Assignment of Electric Towing Vehicles for Flights and Balanced Battery Recharging

Master Thesis Report

Edward Hyde

Technische Universiteit Delft

Assignment of electric towing vehicles for flights and balanced battery recharging

Master Thesis Report

by

Edward J.A. Hyde

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Thursday January 18th 2024 at 10:30 hours.

Version 1.0
Publication date: January 9, 2024

Student number:	4285174	
Project duration:	September 2022 – January 2024	
Thesis committee:	Dr. Alessandro Bombelli	TU Delft, Chair
	Dr. ir. Joost Ellerbroek	TU Delft, Examiner
	Ir. Paul C. Roling	TU Delft, Responsible Thesis Supervisor
	Ir. Eneko Rodriguez	To70, Daily supervisor

Cover Image: TaxiBot and Corendon Boeing 737 tests. Schiphol, 15-04-2020 by RCremers |
https://news.schiphol.com/schiphol-and-partners-to-begin-sustainable-aircraft-taxiing-trial/

An electronic version of this thesis is available at http://repository.tudelft.nl/.

TU Delft

Acknowledgements

By handing in this thesis, I will conclude my studies at TU Delft and obtain my master's degree in aerospace engineering. Ever since high school I have had the ambition to say this. After my time at the TU Eindhoven and getting my bachelor's in mechanical engineering, it was possible for me to study aerospace engineering. I must say that Air Transport and Operations was the perfect mix of subjects for me that kept sparking my enthusiasm. Next, I want to thank the following people that played an important role for me throughout my thesis.

Paul, I greatly value your enthusiasm, patience and our discussions throughout my thesis. I enjoyed coming to the many meetings we had and will honestly miss them. There was always an array of questions I could ask to you but I also went away with an array of input for my research after the meeting. Not only on a professional level were you able to support me but also on a personal level.

I want to thank Kjeld and Ruud from To70 for the opportunity of doing my thesis with you. And I want to thank all my colleagues at To70 for making this final part of my studies an extra enjoyable experience. Not only have I learned so much more about aviation, but I also developed my personal (Fußball) skills. Arwin and Eneko, I could not have wished for a better set of mentors. Arwin, I appreciate your unique insights and engagement throughout my thesis. I value that you let me tell my story and brainstorm together to come to new ideas. Eneko, the pace at which you came up to speed with my subject really tells it all. You have a talent in knowing what I needed in every phase and what I needed to pay extra attention to. I look very much forward to continue working together with all of you after my graduation.

Sarah, Astrid and Kirsten thank you for supporting me with your sisterly love. You have always given me the feeling that I can come to you with anything but especially during the phases when I could not think of anything else.

Peter, thank you for that extra push you gave me to pursue this master. As agreed, now comes the time to keep to our promise and to give that push for our parachute jump over Texel.

I don't really know how to thank you Thyra. Your advice and skills in making visuals made this thesis and the presentations look so much better and also partly yours. Thanks for always being there for me and making some challenging phases feel so much easier to overcome.

Edward Hyde
Rotterdam, January 2024

Revision History

Version	Date	Changes
0	**Thursday 4th January, 2024**	**Thesis report**
1.0	**Tuesday 9th January, 2024**	**Final thesis report** Scientific paper, section 2.9: - Table 3: added symbols F_e and R_e. - Equation 14a: reversed the summations of the first term and the third term. - Equation 14b: changed summation $e \in E$ into $e \in E_f$. - Equation 14c: reversed notations $e \in E_f$ and $t \in T$. - Equation 14d: changed notation $e \in E$ into $e \in E_f$. - Equation 14f&g: changed and reversed notations $e \in E$, $f \in F$ into $f \in F_e$, $e \in E_f$. - Equation 14h: changed notation $e \in E$ into $e \in E_f$.

Contents

List of Figures

List of Tables

List of Symbols

Symbol	Definition	Unit	Page
μ_0	rolling resistance base coefficient	-	5
μ_g	rolling resistance	-	5
B_e^C	percentage for balanced recharging of ETV e	-	7
C	cost	-	6
FF	fuel flow	$\mathrm{kg\,s^{-1}}$	5
F	fuel	kg	5
g	gravitational acceleration	$\mathrm{m\,s^{-2}}$	5
m_e	ETV mass	t	3
m_f	mass of flight f	t	5
N_{eng_f}	number of engines	min	5
P_e^C	charging power	kW	4
P	power	kW	5
Q_e^C	battery capacity	kWh	3
Q_r^C	energy per charging block r	kWh	6
Q	energy consumption	kWh	6
t_e^E	task end time	min	3
T_f^E	tow end time	min	4
t_e^S	task start time	min	3
T_f^S	tow start time	min	4
t_f	ferry time	min	4
t_h	handling time	min	4
t_p	processing time	min	4
t_r	ready time	min	4
t_{ECD}	engine cool-down time	min	5
t_{EWU}	engine warm-up time	min	5
$t_{horizon}$	horizon duration	h	4
$t_{overlap}$	horizon overlap	h	4
t_{taxi_f}	taxiing time	min	5
t_{tow_f}	towing time	min	5
v_0	rolling resistance base velocity	$\mathrm{m\,s^{-1}}$	5
v_s	service road velocity	$\mathrm{m\,s^{-1}}$	2
v_t	towing velocity	$\mathrm{m\,s^{-1}}$	3

List of Abbreviations

Abbreviation	Definition	Page
CO_2	Carbon Dioxide	47
NO_x	Nitrogen Oxides	47
A-CDM	Aiport Collaborative Decision-Making	38
ACGT	Actual Commence Ground Handling Time	39
AEON	Advanced Engine-Off Navigation	33
AGM	Airport Ground Movement	53
AIBT	Actual In-Block Time	39
ALDT	Actual Landing Time	39
AMS	Amsterdam Airport Schiphol	33
AOBT	Actual Off-Block Time	39
APU	Auxiliary Power Unit	36
ARDT	Actual Ready Time	40
ASAT	Actual Start-up Approval Time	39
ATC	Air Traffic Control	40
ATFM	Air Traffic Flow Management	46
ATOT	Actual Take-off Time	38
CFMU	Central Flow Management Unit	54
CO	Carbon Monoxide	35
DIT	Dispatch Inbound Tow	41
DOT	Dispatch Outbound Tow	41
E-VRP-TW	Electric Vehicle Routing Problem with Time windows	56
EIBT	Estimated In-Block Time	39
ELDT	Estimated Landing Time	39
EOBT	Estimated Off-Block Time	39
ETV	Electric Towing Vehicle	37
EVRP	Electric Vehicle Routing Problem	55
EXIT	Estimated Taxi-In Time	39
EXOT	Estimated Taxi-Out Time	39
FOCA	Federal Office of Civil Aviation	24
GA	Genetic Algorithm	55
GAP	Gate Assignment Problem	52
GSE	Ground Support Equipment	36
HC	Hydrocarbons	47
IATA	International Air Transport Association	33
ICAO	International Civil Aviation Organization	33
ICP	Integral Capacity Plan	3
MILP	Mixed-Integer Linear Programming	48
MIP	Mixed Integer Programming	48
MTOW	Maximum Take-off Weight	38
MTTT	Minimum Turnaround Time	39
NB	Narrow Body	37
NLG	Nose Landing Gear	36
PM	Particulate Matter	47
SAF	Sustainable Aviation Fuels	33
SET	Single-engine Taxiing	35
SOBT	Scheduled Off-Block Time	39
TBLT	Towbarless Tractor	36
TOBT	Target Off-Block Time	39
TSAT	Target Start-Up Approval Time	39
TTOT	Target Take-Off Time	39
UHC	Unburned Hydrocarbons	35
UID	Unique Identification Number	5
VRP	Vehicle Routing Problem	55
WB	Wide Body	37
WTC	Wake Turbulence Category	8

Introduction

In this report, a thesis project containing a scientific paper, literature study and appendices are presented. The overall goal that started this project was to look into the sustainable developments made possible by towing aircraft with the TaxiBot [64].

With this goal in mind, discussions with TU Delft and To70 took place to formalise the project. The daily work of this project was carried out at To70, an aviation consultancy located in The Hague. To70 employs various aviation experts and specialists such as pilots and Air Traffic Control Operators (ATCOs) but also analysts with experience in the same topic, with whom interviews were held. Furthermore, To70 provided the flight schedule data of which the analyses of this research are based on. At TU Delft, the research project was supported by main supervision from the lecturer and various research facilities, such as software licences for the commercial solver and the library.

First a literature study was conducted to look into the background of the topic, formulate a research scope and objective. The objective in the literature study has been deviated from in the eventual scientific paper. Therefore, for the discrepancies between the paper and the literature study the content of the scientific paper should be considered the most actual version.

In this research, new insights of towing aircraft at airports with a conceptual electric towing vehicle are obtained. The most considerable contribution is the insight in what amounts of fuel costs are saved for different towing vehicle fleet sizes. Furthermore, the (operational) challenges of how to achieve these savings are discussed for the specific implementation at Amsterdam Airport Schiphol.

This thesis report is organised as follows: In Part I, the scientific paper is presented. Part II contains the literature study that supports the scientific paper. Finally, in Part III, the additional results that were not shown in the scientific paper are presented.

I

Scientific Paper

Assignment of electric towing vehicles for flights and balanced battery recharging

Edward J.A. Hyde*, Ir. Paul C. Roling†, Ir. Arwin Khoshnewiszadeh‡, Ir. Eneko Rodriguez‡

Delft University of Technology, Delft, The Netherlands

Abstract

As the aviation industry has agreed on the goal of achieving net-zero CO_2 emissions by 2050, various mitigation strategies are being deployed and developed. This paper focuses on reducing emissions at airports by towing aircraft instead of taxiing with their main engines; dispatch towing. This is done by developing a model to optimise the assignment of Electric Towing Vehicles (ETVs) at Amsterdam Airport Schiphol (AMS), in line with the airport's emission-free target for 2030. The developed model is able to assign ETVs to flights and charging moments for the tactical planning phase, minimising fuel consumption, charging cost and number of chargers. The results of the model are illustrated for two peak days at AMS. Both a small and a large fleet of ETVs are assigned on both days for a northbound and southbound runway operation. The total fuel cost savings for the small fleet are to 25% and 45% for the large fleet, which are similar on both days. On both days, outbound flights are most preferred direction to be towed due to the distribution of towing times. The savings per ETV are highest for a small fleet and decrease until all flights are towed. Furthermore, the load on the charging infrastructure at AMS for different fleet sizes shows what average and peak power can be expected. It is shown that ETV utilisation and computation time can be improved significantly, by implementing costs on time and introducing utilisation and symmetry constraints. However, with the important limitation that these improvements are observed only for small planning horizons. Finally, a sensitivity analysis on charging power showed that increasing the charging rate has a positive impact on both fuel cost savings and the minimum number of chargers required. In conclusion, this study shows the potential impact of dispatch towing at AMS in terms of fuel savings, charging infrastructure and operational challenges.

Keywords: Assignment Model, Balancing Constraints, Dispatch Towing, Electric Towing Vehicles, Mixed-Integer Linear Programming, Operations Research

1 Introduction

The aviation sector faces a formidable challenge for full decarbonisation, with possible alternatives such as electric or hydrogen aircraft still in the developmental stage. While alternative fuels show potential, challenges in Sustainable Aviation Fuels (SAF) production persist. At airports, various efforts to reduce ground-related emissions are being undertaken, with sustainable taxiing methods emerging as a promising avenue. Among these methods, dispatch towing stands out, demonstrating a substantial reduction to 55-80% in taxiing-related fuel consumption compared to conventional methods [Schiphol Airport, 2021].

Dispatch towing operations utilise modified pushback trucks, towing flights with engines off from the gate to the runway and vice versa. Operationally this is attractive as no adaptations to aircraft need to be made. Currently, only the diesel-electric TaxiBots [TaxiBot International, 2022] are used in the real-world for such operations. While there are ETVs in use at airports, they are currently only used for pushbacks or maintenance towing. In this study, we focus on a fleet of ETVs capable of dispatch towing, in line with AMS's goal of achieving an emission-free airport operation by 2030 [Schiphol Airport, 2022].

To fully benefit from dispatch towing operations, the characteristics in assigning ETVs to flights are crucial as they impacts choices such as fleet size and number of chargers. Therefore, this research focuses on the assignment of ETVs to flights and charging moments at AMS. Specifically, the assignment involves a limited fleet of ETVs, aiming to minimise the number of chargers required. The primary objective of this research is:

> *To develop a mathematical model for assigning a limited fleet of ETVs to flights and charging moments at AMS, minimising fuel consumption, charging cost and the number of chargers required.*

*MSc Student, Air Transport and Operations, Faculty of Aerospace Engineering, Delft University of Technology

†Lecturer and researcher, Air Transport and Operations, Faculty of Aerospace Engineering, Delft University of Technology

‡Aviation Consultant, To70 Aviation Consultancy The Hague

The paper is structured as follows. First, section 2 details the methodology, encompassing fuel consumption, energy calculations, and the mathematical assignment model. Second, the case studies are described in section 3. Third, section 4 presents the results of the case studies and their interpretation. Finally, in section 5 the conclusions and recommendations of this research regarding both the academical and operational aspects are outlined.

2 Methodology

In this methodology, it is described how dispatch towing operations are modelled and how the optimisation model is constructed. First, the different aspects of dispatch towing operations which have been taken into account are described; airport model, input data, ETV specifications, towing tasks, charging policy, fuel consumption and energy model. Second, the model that is able to assign the fleet of ETVs is described by its cost functions, symbols, objective function and constraints. The dispatching of a fleet of ETVs is considered throughout one day of operations on one airport.

2.1 Airport model

This section describes the modelling choices of the airport where the dispatch towing operations take place. In dispatch towing operations, an ETV performs two types of movements; a towing movement and a ferry movement.

The towing movement of an ETV towing an aircraft from the gate to the runway and vice versa, is performed via the taxiways. This research does not take into account the modelling of the towing routes, as the realised taxi times of every flight are used as input instead.

The ferry movement takes place before or after a tow, when an ETV does not tow an aircraft and needs to drive to the gate or runway in order to pick up an aircraft. Since the routes for these ferry movements are unknown, a model of the airport is made.

To model the airport, a series of nodes and edges is required to discretise the ferry routes. On the airport, three types of nodes and one type of edge are modelled. The description of the nodes and edges that are modelled for dispatch towing operations are shown in Table 1.

Table 1: Description of airport nodes and edges

Node/edge name	**Description**
Ramp nodes	- Starting node for outbound tows - Ending node for inbound tows - Location of charger(s)
Runway nodes	- Ending node for outbound tows - Starting node for inbound tows
Service road nodes	- ETVs ferry via the service roads (nodes and edges), to a ramp node or runway node
Service road edges	- Bidrectional - Constant service road velocity (v_s)

From an outbound point of view, a flight starts from the ramp node where it is parked, from where it is towed via the taxiways to the runway node. After a flight is towed from the ramp node to the runway node, the ETV ferries back via the modelled service road network to ensure complete separation between flights on the taxiways and ETV ferrying.

From an inbound point of view the opposite holds, where first an ETV ferries to the runway node, then after a flight lands it taxis to the runway node where it is connected to the ETV and is towed to its ramp node via the taxiway.

2.1.1 Ferrying

The ferrying movement is performed via the service nodes and edges. To allow for the quickest route possible, the shortest path from the start node to the end node is determined with the assumption that a constant service road velocity (v_s) is maintained. On the service roads, it is assumed that the ETVs can drive in both directions and no separation for other traffic is taken into account. An important modelling aspect has to be noted. The formulation of the mathematical model (section 2.9) is an adapted form of an assignment model. As no sequence of flights to be towed is made, there is no information available during optimisation about what flight has to be towed next. Therefore, the ferrying movements are modelled as follows:

- After an outbound tow, the ETV always ferries back to the ramp node from where it started the tow.
- Before an inbound tow, the ETV always starts the ferry movement from the ramp node where it will tow the flight to.
- In between two tows, no routing for an ETV is modelled. Instead, the ETV is relocated to the next ramp node without travelling time.

These modelling choices impact ETV availability. On the one hand, ferrying to/from the same ramp node results in part of the ferry movements with a longer duration and the other part with a shorter duration compared to reality. Since in reality, the distance to the next gate or runway can be closer or further away. On the other hand, considering that the ferrying time between the ramp nodes of two tows is not modelled, results in a shorter duration compared to reality.

2.2 Input data

In this research, the flight schedule data from the Integral Capacity Plan (ICP) of Schiphol is used. This data gives information about the scheduled as well as the actual times of in- and outbound flights. Therefore, the taxi times can be determined by subtracting arrival time at the runway and the arrival/departure time at the gate. Furthermore, information about the flight, aircraft, ramp and runway are given. The flight schedule that is used covers two consecutive days of in- and outbound flights.

2.3 ETV specifications

Two types of ETVs are considered in this research, one for a selected set of compatible Narrow Body (NB) aircraft and one for a selected set of compatible Wide Body (WB) aircraft. The compatible aircraft are based on aircraft type indicators that are compatible to be towed by the TaxiBot [TaxiBot International, 2022], currently in operation on several airports. Each ETV type has its own set of specifications, which consist of a battery capacity (Q_e^C), a constant towing velocity (v_t) and an ETV mass (m_e). Although the towing times are derived from the input data, the towing speed is required to calculate the energy consumption during the tow, as shown in section 2.7.

2.4 Modelling towing tasks

A day of operations is considered to take 24 hours. During this day, both outbound and inbound flights are considered for towing tasks. From all flights, the towable flights are selected by either their International Air Transport Association (IATA) or International Civil Aviation Organization (ICAO) aircraft type designator. The timeline and considered activities of ETVs and flights during the towing process is depicted in Figure 1.

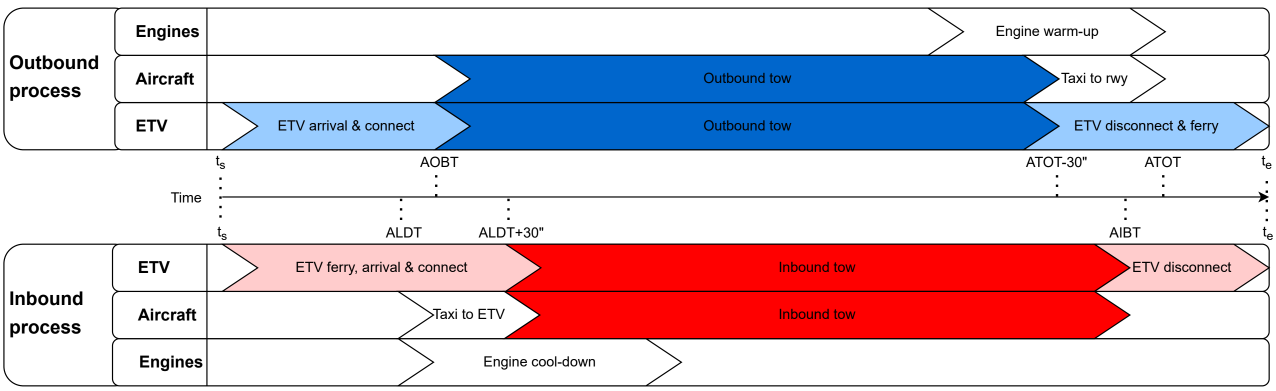


Figure 1: Outbound and inbound towing tasks

It can be seen that a towing task is split in a task part as a whole and the towing part within. The reason being that an ETV needs to be ready at the the node before the flight needs to be towed, not only as a buffer but also to account for connecting the ETV to the aircraft. For the task, there is a task start time (t_e^S) and a task end time (t_e^E) which are the times that an ETV needs to be at the start node of the flight. The reason that an ETV returns to the start node is explained in section 2.1. For the tow itself, there is a start- and end time between which a flight is towed from its starting node to its destination node. These timestamps are based on the so-called milestones of Aiport Collaborative Decision-Making (A-CDM) [EUROCONTROL

Airport CDM Team, 2017]. For the outbound tow, the Target Start-Up Approval Time (TSAT), Actual Off-Block Time (AOBT) and Actual Take-off Time (ATOT) are used. And for the inbound tow, the Actual Landing Time (ALDT) and Actual In-Block Time (AIBT) are used. The outbound timestamps are explained in set of Equations 1.

$$t_e^S = \text{TSAT} - t_r \quad (1a)$$
$$T_f^S = \text{AOBT} \quad (1b)$$
$$T_f^E = \text{ATOT} - 30 \text{ seconds} \quad (1c)$$
$$t_e^E = T_f^E + t_f \quad (1d)$$

The inbound timestamps are clarified in set of Equations 2.

$$t_e^S = \text{ALDT} - t_r - t_f \quad (2a)$$
$$T_f^S = \text{ALDT} + 30 \text{ seconds} \quad (2b)$$
$$T_f^E = \text{AIBT} \quad (2c)$$
$$t_e^E = T_f^E + t_p \quad (2d)$$

After the task and tow timestamps are determined, the task start timestamps t_e^S are rounded down to the nearest 5 minutes and the task end timestamps t_e^E are rounded up to the nearest 5 minutes. This provides for an extra buffer for back-to-back towing tasks and also results in less variables for the optimisation model. Consequently, improving the computation time. Furthermore, ETV availability is impacted as the total task time of an ETV is slightly longer than it would be without the rounding. In combination with the modelling choices from section 2.1, the impact on ETV availability differs per tow as one could have a slightly longer or shorter duration compared to reality.

2.5 Balanced charging policy

Throughout a day of operation, the ETV batteries will require a recharge. The approach in this research is to balance the consumption of the battery with the recharging of the battery. The balancing is performed over time horizons, where the flights are split in sets of equal time horizons. The flights in a horizon, with horizon duration ($t_{horizon}$) are selected by their t_e^S. For example, flights in the first horizon h_1 are $h_1 \leq t_e^S \leq h_2$. Besides dividing flights in sets of horizons, a horizon overlap ($t_{overlap}$) is in place. The $t_{overlap}$ parameter is constant within the range; $0 < t_{overlap} < t_{horizon}$. This ensures that a flight is present in multiple horizons, except for the first and last horizon(s). The balancing policy ensures that the energy an ETV consumes for towing, needs to be recharged by a fixed percentage of this consumption. By putting this percentage to less than 100%, partial recharging is imposed.

The amount of energy an ETV can recharge is limited by a fixed number of charging blocks. The charging blocks ensure that an ETV recharges for a minimum amount of time. A charging power (P_e^C) is set, depending on the battery capacity of an ETV. To limit risks of overheating during charging and discharging, a maximum C-rate of 1C is assumed. The C-rate of the battery is the rate at which the battery capacity can be (dis)charged in one hour. Considering for example a battery with a 100 kWh capacity that has a 1C rating, the maximum charging power is 100 kW assuming a constant voltage. Furthermore, it is assumed that charging speed remains constant throughout the entire charge. Therefore, charging for 1 hour with P_e^C of 100 kW results in an energy of 100 kWh. To assign ETVs to charging blocks, a charging block schedule is generated. Besides the charging power(s) and duration of the blocks, also an interval between blocks and a handling time (t_h) are introduced. In this example, charging blocks are generated every 5 minutes with two different durations. To account for handling activities at the chargers such as parking and (dis)connecting, a handling time before and after the actual charging is set. A section of the charging schedule with two consecutive charging block intervals is shown in Table 2.

