2	78220
758	5/15/13 7:40	5/15/13 7:45	99	10	ARR	NB	320	0.0278	0.117	2	73500
113	5/15/13 7:40	5/15/13 7:40	94	9	DEP	NB	73W	0.0321	0.1106	2	69400
114	5/15/13 7:40	5/15/13 7:35	95	6	DEP	WB	M11	0.0583	0.2105	3	283720
115	5/15/13 7:40	5/15/13 7:30	94	11	DEP	NB	F70	0.0169	0.11	2	36740
116	5/15/13 7:42	5/15/13 7:40	95	9	DEP	NB	319	0.0278	0.1164	2	64000
117	5/15/13 7:44	5/15/13 7:45	94	8	DEP	NB	73W	0.0321	0.1106	2	69400
118	5/15/13 7:45	5/15/13 7:25	95	11	DEP	NB	F70	0.0169	0.11	2	36740
119	5/15/13 7:47	5/15/13 7:40	94	10	DEP	NB	73W	0.0321	0.1106	2	69400
120	5/15/13 7:47	5/15/13 7:40	95	11	DEP	NB	F70	0.0169	0.11	2	36740
121	5/15/13 7:48	5/15/13 7:40	94	10	DEP	NB	73H	0.0321	0.1106	2	78220
122	5/15/13 7:48	5/15/13 7:25	95	7	DEP	NB	320	0.0278	0.117	2	73500
123	5/15/13 7:48	5/15/13 7:35	94	1	DEP	NB	320	0.0278	0.117	2	73500
759	5/15/13 7:48	5/15/13 8:00	99	9	ARR	NB	73W	0.0321	0.1106	2	69400
124	5/15/13 7:49	5/15/13 7:40	95	8	DEP	NB	73H	0.0321	0.1106	2	78220
125	5/15/13 7:50	5/15/13 7:30	94	9	DEP	NB	321	0.0278	0.1272	2	89000
126	5/15/13 7:50	5/15/13 7:50	95	10	DEP	NB	ER4	0.0188	0.05	2	19200
127	5/15/13 7:50	5/15/13 7:45	94	11	DEP	NB	E90	0.0188	0.05	2	47790
128	5/15/13 7:50	5/15/13 7:40	95	10	DEP	NB	DH4	0.0087	0.051	2	16465
760	5/15/13 7:50	5/15/13 7:40	99	7	ARR	NB	319	0.0278	0.1164	2	64000
129	5/15/13 7:51	5/15/13 7:45	94	11	DEP	NB	F70	0.0169	0.11	2	36740
130	5/15/13 7:51	5/15/13 7:45	95	11	DEP	NB	E90	0.0188	0.05	2	47790
761	5/15/13 7:51	5/15/13 8:05	99	9	ARR	NB	AR8	0.0231	0.0453	4	42184

Table B.3: Processed flight schedule dataset sample of May 15th 2013, 06:55-08:45 for arrivals & 07:15-08:45 for departures. Part B