Table 2: Section of a charging schedule example

Day	Charging power	Duration	Start block	Start charge	End charge	End block	Energy
[-]	[kW]	[min]		[hh:mm]			[kWh]
1	204	30	12:00	12:05	12:25	12:30	68
1	204	60	12:00	12:05	12:55	13:00	170
1	204	30	12:05	12:10	12:30	12:35	68
1	204	60	12:05	12:10	13:00	13:00	170
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
2	204	30	11:00	11:05	11:25	11:30	68
2	204	60	11:00	11:05	11:55	12:00	170
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
2	204	30	11:30	11:35	11:55	12:00	68

In this example, only one type of charging block is generated as P_e^C is constant. As this research considers two types of ETVs, two types of charging blocks are considered with different charging powers P_e^C, in section 3.

2.6 Fuel consumption

The goal of assigning ETVs to flights is to save as much aircraft fuel as possible. To determine these fuel cost savings, both the fuel consumption of conventional taxiing and that of dispatch towing need to be calculated. The fuel consumption model from the Airport Air Quality Manual of the ICAO Doc. 9889 is followed [ICAO, 2011]. The fuel consumption during conventional taxiing stems from the main engines, which is calculated as stated in Equations 3 and 4.

$$FF_{taxi_f} = FF_{idle_f} \times N_{eng_f} \tag{3}$$

$$F_{taxi_f} = FF_{taxi_f} \times t_{taxi_f} \times 60 \tag{4}$$

Where the fuel flow (FF) for the total taxi duration FF_{taxi_f} depends on the idle FF of the flight's main engine FF_{idle_f} and the number of engines (N_{eng_f}). The total fuel (F) for conventional taxiing F_{taxi_f} depends on FF_{taxi_f}, the total taxiing time (t_{taxi_f}) which is multiplied with a factor of 60 to convert the fuel flow to minutes.

For every flight f in the flight schedule, the IATA code of the aircraft is looked up in Table 11 in Appendix A. This table is composed by data of [The Aviation Codes Web Site, 2023, Federal Office of Civil Aviation (FOCA) and Rindlisbacher, 2007, Seymour et al., 2020, Segeren, 2022]. With the Unique Identification Number (UID) of the engine, FF_{idle_f} is looked up in the ICAO Aircraft Engine Emissions Databank [EASA, 2022].

During a towing task, fuel is consumed by the Auxiliary Power Unit (APU) of an aircraft which is used to power the electrical systems required in the cockpit. The calculations differ for an outbound and an inbound tow, because of the engine warm-up time (t_{EWU}) and engine cool-down time (t_{ECD}) respectively. The calculation for the fuel used during an outbound tow F_{OT_f} is shown in Equation 5.

$$F_{OT_f} = (FF_{APU_f} \times (t_{taxi_f} - t_{EWU}) + FF_{taxi_f} \times t_{EWU}) \times 60 \tag{5}$$

The calculation for the fuel used during an inbound tow F_{IT_f} is shown in Equation 6.

$$F_{IT_f} = (FF_{APU_f} \times (t_{taxi_f} - t_{ECD}) + FF_{taxi_f} \times t_{ECD}) \times 60 \tag{6}$$

The total fuel for a tow depends on the flight's APU fuel flow FF_{APU_f}, the t_{EWU} or t_{ECD} and towing time (t_{tow_f}). For an outbound tow, it is assumed that the main engines will commence warming-up t_{EWU} minutes before ATOT. In the case of an inbound tow, the engines are cooled-down from ALDT and before connecting to the ETV. In this research it is assumed that these times are both equal, see also section 3.

2.7 Energy model

In this energy model, the consumption of energy during tasks of an ETV, a tow or ferry movement, is described. To determine the power (P) required for a tow or ferry movement, Equations 7 and 8 are used.

$$P(v, m) = \mu_g v(m_e + m_f)g \tag{7}$$

$$\mu_g(v) = \mu_0(1 + \frac{v}{v_0}) \tag{8}$$

Where in Equation 7, the P depends on the rolling resistance (μ_g), towing or ferrying velocity $v = v_t or v_s$, ETV mass (m_e), mass of flight f (m_f) and the gravitational acceleration (g). And in Equation 8, μ_g depends on v_t, and the constants of the rolling resistance base coefficient (μ_0) and rolling resistance base velocity (v_0) [Zoutendijk et al., 2023]. In this research, a constant velocity is assumed during the entirety of the tow or ferry task. Therefore, the energy consumption (Q) of a towing task or ferry movement is calculated in Equation 9.

$$Q = P(v, m) \times t \tag{9}$$

2.8 Cost functions

The equations used to calculate the fuel consumption, charging energy and number of chargers have to be converted to the same unit in order to compare and combine them into one model. Therefore, all equations are converted to an estimate of cost per unit.

For the fuel consumption, both the taxi and tow equations are converted to cost functions. Since both equations calculate the amount of kilograms kerosene, the conversion is performed the same. The cost (C) per kg of kersosene in €, is determined in Equation 10.

$$C_{\text{kg}} = \frac{115\frac{\$}{\text{bbl}}}{127.19\text{kg}} \times 0.92\frac{€}{\$} \tag{10}$$

Where the price in dollars per barrel $[\frac{\$}{\text{bbl}}]$ [IATA, 2023], is converted to dollars per kg with conversion 1 barrel = 127.19 kg [Aqua-calc, 2023], and finally this amount in dollars is converted to €1/kg with the currency exchange rate of dollars to euros.

$$C_{taxi_f} = F_{taxi_f} \times C_{kg} \tag{11a}$$

$$C_{tow_f} = F_{tow_f} \times C_{kg} \tag{11b}$$

Next, the cost for the charging energy is determined.

$$C_{charging_r} = Q_r^C \times \frac{€0.10}{\text{kWh}} + €10 \tag{12}$$

The amount of energy per charging block r (Q_r^C) is multiplied with energy and handling costs. Where the energy is converted to euros with the cost per energy unit $[\frac{€}{\text{kWh}}]$ [CBS, 2023] and an additional handling cost is charged per block.

The cost for the number of chargers is determined by an estimation of the investment required for a charger. It is estimated that a charger costs 200 euros per kW of charging power and that this investment is spread out over 5 years [Virta, 2023]. The cost for the number of chargers is stated in Equation 13.

$$C_{charger_c} = C_c \times \text{charger}_c \tag{13}$$

Where the cost of a charger type c, is multiplied with the selected charger type charger_c.

Lastly the cost for start time C_{start} and end time C_{end} are described. These costs are constant, depending on the preference of the desired effect on utilisation and symmetry. As the costs are multiplied with a maximum of 1440 minutes during a day, the range of the costs is between 0 and 1.

2.9 Mathematical model

With the model setup as described in sections 2.1-2.8, the mathematical model can be formulated. The assignment of the fleet of ETVs to flights and charging moments is optimised using an assignment model. The assignment model is classified as a Mixed-Integer Linear Programming (MILP). First, the symbols used in the assignment model are shown in Table 3. Next, the mathematical formulation of the assignment model is described in Equations 14a-14h.

Table 3: Overview of the symbols used in the mathematical formulation

Sets	
E	ETVs, indexed by e
$E_f \subset E$	ETVs that can tow aircraft types f
F	Flights that can be towed, indexed by f
$F_e \subset F$	Flights towable by ETV e
$F_{et} \subset F$	Flights towable by ETV e, active at timestamp t
$F_h \subset F$	Flights within time horizon h
H	Horizons, indexed by h
R	Charging blocks, indexed by r
$R_e \subset R$	Charging blocks compatible for ETV e
$R_{et} \subset R$	Charging blocks compatible for ETV e, active at timestamp t
$R_h \subset R$	Charging blocks in horizon h
T	Timestamps, indexed by t
Parameters	
B_e^C	Percentage for balanced recharging
C_{taxi_f}	Cost for flight f to taxi conventionally in kg of fuel
C_{tow_f}	Cost to tow flight f in kg of fuel
Q_f^T	Required energy to tow and ferry flight f
Q_r^C	Energy per charging block r
T_f^S	Tow start time of flight f
T_f^E	Tow end time of flight f
Variables	
n_c	Non-negative integer; number of chargers c
t_e^S	Non-negative continuous; start time of ETV e in minutes
t_e^E	Non-negative continuous; end time of ETV e in minutes
x_{ef}	Binary; 1 if ETV e is assigned to tow flight f, 0 otherwise
y_f	Binary; 1 if flight f taxis conventionally, 0 otherwise
z_{er}	Binary; 1 if ETV e is assigned to charging block r, 0 otherwise

The mathematical formulation of the assignment model with its objective and constraints:

$$\min \quad \sum_{f\in F_e}\sum_{e\in E_f} C_{tow_f}\cdot x_{ef} + \sum_{f\in F} C_{taxi_f}\cdot y_f + \sum_{r\in R_e}\sum_{e\in E_f} C_{charging_r}\cdot z_{er} + C_{charger}\cdot n_C + \sum_{e\in E} C_{end}\cdot t_e^E - \sum_{e\in E} C_{start}\cdot t_e^S \tag{14a}$$

s.t.

$$\sum_{e\in E_f} x_{ef} + y_f = 1 \qquad \forall f\in F_e, \tag{14b}$$

$$\sum_{f\in F_{et}} x_{ef} + \sum_{r\in R_{et}} z_{er} \leq 1 \qquad \forall t\in T, e\in E_f, \tag{14c}$$

$$B_e^C\cdot \sum_{f\in F_h} Q_f^T\cdot x_{ef} - \sum_{r\in R_h} Q_r^C\cdot z_{er} \leq 0 \qquad \forall h\in H, e\in E_f, \tag{14d}$$

$$\sum_{e\in E}\sum_{r\in R_{et}} z_{er} - n_c \leq 0 \qquad \forall t\in T, \tag{14e}$$

$$t_e^S + (M - T_f^S)x_{ef} \leq M \qquad \forall f\in F_e, e\in E_f, \tag{14f}$$

$$t_e^E - T_f^E x_{ef} \geq 0 \qquad \forall f\in F_e, e\in E_f, \tag{14g}$$

$$t_{e+1}^S - t_e^S \geq 0 \qquad \forall e\in E_f \tag{14h}$$

2.10 Objective function

The objective function, shown in Equation 14a, minimises the total cost of consumed fuel and energy for all flights of a flight schedule. The first term in the objective function, calculates the total cost of all flights that have been towed. In the second term of the objective function, the fuel of the flights that taxi conventionally is determined by using cost matrix C_{taxi_f}. Next, the cost of charging is calculated for all the chosen charging blocks r. In the fourth term, the number of chargers n_c is minimised. Lastly, the cost of the start and end time of all ETVs is calculated. Since there is a minus sign for t_e^S, this start time value is maximised.

2.11 Assignment constraints

Constraint 14b, ensures that every flight is either towed or taxis itself. Equation 14c, ensures an ETV does not perform more than one task per time step. This limits an ETV from performing multiple tasks at the same time. The constraint ensures that an ETV can either tow a flight, recharge itself or remain idle at the same time.

2.12 Charging constraints

In constraint 14d, the balancing charging constraint is stated. The recharging is assigned for a planning horizon of h, which is replanned every hour. The energy that is recharged for all the ETVs is balanced. Balancing the energy is done by recharging up to at least a percentage B_e^C of the energy that an ETV has consumed whilst performing tows and ferry movements. The second charging constraint in Equation 14e, ensures that the number of ETVs recharging at a time is limited by the number of chargers.

2.13 Utilisation constraints

The utilisation constraints are listed in constraints 14f and 14g. In constraint 14f, it is ensured that the start time of an ETV t_e^S is less or equal to the start time of a flight T_f^S. When a flight is not towed, the start time has to be smaller or equal to a very large number M. Lastly, constraint 14g makes sure that the end time of an ETV t_e^E is greater or equal than the end time of a tow T_f^E.

2.14 Symmetry breaking constraints

During the solving of the model in Gurobi, it takes a significant time to come to an optimal solution. This is due to that Gurobi executes many iterations for different orders of schedules that have the same objective. Without symmetry constraints, all these solutions are considered distinct from each other, generating a large feasible set with many equivalent solutions [Trindade et al., 2018]. Therefore, in an effort to make the model solve faster, symmetry breaking constraints were introduced. The symmetry breaking constraints are listed in constraints 14h. Here it is ensured that the first task start time t_e^S of every successive ETV is greater or equal to the one preceding it.

3 Description of the case studies

In this section, the modelling aspects that were described in section 2 are translated to case studies. The case studies considered are; assigning two different fleet sizes and assignment on two different days. First, the airport and the parameters considered are discussed in the section 3.1. Then, the case studies are described in sections 3.2 and 3.3.

3.1 Airport and parameters

The airport where the case study of this research focuses on is Amsterdam Airport Schiphol, as already stated in the introduction in section 1. One of the most important reason that AMS is relevant to analyse for dispatch towing operations is its size. Both in being one of the busiest European airports [Schiphol Airport, 2019] and its surface area with long taxiing distances and six different runways. Because of the amount of traffic, there is a spread in different aircraft types. Which makes it relevant to study assigning different types of ETVs. Furthermore, the layout of AMS provides for a range of choice between short and long tows because of the presence of runways with both close and distant proximity to gates. This is therefore also analysed in the case study.

The choice has been made to analyse the assignment of two types of ETVs, named NB ETV and WB ETV. The naming corresponds generally speaking with the Wake Turbulence Category (WTC) of the aircraft that are compatible to be towed by one of the ETVs. The compatible aircraft to both ETV types along with other parameters are shown in Table 4. All detailed IATA codes and the corresponding (non-)compatibility to an ETV type are shown in Table 11.

Table 4: ETV parameters

ETV type	**Compatible aircraft**	m_e **[t]**	P_e^C **[kW]**	Q_e^C **[kWh]**	v_t **[kts]**
NB	A318-321, A330 B733-739, B752/3/7	15	408	400	23
WB	A330/2/3, A343/5/6, A351/9, A380, B744/7, B762/3/4/7, B781/7/8/9	35	804	1250	

Implementing the airport modelling choices of section 2.1 on AMS, a network of nodes and service roads is created that can accurately determine ETV ferrying times from the ramp node to the runway node and conversely. The network is shown in Figure 2, which was created with the use of Google Earth Pro [Google Earth Pro, 2023]. As stated previously in section 2.1, the ETVs drive on the service roads with a v_s that has value 30 km/h. Only the numbers of the ramp and runway nodes are shown. The list of runway nodes coupled to inbound and outbound traffic per runway is shown in Table 5. The list of ramp node couplings to the gates is shown in Table 12 in Appendix B.

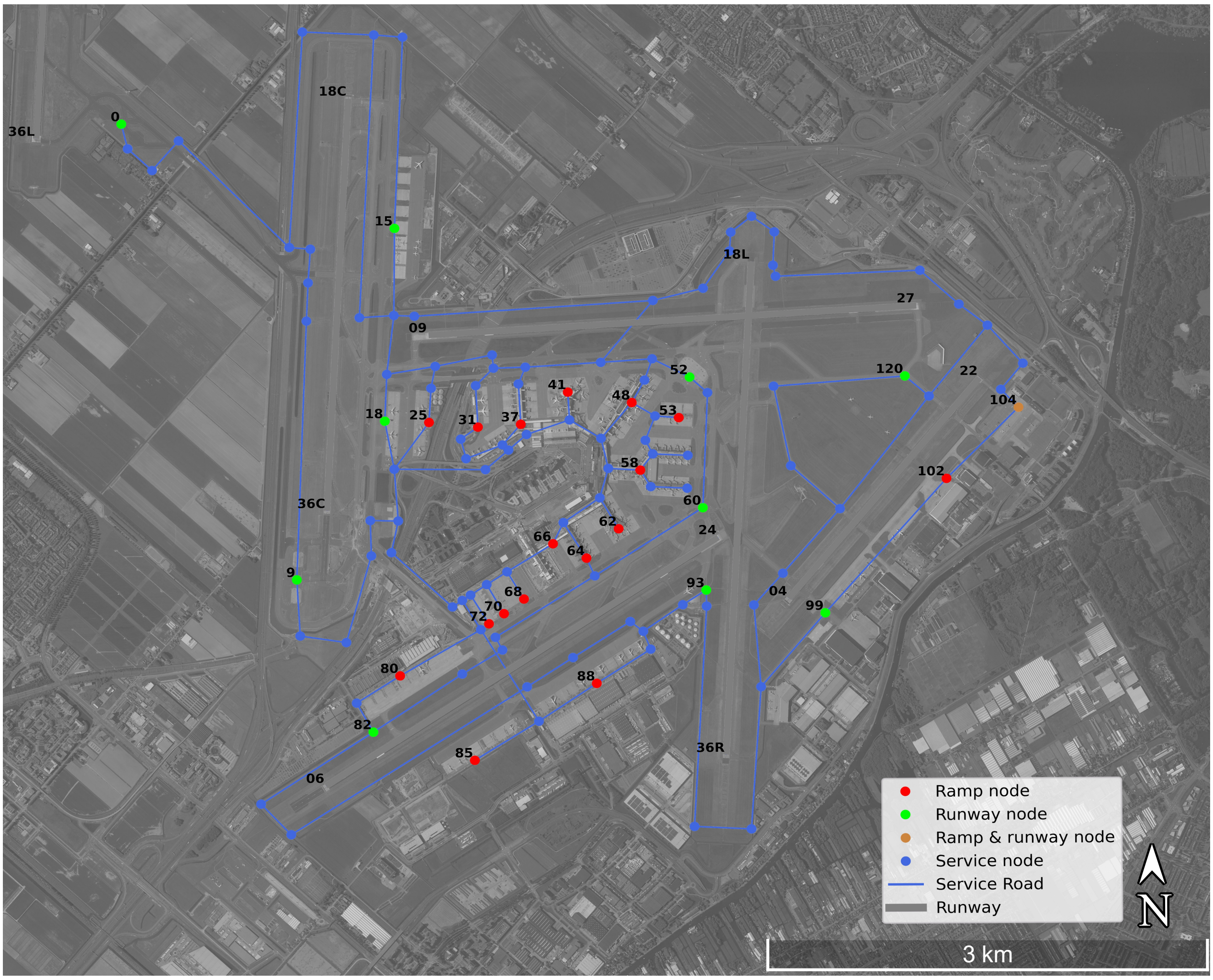


Figure 2: ETV ferrying network model of AMS.

It is important to note that there are two crossings of the service roads with runways, which are over runway 9-27 and a tunnel under 06-24. The crossing over runway 9-27 was created as it is currently already in operation at AMS for the ferrying movements of maintenance towing operations [Schiphol Airport, 2023]. As runway 9-27 is not in operation in the flight schedule of this research, it also does not interfere with flights departing and

Table 5: Runway node couplings with inbound and outbound runways

Runway node	Inbounds	Outbounds
0	18R	36L
9	-	36C
15	36C	18C
18	18C, 27	9
52	36R	18L
60	6	-
82	24	6
93	-	24
99	22	4
104	4	22
120	-	27

arriving from that runway. For the tunnel crossing under runway 06-24, it is assumed that it is accessible for ETVs in both directions.

The input flight schedule data of AMS is that of 17 and 18 July 2019. The distribution of towable flights is shown in Figure 3, where for all outbound flights the AOBT and for inbound flights the ALDT is considered. In total, the flight schedule contains 3013 flights, out of which there are 1587 NB compatible flights and 373 WB compatible flights. The days considered represent relatively busy days of operation at AMS, considering an average of 1360 flights per day in 2019 [Schiphol Airport, 2019]. The peaks of NB flights for both days are at 19:00 with 61 and 65 flights on the 17 and 18 July respectively. For compatible WB flights, at most there are 20 flights at 14:00 on 17 July and 19 flights at both 10:00 and 12:00 on 18 July.

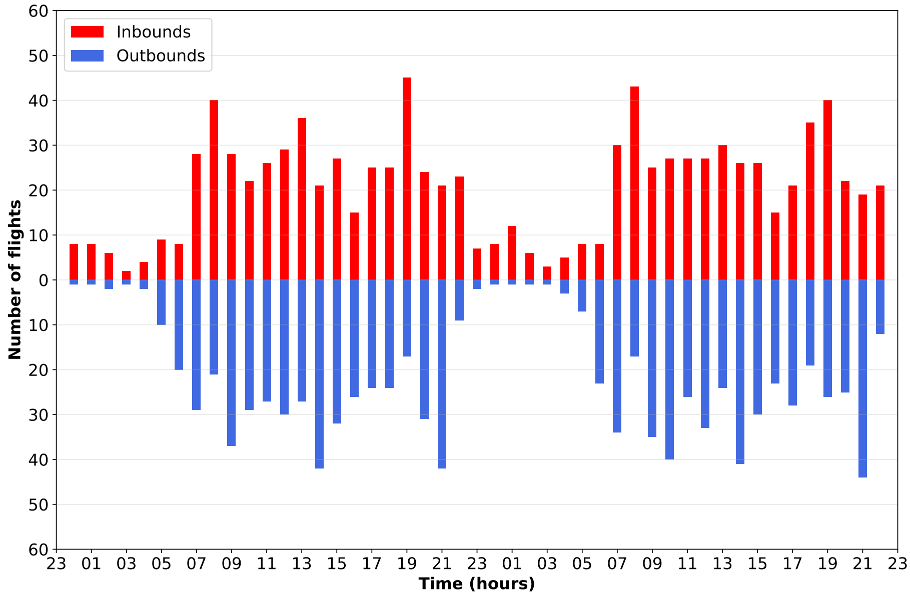


Figure 3: Distribution of towable inbound (red) and outbound (blue) flights between 17 and 18 July 2019 at AMS.

In Figure 4, the runway distribution on both the 17th and 18th of July is shown. The main difference on the two days is that on the 17th of July a northbound runway configuration is in use, whilst on the 18th of July a southbound runway configuration is in operation. On the 17th of July, the majority of runways used are 36L, 36C, 36R and 6. The one exception is one NB flight that lands on runway 4 at 18:45. This northbound operation continues until 2:00 AM the next day. From 2:00 AM onwards on the 18th of July, the runways 18L, 18C, 18R, and 24 are in use for the majority of the time, indicating a southbound runway operation.

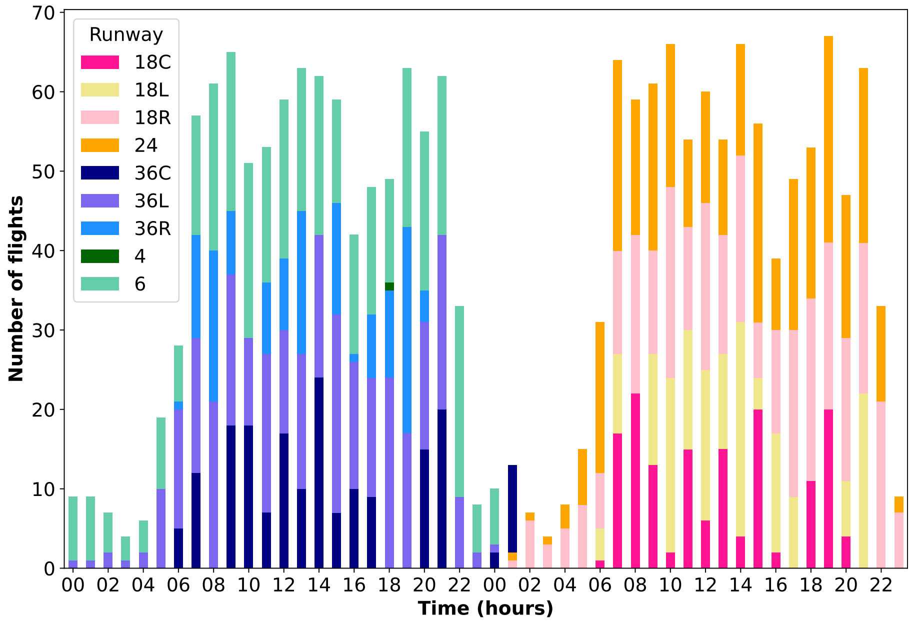


Figure 4: Distribution of runways between 17 and 18 July 2019 at AMS.

Besides the ETVs specifications, other parameters that have been used in the model are shown in Table 6. First, the parameters used for the energy calculations in section 2.7 are stated: μ_0, v_0. To calculate the ferry times, as stated in section 2.1, the velocity of the ETVs on the service roads v_s is stated. Lastly, the model parameters of t_p, t_h, R, $t_{horizon}$, $t_{overlap}$, C_{start} and C_{end} remain constant for all case studies. The reason that cost parameters for start and end time are zero except when stated otherwise, is explained in section 4.3.

Table 6: Model parameters

Name	Symbol	Unit	Value(s)
Rolling resistance coefficient	μ_0	[-]	0.01
Rolling resistance base velocity	v_0	[m/s]	11.43
Service road velocity	v_s	[km/h]	30
Processing time	t_{proces}	[min]	1
Handling time	t_{handle}	[min]	2
Charging blocks	R	[min]	[35, 40, 45, 50, 55, 60, 65, 70]
Horizon duration	t_h	[hours]	3
Horizon overlap	$t_{overlap}$	[hours]	2
Start time cost	C_{start}	-	0
Emd time cost	C_{end}	-	0

3.2 ETV fleet sizes

Two different fleet sizes are considered for this case study:

- **Small fleet:** 10 NB and 5 WB ETVs, B_e^C 80% for NB ETV and 75% for WB ETV.
- **Large fleet:** 40 NB and 15 WB ETVs, B_e^C 50% for NB ETV and 55% for WB ETV.

The reason for analysing two different fleet sizes is a trade-off between operational implications and computation time. An airport would like to know the impact of various fleet sizes mainly because of the significant investment of ETVs. Another operational implication is that when a fleet is acquired, there will be a beginning period with a smaller fleet. Furthermore, it depends on the stakeholders for what purpose the ETVs will be purchased. Computationally it is intensive to run a broad range of fleet sizes and to analyse these. In line with the objective of this thesis, it was therefore decided that two fleet sizes can show a range of operational effects to be expected whilst maintaining within the range of the thesis time commitment.

3.3 Assignment for different runway configurations

Both days of the available flight schedule data at AMS on the 17th and 18th of July in 2019 are analysed. The total amount of flights to be analysed on both days were shown in Figure 3. The amount of flights on each day are as follows:

- **17 July, northbound:** a total of 1503 flights, out of which towable; 787 NB and 183 WB flights.
- **18 July, southbound:** a total of 1507 flights, out of which towable; 797 NB and 190 WB flights.

4 Results

The results of the case studies of assigning ETVs, using the created assignment model are explained in this section. First, the results for the assignment of both fleet sizes are shown in section 4.1. Second, in section 4.2 the results of dispatching ETVs for different runway configurations is shown. Furthermore, the impact of utilisation and symmetry breaking constraints is shown in section 4.3. Next, the fuel savings for a range of NB and WB fleet sizes is shown in section 4.4. Lastly, a sensitivity analysis is performed on the charging rate in section 4.5.

4.1 ETV fleet assignment

The ETV schedule of assigned tows and charging moments of the large fleet, during the 17th of July along with the state-of-charge of the batteries is shown Figure 5. A total of 859 flights are towed, out of which 693 NB and 166 WB are towed.

The ETVs are not able to tow all flights, because of the amount of conflicts and charging. For the NB flights, there are a maximum of 44 conflicts at 19:15 whilst there are 40 ETVs available. The maximum amount of active WB flight at 12:40 and 13:10 are 15, which without charging should make it possible to tow all flights. Because of charging, not all WB ETVs are available at that timestamp. Also the fact that the peak timestamps are within 30 minutes of each other further limits the possibility of towing all WB flights during the peak. In case of a short peak, the charging moments can take place before or after all flights from the peak are towed.

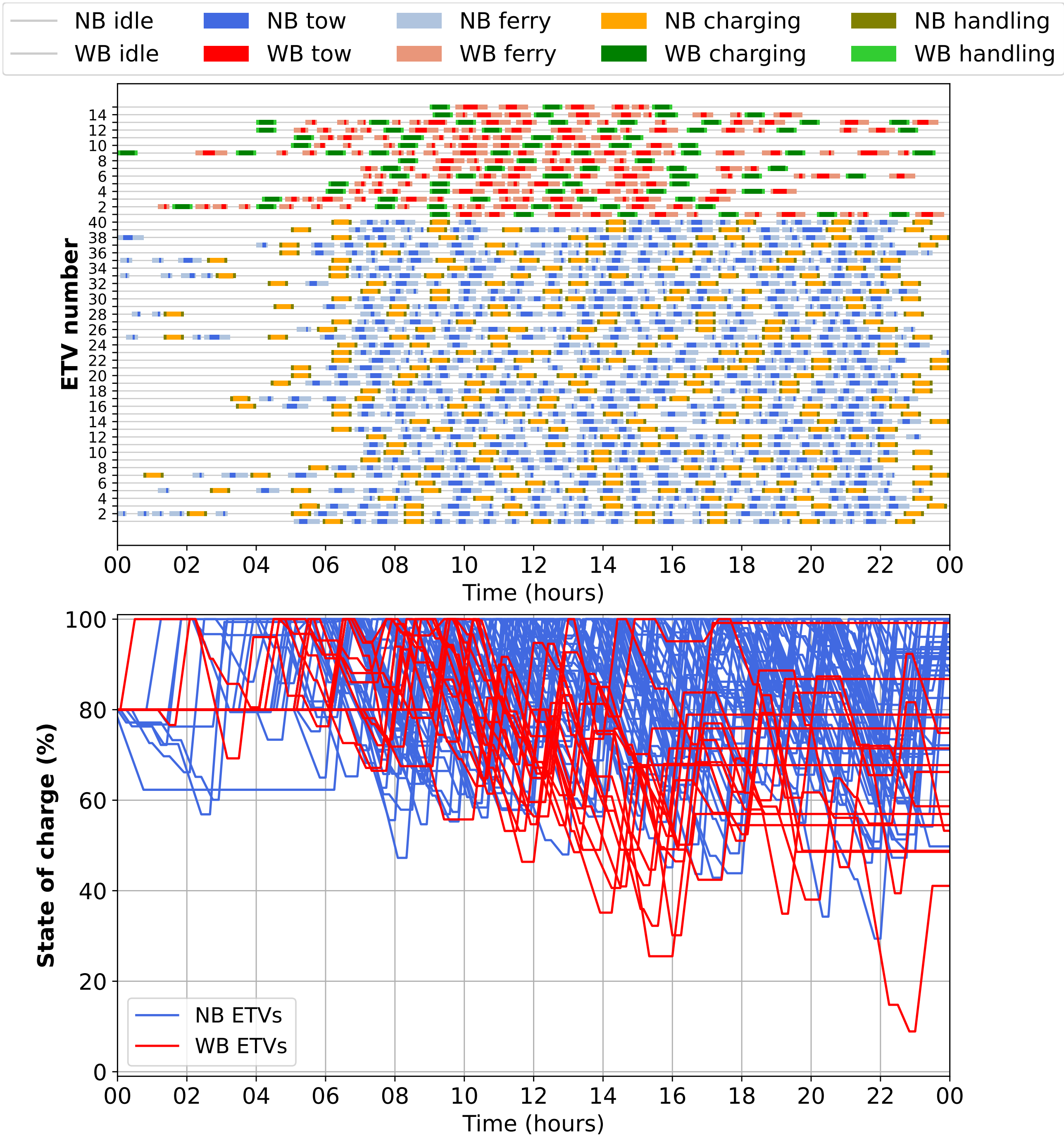


Figure 5: ETV assignment schedule and battery state-of-charge for the large fleet on 17 July.

The distribution of flights that are towed by both fleets and the resulting total fuel cost savings, are summarised in Table 7. In general, the distributions are similar for both days. This similarity can be expected as both days are very similar in amount of flights.

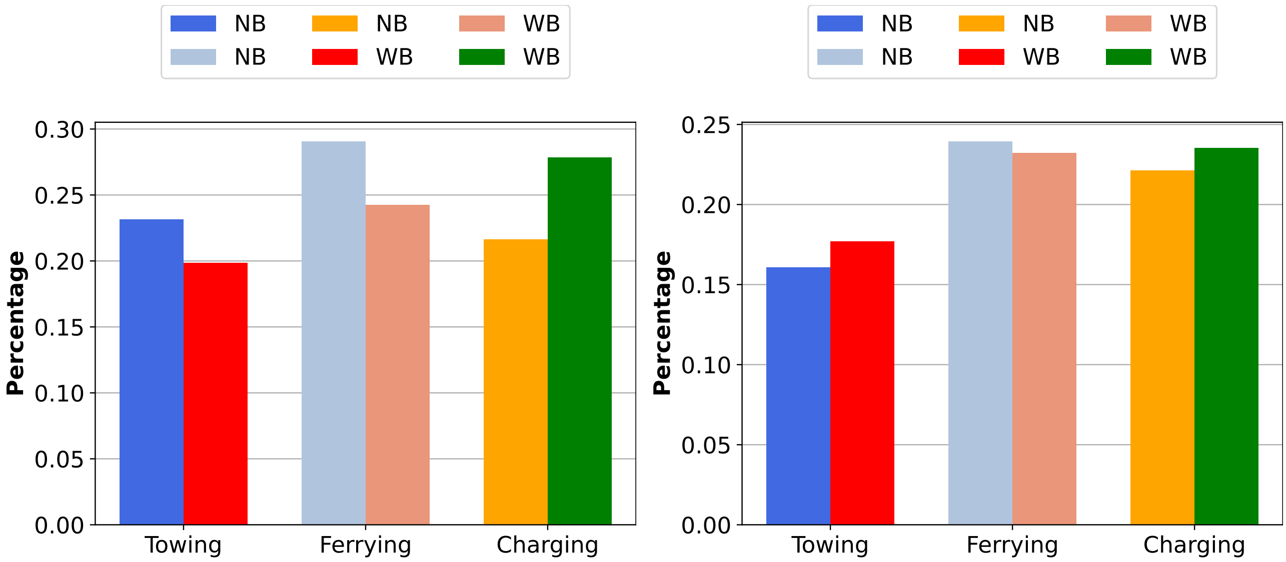
Table 7: Distribution of flights towed versus taxiing for two fleet sizes on both days.

Fleet	**Day**	**Flights towed** [%]		**Flights taxiing** [%]	**Fuel cost savings** [%]
		NB	WB		
Small fleet:	17 July	14	5	81	25
10 NB, 5 WB	18 July	17	5	78	23
Large fleet:	17 July	46	11	43	45
40 NB, 15 WB	18 July	50	11	39	45

One difference is that the fraction of flights towed by NB ETVs is higher on 18 July but the fuel cost savings remain similar, or even slightly decrease. This difference is present for both fleet sizes. This observation can be explained by the model runtime and runway configuration. For the large fleet, part of the explanation is found in the runtime. The model for the schedule of 18 July was run 20 minutes longer compared to the schedule of 17 July. And where the schedule on 17 July shows a couple of ETVs with long idle times in between tasks Figure 5, the schedule on 18 July has less gaps. The explanation with respect to the runway configuration is described in section 4.2.

It is also observed that not all ETVs are utilised optimally, having long idle times between towing and/or charging tasks in Figure 5. This difference of utilisation is especially present for NB ETVs, shown in Figure 6. Where the average time an ETV spends on the tasks of either towing, ferrying or charging for both fleets is visualised. The utilisation is measured in the time that an ETV is active, between the first task start time and the last task end time. NB ETVs spend 7% less time towing in the large fleet compared to the small fleet. Contributing most to this difference in utilisation are the long idle times between tasks. As the distribution of NB flights during the day is relatively constant, the presence of these idle times could be due to computational restrictions as mentioned before. As the flight schedule is larger, the model has an optimality gap of 6%, whereas the small fleet results in a gap of 2% and a runtime that is 3.5 times faster.

For both fleets, it is shown that the NB ETVs spend the most time ferrying and the WB ETVs spend most time recharging. The ferrying times also include non-driving times; t_r, t_p for inbounds, the time between TSAT-AOBT for outbounds and the rounding to the nearest 5 minute timestamp. Therefore, the ferrying time is significantly longer than the actual towing time of a towing task. The fact that WB ETVs spend most time recharging can be explained due to the fact that P_e^C is half of Q_e^C for WB ETVs.



(a) Small fleet

(b) Large fleet

Figure 6: ETV Utilisation distribution on 17 July.

Figure 7 shows the charging power per timestep of all 19 chargers, with an average power of 3294 kW throughout the day. When dispatching the large fleet at AMS, the infrastructure for this amount of power needs to be available. Furthermore, there are many peaks throughout the day up to a maximum of 8904 kW. The differences between the average power and peaks need to be absorbed by batteries. This graph gives an insight in how to adapt the charging policy. Both the charging infrastructure and the energy costs are impacted by this. Whether or not to change the rolling time horizon parameters to delay the time at which peaks occur is an example of its use. What the model of this research does account for is to minimise the total value of the peaks by minimising the number of chargers. The average and maximum peak power for the different fleet sizes, are shown in Table 8.

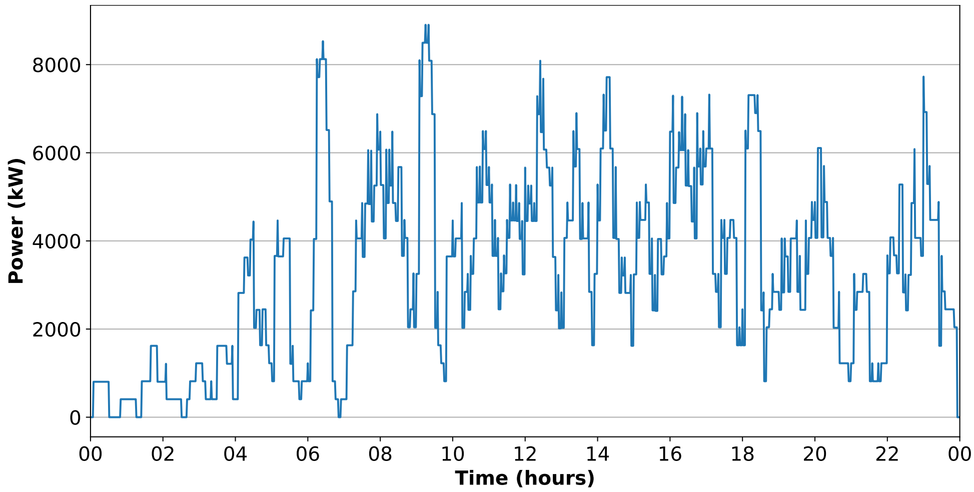


Figure 7: Cumulative charging power per timestamp of all chargers throughout the day on 17 July, dispatching the large fleet.

Table 8: Charging powers for different fleet sizes

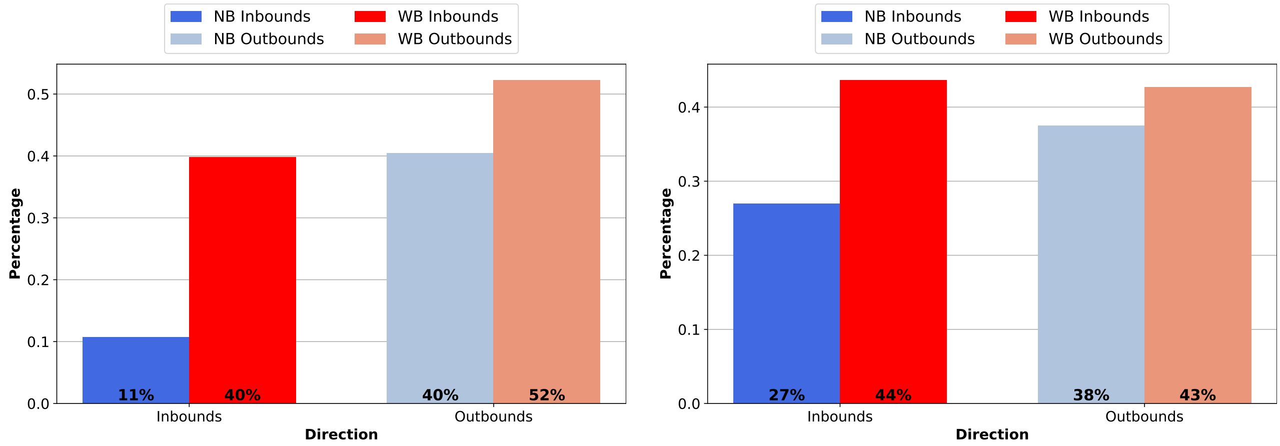
Fleet	**Day**	**Number of chargers**	**Average power [kW]**	**Maximum power [kW]**
Small fleet:	17 July	7	1339	3636
10 NB, 5 WB	18 July	19	3294	8904
Large fleet:	17 July	7	1343	3636
40 NB, 15 WB	18 July	23	3603	10128

4.2 Assignment of ETVs on different runway configurations

This section analyses the effects of dispatching on different runway configurations. The difference between the analysed runway configurations is as follows:

- **17 July:** inbound flights land on runways 36R and 6: relatively short taxi times.
  outbound flights take-off from 36C and 36L: relatively long taxi times.
- **18 July:** inbound flights land on runways 18C and 18R: relatively long taxi times.
  outbound flights take-off from 18L and 24: relatively short taxi times.

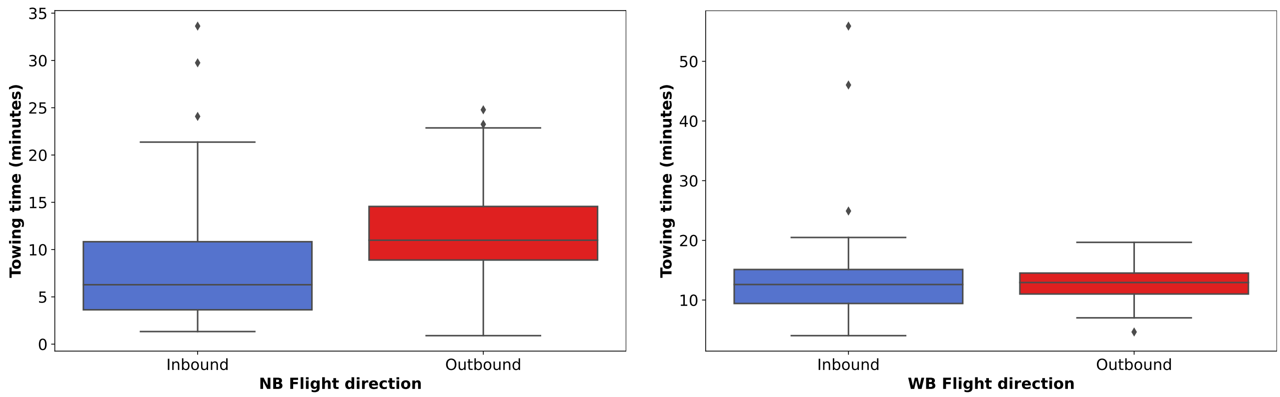
The effect on the distribution of towed inbounds versus towed outbounds is observed when dispatching the small fleet. As when dispatching the large fleet, most towable flights are towed. The distributions for both runway configurations are shown in Figure 8.



(a) Northbound (b) Southbound

Figure 8: Distribution of towed NB/WB inbounds versus outbounds.

For NB flights, it can be seen that outbounds are preferred for both configurations. As expected, the ratio of inbounds towed is significantly higher in the southbound operation because of the longer towing times for the arrival runways. The distributions of towing times for compatible NB and WB flights are shown in Figure 9(a) and 9(b) respectively. Where it can directly be seen that for NB flights, the outbound towing times are significantly longer on both days.

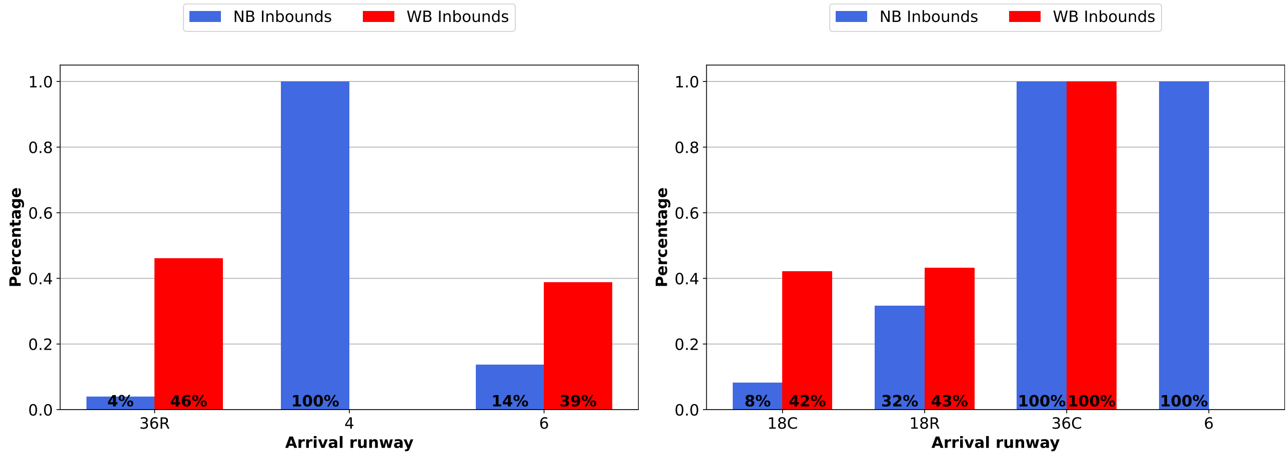


(a) NB Towing time distribution 17 and 18 July (b) WB Towing times distribution 18 July

Figure 9: Towing time distribution of towable NB/WB flights on 17 and/or 18 July.