ID	StartTime (block)	StartTime (Scheduled)	Runway	Gate node	Kind	Aircraft type	IATA aircraft code	APU fuel flow [kg/s]	Engine fuel flow 7% [kg/s]	Number of engines	MTOW [kg]
131	5/15/13 7:52	5/15/13 7:30	94	7	DEP	NB	321	0.0278	0.1272	2	89000
762	5/15/13 7:52	5/15/13 8:10	99	11	ARR	NB	F70	0.0169	0.11	2	36740
763	5/15/13 7:52	5/15/13 8:00	99	8	ARR	NB	E70	0.0188	0.05	2	34000
132	5/15/13 7:54	5/15/13 7:40	95	6	DEP	NB	73H	0.0321	0.1106	2	78220
133	5/15/13 7:55	5/15/13 7:50	94	3	DEP	WB	744	0.1087	0.241	4	396830
134	5/15/13 7:55	5/15/13 7:55	95	1	DEP	NB	319	0.0278	0.1164	2	64000
135	5/15/13 7:56	5/15/13 7:45	94	10	DEP	NB	320	0.0278	0.117	2	73500
136	5/15/13 7:57	5/15/13 7:45	95	10	DEP	NB	73H	0.0321	0.1106	2	78220
764	5/15/13 7:57	5/15/13 7:50	99	9	ARR	NB	E75	0.0188	0.05	2	38790
137	5/15/13 7:58	5/15/13 8:00	94	10	DEP	NB	ER4	0.0188	0.05	2	19200
138	5/15/13 7:58	5/15/13 8:00	95	11	DEP	NB	E90	0.0188	0.05	2	47790
139	5/15/13 7:58	5/15/13 7:50	94	9	DEP	NB	DH4	0.0087	0.051	2	16465
140	5/15/13 7:59	5/15/13 8:00	95	6	DEP	NB	73W	0.0321	0.1106	2	69400
765	5/15/13 8:00	5/15/13 8:25	99	1	ARR	NB	320	0.0278	0.117	2	73500
141	5/15/13 8:00	5/15/13 7:50	94	2	DEP	WB	744	0.1087	0.241	4	396830
142	5/15/13 8:00	5/15/13 7:50	95	10	DEP	NB	733	0.0296	0.1181	2	56700
143	5/15/13 8:01	5/15/13 8:05	94	6	DEP	WB	332	0.0675	0.2736	2	230000
144	5/15/13 8:01	5/15/13 7:55	95	10	DEP	NB	319	0.0278	0.1164	2	64000
145	5/15/13 8:01	5/15/13 7:55	94	1	DEP	NB	319	0.0278	0.1164	2	64000
146	5/15/13 8:02	5/15/13 8:05	95	8	DEP	NB	73W	0.0321	0.1106	2	69400
147	5/15/13 8:02	5/15/13 8:00	94	11	DEP	NB	F70	0.0169	0.11	2	36740
148	5/15/13 8:02	5/15/13 8:00	95	3	DEP	WB	74E	0.1087	0.241	4	396830
766	5/15/13 8:03	5/15/13 7:40	99	11	ARR	NB	73H	0.0321	0.1106	2	78220
149	5/15/13 8:05	5/15/13 8:05	94	2	DEP	WB	772	0.0675	0.275	2	242670
150	5/15/13 8:05	5/15/13 8:05	95	10	DEP	NB	73H	0.0321	0.1106	2	78220
151	5/15/13 8:05	5/15/13 8:05	94	9	DEP	NB	E90	0.0188	0.05	2	47790
767	5/15/13 8:05	5/15/13 8:20	99	3	ARR	WB	772	0.0675	0.275	2	242670
152	5/15/13 8:06	5/15/13 8:05	95	6	DEP	WB	772	0.0675	0.275	2	242670
153	5/15/13 8:07	5/15/13 8:00	94	1	DEP	WB	772	0.0675	0.275	2	242670
154	5/15/13 8:08	5/15/13 7:55	95	3	DEP	WB	772	0.0675	0.275	2	242670
768	5/15/13 8:09	5/15/13 8:10	99	10	ARR	NB	320	0.0278	0.117	2	73500
769	5/15/13 8:10	5/15/13 8:10	99	7	ARR	NB	319	0.0278	0.1164	2	64000
770	5/15/13 8:11	5/15/13 8:15	99	10	ARR	NB	738	0.0321	0.1106	2	78220
155	5/15/13 8:12	5/15/13 8:05	94	7	DEP	NB	73H	0.0321	0.1106	2	78220
771	5/15/13 8:12	5/15/13 8:20	99	3	ARR	WB	772	0.0675	0.275	2	242670
772	5/15/13 8:12	5/15/13 8:15	99	10	ARR	NB	733	0.0296	0.1181	2	56700
156	5/15/13 8:13	5/15/13 8:05	95	11	DEP	NB	E90	0.0188	0.05	2	47790
157	5/15/13 8:13	5/15/13 8:00	94	10	DEP	NB	320	0.0278	0.117	2	73500
158	5/15/13 8:14	5/15/13 8:10	95	9	DEP	NB	F70	0.0169	0.11	2	36740
159	5/15/13 8:15	5/15/13 8:05	94	9	DEP	NB	DH4	0.0087	0.051	2	16465
160	5/15/13 8:16	5/15/13 8:10	95	10	DEP	NB	319	0.0278	0.1164	2	64000
773	5/15/13 8:19	5/15/13 8:00	99	11	ARR	NB	321	0.0278	0.1272	2	89000
161	5/15/13 8:20	5/15/13 7:35	94	11	DEP	NB	E90	0.0188	0.05	2	47790
162	5/15/13 8:20	5/15/13 7:50	95	1	DEP	WB	744	0.1087	0.241	4	396830
163	5/15/13 8:20	5/15/13 8:20	94	9	DEP	NB	73W	0.0321	0.1106	2	69400
164	5/15/13 8:20	5/15/13 8:10	95	1	DEP	WB	772	0.0675	0.275	2	242670
165	5/15/13 8:24	5/15/13 8:25	94	6	DEP	NB	73J	0.0321	0.1106	2	85130
774	5/15/13 8:24	5/15/13 8:40	97	3	ARR	WB	333	0.0675	0.2797	2	217000
166	5/15/13 8:25	5/15/13 8:15	95	7	DEP	NB	73J	0.0321	0.1106	2	85130
775	5/15/13 8:26	5/15/13 8:25	99	1	ARR	NB	320	0.0278	0.117	2	73500
167	5/15/13 8:28	5/15/13 8:15	94	11	DEP	NB	F70	0.0169	0.11	2	36740
168	5/15/13 8:29	5/15/13 8:20	95	7	DEP	NB	73H	0.0321	0.1106	2	78220
169	5/15/13 8:29	5/15/13 8:20	94	8	DEP	NB	320	0.0278	0.117	2	73500
776	5/15/13 8:29	5/15/13 8:30	97	8	ARR	NB	100	0.0231	0.1200	2	43090
170	5/15/13 8:31	5/15/13 8:15	95	9	DEP	NB	73H	0.0321	0.1106	2	78220
171	5/15/13 8:31	5/15/13 8:25	94	10	DEP	NB	M81	0.0296	0.1363	2	63500
172	5/15/13 8:32	5/15/13 8:20	95	3	DEP	WB	333	0.0675	0.2797	2	217000
173	5/15/13 8:32	5/15/13 8:35	94	9	DEP	NB	E75	0.0188	0.05	2	38790
777	5/15/13 8:32	5/15/13 8:30	99	10	ARR	NB	E95	0.0188	0.05	2	48790
174	5/15/13 8:33	5/15/13 8:35	95	6	DEP	WB	332	0.0675	0.2736	2	230000
175	5/15/13 8:33	5/15/13 8:20	94	10	DEP	NB	73G	0.0321	0.1106	2	69400
176	5/15/13 8:34	5/15/13 8:35	95	2	DEP	WB	332	0.0675	0.2736	2	230000
177	5/15/13 8:34	5/15/13 8:35	94	3	DEP	WB	333	0.0675	0.2797	2	217000
178	5/15/13 8:35	5/15/13 8:35	95	4	DEP	WB	333	0.0675	0.2797	2	217000
179	5/15/13 8:35	5/15/13 8:20	94	10	DEP	NB	736	0.0321	0.1006	2	65090
180	5/15/13 8:36	5/15/13 8:20	95	2	DEP	WB	343	0.0675	0.1204	4	271000
778	5/15/13 8:36	5/15/13 8:45	97	10	ARR	NB	73W	0.0321	0.1106	2	69400
181	5/15/13 8:37	5/15/13 8:35	94	4	DEP	WB	332	0.0675	0.2736	2	230000
182	5/15/13 8:38	5/15/13 8:55	95	1	DEP	NB	320	0.0278	0.117	2	73500
183	5/15/13 8:40	5/15/13 8:30	94	7	DEP	NB	319	0.0278	0.1164	2	64000
779	5/15/13 8:40	5/15/13 8:35	99	10	ARR	NB	735	0.0296	0.1148	2	52390
780	5/15/13 8:40	5/15/13 8:40	97	11	ARR	NB	320	0.0278	0.117	2	73500
184	5/15/13 8:42	5/15/13 8:50	95	4	DEP	WB	75W	0.0338	0.19	2	115900
781	5/15/13 8:42	5/15/13 8:30	99	11	ARR	WB	752	0.0338	0.19	2	115900
782	5/15/13 8:44	5/15/13 8:50	97	10	ARR	NB	73W	0.0321	0.1106	2	69400
783	5/15/13 8:45	5/15/13 8:55	99	10	ARR	NB	73H	0.0321	0.1106	2	78220
784	5/15/13 8:45	5/15/13 8:40	97	7	ARR	NB	73H	0.0321	0.1106	2	78220