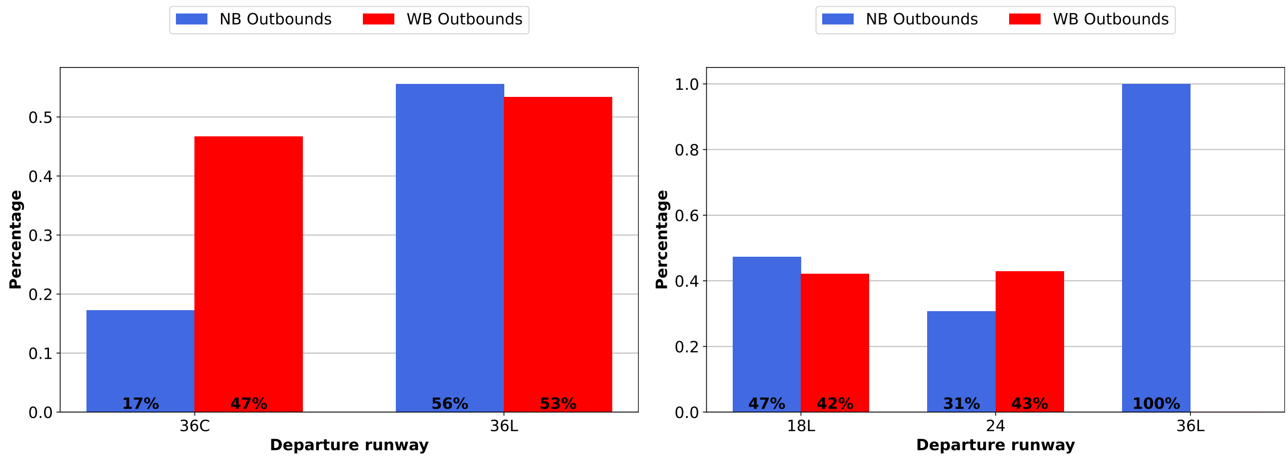
For WB flights, the preferred tow direction depends more on runways used and the corresponding towing times. This effect is shown more pronounced since there are fewer WB flights compared to NB flights. For a northbound operation, outbound flights are preferred as the runways used have longer taxiing times. For a southbound operation, both directions are preferred with similar ratios. This is also shown in the towing time distribution Figure 9(b), where due to some inbound outliers and more inbound flights in general, the inbound direction is preferred with a similar ratio. Furthermore, on this day with a southbound operation the towed WB flights versus towable WB flights ratio is similar on all runways, shown in Figures 10-11.

The higher amount of NB flights towed on the day of the southbound operation, observed in section 4.1, cannot directly be attributed to the shift to a southbound operation. In case of a constant runway configuration, the tows are balanced by the possible amount of savings and how many other potential (less saving) flights have to be skipped due to this assignment. While the tows with a long towing time save the most fuel in absolute terms, the total savings can be impacted if more shorter tows with an equal or higher amount of savings could be towed instead. This is where part of the explanation can be found; in the shift during nighttime from northbound to southbound. Here, arrival runways 36C and 6 are shifted to arrival 18C and 18R. Whilst the departure runway 36L is shifted to 18L and 24. This shift from short arrival tows to longer arrival tows and from long departure tows to shorter departure tows is absorbed by the decrease in ferrying times. Which results in more tows and utilisation during nighttime. This is also shown in Figures 10-11, where nighttime arrival runways 36C and 6 and departure runway 36L are fully utilised and the other runway distributions for southbound show similar ratios compared to the northbound operation.



(a) Northbound (b) Southbound

Figure 10: Runway distributions of towed inbounds for both a northbound and southbound operation.



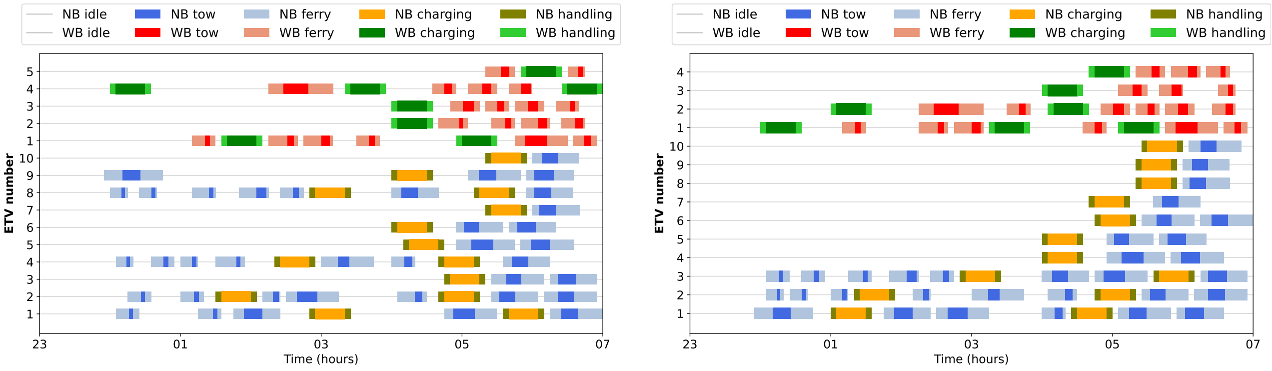
(a) Northbound (b) Southbound

Figure 11: Runway distributions of towed outbounds for both a northbound and southbound operation.

The additional results of assigning the small and large fleet on both days can be found in Appendices A-D, the additional distributions of the towing times are found in Appendix H.

4.3 Impact of utilisation and symmetry constraints

The results of the model from previous sections were retrieved by running the assignment model without utilisation and symmetry constraints. In this section, the model is compared when utilisation and symmetry constraints are included. Three different sets of starttime and endtime costs are given in Table 9, resulting in the schedules of Figures 12 and 13. Where a total of 10 NB and 5 WB ETVs is dispatched between 00:00 and 07:00 on 17 July with both B_e^C at 60%.



(a) No costs

(b) Low costs

Figure 12: ETV schedules with no costs and low costs on start and end time.

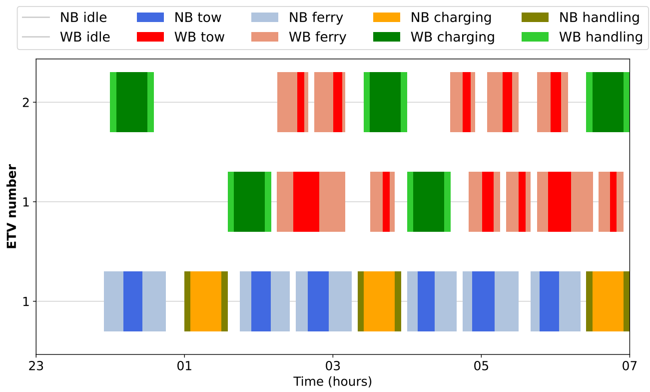


Figure 13: ETV schedule with high costs on start and end time.

Table 9: Start time and end time cost sets

Name	C_{start}	C_{end}
No costs	0	0
Low costs	0.1	0.1
High costs	1	0.5

The difference in the results between no costs in Figure 12(a) and low costs in Figure 12(b) can be directly observed by the order of the task start times, which are increasing for every next ETV. Indicating that the symmetry constraints have been ensured. Furthermore, because costs are given to utilisation the assignment model decides to not dispatch one WB ETV. The extreme case of this is shown in Figure 13, where only 1 NB and 2 WB ETVs are dispatched. The results for the three different cost sets are shown in Table 10.

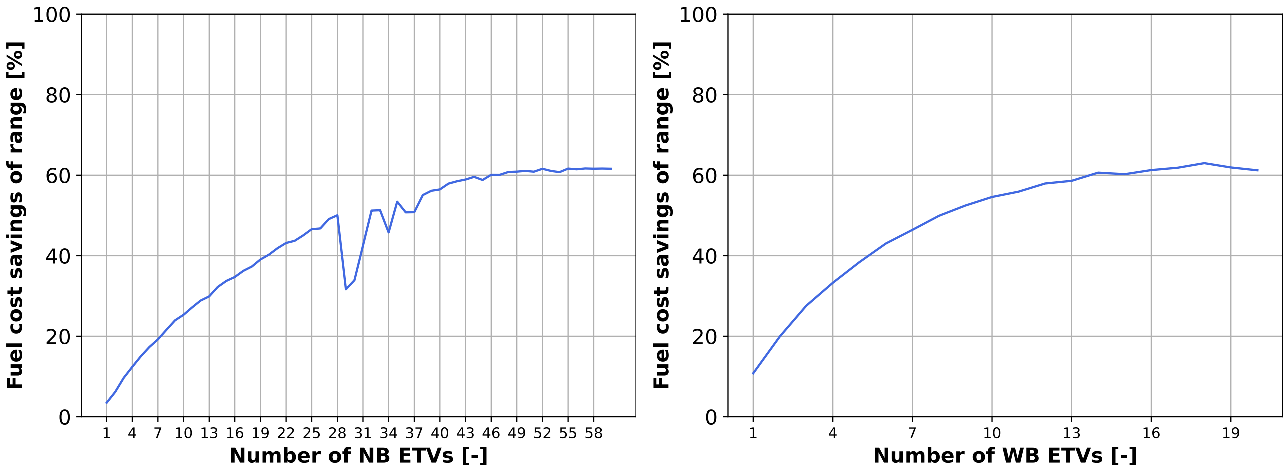
Table 10: Results of three cost sets

Result	**No costs**	**Low costs**	**High costs**
Fuel cost savings[%]	49	48	25
Runtime [s]	10	465	6
Number of chargers	5	5	2
ETV Utilisation [%]			
NB ETVs	100	100	10
NB Towing	17	18	23
NB Ferrying	28	30	34
NB Charging	24	29	25
WB ETVs	100	80	40
WB Towing	14	14	14
WB Ferrying	22	21	20
WB Charging	26	24	23

From the results it can be concluded that there is no significant difference in savings and number of chargers, between the cases of no costs and low costs. However, as the runtime for an optimal solution for low costs is 46 times higher, it is not deemed a realistic scenario. The high costs on utilisation do have positive effect on the runtime, number of chargers and utilisation of NB ETVs. The utilisation of WB ETVs is impacted by the minimisation of chargers. Although the savings are half of that compared to no costs, it is accomplished with 10% of the NB ETVs and 40% of the WB ETVs. An important limitation however is that to see these results, the solution needs to be near optimal. Therefore, for a full day of operations these beneficial effects could not be observed. Additional results on the analysis of utilisation and symmetry constraints can be found in Appendix E.

4.4 Impact of ETV fleet on fuel cost savings and number of chargers

Two fleets sizes have been analysed on the characteristics of utilisation, runway distribution and charging power. However, as the model objective is the minimisation of fuel consumption and number of chargers, this is analysed for a more extensive range of fleet sizes. The model has been run separately for a range of 60 NB ETVs and 20 WB ETVs both with constant B_e^C 75%, ensuring a positive state-of-charge at all timestamps. Furthermore, the time limit per fleet run was set to 10 minutes. The choice for the fleet size ranges is due to the maximum peak amounts of NB and WB flights. The fuel cost savings of towed NB/WB flights with respect to no NB/WB flights towed for both fleet ranges are shown in Figure 14.



(a) NB

(b) WB

Figure 14: Fuel cost of a range of NB and WB ETVs compared to the fuel cost of all NB or WB flights taxiing.

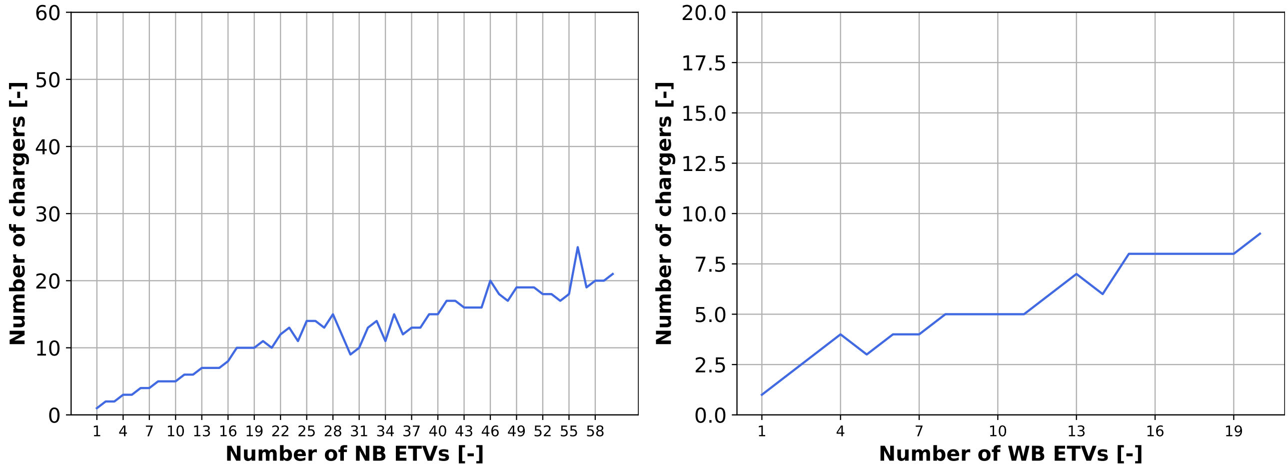
Most savings per ETV are made when the fleet consists of only 1 ETV for both flight categories. The reason for this is that all towable flights are available. With 1 ETV to assign to all available towable flights, the optimal solution is to assign as many flights that have the highest savings amount for the whole day. When adding ETVs to the fleet, the amount saved per ETV decreases as the amount of flights with the highest savings is limited.

The maximum amount of savings is capped at around 60% for both ranges. Part of the explanation is due to the fuel that still is consumed during towing by the APU and by the main engines during warming-up/cooling-down. The other factor limiting the amount of savings is the constant B_e^C of 75%. Whilst this ensures that the whole range of ETVs maintains a positive and feasible state-of-charge, it limits the savings potential for the larger fleet sizes due to its impact on ETV towing utilisation.

Another observation made is that savings per WB flights are approximately 3 times higher compared to NB flights. This effect can already be seen for 1 ETV, where the savings for NB flights is under 5% whilst the savings for WB flights is above 10% even with a lower utilisation due to the different charging rate. The reason for the higher savings per WB flight is due to the higher fuel consumption of the main engines.

Lastly, the sudden drops in the graph for the NB ETVs between 28 and 40 ETVs are due to computational limitations. The runtime for every fleet size was 10 minutes. The towable flights are more difficult to assign in the range between 25 and 40 NB ETVs. With fewer ETVs, the decision space is small as the flights that have the most savings can only be towed by few ETVs. Whilst for a higher amount of ETVs there are only a few flights that result in less fuel cost savings and are not profitable to be towed.

In addition to these results, both NB and WB ETV ranges with respect to the total fuel cost savings are shown in Appendix F.



(a) NB

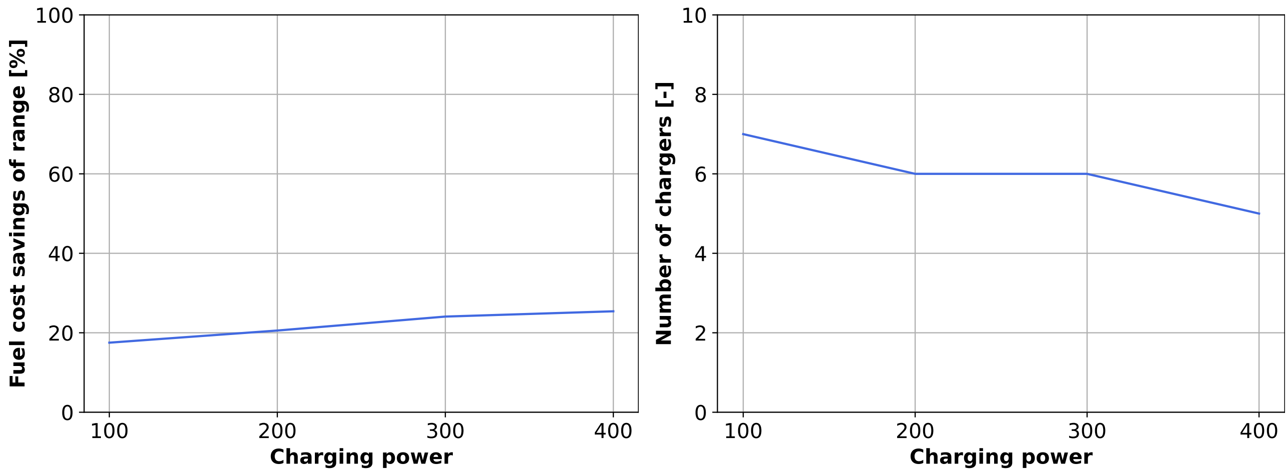
(b) WB

Figure 15: Minimum number of chargers required for a range of NB and WB ETVs.

The minimum amount of chargers required for a specific fleet size is shown in Figure 15. The slope for both fleet sizes is near 0.5, especially for a smaller fleet size. For a fleet of 10 ETVs, 5 chargers are required at least. For increasingly larger fleets, the slope drops to about 0.4. This drop in minimum required number of chargers can be explained due to the utilisation of ETVs dropping for a larger fleet size.

4.5 Sensitivity analysis: charging power

The charging powers P_e^C for all the case studies are constant at 408 kW and 804 kW for NB and WB ETVs respectively. Where the charging rate for NB ETVs is equal to 1C, so charging one hour fully recharges the battery. The charging rate for WB ETVs is equal to 0.6C meaning that a WB ETV has to charge slightly longer than 1,5 hours to get a full charge. The effect of the different charging rates was already observed in the utilisation in section 4.1. In Figure 16, the NB charging power is shown between 100 and 400 kW for a fleet of 10 NB ETVs with a constant B_e^C of 75%, ensuring a state-of-charge above 20% in all cases.



(a) Fuel cost savings

(b) Number of chargers

Figure 16: Impact of charging power on savings and number of chargers.

It is seen that an increase of charging power contributes positively on both the fuel cost savings and the minimum number of chargers required. This is to be expected as longer recharges are required for a lower charging power/charging rate. The longer recharges reduce towing utilisation which reduces the fuel cost savings.

Due to increasing the charging power, less chargers are required. Since the batteries are recharged faster, the longest chosen charging block length is 40 minutes. Compared to a charging power, the longest chosen block length is 90 minutes. Therefore, the amount of available timestamps for 40 minute blocks increases with at least 12.5% compared to block length of 45 minutes. As seen in section 4.4, an even higher decrease can be expected for larger fleet sizes.

Lastly, the peak power is affected by increasing the charging power. Although the number of chargers drops to a maximum of 70% for a fleet size of 10, the charging power increases with steps of 200%. Therefore, increasing charging power will contribute to increasing the peak power.

In addition to the results shown for the NB charging power, the sensitivity analysis for WB charging power and the graphs with total fuel cost savings are shown in Appendix G.

5 Conclusions and recommendations

The objective of this research is considered to be achieved. The developed assignment model is able assign a given fleet size of two types of ETVs to flights and charging blocks at AMS on peak days. Assignment to flights is performed by selecting the flights that save the most fuel. Recharging is performed using a balanced recharging policy, where the charging moments depend on balancing the energy consumed within every defined horizon up to at least a predefined percentage.

The fuel cost savings of a given fleet remain similar on days with similar traffic amounts. A different runway configuration does not impacts these savings significantly. A relative small combined fleet of 10 NB and 5 WB ETVs is able to achieve 25% of total fuel cost savings. Whilst a larger fleet saves 45% of fuel cost savings. The main factors limiting the amount of savings are charging rate and aircraft compatibility. Furthermore, the most savings per ETV are made with a fleet size of 1. All in all, it can therefore be considered that implementing dispatch towing at AMS is attractive. During the starting period, ETVs are able to tow the most fuel consuming flights. While with a large fleet, significant savings can be expected. However, the considered ETVs are conceptual so decision-makers should stimulate production of such vehicles. Lastly, the compatible aircraft and their amounts on airports will need to be certified for towing and will also change dynamically due to the ever evolving aircraft industry.

The balanced charging policy has a limiting impact on the amount of fuel cost savings. Most fuel savings would be achieved by a balancing percentage that results in a large bandwidth of the ETV state-of-charge, whilst ensuring a feasible state-of-charge. For small fleets, the percentage needs to be around 75% to ensure a feasible state-of-charge for all ETVs. As for a small fleet, the towing utilisation is high since there are many flights with high savings available to few ETVs. The higher the ETV towing utilisation, the more energy is consumed requiring a high percentage. However, for a large fleet of ETVs the towing utilisation decreases. As for a large fleet, more flights can be towed by the higher amount of ETVs while not all compatible flights have fuel cost savings because of short taxiing times.

The tow direction that is most preferred on peak days is outbound. NB flights are always preferred to be towed outbound, for both a north- and southbound operation and for different fleet sizes. This can be explained due to the towing times for outbounds being longer than for inbounds and longer towing times yield higher savings. For WB flights, the outbound direction is not always preferred. However, if the inbound direction is preferred the outbounds are towed by a similar ratio. The reason is the same for the NB flights, in that the towing time distribution is most important in determining the preferred towing direction. This result can impact decisions regarding infrastructural adaptations on hub airports. Where focusing on suitable platforms for (dis)connecting ETVs to outbound flights will support in returning the investment more quickly.

Increasing the charging rates results in a decrease of fuel costs and the minimum number of chargers required. Increasing charging rates however impacts average and maximum power consumption during a day. Therefore, a trade-off needs to be made between the fuel cost savings and investment in amount of chargers, versus the grid infrastructure investments.

5.1 Recommendations

It is recommended to develop a similar model in a rolling horizon approach. The solutions of this research are a result of considering all the ETV to flight assignments during 24 hours. Whilst capturing the effects to be expected on peak days at a busy airport, this impacted the computation time significantly. Implementing a rolling horizon approach provides for faster computation times as the solution space is smaller. Furthermore, this approach would be especially suitable for analysing the assignment during a real-time operation.

The assumptions regarding ferrying should be taken into account, for a different modelling approach. Due to the model formulation of this research, there is no information available in the decision variables about the next flight assignment. In a model such as vehicle scheduling, such a sequence is stored in the decision variables. This can result in a more accurate representation of reality whilst potentially increasing utilisation. However, this comes at a cost of computational complexity.

The location of chargers have not been taken in to account in this research. The minimum number of chargers required for different fleet sizes follow from this research. Also, the flexible service network can be used to include the location of chargers. Together with the amount of chargers, this can be taken as a guideline for the setup of such a future study.

The balancing recharging policy limits the potential fuel savings. If the model can track battery level, choosing the moments for recharging and durations causes for a more operationally accurate solution. This also removes the requirement of the balancing percentage and to generate charging blocks that are not always sufficiently long.

Other limitations of this study are due to the input data. The input flight schedule does not consider the effects of seasonality. Another limitation due to the input data are the fuel calculations, because the lack of publicly available data on engine types and APU fuel flow.

An important operational limitation is the assumption that ETVs can drive in both directions with a constant speed on the service road at AMS. The combination of the road width and dimensions of an ETV will probably not make this a realistic assumption. Therefore, it could be considered driving in only one direction corresponding with the runway operation both in a future study or in the beginning phase of operational implementation. Furthermore, as the fleet grows both the savings increase as well as the need to invest in roads that are wide enough to avoid delays.

Lastly, another operational limitation is that it is challenging to assume that engine warm-up and engine cool-down can take place during the tow. This will impact the workload for pilots in addition to the new procedure of towing. The actual decision on how and at when to implement this procedure will therefore need to be reconsidered in consultation with relevant stakeholders to ensure safety at all times. Furthermore, it is assumed that there is a constant warm-up/cool-down time which in reality varies per aircraft and weather conditions to begin with.

References

[Aqua-calc, 2023] Aqua-calc (2023). Volume to weight conversions.

[CBS, 2023] CBS (2023). Average energy prices for consumers, 2018-2023.

[EASA, 2022] EASA (2022). European Aviation Environmental Report.

[EASA, 2023] EASA (2023). ICAO Aircraft Engine Emissions Databank.

[EUROCONTROL Airport CDM Team, 2017] EUROCONTROL Airport CDM Team (2017). Airport CDM Implementation Manual. Technical report, EUROCONTROL.

[FAA, 2023] FAA (2023). Aircraft Characteristics Data.