Table B.4: Processed flight schedule dataset sample of May 15th 2013, 10:25-11:45 for arrivals & 10:45-11:45 for departures. Part A

ID	StartTime (block)	StartTime (Scheduled)	Runway	Gate node	Kind	Aircraft type	IATA aircraft code	APU fuel flow [kg/s]	Engine fuel flow 7% [kg/s]	Number of engines	MTOW [kg]
853	5/15/13 10:25	5/15/13 8:40	99	3	ARR	WB	763	0.0338	0.2542	2	156489
854	5/15/13 10:29	5/15/13 10:20	99	11	ARR	NB	F70	0.0169	0.11	2	36740
855	5/15/13 10:31	5/15/13 10:30	99	2	ARR	WB	772	0.0675	0.275	2	242670
856	5/15/13 10:32	5/15/13 10:30	99	7	ARR	NB	73W	0.0321	0.1106	2	69400
857	5/15/13 10:33	5/15/13 10:25	99	11	ARR	NB	F70	0.0169	0.11	2	36740
858	5/15/13 10:35	5/15/13 10:35	99	11	ARR	NB	F70	0.0169	0.11	2	36740
859	5/15/13 10:35	5/15/13 10:35	99	11	ARR	NB	E90	0.0188	0.05	2	47790
860	5/15/13 10:37	5/15/13 10:30	99	11	ARR	NB	E90	0.0188	0.05	2	47790
861	5/15/13 10:40	5/15/13 10:00	97	11	ARR	WB	752	0.0338	0.19	2	115900
862	5/15/13 10:44	5/15/13 11:00	99	3	ARR	WB	332	0.0675	0.2736	2	230000
863	5/15/13 10:46	5/15/13 10:00	97	10	ARR	NB	320	0.0278	0.117	2	73500
260	5/15/13 10:46	5/15/13 10:40	94	10	DEP	NB	73H	0.0321	0.1106	2	78220
261	5/15/13 10:48	5/15/13 10:45	94	6	DEP	NB	73H	0.0321	0.1106	2	78220
262	5/15/13 10:48	5/15/13 10:25	94	7	DEP	NB	738	0.0321	0.1106	2	78220
864	5/15/13 10:49	5/15/13 10:50	99	9	ARR	NB	73H	0.0321	0.1106	2	78220
263	5/15/13 10:50	5/15/13 10:55	94	9	DEP	NB	F70	0.0169	0.11	2	36740
264	5/15/13 10:50	5/15/13 10:45	94	9	DEP	NB	F70	0.0169	0.11	2	36740
265	5/15/13 10:51	5/15/13 10:50	94	6	DEP	NB	73H	0.0321	0.1106	2	78220
865	5/15/13 10:53	5/15/13 11:00	97	2	ARR	NB	73H	0.0321	0.1106	2	78220
866	5/15/13 10:54	5/15/13 10:40	99	10	ARR	NB	320	0.0278	0.117	2	73500
867	5/15/13 10:55	5/15/13 11:10	97	10	ARR	NB	73H	0.0321	0.1106	2	78220
868	5/15/13 10:56	5/15/13 10:40	99	10	ARR	NB	E95	0.0188	0.05	2	48790
266	5/15/13 10:56	5/15/13 10:55	94	1	DEP	WB	343	0.0675	0.1204	4	271000
869	5/15/13 10:58	5/15/13 11:10	97	11	ARR	NB	F70	0.0169	0.11	2	36740
870	5/15/13 10:59	5/15/13 11:00	99	11	ARR	NB	734	0.0296	0.1238	2	62820
871	5/15/13 11:00	5/15/13 10:45	97	11	ARR	NB	320	0.0278	0.117	2	73500
267	5/15/13 11:00	5/15/13 11:00	94	11	DEP	NB	F70	0.0169	0.11	2	36740
872	5/15/13 11:01	5/15/13 10:55	99	9	ARR	NB	320	0.0278	0.117	2	73500
873	5/15/13 11:01	5/15/13 11:00	97	10	ARR	NB	73H	0.0321	0.1106	2	78220
874	5/15/13 11:02	5/15/13 10:50	99	6	ARR	NB	73H	0.0321	0.1106	2	78220
875	5/15/13 11:02	5/15/13 10:55	97	11	ARR	NB	F70	0.0169	0.11	2	36740
268	5/15/13 11:02	5/15/13 9:45	94	4	DEP	WB	332	0.0675	0.2736	2	230000
876	5/15/13 11:03	5/15/13 9:40	99	3	ARR	NB	313	0.0338	0.1959	2	150000
877	5/15/13 11:04	5/15/13 11:05	97	4	ARR	WB	333	0.0675	0.2797	2	217000
878	5/15/13 11:05	5/15/13 11:10	99	11	ARR	NB	E90	0.0188	0.05	2	47790
269	5/15/13 11:05	5/15/13 11:05	94	4	DEP	WB	77W	0.0675	0.3	2	299370
270	5/15/13 11:05	5/15/13 11:05	94	4	DEP	WB	763	0.0338	0.2542	2	156489