[Federal Office of Civil Aviation (FOCA) and Rindlisbacher, 2007] Federal Office of Civil Aviation (FOCA) and Rindlisbacher, T. (2007). Aircraft Piston Engine Emissions Summary Report.

[Google Earth Pro, 2023] Google Earth Pro (2023). Amsterdam Airport Schiphol | Created with Google Earth Pro version 7.3.6.9345 (64-bit).

[IATA, 2023] IATA (2023). Jet Fuel Price Monitor.

[ICAO, 2011] ICAO (2011). Airport air quality manual. Technical report.

[Schiphol Airport, 2019] Schiphol Airport (2019). 2019 Traffic Review.

[Schiphol Airport, 2021] Schiphol Airport (2021). Duurzaam taxiën halveert brandstofverbruik van vliegtuigen tijdens taxiproces.

[Schiphol Airport, 2022] Schiphol Airport (2022). Sustaining your world | Op de luchthaven.

[Schiphol Airport, 2023] Schiphol Airport (2023). Aircraft process maps.

[Segeren, 2022] Segeren, M. (2022). *Potential Impact of Operational Towing on Aircraft Emissions*. PhD thesis, TU Delft, Delft.

[Seymour et al., 2020] Seymour, K., Held, M., Georges, G., and Boulouchos, K. (2020). Fuel Estimation in Air Transportation: Modeling global fuel consumption for commercial aviation. *Transportation Research Part D: Transport and Environment*, 88:102528.

[TaxiBot International, 2022] TaxiBot International (2022). Products.

[The Aviation Codes Web Site, 2023] The Aviation Codes Web Site (2023). Aircraft Type Codes.

[Trindade et al., 2018] Trindade, R. S., de Araújo, O. C. B., Fampa, M. H. C., and Müller, F. M. (2018). Modelling and symmetry breaking in scheduling problems on batch processing machines. *International Journal of Production Research*, 56(22):7031–7048.

[Virta, 2023] Virta (2023). DC charging station: Costs, delivery times & ideal locations.

[Zoutendijk et al., 2023] Zoutendijk, M., van Oosterom, S. J., and Mitici, M. (2023). Electric Taxiing with Disruption Management: Assignment of Electric Towing Vehicles to Aircraft. American Institute of Aeronautics and Astronautics (AIAA).

Appendices

A IATA codes for fuel calculations and compatibility

This table shows all IATA codes from the flight schedule at AMS coupled with the ICAO code in column 2, aircraft type/name in column 3, WTC in column 4, UID [EASA, 2023] in column 5, number of engines $N_{\mathbf{eng}}$ [FAA, 2023] in column 6, Maximum Take-off Weight (MTOW) [FAA, 2023] in column 7, FF [EASA, 2023, Federal Office of Civil Aviation (FOCA) and Rindlisbacher, 2007] of the APU in column 8 and the its compatibility to an ETV if available in column 9. The UID, number of engines and MTOW were not available for all aircraft as can be seen by '-'. For the UID and the number of engines, this was the case for some of the piston and turboprop powered aircraft. Therefore, the following assumption was made; piston aircraft have an idle fuel flow of 0.0038 kg/s and 2 engines and turboprops have an idle fuel flow of 0.015 kg/s and 2 number of engines. Where the fuel flow was based on the source of Federal Office of Civil Aviation (FOCA) [Federal Office of Civil Aviation (FOCA) and Rindlisbacher, 2007]. The aircraft of which the MTOW was missing, the following MTOWs were assumed based on WTC: 15 t for L, 100 t for M, 150 t for H, 500 for J.

Table 11: Lookup table with IATA codes

IATA	ICAO	Aircraft type	WTC	UID	$N_{\mathbf{eng}}$	MTOW	FF APU	ETV
100	F100	Fokker 100	M	1RR017	2	100	1,75	-
141	B461	BAe 146-100 Pax	M	LF507-1F	4	38,052	1,75	-
142	B462	BAe 146-200 Pax	M	LF507-1F	4	42,129	1,75	-
290	E290	Embraer E190-E2	M	11GE147	2	56,32602	1,75	-
313	A310	Airbus A310-300 pax	H	CF680C	2	143,811645	4	-
318	A318	Airbus A318	M	CFM56-5B5/3	2	67,911042	1,75	NB
319	A319	Airbus A319 Ceo	M	01P18PW153	2	76,399809	1,75	NB
320	A320	Airbus A320-100/200 Ceo	M	7CM050	2	77,898333	1,75	NB
321	A321	Airbus A321-100/200 Ceo	M	1IA003	2	90,881313	1,75	NB
330	A330	Airbus A330 all models	H	7PW082	2	150	4	WB
332	A332	Airbus A330-200	H	5GE085	2	241,684107	4	WB
333	A333	Airbus A330-300	H	7PW082	2	241,684107	4	WB
340	A340	Airbus A340 all models	H	CT79B	2	150	4	-
343	A343	Airbus A340-300	H	1CM011	4	276,138834	4	WB
345	A345	Airbus A340-500	H	8RR045	4	379,503468	4	WB
346	A346	Airbus A340-600	H	8RR045	4	379,503468	4	WB
351	A35K	Airbus A350-1000	H	01P18RR124	2	315,587433	4	WB
359	A359	Airbus A350-900	H	01P18RR124	2	279,634635	4	WB
380	A388	Airbus A380 pax	J	01P18RR104	4	574,249074	5	WB
388	A388	Airbus A380-8	J	01P18RR104	4	574,249074	5	WB
717	B712	Boeing 717	M	4BR007	2	53,454	1,75	-
733	B733	Boeing 737-300 pax	M	1CM007	2	63,1935	1,75	NB
734	B734	Boeing 737-400 pax	M	1CM007	2	67,95	1,75	NB
735	B735	Boeing 737-500 pax	M	1CM007	2	61,608	1,75	NB
736	B736	Boeing 737-600 pax	M	01P11CM116	2	65,4585	1,75	NB
737	-	Boeing 737 all pax models	M	3CM032	2	100	1,75	NB
738	B738	Boeing 737-800 pax	M	01P11CM116	2	78,9126	1,75	NB
739	B739	Boeing 737-900 pax	M	3CM032	2	85,0281	1,75	NB
744	B744	Boeing 747-400 pax	H	01P03GE187	4	412,23	4	WB
747	-	Boeing 747 all pax models	H	1PW041	4	150	4	WB
752	B752	Boeing 757-200 pax	H	3RR028	2	115,7415	4	NB
753	B753	Boeing 757-300 pax	H	3RR028	2	122,31	4	NB
757	-	Boeing 757 all pax models	H	13AA008	2	150	4	NB
762	B762	Boeing 767-200 pax	H	1PW026	2	142,695	4	WB
763	B763	Boeing 767-300 pax	H	1RR011	2	186,636	4	WB
764	B764	Boeing 767-400 pax	H	8GE101	2	203,85	4	WB
767	-	Boeing 767 all pax models	H	1PW026	2	150	4	WB
772	B772	Boeing 777-200 pax	H	8GE100	2	297,168	4	-
773	B773	Boeing 777-300 pax	H	9GE128	2	298,98	4	-
777	-	Boeing 777 all pax models	H	9GE128	2	150	4	-

Table 11 – continued from previous page

IATA	ICAO	Aircraft type	WTC	UID	$N_{\mathbf{eng}}$	MTOW	FF APU	ETV
781	B78X	Boeing 787-10 pax	H	11GE138	2	253,68	4	WB
788	B788	Boeing 787-8 pax	H	12GE150	2	227,6325	4	WB
787	B789	Boeing 787-9 pax	H	12GE150	2	253,68	4	WB
789	B789	Boeing 787-9 pax	H	12GE150	2	253,68	4	WB
31Y	A310	Airbus A310-300 Freighter	M	2GE037	2	143,811645	1,75	-
32A	A320	Airbus A320-200 Ceo (Sharklets)	M	1IA003	2	77,898333	1,75	-
32N	A20N	Airbus A320-200 Neo	M	8IA010	2	78,896745	1,75	NB
32Q	A21N	Airbus A321-200 Neo	M	8IA010	2	94,875867	1,75	-
32S	A21N	Airbus A318/319/320/321	M	8IA010	2	94,875867	1,75	NB
33X	A332	Airbus A330-200 Freighter	H	5GE085	2	241,684107	4	WB
73C	B733	Boeing 737-300 (winglets) pax	M	1CM007	2	63,1935	1,75	NB
73E	B735	Boeing 737-500 (winglets)pax	M	1CM007	2	61,608	1,75	NB
73F	B737	Boeing 737 all Freighter models	M	1CM007	2	69,9885	1,75	NB
73G	B737	Boeing 737-700 pax	M	3CM032	2	69,9885	1,75	NB
73H	B738	Boeing 737-800 (winglets) pax	M	3CM034	2	78,9126	1,75	NB
73J	B739	Boeing 737-900 (winglets) pax	M	3CM032	2	85,0281	1,75	NB
73L	B732	Boeing 737-200 Combi	M	01P11CM116	2	52,3215	1,75	NB
73M	B737	Boeing 737 Combi	M	01P11CM116	2	69,9885	1,75	NB
73P	B734	Boeing 737-400 Freighter	M	1CM007	2	67,95	1,75	NB
73Q	B734	Boeing 737-400 Combi	M	01P11CM116	2	67,95	1,75	NB
73W	B737	Boeing 737-700 (winglets) pax	M	3CM032	2	69,9885	1,75	NB
73Y	B733	Boeing 737-300 Freighter	M	01P11CM116	2	63,1935	1,75	NB
74E	B744	Boeing 747-400 Combi	H	1PW041	4	412,23	4	WB
74F	B744	Boeing 747 all Freighter models	H	1PW041	4	412,23	4	WB
74H	B744	Boeing 747-8I Passenger	H	1PW041	4	412,23	4	WB
74N	B744	Boeing 747-8F	H	11GE139	4	412,23	4	WB
74X	B742	Boeing 747-200 Freighter	H	11GE139	4	377,349	4	WB
74Y	B744	Boeing 747-400 Freighter	H	01P03GE187	4	412,23	4	WB
74Z	B744	Boeing 747-400	H	01P03GE187	4	412,23	4	WB
75F	B752	Boeing 757 Freighter	H	3RR028	2	115,7415	4	NB
75T	B753	Boeing 757-300 (winglets) pax	H	3RR034	2	122,31	4	NB
75W	B752	Boeing 757-200 (winglets) pax	H	3RR028	2	115,7415	4	NB
76F	-	Boeing 767 all Freighter models	H	1GE025	2	150	4	WB
76W	B763	Boeing 767-300 (winglets) pax	H	01P02GE188	2	186,636	4	WB
76Y	B763	Boeing 767-300 Freighter	H	1GE025	2	186,636	4	WB
77F	-	Boeing 777 Freighter	H	8PW085	2	150	4	-
77L	B772	Boeing 777-200LR pax	H	01P21GE217	2	297,168	4	-
77W	B77W	Boeing 777-300ER pax	H	01P21GE217	2	351,075	4	-
77X	B77L	Boeing 777-200 Freighter	H	8PW085	2	347,046018	4	-
7M8	B38M	Boeing 737 MAX 8 pax	M	01P20CM138	2	82,0836	1,75	NB
7M9	B39M	Boeing 737 MAX 9 pax	M	01P20CM138	2	88,1991	1,75	NB
A32	AN32	Antonov AN-32	L	Turboprop	-	15	1	-
A38	AN38	Antonov AN-38	L	Turboprop	-	15	1	-
A40	A140	Antonov AN-140	M	Turboprop	-	100	1,75	-
A4F	A124	Antonov AN-124 Ruslan	H	1AA005	4	404,470563	4	-
A81	A148	Antonov AN-148-100	M	1AA005	4	100	1,75	-

Table 11 – continued from previous page

IATA	ICAO	Aircraft type	WTC	UID	N_{eng}	MTOW	FF APU	ETV
AB6	A306	Airbus Industrie A300-600 pax	H	2GE040	2	164,78328	4	-
ABF	A30B	Airbus Industrie A300 Freighter	H	2GE039	2	164,78328	4	-
ABX	A30B	Airbus Industrie A300C4/F4	H	1PW026	2	164,78328	4	NB
ABY	A306	Airbus Industrie A600-600F	H	2GE040	2	164,78328	4	-
AN4	AN24	Antonov AN-24	M	Turboprop	-	100	1,75	-
AN6	-	Antonov AN-26/30/32	M	Turboprop	-	100	1,75	-
AR8	RJ85	Avro RJ85 Avroliner	M	AS907-3-1E-A3	4	43,941	1,75	-
ARJ	-	Avro RJ70/85/100	M	CF34-10A16	2	100	1,75	-
AT4	AT43	Alenia ATR 42-300	M	Turboprop	-	16,681725	1,75	-
AT5	AT45	Alenia ATR 42-500	M	Turboprop	2	18,575265	1,75	-
AT7	AT72	Alenia ATR 72	M	Turboprop	-	21,4722	1,75	-
ATF	AT72	Alenia ATR 72F	M	Turboprop	-	21,4722	1,75	-
ATP	ATP	British Aerospace ATP	M	Turboprop	-	100	1,75	-
ATR	-	Alenia ATR 42/72	M	Turboprop	-	100	1,75	-
AW1	A139	Augusta Westland	L	-	-	15	1	-
BE1	B190	Beechcraft 1900/C/D	M	Turboprop	2	7,75536	1,75	-
BE2	-	Beechcraft twin piston	L	Piston	-	15	1	-
BEC	-	Beechcraft light aircraft	L	Turboprop	-	15	1	-
BEH	B190	Beechcraft 1900D	M	Turboprop	-	7,75536	1,75	-
BEP	-	Beechcraft light aircraft	L	Piston	-	15	1	-
BES	B190	Beechcfrat 1900/1900C	M	Turboprop	2	7,75536	1,75	-
BET	-	Beechcraft light aircraft	L	Turboprop	-	15	1	-
BNI	BN2P	Pilatus BN-2A/B Islander	L	Piston	-	15	1	-
CL3	CL30	Bombardier Challenger 300	M	1TL001	2	17,59905	1,75	-
CL6	CL60	Bombardier Challenger 600-605	M	1TL001	2	21,5628	1,75	-
CN1	-	Cessna light aircraft	L	Piston	-	15	1	-
CN2	-	Cessna light aircraft	L	Piston	-	15	1	-
CNA	-	Cessna light aircraft	L	Piston	-	15	1	-
CNC	-	Cessna light aircraft	L	Turboprop	-	15	1	-
CNJ	C750	Cessna Citation	L	01P16PW143	2	16,3533	1	-
CNT	-	Cessna light aircraft	L	Turboprop	-	15	1	-
CR2	CRJ2	Canadair Regional Jet 200	M	CF34-8C5	2	21,49485	1,75	-
CR7	CRJ7	Canadair Regional Jet 700	M	CF34-8C5A1	2	33,975	1,75	-
CR9	CRJ9	Canadair Regional Jet 900	M	CF34-8C5A2	2	36,4665	1,75	-
CRF	-	Canadair Regional Jet F	M	CF34-8C5	2	100	1,75	-
CRJ	-	Canadair Regional Jet	M	CF34-8C5	2	100	1,75	-
CRK	CRJ9	Canadair Regional Jet 1000	M	CF34-8C5A3	2	36,4665	1,75	-
CS1	BCS1	Bombardier C Series CS100	M	01P20PW184	2	63,0123	1,75	-
CS3	BCS3	Bombardier C Series CS300	M	01P20PW184	2	70,807071	1,75	-
CV5	CVLT	Convair CV-580 pax	M	Turboprop	2	26,5005	1,75	-
D08	J328	Fairchild Dornier Do.228	L	Turboprop	2	15,639372	1	-
D28	D228	Fairchild Dornier Do.228	L	Turboprop	-	15	1	-
D38	D328	Fairchild Dornier Do.328	M	Turboprop	-	13,971879	1,75	-
DA4	DA40	DAI Diamond DA40	L	Piston	1	1,308264	1	-
DF9	F900	Dassault Falcon 900	M	11CM080	3	22,197	1,75	-
DFL	FA7X	Dassault Falcon	M	11CM080	3	31,71	1,75	-
DH1	DH8A	DHC-8-100 Dash 8 / 8Q	M	Turboprop	-	15,6285	1,75	-
DH2	DH8B	DHC-8-200 Dash 8 / 8Q	M	Turboprop	2	16,4439	1,75	-
DH3	DH8C	DHC-8-300 Dash 8 / 8Q	M	Turboprop	-	18,6183	1,75	-
DH4	DH8D	DHC-8-400 Dash 8Q	M	Turboprop	-	29,2185	1,75	-
DH7	DHC7	DHC-7 Dash 7	M	Turboprop	4	19,932	1,75	-
DH8	-	DHC-8 Dash 8 all models	M	Turboprop	-	100	1,75	-
DHD	DOVE	DH.104 Dove	L	Piston	-	15	1	-
DHL	DHC3	DHC-3 Turbo Otter	L	Piston	-	15	1	-

Table 11 – continued from previous page

IATA	ICAO	Aircraft type	WTC	UID	$N_{\mathbf{eng}}$	MTOW	FF APU	ETV
DHP	DHC2	DHC-2 Beaver	L	Piston	1	2,3103	1	-
DHT	DHC6	DHC-6 Twin Otter	L	Turboprop	2	5,6625	1	-
DO8	J328	Fairchild Dornier Do.228	L	Turboprop	2	15,639372	1	-
E55	E55P	EMB 505 Phenom 300	M	01P16PW143	2	8,139504	1,75	-
E70	E170	Embraer 170	M	01P22PW169	2	38,549394	1,75	-
E70	E170	Embraer 170	M	01P22PW169	2	38,549394	1,75	-
E75	E75L	Embraer 175 (Long Wing)	M	CF34-8E5	2	38,739201	1,75	-
E75	E75S	Embraer 175 (Short wing)	M	CF34-8E5	2	37,450869	1,75	-
E90	E190	Embraer 190	M	11GE147	2	50,234076	1,75	-
E90	E190	Embraer 190	M	11GE147	2	50,234076	1,75	-
E95	E195	Embraer 195	M	11GE147	2	52,22184	1,75	-
EM2	E120	Embraer EMB.120	M	Turboprop	-	11,974149	1,75	-
EM4	E145	Embraer EMB.145	M	01P06AL028	2	21,971406	1,75	-
EMB	E110	Embraer EMB.110	M	Turboprop	2	5,89353	1,75	-
ER3	E35L	Embraer Legacy 600/650	M	01P06AL034	2	19,973676	1,75	-
ER3	E135	Embraer RJ135	M	01P06AL034	2	20,173449	1,75	-
ER4	E145	Embraer RJ145 Amazon	M	01P06AL030	2	21,971406	1,75	-
ERD	-	Embraer RJ140	M	01P06AL030	2	100	1,75	-
ERJ	-	Embraer RJ135/40/45	M	01P06AL030	2	100	1,75	-
F21	F28	Fokker F.28 Fellowship 1000	M	Turboprop	-	100	1,75	-
F22	F28	Fokker F.28 Fellowship 2000	M	Turboprop	-	100	1,75	-
F23	F28	Fokker F.28 Fellowship 3000	M	Turboprop	-	100	1,75	-
F24	F28	Fokker F.28 Fellowship 4000	M	Turboprop	-	100	1,75	-
F27	F27	Fokker F.27	M	Turboprop	-	100	1,75	-
F28	F28	Fokker F.28 Fellowship	M	Turboprop	-	100	1,75	-
F50	F50	Fokker 50	M	Turboprop	-	100	1,75	-
F5F	F50	Fokker 50 Freighter	M	Turboprop	-	100	1,75	-
F70	F70	Fokker 70	M	Turboprop	-	100	1,75	-
FRJ	J328	Fairchild Dornier 328JET	M	PW306A	2	15,639372	1,75	-
GJ5	GLF5	Gulfstream Aerospace G-1159	M	3BR001	2	40,9965	1,75	-
GRJ	GLF5	Gulfstream Aerospace G-1159	M	3BR001	2	40,9965	1,75	-
IL9	IL96	Ilyushin IL96 pax	H	1AA005	4	150	4	-
J31	JS31	British Aerospace J31	L	Turboprop	-	6,940866	1	-
J32	JS32	British Aerospace J32	L	Turboprop	-	6,945396	1	-
J41	JS41	British Aerospace J41	M	Turboprop	2	10,872	1,75	-
L4T	L410	LET 410	L	Turboprop	-	15	1	-
LRJ	-	Gates Learjet	M	1AS001	2	100	1,75	-
M1F	MD11	McDonnell Douglas MD11F	H	12PW102	3	272,9325	4	-
M80	MD80	McDonnell Douglas MD80	M	1PW007	2	100	1,75	-
M82	MD82	McDonnell Douglas MD82	M	4PW068	2	67,7235	1,75	-
M83	MD83	McDonnell Douglas MD83	M	JT8D-219	0	72,48	1,75	-
M88	MD88	McDonnell Douglas MD88	M	1PW018	2	67,7235	1,75	-
M90	MD90	McDonnell Douglas MD90	M	11GE147	2	70,668	1,75	-
PA1	-	Piper light aircraft	L	Piston	-	15	1	-
PA2	-	Piper light aircraft	L	Piston	-	15	1	-
PAG	-	Piper light aircraft	L	Piston	-	15	1	-
PAT	-	Piper light aircraft	L	Turboprop	-	15	1	-
PL2	PC12	Pilatus PC-12	L	Turboprop	-	4,73385	1	-
S20	SB20	Saab 2000	M	Turboprop	2	22,969818	1,75	-
SF3	SF34	Saab SF340	M	Turboprop	2	12,684	1,75	-
SF5	SF50	Cirrus Vision SF50	M	01P16PW143	1	2,718	1,75	-
SH6	SH36	Shorts SD.360	M	Turboprop	-	12,284001	1,75	-
SU9	SU95	Sukhoi Superjet 100-95	M	SaM146-1S18	2	45,820044	1,75	-
SWM	-	Fairchild (Swearingen)	L	Turboprop	-	15	1	-
T20	T204	Tupolev Tu-204 / Tu-214	M	PS-90A2	-	100	1,75	-
TB7	TBM7	Daher Socata TBM 900	L	Piston	1	2,996142	1	-

Table 11 – continued from previous page

IATA	ICAO	Aircraft type	WTC	UID	$N_{\mathbf{eng}}$	MTOW	FF APU	ETV
YN2	Y12	Harbin Yunshuji Y12	M	Turboprop	-	100	1,75	-

B Ramp node couplings

This table shows the couplings/connections between the ramp nodes and the ramp and/or gate number from the flight schedule at AMS

Table 12: Ramp node couplings with ramp/gate number at AMS

Ramp node	Ramp/gate number
25	J80-J87
31	G71-G79
37	G02-G09, H01-H07
41	F02-F09
48	E02-E24
53	D88-D95, E72-E77
58	D02-D57
62	C04-C18
64	B13-B36
66	B91-B95
68	A61-A75
70	A41-A60
72	A31-A40
80	R71-R83
85	S64-S71
88	S72-S96
102	HG01-HG32
104	K01-K78

II

Literature Study

previously graded under AE4020

1 Introduction

The contribution of aviation to worldwide CO_2 emissions is in the range of 2% to 2.5% [54]. Recently, two of the world's largest aviation organisations International Air Transport Association (IATA) and International Civil Aviation Organization (ICAO) have both adopted the goal to reach net-zero CO_2 emissions by 2050, which brings air transport in line with the Paris Agreement to limit global warming to 1.5degC [65]. To reach these climate goals for the aviation sector by 2050, four major emission reduction strategies have been identified. These four strategies are; (1) sustainable aviation fuels, (2) new propulsion and aircraft design technologies, (3) offsetting and (4) operational improvements [41]. Although the emissions reduction potential of the fourth strategy is the lowest of all four, it can be deployed at a faster rate when compared to new aircraft technologies or the development of Sustainable Aviation Fuels (SAF). Within operational improvements, the topic of sustainable taxiing is the topic of recent research initiatives. The contribution of aircraft taxiing related emissions can go up to almost 20% of an airport's total carbon emissions [26, 59]. Amsterdam Airport Schiphol (AMS) or informally known as Schiphol Airport, one of the world's busiest airports, have announced their ambition to run emission-free airport operations by 2030 [**?**]. One of the measures in the emissions reduction strategy envisioned by the Schiphol is sustainable taxiing. Sustainable taxi tests at Schiphol, carried out with the TaxiBot [64], have shown that on average 50% of fuel consumption is saved [**?**]. However, the trial tests carried out at Schiphol also identified necessary measures before sustainable taxiing can be applied as a standard process. These identified measures are divided in the areas of infrastructure, processes and technology. One aim of this study is to develop insight for process related measures to incorporate sustainable taxiing. The other aim is to identify the contribution that can be made on the academic perspective.