271	5/15/13 11:06	5/15/13 11:00	94	8	DEP	NB	320	0.0278	0.117	2	73500
272	5/15/13 11:07	5/15/13 10:55	94	10	DEP	NB	73H	0.0321	0.1106	2	78220
273	5/15/13 11:08	5/15/13 9:45	94	1	DEP	WB	763	0.0338	0.2542	2	156489
879	5/15/13 11:09	5/15/13 10:40	97	9	ARR	WB	75W	0.0338	0.19	2	115900
880	5/15/13 11:10	5/15/13 11:10	99	9	ARR	NB	73H	0.0321	0.1106	2	78220
881	5/15/13 11:10	5/15/13 10:05	97	11	ARR	NB	73H	0.0321	0.1106	2	78220
882	5/15/13 11:12	5/15/13 11:00	99	4	ARR	WB	332	0.0675	0.2736	2	230000
883	5/15/13 11:12	5/15/13 11:30	97	10	ARR	NB	73J	0.0321	0.1106	2	85130
884	5/15/13 11:12	5/15/13 11:25	99	10	ARR	NB	73W	0.0321	0.1106	2	69400
274	5/15/13 11:13	5/15/13 11:20	94	3	DEP	WB	333	0.0675	0.2797	2	217000
275	5/15/13 11:13	5/15/13 11:00	94	9	DEP	NB	73H	0.0321	0.1106	2	78220
885	5/15/13 11:16	5/15/13 11:05	97	8	ARR	NB	319	0.0278	0.1164	2	64000
276	5/15/13 11:16	5/15/13 11:20	94	3	DEP	WB	772	0.0675	0.275	2	242670
886	5/15/13 11:19	5/15/13 11:30	99	11	ARR	NB	ER4	0.0188	0.05	2	19200
887	5/15/13 11:19	5/15/13 11:40	97	10	ARR	NB	73H	0.0321	0.1106	2	78220
888	5/15/13 11:19	5/15/13 11:45	99	9	ARR	NB	73H	0.0321	0.1106	2	78220
277	5/15/13 11:19	5/15/13 11:10	94	11	DEP	NB	E90	0.0188	0.05	2	47790
889	5/15/13 11:20	5/15/13 11:00	97	7	ARR	NB	738	0.0321	0.1106	2	78220
278	5/15/13 11:20	5/15/13 11:05	94	11	DEP	NB	E90	0.0188	0.05	2	47790
890	5/15/13 11:21	5/15/13 11:20	99	11	ARR	NB	E90	0.0188	0.05	2	47790
891	5/15/13 11:21	5/15/13 11:30	97	7	ARR	NB	73W	0.0321	0.1106	2	69400
892	5/15/13 11:22	5/15/13 11:40	99	11	ARR	NB	E90	0.0188	0.05	2	47790
279	5/15/13 11:22	5/15/13 9:10	94	9	DEP	WB	76W	0.0338	0.2044	2	136078
280	5/15/13 11:23	5/15/13 11:10	94	4	DEP	NB	321	0.0278	0.1272	2	89000
893	5/15/13 11:24	5/15/13 11:30	97	1	ARR	WB	388	0.1305	0.4	4	540000
894	5/15/13 11:25	5/15/13 11:30	99	10	ARR	NB	73H	0.0321	0.1106	2	78220
895	5/15/13 11:26	5/15/13 11:30	97	6	ARR	NB	73W	0.0321	0.1106	2	69400
281	5/15/13 11:26	5/15/13 11:25	94	6	DEP	WB	333	0.0675	0.2797	2	217000
896	5/15/13 11:27	5/15/13 11:40	99	10	ARR	NB	320	0.0278	0.117	2	73500
282	5/15/13 11:27	5/15/13 11:25	94	3	DEP	WB	744	0.1087	0.241	4	396830
897	5/15/13 11:28	5/15/13 11:25	97	10	ARR	NB	73W	0.0321	0.1106	2	69400
898	5/15/13 11:28	5/15/13 11:30	99	11	ARR	NB	E90	0.0188	0.05	2	47790
283	5/15/13 11:29	5/15/13 11:10	94	6	DEP	NB	73H	0.0321	0.1106	2	78220
899	5/15/13 11:30	5/15/13 11:35	99	7	ARR	NB	73W	0.0321	0.1106	2	69400
284	5/15/13 11:30	5/15/13 11:25	94	7	DEP	NB	73W	0.0321	0.1106	2	69400
285	5/15/13 11:30	5/15/13 11:35	94	3	DEP	WB	333	0.0675	0.2797	2	217000
900	5/15/13 11:31	5/15/13 11:35	99	10	ARR	NB	73W	0.0321	0.1106	2	69400
901	5/15/13 11:32	5/15/13 11:40	99	11	ARR	NB	E90	0.0188	0.05	2	47790
286	5/15/13 11:32	5/15/13 11:20	94	2	DEP	WB	332	0.0675	0.2736	2	230000
902	5/15/13 11:33	5/15/13 11:15	99	10	ARR	NB	320	0.0278	0.117	2	73500
903	5/15/13 11:34	5/15/13 11:35	99	9	ARR	NB	73W	0.0321	0.1106	2	69400

Table B.5: Processed flight schedule dataset sample of May 15th 2013, 10:25-11:45 for arrivals & 10:45-11:45 for departures. Part B

ID	StartTime (block)	StartTime (Scheduled)	Runway	Gate node	Kind	Aircraft type	IATA aircraft code	APU fuel flow [kg/s]	Engine fuel flow 7% [kg/s]	Number of engines	MTOW [kg]
904	5/15/13 11:34	5/15/13 11:40	99	11	ARR	NB	F70	0.0169	0.11	2	36740
905	5/15/13 11:35	5/15/13 11:40	99	1	ARR	NB	321	0.0278	0.1272	2	89000
287	5/15/13 11:35	5/15/13 11:20	94	10	DEP	NB	E95	0.0188	0.05	2	48790
906	5/15/13 11:36	5/15/13 11:30	99	11	ARR	NB	ER4	0.0188	0.05	2	19200
907	5/15/13 11:37	5/15/13 11:35	99	11	ARR	NB	F70	0.0169	0.11	2	36740
288	5/15/13 11:37	5/15/13 11:20	94	11	DEP	NB	F70	0.0169	0.11	2	36740
908	5/15/13 11:38	5/15/13 11:40	99	11	ARR	NB	E90	0.0188	0.05	2	47790
909	5/15/13 11:38	5/15/13 10:15	99	11	ARR	NB	73H	0.0321	0.1106	2	78220
910	5/15/13 11:39	5/15/13 11:35	99	11	ARR	NB	F70	0.0169	0.11	2	36740
911	5/15/13 11:41	5/15/13 11:05	99	2	ARR	WB	772	0.0675	0.275	2	242670
912	5/15/13 11:42	5/15/13 11:25	99	11	ARR	NB	F70	0.0169	0.11	2	36740
913	5/15/13 11:42	5/15/13 11:40	99	8	ARR	NB	73W	0.0321	0.1106	2	69400
289	5/15/13 11:42	5/15/13 11:05	94	11	DEP	NB	F70	0.0169	0.11	2	36740
914	5/15/13 11:43	5/15/13 11:20	99	1	ARR	NB	319	0.0278	0.1164	2	64000
915	5/15/13 11:44	5/15/13 11:35	99	9	ARR	NB	73W	0.0321	0.1106	2	69400
916	5/15/13 11:45	5/15/13 11:20	99	11	ARR	NB	734	0.0296	0.1238	2	62820
290	5/15/13 11:45	5/15/13 11:45	94	10	DEP	NB	320	0.0278	0.117	2	73500

C
Appendix

See next page.