The conclusions of Schiphol after their trial tests indicate that technological advancements are needed before implementation of sustainable taxiing can be realised. From an airport operational point of view, various technological aspects are of interest of which how they are managed exactly is an important one. This is supported by the research effort of the Advanced Engine-Off Navigation (AEON) project. The project researches three more environmentally friendly taxiing alternatives among which is the TaxiBot. The efforts that AEON performs in the area of optimisation is researching how the fleet management of such vehicles is performed. More specifically, the management of towing vehicles during the tactical operation under the influence of delay are investigated [20]. To the best of our knowledge, it is found that no exclusive solution exists for the planning and assignment of towing vehicles on the day of operations, subject to uncertainty and delays. Combined with the aim of Schiphol to provide for emission-free operations, the use of fully electrical towing vehicles is considered. The research objective of this study therefore is:

> To develop an approach that assigns a limited set of electric towing vehicles to aircraft for real-time dispatch towing operations at AMS, while accounting for uncertainties in the operation by using optimisation methods.

This literature study firstly looks into the concept of dispatch towing in chapter 2. In this chapter, also the characteristic of such a towing vehicle are specified and airport processes impacted by dispatch towing are discussed. Furthermore, the research gap is identified and the layout and procedures at AMS are discussed. Second, in chapter 3, different mathematical models with their objectives and constraints are discussed, that could be of use or are already known to be applied for planning towing operations and a trade-off is made for the model that will be used in the thesis. Thirdly, the solution methods for the assignment problem are discussed in chapter 4. Lastly, the research proposal for the thesis is drawn in chapter 5.

2
Dispatch towing

Up to this day, aircraft ground movement also known as taxiing, is mostly performed with the use of all the aircraft's engines. With more pressure on climate goals, recent research initiatives have looked into the development of alternative and more sustainable methods for aircraft taxi operations. Operational tests at Schiphol have shown the potential of sustainable taxiing being able to achieve on average a reduction of 50% in fuel consumption compared to conventional taxiing. In this chapter, the alternative taxiing method of dispatch towing, that this study will focus on, is introduced in section 2.1. Second, the specifications of this new method are discussed in section 2.2. Next, the airport operations that are being impacted by introducing dispatch towing are explored in section 2.3. And the layout of Schiphol Airport with regards to dispatch towing is discussed in section 2.4. Lastly, the state-of-the-art literature both on the environmental impact and the planning of dispatch towing operations are discussed in section 2.5. After having discussed the relevant literature, this chapter will conclude with the research gap that is identified.

2.1. Overview on sustainable taxiing

This section discusses different taxiing solutions that offer a more sustainable and a more environmentally friendly alternative to conventional taxiing operations. First, an overview is given on the alternative taxiing methods that offer a more sustainable solution compared to conventional taxiing operations. Second, the concept of dispatch towing that is studied in this research is introduced and discussed.

2.1.1. Sustainable taxiing alternatives

Using the aircraft's engines to propel the aircraft and move on the ground is the conventional method of taxiing on the ground. During conventional taxiing the engines are set at 7% of thrust [26]. This thrust setting of 7% causes for a high fuel burn and a substantial amount of Carbon Monoxide (CO) and Unburned Hydrocarbons (UHC) emissions to be released [32]. More efficient taxiing operations have been identified in [49]. These alternatives are also the topic of research in the AEON project. Although the naming is different, the three taxiing solutions are discussed more in depth. These solutions are directly more sustainable since at least half of the engines are off during the major part of taxiing. The three solutions considered in the AEON project [21] and their respective operational implications are summarised here:

1. **Single-engine Taxiing (SET) solutions:** Half of the aircraft's engines are used, which in most cases implicates the use of one engine instead of two to propel the aircraft. The expected reduction in taxi fuel consumption at Schiphol can go up to 30% [24], compared to conventional taxiing. Major implications impeding the usage of this method include the effect on the aircrafts manoeuvrability and balance. Furthermore, the usage is currently limited to 50% of taxi-in procedures and only 10% of taxi-out procedures. An accurate take-off time indication is the most limiting factor in taxi-out usage because this influences starting the other engine on time.

2. **Non-autonomous taxiing solutions:** By using external towing vehicles, similar to a pushback tractor. These external towing vehicles are suited for towing revenue aircraft at near-regular taxi speeds to the runway without using the aircraft's jet engines. Tests at Schiphol carried out with a certified towing vehicle called TaxiBot, have shown a reduction in fuel burn between 50%-85% [15], depending on the

engine-off taxi time and distance. While the expected environmental benefits are higher than the SET solution, the usage of this solution is still in a trial phase. Measures on infrastructure, processes and technology are necessary mainly due to the introduction of extra traffic movement. Besides the AEON project, these challenges are also identified by Schiphol [2].

3. **Autonomous taxiing solutions:** Use an on-board electrical motor that is built-in the aircraft's Nose Landing Gear (NLG) that can be powered by the Auxiliary Power Unit (APU). This solution makes it possible to pushback and taxi autonomously without using the aircraft's engines. And the fuel savings for this solution are expected to be the same as for the non-autonomous solution. Various manufacturers have built and tested these electrical motors, of which the most commonly known system is that of Wheeltug [70]. However this solution is yet to be certified. The main issue herein are the structural changes necessary which influence the aircraft's weight and balance.

The second solution has been certified but is yet to be fully implemented due to adaptations needed on infrastructure, processes and technology. One of the goals of this study is to stimulate the further development of this sustainable taxiing solution by adding to the existing body of science for non-autonomous taxiing. In this study, instead of non-autonomous taxiing this method of sustainable taxiing is named dispatch towing, due to this being a more consistent name in literature. Dispatch towing is further detailed in the next section.

2.1.2. Dispatch towing

Before the concept of dispatch towing is explained, a short history of aircraft ground movement is described first in order to better understand the different vehicles used.

In the beginnings of aviation, aircraft could be moved on ground by hand. After the development of the aeroplane's tail and nose wheel, it became easier and more cost effective for aircraft to move on the ground under their own propulsion system. Due to the growth in the amount of aircraft in World War II, the market for Ground Support Equipment (GSE) began to take its first forms. It was in this period that agricultural tractors where being used intensively to move aircraft on ground. In the 1950s, the French company TracMa introduced one of the first dedicated towing tractors built to replace the agricultural tractors [4, 5].

After the introduction of a dedicated towing tractor or also known as a 'tug', different designs were made, all of which are in operation up until this day. At first, the tractors were designed to be able to pull aircraft on the basis of a tow bar connection between the aircraft's nose wheel and the tractor. Both the bobtail cargo tractor and the tow bar tractors are designed for operations with tow bars.

The use of tow bars for pushing and towing aircraft also has its drawbacks. Firstly, every aeroplane type requires a specific tow bar. Second, it is difficult to control the combination during pushback and manoeuvring in tight spaces for remote parking. To overcome these operational challenges, the first Towbarless Tractor (TBLT) was developed at the end of the 1960s [9]. The TBLT takes away the need of a tow bar and controls the aeroplane's steering by loading the nose wheel on a rotating turret on the back of the tractor. This results in one type of TBLT being suitable for multiple types of aeroplanes and being able to manoeuvre more tightly.

The first TBLT's were originally designed to tow loaded aeroplanes from the terminal to the runway to save fuel costs [18]. This idea is the basis for the concept and operation of dispatch towing, of which the definition is best summarised by the adjusted definition of [7]:

> **Dispatch towing** is the movement of a revenue aircraft propelled by an external towing vehicle, from the parking position to a position near the active runway with the engines stopped, or conversely, made possible by the increased towing speeds achievable with a TBLT.

Although the concept of dispatch towing has existed at least since the development of a TBLT, it has not been successfully implemented up to this day. The reason earlier attempts have been unsuccessful at implementing dispatch towing is due to the following two design related issues:

1. Regulations require the aircraft to be controlled by the pilot and not the tug driver.

2. Using conventional pushback tugs increases fatigue loads on the NLG which shorten its expected life cycle.

The TaxiBot [16] is currently the only certified TBLT which overcomes these design issues.

Figure 2.1: A TaxiBot towing a Lufthansa Boeing 737-500 [6]

As can be seen in Figure 2.1, the TaxiBot has a similar appearance as a conventional TBLT but as the name suggests it is a semi-robotic TBLT. The robotic part refers to the wheel assembly which enables the TaxiBot to be controlled from the cockpit. This special wheel support turret assembly, or wheel assembly, is mounted on the back part of the TaxiBot to support the aircraft's NLG and free rotation is made possible. With the use of rotation sensors in the wheel assembly, steering control by the pilot is made possible using existing controls [17]. By using the aircraft's brakes, the taxiing speed is controlled. This design feature of the TaxiBot offers the capability of both steering and controlling the taxiing speed from the cockpit and resolves the first technological issue (item 1). The wheel assembly is shown in Figure 2.2.

Figure 2.2: The clamping mechanism between the NLG and TaxiBot [40]. 1 & 2: The nose wheel enters the clamping mechanism. 3 & 4: The nose wheel is clamped and lifted and is able to rotate freely.

Furthermore, there is an energy absorber assembly mounted between the wheel assembly and the chassis. In combination with a control system and force sensors, the acceleration of the tug is governed to ensure that the NLG does not exceed predetermined limits [17], resolving the second issue regarding fatigue loads (item 2). Therefore, it can be concluded that the TaxiBot meets the requirements to carry out dispatch towing operations.

2.2. Electric towing vehicle characteristics

TaxiBot has produced two types of TBLT vehicles. The Narrow Body (NB) TaxiBot is suited to tow medium sized aeroplanes and was first certified in November of 2014 [16] for dispatch towing with the Boeing 737. The Wide Body (WB) TaxiBot is able to tow up to the super-heavy category planes. Currently, the WB TaxiBot has not been certified yet for dispatch towing operations and is still in the process of certification. Currently, both versions of the TaxiBot are powered by a hybrid combination of a diesel engine and electromotors. In the future, it is anticipated that a fully Electric Towing Vehicle (ETV) will be developed. However, currently there are no specifications available for a fully electric vehicle certified for dispatch towing.

The company Goldhofer have developed the Phoenix E ETV [33], and describe various specifications such as the battery, speed and aircraft compatibility. The work of Segeren [58] has considered fully electric operational (dispatch) towing with the Phoenix E. This gives an idea of some feasible characteristics including battery specifications. However, since it is not known if this vehicle is certified for dispatch towing as it is currently only being used for pushbacks and maintenance towing [34], the full specifications are not considered for dispatch towing in this thesis. The Phoenix E is able to perform a maintanence tow with aircraft up to a Maximum Take-off Weight (MTOW) of 352 tonnes with a maximum speed of 13 knots. The maximum weight specification means that it is compatible with around 70% of aircraft on the market today [34]. Considering that the Phoenix E is not able to dispatch tow combined with its maximum speed, forms an important limitation. Furthermore, the Phoenix E does not provide the possibility of becoming autonomous. Therefore the characteristics of the Phoenix E are adjusted into a more compatible and conceptual ETV.

The conceptual ETV should be suitable for dispatch towing and be able to tow with regular taxiing speeds, such as the TaxiBot. Therefore the possibility of potential congestion on the taxiway is reduced. Comparing this to the Phoenix E, it becomes apparent that for increasing the maximum speed, adjustments are required in the specifications. The thesis of van Baaren [66] investigates among others the required operational design with regards to an ETV. Most of the specifications stated by van Baaren are also adapted by Kroese and Oosterom [47, 68]. Since van Baaren concludes that the battery capacity is over-dimensioned, the specifications of the lighter version will be used for the ETVs which are shown in Table 2.1.

Table 2.1: The specifications of the conceptual electric towing vehicles

Specification	**ETV Values**		**Reference**
ETV type	**NB**	**WB**	
Total mass [kg]	15000	35000	[66, 68]
Charging power [kW]	100	350	[68]
Battery capacity [kWh]	390	1250	[66, 68]
Maximum speed [kts]	23	20	[16, 49, 68]

From this point forward, in this study the choice is made to perform dispatch towing operations with the conceptual ETV. On the one hand, ETVs fulfil the goal of AMS to have an emission free airport ground operations. On the other hand, the deployment of ETVs requires the need to schedule recharging, which is one of the identified research gaps that this study aims to contribute to. Further explanation on the research gaps is given in section 2.5.

2.3. Introducing dispatch towing on airports

In this section different processes that will be impacted by dispatch towing are explained. The processes can be divided into two main subsections being Aiport Collaborative Decision-Making (A-CDM) and airport operations. First, subsection 2.3.1 the A-CDM process is described where the timeline is introduced together with uncertainties encountered. Second, the different changes in operations expected by introducing dispatch towing on airports are discussed in subsection 2.3.2.

2.3.1. Airport Collaborative Decision-Making

A-CDM is a concept designed by EUROCONTROL that facilitates the sharing of operational processes and data among different airport stakeholders, to allow for better informed decision-making. Within the A-CDM concept, the Milestone Approach aims to achieve common situational awareness by tracking the progress of a flight and to predict forthcoming events for each flight with the off-blocks and take-off events being the most critical [31]. In the light of dispatch towing, the off-blocks event is the moment where an ETV needs to be connected to the aeroplane. The concept of A-CDM therefore provides an important reference for a timeline and the planning of ETVs. A total of 16 milestones are selected along the progress of a flight, which are depicted in a timeline in Figure 2.3. It should be noted that in Figure 2.3, two of the milestones (3&16) are named Actual Take-off Time (ATOT) in the timeline. This is because the Milestone Approach is viewed from a turnaround process perspective. Therefore the first take-off in milestone 3 is from the so-called ’outstation’, whereas the naming for where the turnaround is performed remains ’airport’.

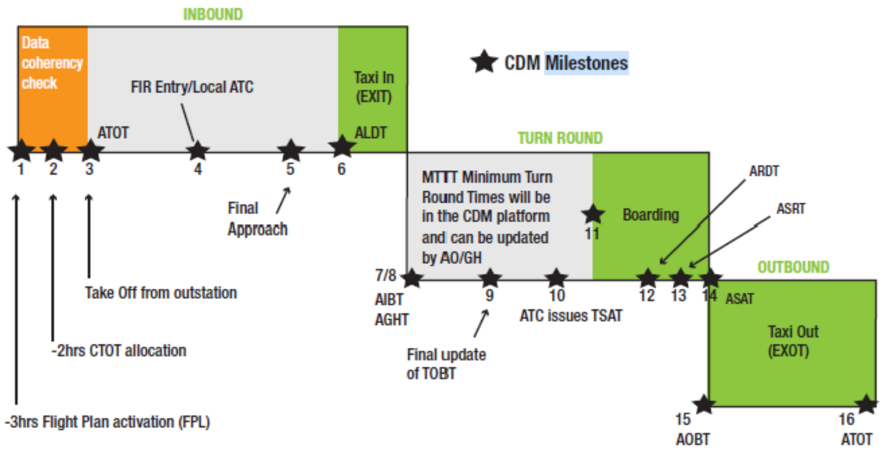


Figure 2.3: The visual timeline of milestones from the A-CDM Milestone Approach [31]

From the Schiphol CDM operations manual [19], it is stated that a pushback tug should be available at Target Start-Up Approval Time (TSAT) minus 5 minutes. In the tactical planning of dispatch towing operations at Schiphol, TSAT-5' should therefore be accounted for to assure the on time arrival of the ETV. The preceding milestones to Actual Start-up Approval Time (ASAT) are important to keep track of since they influence the progression of a flight, the decision-making process and the accuracy of the prediction. Considering the A-CDM timeline, all milestones before the Actual Off-Block Time (AOBT) are therefore relevant to dispatch towing. Below, these milestones are addressed:

- **Milestone 1 - ATC Flight Plan Activated:** this milestone take place once a flight plan is submitted at the outstation and sets the a-cdm timeline in motion. The consistency of the flight plan is checked for consistency with the airport slot programme. The earliest a flight plan is submitted is 3 hours before Estimated Off-Block Time (EOBT). Any discrepancy with the airport slot Scheduled Off-Block Time (SOBT) should be resolved here before commencing.

- **Milestone 2 - EOBT-2h:** at EOBT-2hrs, another slot discrepancy check is performed to check the feasibility of the flight plan's EOBT. Here a potential delayed or early arrival can be checked. This check is performed by comparing the Estimated Landing Time (ELDT), Estimated Taxi-In Time (EXIT) and Minimum Turnaround Time (MTTT) against the flight plan's EOBT with a tolerance of 15 minutes. Alternatively, if a Target Off-Block Time (TOBT) is available than this is checked against the EOBT with the same tolerance.

- **Milestone 3 - ATOT outstation:** when the aircraft takes-off from the outstation, the ELDT is updated and feasibility of the flight plan is checked. Furthermore, at this milestone a Target Take-Off Time (TTOT) tolerance of 5 minutes is checked for the first time. Tolerance for TTOT at the airport is checked based on Estimated In-Block Time (EIBT), MTTT, Estimated Taxi-Out Time (EXOT) or further updates on either EOBT or TOBT. At Schiphol, this milestone is not incorporated.

- **Milestone 4/5 - Local Radar Update/Final Approach:** is triggered when the flight is detected by radar or on its final approach. Here, an update on TOBT and TTOT is given. The feasibility of the flight plan with regards to its EOBT and TTOT is checked. When a flight does not make a turnaround, in the case of a long layover or aircraft home base, a local procedure has to be defined such as a check within EOBT minus x minutes.

- **Milestone 6-8 - Landed, In-blocks and Ground handling:** These processes are set in motion by the Actual Landing Time (ALDT), Actual In-Block Time (AIBT) and Actual Commence Ground Handling Time (ACGT) respectively. Again, a check with updated times is performed on TOBT and TTOT tolerance.

- **Milestone 9 - TOBT Confirmation:** whenever a new TOBT or TTOT is issued, it is checked whether or not the flight is consistent with the flight plan. This timestamp specifically verifies feasibility of the flight plan estimates given the updated TOBT at a predefined time before EOBT.

- **Milestone 10 - TSAT Issued:** Air Traffic Control (ATC) issues the TSAT during the turnaround at a defined time, which is 40 minutes before TOBT at Schiphol [19]. In case another update of the TOBT occurs, then TSAT is also updated. Within a window of 5 minutes before and 5 minutes after TSAT, the flight is not subject to re-planning and in the stable-zone [19]. Therefore, an ETV should arrive 5 minutes before TSAT.

- **Milestone 11 - Boarding started:** when actual boarding occurs, the gate agent updates the information to the A-CDM system. Usually this occurs at 10 minutes before TOBT.

- **Milestone 12 - Aircraft ready:** occurs when the flight is ready for start-up or pushback. A check is performed if Actual Ready Time (ARDT) is within a TOBT tolerance of 3 minutes. At Schiphol however, this milestone is not incorporated.

- **Milestone 13 - Actual Start-up Request Time:** when the start-up request is filed to ATC. This update triggers a manual update of the TTOT.

- **Milestone 14/15 - Start-up Approved/Off-blocks:** The 14th milestone corresponding to the start-up approval is not incorporated at Schiphol. The last milestone considered before take-off is when the actual off-block time is updated. At this moment, the flight has commenced pushback or taxi from its parking position.

2.3.2. Impact of dispatch towing on airport operations

The introduction of dispatch towing will impact different airport operations processes. This section describes the different operations of dispatch towing, starting at the gate stand and ending at the stand or charging location when finished with towing. Some operations of dispatch towing are similar to conventional taxiing processes and will require little to no adaptations on the airport operations. Other dispatch towing operations will introduce challenges on the airport operations before dispatch towing can become a standard procedure. To identify which impacts this study will consider, the different dispatch towing operations and its impact on the airport are described. Some of these processes and implications have also been identified during the trial tests and feasibility study at Schiphol [**?**].

As mentioned before, dispatch towing starts at the gate stand where the ETV is coupled to the aircraft. This occurs near the end of the turnaround process. As described in the previous section on A-CDM procedures at Schiphol, it is advised to have an ETV ready at TSAT-5'.

Coupling

The ETV will be assigned to a departing aircraft at a given (gate) stand and needs to arrive at TSAT-5' the latest. In the TSAT window, the pilot needs to confirm that it is ready to start-up. Here the first two differences with the conventional process take place.

The first difference with the conventional process is in case of any delays that might occur. When the flight is delayed, the ETV will have the possibility to charge if the (gate) stand is supplied with a charger. The process of recharging will be discussed further on in this section.

The second difference is that none of the main engines are started at this phase and only the APU has to be started. Starting the main engines is shifted to the dispatch outbound tow, which is explained later on in this section. After the start-up clearance from ATC is received, any charging has stopped and the parking blocks are removed from the nose wheel, the ETV can commence the coupling with the aircraft. The process of coupling the ETV to the aircraft is considered the same as the TaxiBot, which is shown visually before in Figure 2.2.

ETV Pushback

After the coupling is performed, the pushback movement can begin. As will be discussed later on in this chapter, a pushback at AMS is almost always required before taxiing can commence. Before beginning the actual pushback movement, another clearance from ATC is required which is relayed to the ETV driver. The actual pushback movement with an ETV is identical to the conventional pushback. As is the responsibility of the control, which lies in the hands of the ETV driver.

Dispatch Outbound Tow

After any additional checks are performed between the ETV driver, pilot and ATC, the taxi can commence. The ETV does not have to be uncoupled after pushback but instead can continue towing for the whole taxi process. The pilot controls the Dispatch Outbound Tow (DOT) movement and speed from the gate (runway) to the runway (gate). Near the end of the DOT the main engines will be started and warmed up. The DOT stops when it arrives at the uncoupling location.

Compared to conventional taxiing, the DOT implies two changes in the process. The first of which regards the maximum taxiing speed. For conventional aircraft this is 30 knots and limited due to safety reasons, whereas for an ETV this is 23 knots and limited due to ETV specifications. This will result in longer taxiing times for dispatch towing with the envisioned ETVs.