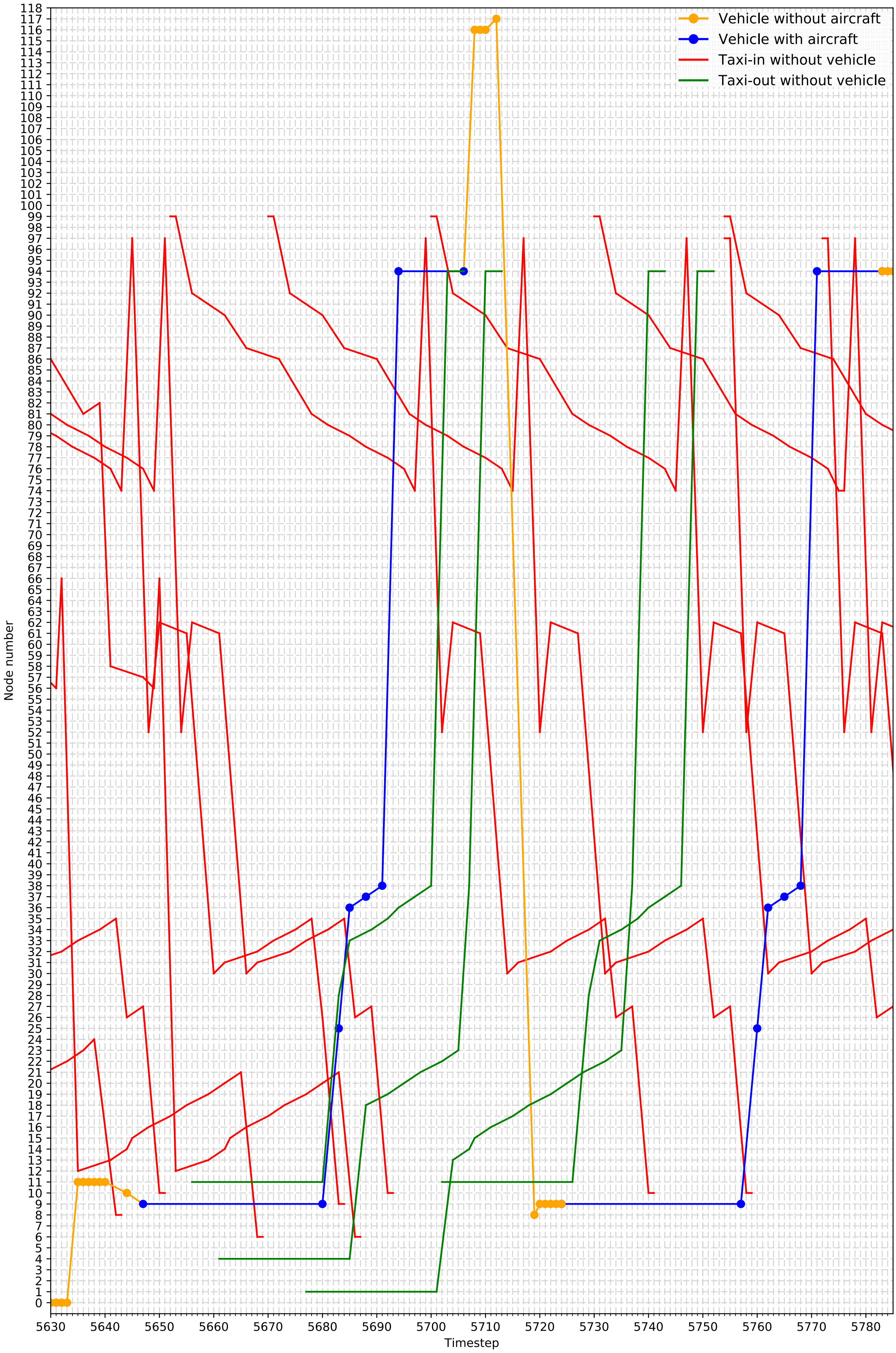
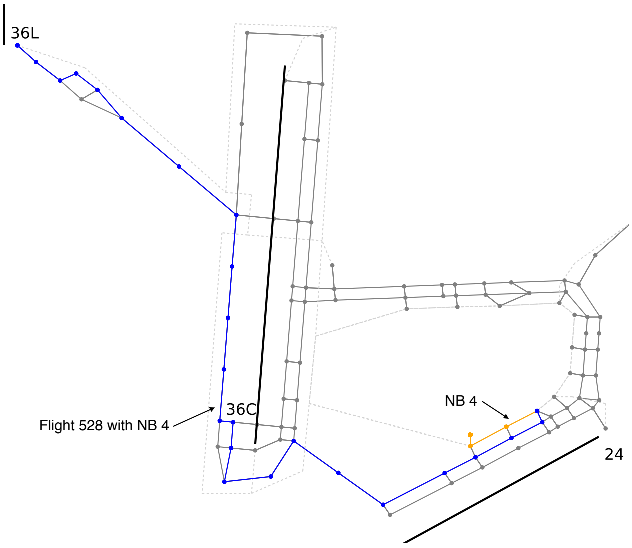


Figure C.1: Time-space graph of in-bound and out-bound taxiing traffic at the surface of AAS using one WB AGV.

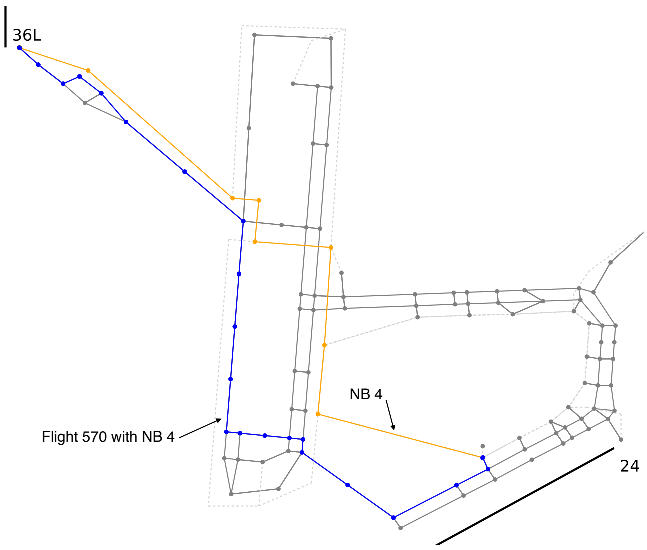
Figure C.2: Time-space graph of in-bound and out-bound taxiing traffic at the surface of AAS using two WB AGVs.

Table C.1: Time-space table of vehicle NB4. When NB4 is connected to a flight, this is indicated in bold.