The second difference is due to the postponed main engines start up. Before taking off, the main engines of the aircraft need to be warmed up before operating, in order to avoid thermal shock. The thrust after engine-start should be operated in idle or near idle for two minutes before setting the thrust to high power [53]. This warm-up can include any taxi time at idle. It will be assumed in this thesis that main engines start up will be performed near the end of the DOT, enabling the warm up to be completed at the end of the DOT. During trial tests at Schiphol, the engines were not yet started during towing. This is due to current operating procedures of aircraft manufacturers not allowing engine start during taxiing. However, in the future if regulations will allow, the DOT will be performed autonomously. Since the autonomous DOT will, among others, significantly reduce the pilot workload, it is assumed that engine start can be incorporated during the DOT.

(Un-)Coupling

After the DOT is finished, the uncoupling process takes place. Where in conventional operations the uncoupling takes place at the apron, in dispatch towing the uncoupling is postponed to when the aircraft is at a location near the runway. The (un)coupling process encompasses four steps, considering an autonomous process. Since this process is similar to coupling at a location near the runway exit point for arrivals, the process is described for both:

- **Pilot**: parking the aircraft at the (un)coupling location;
- **Pilot**: determine the moment to (un)couple to make sure the engines have warmed up/cooled down;
- **ETV**: (un)coupling the aircraft from the ETV;
- **Pilot**: request taxi clearance to the runway/gate.

Assumptions: the (un)coupling is performed at a location near the runway. It is assumed for this thesis that every (un)coupling location is situated in such a way that it does not conflict with conventional taxiing traffic. Since the pilot needs to request taxi clearance before commencing conventional taxiing, it is also assumed that this part will also not conflict with the flow of other taxiing aircraft.

Dispatch Inbound Tow

After uncoupling has taken place, the ETV has three possible assignments; perform a Dispatch Inbound Tow (DIT), return to the gate for a new DOT or return to a recharging location. The decision for a DIT will be made on the spot, one of the reasons being is that the fuel savings for a DOT are considered to be higher [51]. When an ETV is assigned to a DIT, the ETV has to drive from the uncoupling location to the runway exit point of the arriving flight. This movement has to take place via the taxiway network and/or the service road network. After arriving at the coupling location near the runway, the ETV couples with the aircraft as described in the process above. After receiving the taxi clearance, the aircraft and ETV combination commences the DIT similar to conventional taxiing. When arriving near the assigned stand, the ETV is able to precisely determine the stopping point at the stand for the aircraft being towed. since the ETV is close to the ground and has a view on the road markings directly below the nose wheel, it has a high degree of situational awareness to park the aircraft.

Assumptions: Although no literature was found on this, it is assumed that the control of the ETV is preferred over the control of the pilot on the last part of the DIT. Furthermore, it is assumed that the engine cool down period is completed the moment that the aircraft is coupled. Therefore, the complete DIT process can be considered with the main engines off.

Recharging

Whenever an ETV is not coupled to an aircraft, the assignment model will determine if it needs to recharge. This thesis will consider the possibility to recharge at the gate. Therefore when an ETV has to recharge, it becomes more attractive for the assignment model to assign it to the next departure from that same gate. In this way, the ETV does not have to cover extra distance. The exact recharging policy however, will not be worked out in this literature study but in the thesis itself.

Return Movement

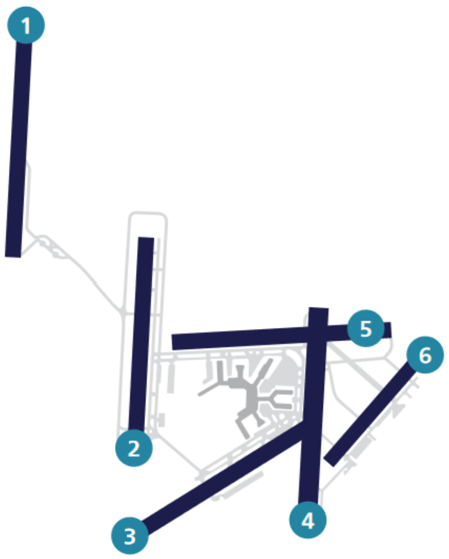
Regardless of being assigned to a DIT, the ETV needs to make a return movement. This results in extra traffic on the taxiway network and can cause potential conflicts. Therefore, in this thesis it is assumed that after uncoupling the ETV will be able to drive immediately via the service road network and not conflict with other taxiing traffic.

2.4. Dispatch towing at AMS

The case study of this research is focused on dispatch towing operations at Amsterdam Airport Schiphol. In this section, characteristics of AMS that play a role in dispatch towing are described. Firstly, the layout of AMS and runway usage is discussed and how it will play a role in this research. Second, the apron area is looked into. Last, the taxiway network and procedures on AMS will be discussed.

2.4.1. Layout

AMS is a hub airport located about 15 kilometers southwest of Amsterdam. Schiphol Airport is Europe's third largest airport, after Heathrow and Charles de Gaulle, with a yearly amount with 71.7 million passengers in 2019 [?]. Schiphol has one terminal and six runways in total. The runway system and characteristics of Schiphol are shown in Figure 2.4.



Runways	Location	Length	Width
1 Polder Runway	18R - 36L	3,800 metres	60 metres
2 Zwanenburg Runway	18C - 36C	3,300 metres	45 metres
3 Kaag Runway	06 - 24	3,500 metres	45 metres
4 Aalsmeer Runway	18L - 36R	3,400 metres	45 metres
5 Buitenveldert Runway	09 - 27	3,453 metres	45 metres
6 Schiphol East Runway	04 - 22	2,014 metres	45 metres

Figure 2.4: Runway layout and characteristics of Amsterdam Airport Schiphol [?]

Besides the usual naming for the runways which are determined by its compass heading, it can be see in Figure 2.4 that the runways are also given a unique name. Out of the six runways, airliners and cargo flights mostly use five. The shorter runway called Schiphol East Runway, is usually only used for general aviation traffic. Only in strong southwestern wind conditions, when other runways are not suitable, it is sometimes used. Furthermore, the runway 1 (Polder) and runway 4 (Aalsmeer) are restricted to one direction for take-offs and landings. For the runway 4, the northerly direction is restricted which means that no landings from and take-offs to the north are permitted. For runway 1, the southerly direction is restricted.

2.4.2. Runway usage

For dispatch towing, the difference between the sorts of tows that can be achieved at Schiphol needs to be investigated. One major factor in assigning a tow is the towing distance. A long distance tow is preferred over a short(er) distance tow for two important reasons. A long distance tow is more beneficial for the airline since more costs are saved due to less fuel usage. This is due to the fact that a longer tow has its major part towing relative to the time and cost intensive (un)coupling process. The second reason is that for the airport and (local) environment, more emissions are saved with a longer tow due to the longer engine-off time. For determining how dispatch towing operations can be performed and most viable, the preferential order of runway combinations is investigated. In addition, the actually most frequently used runway combinations are also discussed.

Schiphol's preferential order of runway combinations is described in their yearly runway usage forecast [12]. This order is mainly in place to avoid flying over and minimise noise pollution for the most densely populated neighbouring areas. The preferential order along with its expected use in 2019 are shown in Table 2.2.

Table 2.2: Schiphol's runway preferential sequence

Preference	Landing		Start/Take-off		Visibility conditions	Expected use 2019 [12]
	L1	L2	S1	S2		Relative [%]
1	06	(36R)	36L	(36C)	Good and UDP:	21,7
2	18R	(18C)	24	(18L)	- Visibility of 5000 m	37,1
3	06	(36R)	09	(36L)	- Cloudbase >1000 ft	2,0
4	27	(18R)	24	(18L)	- During daylight-period (UDP) only	4,8
5a	36R	(36C)	36L	(36C)	Good:	2*18,6
5b	18R	(18C)	18L	(18C)	- Visibility of 5000 m - Cloudbase >1000 ft	
6a	36R	(36C)	36L	(09)	Good or marginal:	2*0,3
6b	18R	(18C)	18L	(24)	- Visibility of 1500 m - Cloudbase >300 ft	
Used during day between 06:00 - 23:00 hrs						
1	06		36L			33,9
2	18R		24			46,3
3	36C		36L			5,0
4	18R		18C			3,3
Used during night between 23:00 - 06:00 hrs						

In Table 2.2, it can be seen that for every preference one landing runway (L1) and one starting runway (S1) are used. For the arrival peak the second landing runway is used (L2) and for the departure peak, the second starting runway is used (S2). When switching between arrival and departure peaks, it can also be the case that four runways are used simultaneously. However, the preference order does not correspond with the expected/actual usage, which can be observed for the higher usage figures for preference 2. This is mainly caused by predominantly southwestern winds in the Netherlands. Primarily though, the Kaag Runway and Polder runway are used for both departures and arrivals taking up 50-60% of all starts and landings yearly.

At Schiphol, the usage of a certain aircraft type has influence on the feasibility of dispatch towing since the towing vehicles have limited compatibility, which has been discussed previously in section 2.2. In Figure 2.5, the most frequently used aircraft type on Schiphol are shown. It can be observed that the aircraft in the MTOW category between 60 and 160 tonnes, which correspond to the Airbus A320 family and the Boeing 737 family, are most frequently used [12]. It should be noted that in this subsection figures before the COVID-19 pandemic are discussed. However, the latest figures available of 2020 and 2021 are not representative and will likely not form a continuing trend in coming years. Which is why figures from 2019 or just before are taken.

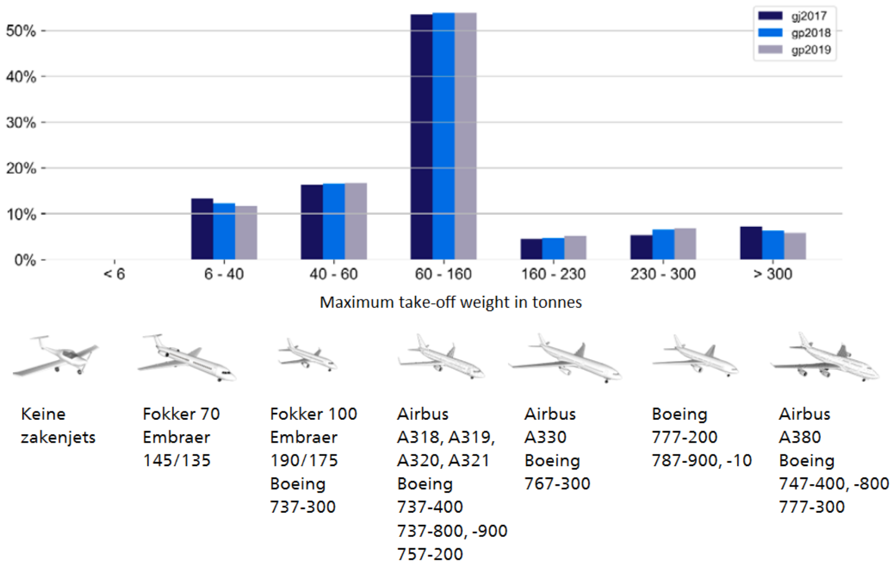


Figure 2.5: Composition of aircraft type usage at Schiphol in 2017 and prognosis for 2018 & 2019, adjusted from [12]

2.4.3. Apron Area

The apron area is where all aircraft are parked and forms the connection for passengers between the terminal and the aircraft, via gate, by bus transfer or by foot. As mentioned before, Schiphol has one main terminal where several piers are connected to. At Schiphol, there are a total of eight piers which are named A up to H. Currently, the A-pier connection to the main terminal is under construction and is expected to be finished after 2025. In between the piers there are bays where the aircraft are parked. In Figure 2.6, the layout of the terminal with its piers is shown.

Figure 2.6: Schiphol Apron with the terminal and piers A-H in dark red [13]

At the apron, arriving aircraft taxi to their assigned gate and the turnaround process commences. Considering the turnaround process, a time limit is in place to decide whether or not to reallocate an aircraft from a gate stand to a (remote) parking stand. Reallocation is possible for aircraft in the MTOW category up to the B737MAX10, with a turnaround of 170 minutes or more. For aircraft in the MTOW category from the A310-300/B757-200, the limit is 210 minutes [10].

For every stand at Schiphol there are standard pushback directions in place. Most aircraft at Schiphol are parked with a nose-in configuration, where the front of the aircraft is pointed towards the terminal. Since aircraft cannot reverse independently, after the turnaround a pushback is required. At Schiphol, there are a total of four different kind of pushback directions:

- **Right or left**: the aircraft is parked nose-in and a pushback is required. At Schiphol, almost all stands connected to a pier have this standard direction, except stands D2 and D4. At most stands, there is a standard direction that the pushback truck needs to push the aircraft to; right or left. For some remote stands, both pushback directions are possible.

- **Backwards**: the aircraft is parked nose-in and a pushback is required. However, an extended pushback backwards is necessary to clear nearby buildings or neighbouring stands and no sharp turn to the right or left is made. Stands D2 and D4 connected to the pier, have this configuration.

- **Taxi-in/out**: the aircraft is able to taxi-in and taxi-out independently, without requiring a pushback. At Schiphol, stands with a taxi-in/out configuration are used as temporary in/outbound holding points when demand exceeds capacity.

- **Nose-out**: at this stand the aircraft is parked in a nose-out direction. To get into the nose-out position a pushback is required. However, after pushback the aircraft is able to taxi independently. Nose-out stands are mostly used for maintenance stands, where aircraft are towed to with a pushback truck.

Furthermore, at most stands there are additional rules in place. At Schiphol, two rules can be in place simultaneously for an individual stand [11, 13]:

- **Pushback limit line**: are in place to assure optimal clearance from neighbouring parked aircraft and optimal capacity is maintained. Furthermore, the pushback limit line aims to reduce nuisance from jet blast. The location where the nose wheel needs to stop after pushback for these stands is indicated on the taxiway.

- **Push-pull**: is a pushback in the backward direction followed by pulling in the forward direction. A push-pull limit line is located on the taxiway to where the pushback needs to be carried out. After which the pull movement can be put in motion.

Further details on the pushback procedures at Schiphol can be found in the pushback manual [11]. Additionally, more detailed maps of Schiphol and the locations of the stands are displayed in **??**.

2.4.4. Taxiways and procedures

The taxiway system connects the runway with the gate stands. With the six runways of Schiphol, the taxiway system is quite extensive with a taxiing distance of 8 km from the D-pier to the Polder runway. Taxiing is controlled by ATC a ATC and a maximum speed of 32 kts is in place in the so-called manoeuvring area, which is the area that is used for take-off, landing and taxiing. For the service roads around the taxiways, a speed limit of 16 kts is in place except for emergency services.

The terminal of Schiphol is surrounded by one main (mostly) dual taxiway. The dual taxiway consist of two parallel taxiways, where the direction of taxiing is opposite. The direction of taxi on the taxiway that is closest to the terminal, named Alpha, is in the clockwise direction. Taxiway Bravo, that is located further from the terminal has an anti-clockwise taxiing direction. The only part without parallel taxiways is taxiway Quebec. However, the part that currently is a single taxiway is negligible after it was recently made almost entirely parallel during a renovation [14]. The taxiway system layout is shown in Figure 2.7.

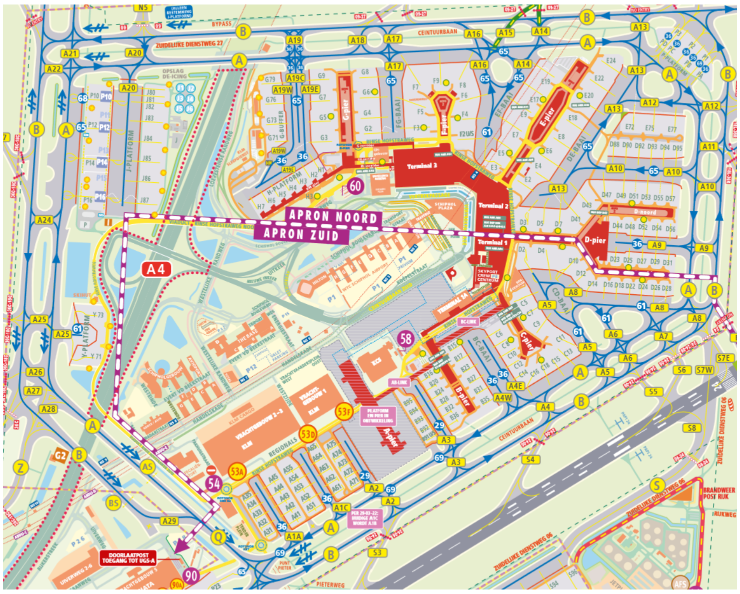


Figure 2.7: Taxiway system of Schiphol [13]

In the Schiphol Rules [11], a manual on towing movements can be found. Towing movements are controlled by Apron Control or the Tower Control/ATC. However, this manual is currently only applicable for operational towing or maintenance towing only. Where operational towing is the towing of a revenue aircraft that is ready but has not yet reached its TSAT and is towed when demand at the gate stands exceeds capacity. Maintenance towing is performed for empty aircraft that are towed to and from the maintenance parking stands, before or after maintenance. To make dispatch towing a viable concept, it needs to be considered similar to regular taxiing and therefore with the same procedures and right of way. Where the current rules in right of way place aircraft that are towed below taxiing aircraft:

1. Aircraft that are taking-off or landing;
2. Emergency services in the service of police, fire brigade or ambulance;
3. Taxiing aircraft and hovering helicopters;
4. Passengers by foot, being guided to and from aircraft;
5. Aircraft being towed;
6. Other vehicles

2.5. State-of-the-art on airport operations for emissions and planning of towing vehicles

Having discussed the different operational aspects of dispatch towing in previous sections, state-of-the-art research will be discussed in this section. In the literature studied related to dispatch towing, two main research areas have been identified. These research areas, which are emissions and planning related studies, will be explained. One of the aims of this literature study is to assess what is already known and in what areas dispatch towing is studied. By explaining these related research areas, understanding is gained in the theories and concepts used.

Furthermore, this literature study aims to identify in what planning phases previous research has been carried out. The definition of the planning phases that will be considered for this study are defined by ICAO in Doc 4444 [42], where three planning phases for the flow management of Air Traffic Flow Management (ATFM) are defined:

- **Strategic planning**: "if the action is carried out more than one day before the day on which it will take effect. Strategic planning is normally carried out well in advance, typically two to six months ahead" [42].

- **Pre-tactical planning**: "if the action is to be taken on the day before the day on which it will take effect" [42]. Otherwise as D-1, where "D" stands for the day of operations and "-1" stands for the number of days that is subtracted, which in this case is minus one day;
- **Tactical operations/operational planning phase**: "if the action is taken on the day on which it will take effect" [42]. Otherwise known as D-0.

In discussing the areas that previous research focused on, also the planning phase which it involves will be discussed.

This section is structured by three subsections. First, in subsection 2.5.1 the studies regarding emissions related to dispatch towing are discussed. Second, the literature on the topic of planning are discussed in subsection 5.3.3. Lastly, the main goal of this literature study is to identify which questions remain unanswered and what still has to be researched. After discussing the different research areas covered in dispatch towing literature, the research gap is identified in subsection 2.5.3.

2.5.1. Emissions

This section explains the research in the area emissions related to dispatch towing. It will summarise the main findings of these studies and relevant recommendations that were made. Lastly, the planning phase of these studies are also discussed.

The three methods already discussed in subsection 2.1.1 are extensively studied. Compared to conventional full engine taxiing, almost all studies show significant fuel reductions and therefore reductions in emissions to be realised for these alternative methods [26, 36, 43, 46, 58, 62, 66, 67]. The most significant reductions are shown for the methods of dispatch towing and on-board systems such as the Wheeltug. Which also corresponds with the trial tests performed at Schiphol, discussed in subsection 2.1.1. The studies show that for towing with a diesel truck, an increase in emissions is found especially in NO_x levels [28, 43, 51, 58]. Additionally, it is found that the variant of the electrical towing vehicle is not as frequently studied as the internal combustion variant similar to the existing TaxiBot. Other emissions outside of Carbon Dioxide (CO_2) and Nitrogen Oxides (NO_x) emissions, such as Hydrocarbons (HC), CO and Particulate Matter (PM), are not commonly addressed for ETVs [26, 28, 43, 58].

The developed model of Khadilkar and Balakrishnan [45], provides a more accurate estimate of the fuel burn, compared to physical models or the fuel consumption estimates of ICAO, by using flight data recorders. compared to physical models or the fuel consumption estimates of ICAO. This model is also used in the study of Zaninotto et al. [71]. In the case that more accurate estimates are needed this model could be implemented in this study.

Three emission related studies looked into the specific impact in case studies at AMS [43, 66, 67]. Where it is shown, among others, that due to the layout of AMS and its longer taxiing distances higher emissions can be expected compared to more compact airports. Furthermore, the composition of aircraft at AMS make it that the majority of fuel savings and emissions savings are a result of the medium/narrowbody aircraft category. A greater impact can be furthermore expected for the taxi-out phase compared to the taxi-in phase. Since during taxi-out, the flights are heavier or that the taxi times are higher due to congestion [51, 66, 67].

The studies that show the impact on fuel savings and emissions using dispatch towing point out some recommendations before it can be considered fully viable. Some of these recommendations have already been accounted for in the meantime such as the design challenge for dispatch towing identified by Deonandan and Balakrishnan [28]. A concrete recommendation made by van Baaren and Roling [67] is to include the effects of traffic and delays which can be done by considering a flight schedule with information coming available throughout the day. A similar recommendation is made by Camilleri and Batra [26] and Soltani et al. [62].

To conclude, these studies that look into the emissions of (electric) dispatch towing operations can be placed in the strategic planning phase. These studies identify the goals that the tactical operations should aim for. No real-time assignment of towing vehicles is performed in this research area.

2.5.2. Planning

This section explains the research in the area of planning of airport ground operations. Operations research methods have been used to model the planning and management of taxiing. Research carried out on the topic of planning within sustainable taxiing methods has been increasingly a topic of interest since 2019. Planning related studies on the topic of airport ground movement or surface traffic however, have been researched for much longer. This problem considers optimising the planning of conventional taxiing aircraft. The oldest article examined in this literature study was written in 1997, by van Velthuizen [69].

In the literature related on planning, it is found that optimisation models in the form of Mixed-Integer Linear Programming (MILP) is most commonly used. This exact optimisation method guarantees an optimal solution unconditionally [32]. A MILP formulation provides model flexibility by adapting different weighting factors of the objectives. Objectives for the surface traffic problem often considered are the minimisation of total taxi time [55, 60, 69], emissions [32], delay [55], number of vehicles [37, 47, 72], taxi distance [57] or a combination of criteria. For planning related dispatch towing literature, objectives found are minimisation of vehicles [47, 72], electricity costs [25], fuel consumption [62], the maximisation of tows [68], or a combination of objectives.

The complexity class of the surface movement problem is NP-hard [27]. Therefore the formulation of the MILP must not be overly complex, since the problem then becomes intractable. The Mixed Integer Programming (MIP) model of van Velthuizen [69] is able to solve the problem within limited computation time, however argues that this is due to the relative small problem size. When expanding the scale of the problem therefore, van Velthuizen recommends to use heuristics to be able to attain realistic computation times. The papers of Smeltink et al. [60] and Roling and Visser [55] employ successful models of the MILP formulation, both models report reasonable computation times. To reduce computation time valid inequalities are added to the formulation such as a minimum taxi speed [60] and a maximum amount of delay [55].