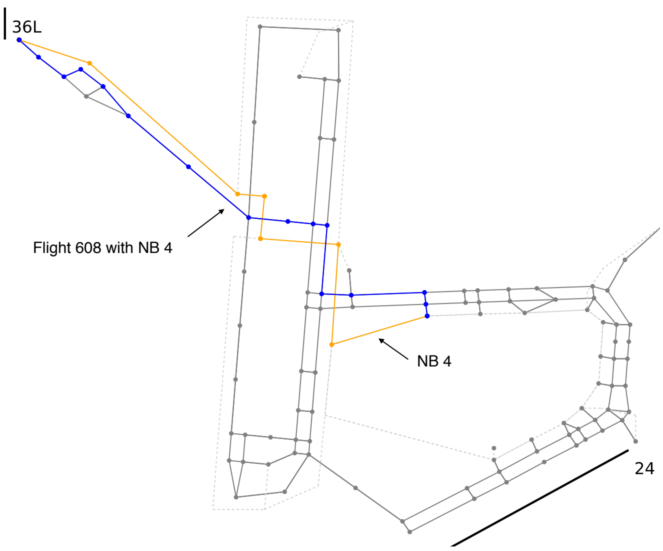
Timestep	Position NB4	Timestep	Position NB4	Timestep	Position NB4	Timestep	Position NB4	Timestep	Position NB4
3738	(0, 0)	3840	**(79, 80)**	3924	(110, 109)	4026	**(80, 81)**	4114	(110, 109)
3739	(0, 11)	3841	**(79, 80)**	3925	(110, 109)	4027	**(81, 86)**	4115	(109, 1)
3740	(0, 11)	3842	**(79, 80)**	3926	(110, 109)	4028	**(81, 86)**	4116	(109, 1)
3741	(11, 11)	3843	**(80, 81)**	3927	(110, 109)	4029	**(81, 86)**	4117	(109, 1)
3742	(11, 10)	3844	**(80, 81)**	3928	(110, 109)	4030	**(81, 86)**	4118	(109, 1)
3743	(11, 10)	3845	**(80, 81)**	3929	(109, 108)	4031	**(81, 86)**	4119	(109, 1)
3744	(11, 10)	3846	**(80, 81)**	3930	(109, 108)	4032	**(81, 86)**	4120	(109, 1)
3745	(11, 10)	3847	**(81, 86)**	3931	(109, 108)	4033	**(81, 86)**	4121	(109, 1)
3746	(10, 10)	3848	**(81, 86)**	3932	(109, 108)	4034	**(86, 87)**	4122	(109, 1)
3747	(10, 9)	3849	**(81, 86)**	3933	(108, 11)	4035	**(86, 87)**	4123	**(1, 1)**
3748	(10, 9)	3850	**(81, 86)**	3934	(108, 11)	4036	**(86, 87)**	|	|
3749	(10, 9)	3851	**(81, 86)**	3935	(108, 11)	4037	**(86, 87)**	4155	**(1, 1)**
3750	**(9, 9)**	3852	**(81, 86)**	3936	(108, 11)	4038	**(86, 87)**	4156	**(1, 13)**
|	|	3853	**(81, 86)**	3937	(108, 11)	4039	**(86, 87)**	4157	**(1, 13)**
3782	**(9, 9)**	3854	**(86, 87)**	3938	(108, 11)	4040	**(86, 87)**	4158	**(1, 13)**
3783	**(9, 26)**	3855	**(86, 87)**	3939	(108, 11)	4041	**(87, 88)**	4159	**(13, 50)**
3784	**(9, 26)**	3856	**(86, 87)**	3940	(108, 11)	4042	**(87, 88)**	4160	**(50, 51)**
3785	**(9, 26)**	3857	**(86, 87)**	3941	(108, 11)	4043	**(87, 88)**	4161	**(50, 51)**
3786	**(26, 27)**	3858	**(86, 87)**	3942	(108, 11)	4044	**(87, 88)**	4162	**(50, 51)**
3787	**(26, 27)**	3859	**(86, 87)**	3943	(108, 11)	4045	**(88, 89)**	4163	**(50, 51)**
3788	**(26, 27)**	3860	**(86, 87)**	3944	**(11, 11)**	4046	**(88, 89)**	4164	**(50, 51)**
3789	**(27, 28)**	3861	**(87, 88)**	|	|	4047	**(88, 89)**	4165	**(50, 51)**
3790	**(27, 28)**	3862	**(87, 88)**	3976	**(11, 11)**	4048	**(89, 91)**	4166	**(51, 67)**
3791	**(27, 28)**	3863	**(87, 88)**	3977	**(11, 28)**	4049	**(89, 91)**	4167	**(51, 67)**
3792	**(27, 28)**	3864	**(87, 88)**	3978	**(11, 28)**	4050	**(91, 92)**	4168	**(51, 67)**
3793	**(28, 29)**	3865	**(88, 89)**	3979	**(11, 28)**	4051	**(91, 92)**	4169	**(67, 68)**
3794	**(28, 29)**	3866	**(88, 89)**	3980	**(28, 29)**	4052	**(91, 92)**	4170	**(67, 68)**
3795	**(28, 29)**	3867	**(88, 89)**	3981	**(28, 29)**	4053	**(92, 99)**	4171	**(67, 68)**
3796	**(29, 30)**	3868	**(89, 91)**	3982	**(28, 29)**	4054	**(92, 99)**	4172	**(67, 68)**
3797	**(29, 30)**	3869	**(89, 91)**	3983	**(29, 30)**	4055	**(92, 99)**	4173	**(67, 68)**
3798	**(29, 30)**	3870	**(91, 92)**	3984	**(29, 30)**	4056	**(99, 99)**	4174	**(67, 68)**
3799	**(29, 30)**	3871	**(91, 92)**	3985	**(29, 30)**	|	|	4175	**(68, 58)**
3800	**(29, 30)**	3872	**(91, 92)**	3986	**(29, 30)**	4067	**(99, 99)**	4176	**(68, 58)**
3801	**(29, 30)**	3873	**(92, 99)**	3987	**(29, 30)**	4068	(99, 99)	4177	**(58, 82)**
3802	**(30, 61)**	3874	**(92, 99)**	3988	**(29, 30)**	|	|	4178	**(58, 82)**
3803	**(30, 61)**	3875	**(92, 99)**	3989	**(30, 61)**	4077	(99, 99)	4179	**(82, 81)**
3804	**(30, 61)**	3876	**(99, 99)**	3990	**(30, 61)**	4078	(99, 100)	4180	**(82, 81)**
3805	**(30, 61)**	|	|	3991	**(30, 61)**	4079	(99, 100)	4181	**(82, 81)**
3806	**(30, 61)**	3887	**(99, 99)**	3992	**(30, 61)**	4080	(99, 100)	4182	**(81, 86)**
3807	**(61, 62)**	3888	(99, 99)	3993	**(30, 61)**	4081	(99, 100)	4183	**(81, 86)**
3808	**(61, 62)**	|	|	3994	**(61, 62)**	4082	(100, 101)	4184	**(81, 86)**
3809	**(61, 62)**	3893	(99, 99)	3995	**(61, 62)**	4083	(100, 101)	4185	**(81, 86)**
3810	**(61, 62)**	3894	(99, 100)	3996	**(61, 62)**	4084	(100, 101)	4186	**(81, 86)**
3811	**(61, 62)**	3895	(99, 100)	3997	**(61, 62)**	4085	(100, 101)	4187	**(81, 86)**
3812	**(62, 72)**	3896	(99, 100)	3998	**(61, 62)**	4086	(100, 101)	4188	**(81, 86)**
3813	**(62, 72)**	3897	(99, 100)	3999	**(62, 63)**	4087	(100, 101)	4189	**(86, 87)**
3814	**(62, 72)**	3898	(100, 101)	4000	**(62, 63)**	4088	(100, 101)	4190	**(86, 87)**
3815	**(62, 72)**	3899	(100, 101)	4001	**(63, 53)**	4089	(100, 101)	4191	**(86, 87)**
3816	**(72, 73)**	3900	(100, 101)	4002	**(63, 53)**	4090	(100, 101)	4192	**(86, 87)**
3817	**(72, 73)**	3901	(100, 101)	4003	**(53, 71)**	4091	(100, 101)	4193	**(86, 87)**
3818	**(72, 73)**	3902	(100, 101)	4004	**(53, 71)**	4092	(100, 101)	4194	**(86, 87)**
3819	**(72, 73)**	3903	(100, 101)	4005	**(71, 75)**	4093	(101, 102)	4195	**(86, 87)**
3820	**(73, 74)**	3904	(100, 101)	4006	**(71, 75)**	4094	(101, 102)	4196	**(87, 88)**
3821	**(73, 74)**	3905	(100, 101)	4007	**(75, 77)**	4095	(101, 102)	4197	**(87, 88)**
3822	**(73, 74)**	3906	(100, 101)	4008	**(75, 77)**	4096	(102, 102)	4198	**(87, 88)**
3823	**(73, 74)**	3907	(100, 101)	4009	**(77, 78)**	4097	(102, 103)	4199	**(87, 88)**
3824	**(74, 75)**	3908	(100, 101)	4010	**(77, 78)**	4098	(102, 103)	4200	**(88, 89)**
3825	**(74, 75)**	3909	(101, 102)	4011	**(77, 78)**	4099	(102, 103)	4201	**(88, 89)**
3826	**(74, 75)**	3910	(101, 102)	4012	**(77, 78)**	4100	(103, 103)	4202	**(88, 89)**
3827	**(75, 77)**	3911	(101, 102)	4013	**(77, 78)**	4101	(103, 110)	4203	**(89, 91)**
3828	**(75, 77)**	3912	(102, 103)	4014	**(78, 79)**	4102	(103, 110)	4204	**(89, 91)**
3829	**(77, 78)**	3913	(102, 103)	4015	**(78, 79)**	4103	(103, 110)	4205	**(91, 92)**
3830	**(77, 78)**	3914	(102, 103)	4016	**(78, 79)**	4104	(103, 110)	4206	**(91, 92)**
3831	**(77, 78)**	3915	(103, 110)	4017	**(78, 79)**	4105	(103, 110)	4207	**(91, 92)**
3832	**(77, 78)**	3916	(103, 110)	4018	**(79, 80)**	4106	(103, 110)	4208	**(92, 99)**
3833	**(77, 78)**	3917	(103, 110)	4019	**(79, 80)**	4107	(110, 109)	4209	**(92, 99)**
3834	**(78, 79)**	3918	(103, 110)	4020	**(79, 80)**	4108	(110, 109)	4210	**(92, 99)**
3835	**(78, 79)**	3919	(103, 110)	4021	**(79, 80)**	4109	(110, 109)	4211	**(99, 99)**
3836	**(78, 79)**	3920	(103, 110)	4022	**(79, 80)**	4110	(110, 109)	|	|
3837	**(78, 79)**	3921	(110, 109)	4023	**(80, 81)**	4111	(110, 109)	4222	**(99, 99)**
3838	**(79, 80)**	3922	(110, 109)	4024	**(80, 81)**	4112	(110, 109)	4223	(99, 99)
3839	**(79, 80)**	3923	(110, 109)	4025	**(80, 81)**	4113	(110, 109)		



(a) Path NB 4 for towing flight 528.



(b) Path NB 4 for towing flight 570.



(c) Path NB 4 for towing flight 608

Figure C.3: Routes taken by NB 4 in time interval 10:45-11:45, depending on the active runways.