Custom made algorithms, named heuristics, are also employed by some of the planning related studies and can find near-optimal solutions. Heuristics are often employed when the exact formulation, such as MILP, is too complex or has unrealistic computation times. In theory, a heuristic is capable of finding a global optimum, the drawback is that in practice it is often not possible to find a global optimal solution [32]. The most commonly employed heuristic in the researched planning literature is the rolling horizon approach [32, 47, 55, 60, 68]. Where the effect of this rolling horizon heuristic is observed to perform well and almost not impact the overall quality of the solution [60, 68]. Other heuristics employed are:

- Atkin et al. [22]: a tabu search for finding a sequencing order;
- Du et al. [30]: column generation to determine the optimal fleet mix;
- Hiermann et al. [38]: an Adaptive Large Neighbourhood Search to find the number of vehicles, routes and recharging times and locations;
- Zhao et al. [72]: standard particle swarm optimisation to find the number of vehicles while balancing the usage;
- Brevoord [25]: a dynamic approximated cost algorithm to model uncertain arrival/departure times made available throughout the day.

The papers that specifically look into the planning of dispatch towing identified in this literature study are discussed here. Although planning of dispatch towing is performed in the studies of Zhao et al. [72], van Baaren and Roling [66, 67], Soltani et al. [62], Zaninotto et al. [71], Kroese [47], and Segeren [58], the flight schedule on which the assignment is based is deterministic. In other words, the authors assume that the flight schedule is known and no unplanned disruptions take place on the day of operations. The paper of Soltani et al. [62] does consider arrival/departure delays and minimising the delay. These papers are therefore considered to take place in the pre-tactical phase, when a flight schedule is issued and an assignment can be generated with these models. However, on the day of operations itself the models are not developed to take into account updates and disruptions to the flight schedule. The articles of Brevoord [25] and Oosterom et al. [68] are identified in this literature study as the only studies that consider tactical operations. Both articles also consider the use of ETVs and schedule recharging. In the thesis of Brevoord [25], the model developed to dynamically assign ETVs does not have realistic computation times. Since changes frequently occur within 15 to 30 min, it is is necessary to have a computation time below 1800 seconds to plan and update the schedule during the day. The model developed by Oosterom et al. [68] does also consider a case with flight delays. An important assumption made here is that the flight delay is known 30 minutes beforehand. Two models are run for this tactical operations case, one is a MILP the other one is a greedy algorithm heuristic. A rolling horizon heuristic is applied to both models to reevaluate and re-plan the assignment every 30 minutes, where the objective is to tow as many flights as possible. Although no exact runtimes are provided, it is shown that the MILP model performs better. Secondly, it is shown that for a busier flight schedule the algorithms assign a smaller fraction of flights to ETVs.

From the investigated literature, there were some that used the flight schedule and layout of AMS [32, 47, 60, 61, 66–69]. The literature on surface traffic found improvements in the taxi delay from 20% to 2%, which also reduced fuel emission levels [60]. For planning dispatch towing at AMS, it can be expected that increasing the maximum towing speed will not significantly impact the minimum fleet required to tow all flights [47]. Furthermore, for the busiest days at AMS a heuristic such as the rolling horizon method applied by Oosterom et al. [68] is expected to be used. Implementing the rolling horizon approach at AMS, it can be expected that the utilisation of ETVs will be slightly lower, with an observed gap between 1.4% and 4.3% compared to the optimal case, especially on the busier days.

Summarising, it is observed that the planning of airport operations, especially surface traffic and dispatch towing, is optimised with the use of a MILP formulation in the pre-tactical phase. Studies that considered busy flight schedules with arrival/departure information becoming available throughout the day, used heuristics to decompose the problem instance, solve the problems within reasonable time and process updated information. To the best of our knowlegde, no paper has been able to handle a real-time, dynamic and stochastic flight schedule. Therefore, the identified research gap is to be able to dynamically plan dispatch towing operations on the day of operations whilst the flight schedule is updated and disruptions occur.

2.5.3. Concluding remarks on the research gap

First, literature on feasibility and emissions has been discussed, since the aim of using ETVs is realising a reduction in fuel consumption and emissions. Various methods to calculate the impact of dispatch towing have been researched. Second, literature focusing on the planning of various airport operations were evaluated, since this is one of the challenges identified withholding the implementation of dispatch towing discussed in subsection 2.1.1.

Considering the discussed literature, a research gap has been identified. Research in the area of optimising the planning of dispatch towing operations has not often been carried out in the tactical operations planning phase. The literature that did consider optimising dispatch towing in the operational phase, did either not realise realistic computation times or did not fully consider real-time planning. Furthermore, the environmental impact of the realised planning in the operational phase were not shown. Therefore, this thesis aims to contribute to the literature by dynamically planning dispatch towing operations of ETVs on the day of operations and to show the realised emissions or fuel savings. This will support in the practical implementation on airports. From an academic perspective, operational planning of dispatch towing adds value in the field of operations research.

3
Model formulations

In this chapter different types of model formulation for dispatch towing are examined. As research on the problem of dispatch towing is relatively recent, there is not an established model which can be investigated. Research on related research areas to dispatch towing such as airport gate assignment or the airport ground movement, is more established and has been subject to optimisation for about five decades [63]. Therefore, these models that are used in the areas of gate assignment and ground movement are investigated to find useful methods for the model formulation of this study. Additionally, mathematical optimisation models within research specifically on the topic of dispatch towing are also discussed. After describing the characteristics of these different model formulations, a comparison is made on which aspects need to be included in the model formulation for this study.

To formulate a model that reflects the real world problem as realistically as possible, its objectives and constraints need to be both detailed and extensive enough. The choice of the model's objectives and constraints are therefore important to consider. In the various model formulations relevant to dispatch towing, objectives and constraints will be discussed to be able to make a better trade-off for which are appropriate in this study.

First, the general model formulation used in operations research in relevant research is described in section 3.1. Second, the specific applications relevant to the topic of this research are discussed in section 3.2-section 3.4. Lastly, a choice is made on the model formulation to be used in the thesis, in section 3.5.

3.1. Mixed-Integer Linear Programming

The MILP formulation is an exact optimisation technique that is used in the field of operations research to solve large-scale problems. The reason that MILP is called an exact optimisation technique is that the generated solution is guaranteed to be optimal [23, 32]. Usually the solution is generated by a commercially available solver, most commonly used are CPLEX or Gurobi [1, 3]. The way that these solvers and other solution methods work, are explained in the next chapter in chapter 4. When the formulation of the MILP problem is not too complex, an optimal solution can be generated within a low computation time [32]. A mixed-integer linear program uses a linear objective function and constraints, where some of the variables within the formulation are integers and the remaining variables are continuous. The drawback of restricting some variables to be integer is that for large formulations the computation time becomes impractical. A general MILP formulation can be seen in Equation 3.1.

$$\begin{aligned} \text{MAXIMISE/MINIMISE } & \mathbf{c}^T \cdot \mathbf{x} \\ \text{SUBJECT TO } & A \cdot \mathbf{x} \leq \mathbf{b} \\ & \mathbf{x} \geq \mathbf{0} \end{aligned} \tag{3.1}$$

Where c^T is a column vector of costs which is multiplied with the vector of the decision variables x. The matrix A and vector b of coefficients form the constraints. Lastly, the bounds of the decision variables are given in the last line of the equation.

3.2. Gate assignment problem

The Gate Assignment Problem (GAP) considers the assignment of flights to gates or (remote) parking stands. The difference between a gate or a parking stand is that with a gate, the passengers are allowed direct entrance to/from the terminal via a gate connection without needing to transfer with a bus. For a parking stand, passengers need to be connected by a bus to and from the terminal. Another option for a parking stand is a remote stand where empty aircraft are towed to that have long turnaround times or for overnight parking to assure gate availability in the meantime. The GAP takes in consideration multiple constraints such as aircraft size, time constraints or passenger walking distance.

Research on the optimising the GAP has been carried out frequently in the past and also is still performed nowadays, for instance to improve robustness and dealing with uncertainty. Therefore, research in this area provides a lot of exisiting knowledge on the implementation of different methods which can be useful in this research. The main goal of the GAP is to efficiently allocate the resources of the airport, the gates or stands, to all flights uniquely and assure that ground handling is able to perform all turnaround activities within the allocated time.

First some attributes of different models are discussed in subsection 3.2.1. Lastly, the objectives and constraints are discussed in subsection 3.2.2 and subsection 3.2.3 respectively.

3.2.1. Classification

An important classification of a GAP model is the method of assignment. Herein, four different methods exist which are sequential, parallel, problem-oriented and distributing methods. The sequential method assigns one aircraft at a time on the basis of arrival time. With the parallel method, all arriving flights, gates and stands are considered at the same time. For the problem-oriented assignment, groups are made for the problem at hand such as a group of flights carrying transfer passengers. Every group within the problem-oriented method is then assigned on the basis of the sequential method again. Lastly, the distributing method deals with the distribution of gates among the terminal and separating these into modules.

The second classification is between preemptive and non-preemptive strategies. Essentially, a preemptive strategy entails the option of re-assignment of a gate when a flight gets delayed. For a non-preemptive strategy, the gate is not released for a delayed flight and is not utilised. This has an effect of extra delay on the rest of the flight schedule.

The third and last classification within the GAP is the one between static and dynamic models. Where static models deal with deterministic variables and also do not take into account any uncertainty. Within dynamic models, the distinction is made between robust and stochastic models. Dynamic models that are robust consider the uncertainty such as the delay to be deterministic. Dynamic models that are stochastic on the other hand, consider the uncertainty to be distributed with certain a probabilistic distribution. Therefore, for dealing with an uncertain and stochastic distribution of for example the delay on the day of operations, a dynamic and stochastic model is the way to go. More detail about this is given in chapter 4.

3.2.2. Objectives

For the GAP it is a challenge to find an objective that takes into account all the different stakeholders. The main stakeholders involved in the objectives are the airport, airlines and the passengers. According to Dorndorf et al. [29], the distinction of objectives can be made between passenger and airport related objectives.

The most commonly used passenger related objective is to minimise passenger walking distance. Choosing between taxi routes for dispatch towing have different priorities, which are mainly related to safety and sequencing. Minimising distance within the assignment problem is therefore not considered a possible objective in this thesis.

An objective from an airport perspective is to minimise the movement on the apron, and possibly taxiways, which aims to improve safety and decreases the risk of delays due to congestion. An example objective is to minimise the number of towing movements, which are movements performed to remote parking stands or when the arrival gate is different than the departure gate. Another possible objective in reducing the movement on the apron and is to minimise the number of flights being assigned to parking stands, which reduces the movement of bus transfers. This objective is however not relevant to the problem at hand for dispatch towing.

An airport-oriented objective that strongly related to the objective of this thesis is the robustness of gate assignment. One study that looks into this is the thesis of Käller [44]. The goal of increasing robustness of the gate assignment is to absorb early or delayed flights. The objective of a robust schedule the day before operations is to minimise gate re-assignment on the day of operations. This objective is the same as the assignment that is aimed to be achieved for in this thesis.

3.2.3. Constraints

Constraints used in various GAP studies are listed by Dorndorf et al. [29]. In all GAP studies, two common constraints can be found which are identical to dispatch towing. The first one being that a flight is assigned to one gate and one gate only. The only difference being that a gate in the case of dispatch towing will be a towing vehicle. The second constraint is that the gate can never be occupied by more than one flight at the same time. Considering dispatch towing, this is identical since an ETV can only tow one flight at a time.

Other constraints in GAP studies mostly depend on preferences, which can be adjusted for every specific problem. Some of these constraints are also relevant and can be adjusted to dispatch towing operations.

Time related constraints are commonly used in order to make the assignment more robust and absorb delays. For example, a minimum buffer time is set between between two flights so that the flight is able to clear the gate in time before the next arrival. Another option is to make sure no conflicts can arise on the apron between two departing flights. In this thesis, the constraints related to time are aimed to be implemented in a stochastic manner.

3.3. Airport ground movement problem

Closely related to the problem at hand, models in the field of Airport Ground Movement (AGM) are discussed here. The problem forms the linking pin between the gate assignment problem and the runway scheduling problem. Research on AGM has been reviewed extensively in the work of Atkin et al. [23]. What follows in this section are the most noteworthy conclusions of that review.

In essence, the airport ground movement problem involves the scheduling and routing of aircraft. The most important resources that have to be allocated are the routes and the times at which these movements need to be executed. Usually the aim is to reduce the total taxi time or to assure the arrival at the agreed time slots. When allocating routes to the aircraft the most important constraint is to avoid conflicts. For an airport with few potential conflicts, an algorithm such as Dijkstra's algorithm can be applied to find the shortest path. The complexity of the problem lies in the case for large (hub) airports and especially during peak times, where the different routes of the aircraft need to be free of conflict.

Within existing research of AGM, distinction can be made between two general types of model formulations. First, the MILP formulation, which has been described in section 3.1, is used in combination with a commercial solver to find an optimal solution. Second, heuristic methods are used when the MILP formulation takes to long to be solved. This section first discusses the objective function and constraints used, in subsection 3.3.1 and subsection 3.3.2. Second, the MILP formulations are discussed in subsection 3.3.3. Lastly, heuristic methods are discussed in subsection 3.3.4.

3.3.1. Objective function

The majority of the research looks into the minimisation of the total taxi time while accounting for the waiting time of aircraft at the runway. Another objective that is considered is the minimisation of the duration from the first to last movement, otherwise known as makespan. Research also looks into the combining one of the previous objectives into one weighted formulation or multi-objective formulation. For example, the minimisation of the total taxi time combined with penalising for deviations on the scheduled arrival or departure time. In the literature identified

3.3.2. Constraints

Constraints within different AGM literature can be categorised into the following categories [23]:

- **Planning of route**: the algorithm can be constrained in a spectrum between having no restrictions to a set of predefined route per aircraft. When the routes of the aircraft are predetermined, the algorithm is limited to a scheduling problem such as in [60]. In many cases there is a set of possible routes for each aircraft which the algorithm can choose from. Lastly, it can also be the case that no constraints for aircraft taxi routes are present.

- **Separation between aircraft**: it is important to avoid conflict of aircraft and separation constraint to maintain a minimal separation distance between two aircraft needs to be defined to avoid conflict.

- **Aircraft movement speed**: speed is taken into account for different type of aircraft type or size. The taxiway can also have an influence on the taxi speed, for example the type of bend, which are taken into consideration for linking the route with the speed.

- **Timing for arrivals**: this constraint considers when the aircraft needs to be routed after arrival. This can be a fixed arrival time or deviations from the time are allowed in order to make it more realistic. Routing for arrivals is performed to its allocated stand which is usually assumed to be available. For the conventional method of taxiing, the aim is to perform this movement as quick as possible. For the assignment of towing vehicles, the aim can be more complex than for the AGM formulation.

- **Timing for departures**: the movement considered is that between the stand and the runway of departure. Here, usually the pushback time is viewed as the earliest time to commence taxiing. In general, three different goals are adopted here. The first aim that can be adopted is to arrive at the runway as soon as possible. A second option herein is to arrive at the runway to meet a predetermined take-off time, or as close as possible to this. Lastly, the aim can also be that the runway is reached in a time window such as in [35], this is since take-off slot times are usually time windows of fifteen minutes which are assigned to each departing flight by Central Flow Management Unit (CFMU).

The constraints described above are especially of importance for the AGM in isolation. However, as mentioned before the AGM problem forms the link between three other airport airside optimisation problems. The first airport operation is the arrival sequence of the aircraft managed by ATC, which defines when aircraft enter the AGM formulation. The gate assignment problem, as described in section 3.2, determines both the exit of arriving aircraft as well as the entry of departures to the AGM system. Third and last is the departure sequencing problem, which determines when aircraft enter or exit the system. Integrating these subproblems into one formulation is very complex if not impossible.

- **Integrating departure sequence**: departure sequencing is mainly done because of either wake vortex separation or en-route separation. It is observed that more recent research apply the integration of AGM with departure sequencing, mostly by including wake vortex separation and occasionally en-route separations.

- **Integrating gate assignment**: an example of integrating the GAP with the AGM could for instance be the consideration of the gate allocation of to reduce the total taxiing distance.

- **Integrating arrival sequence**: improved arrival time predictions can lead to a more coordinated approach between AGM and arrival sequencing. Furthermore, knowledge of the airport layout is crucial since runway crossings might be necessary or the runway could be used for both departures and arrivals, also known as mixed mode, which impact the arrival sequence and departure sequence.

3.3.3. MILP formulations

MILP formulations of previous research that are used in AGM problems, can be characterised by the following three approaches:

- **Space-time approach**: for each part of the aircraft's path, a time is allocated to cross this. In the research that was studied, a space-time network was used. First, the layout of the airport is used to make a spacial representation of nodes and edges. After time is discretised, the space-time network can be created such as in [50].

- **Ordering approach**: in this approach the sequence is solved first. With the input of the sequence, the schedule for every aircraft at each node or edge is made. With the use of binary variables, where an aircraft pair (i,j) at a node/edge, is considered equal to 1 if and only if aircraft i passes before aircraft j. Therefore, the times can be modelled as continuous variables.

- **Immediate predecessor/successor approach**: An alternative to full sequencing is to define the immediate predecessor and successor for each aircraft at each node or edge in the system. However, this approach has not been applied in the research studied as the major sequencing algorithm.

3.3.4. Heuristics: GA formulations

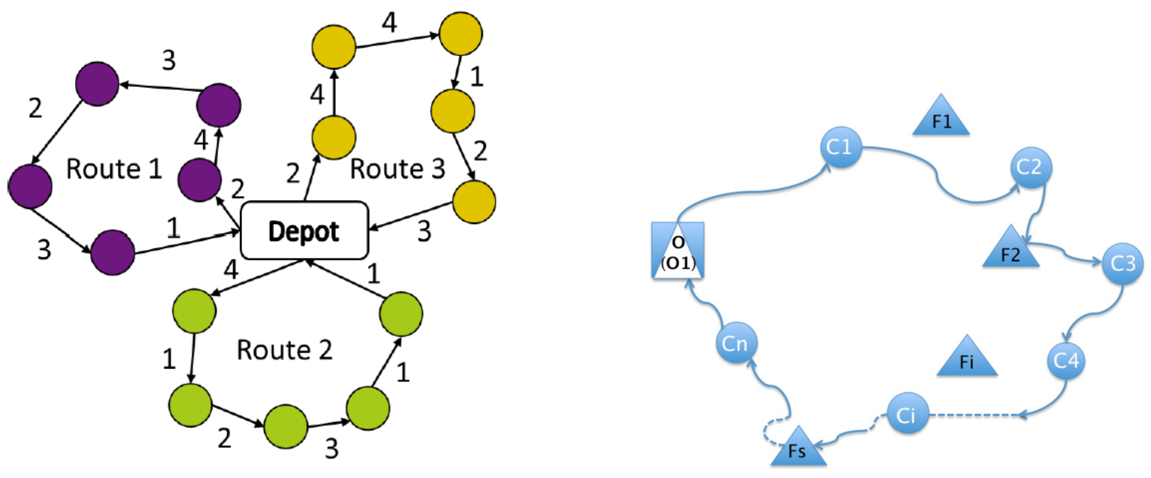
One of the important factors for Genetic Algorithms (GAs) to work successfully is the encoding. One of the common encodings found in most GA implementations is the route allocation information, which includes the route to allocate for each aircraft. Besides this more common encoding can be divided into the following three categories:

- An initial delay time is applied to an aircraft before pushback. The encoding of the GA investigates what delay to assign for every aircraft, together with the routes.
- A delay time is applied to an aircraft somewhere during the movement. This can either be a start or an end time of the delay, or as a total amount of time and position. The GA then determines where to apply the delay with its end time or duration together with the route allocation.
- The prioritisation of aircraft movement, meaning that the GA investigates which aircraft get the priority to be assigned along with the route assignment. In Gotteland et al. [35] every element of the population was described by the path of the aircraft and its priority level.

3.4. Electrical vehicle routing problem

This section describes the Electric Vehicle Routing Problem (EVRP) in general, and its adaptations used in dispatch towing studies or relevant for dispatch towing. The EVRP itself is a variation of the MILP formulation, which is used for optimising a set of routes for a fleet of vehicles travelling from a central location or depot to a set of customers.

The road network of a EVRP can be given by a set consisting of nodes to be visited, which are the customers, and a set of arcs with associated cost, which is usually the distance or time. The vehicles are given a limited capacity. A visual example of the EVRP and the conventional Vehicle Routing Problem (VRP) are given in Figure 3.1.



(a) A graphic example of a VRP solution [66]

(b) A graphic representation of the EVRP [48]

Figure 3.1: The graphic examples of the VRP and EVRP

As is shown in 3.1(b), the EVRP it is characterised by a depot from which the vehicles start and end. Along each route of a vehicle, customers are visited. Every customer is visited exactly once. Any vehicle can recharge at as many times as necessary at the charging stations, denoted by F, in between customers. It is possible for multiple vehicles to recharge at these stations. Furthermore, the locations and distances of the customers and charging stations can be known beforehand. After visiting all the customers, the vehicle returns to the depot where it can be fully recharged at the end of the day. Additionally, the paper of Lin et al. [48] considers the vehicles to be fully charged at the depot at beginning of the day. At the end of the day of operation, the vehicle returns to the depot and fully recharges again. Also it is possible to assume partial recharging [68].

The issue here lies with the statement that every customer must be visited exactly once. Especially when beginning to introduce ETVs in real-life, it is not expected that there are enough ETVs to tow all flights. In this thesis therefore, a limited fleet to tow a selection of flights is assumed. The characteristic of the EVRP has to be somewhat changed. The proposed form is to visit each customer at most once. This statement would change the optimisation into not serving any flight at all.

3.4.1. Objectives

In the literature that has been reviewed, the most common objectives for the EVRP found are to minimise the total distance driven, total costs, total fuel consumption, number of vehicles, number of charging stations or combining this into a convex combination such as the number of vehicles and charging stations [57].

The minimisation of the number of vehicles can be posed when each customer is visited exactly once. However, as discussed before this is not possible for a limited fleet of ETVs needing to serve a flight schedule as it would cause for huge delays. Oosterom et al. [68], relaxes the MILP formulation for making it possible to allow flight to taxi without an ETV. The minimisation of the number of vehicles is then changed into the maximisation of towing flights (customers served). The objective of minimising the fuel consumption poses an interesting objective. The study of Baaren and Roling [67] pose the objective function in two parts. One part consisting of flights being towed and the other part consists of the non-towed flights.

3.4.2. Constraints

The most common EVRP version for dispatch towing is the Electric Vehicle Routing Problem with Time windows (E-VRP-TW). One important adaptation to make the formulation suitable for dispatch towing operations are the battery charging policies. The paper of Soltani et al. [62] consider infinite battery life such that charging throughout the day is not necessary, which is deemed an unrealistic approach for this study. Battery recharging within an E-VRP-TW formulation is considered in the model of Baaren and Roling [67]. The charging strategy applied is to fully recharge in a constant and minimum charging time. Although it has been shown that a constant-time battery recharging strategy results in a lower fleet utilisation, it does reduce model complexity which can be an important consideration. Another charging strategy within an E-VRP-TW model for dispatch towing is used in the study of [68]. The charging strategy is called preemptive charging policy which considers the residual state-of-charge of the batteries [68] allowing the the battery of the ETV to be charged partially.

Another aspect of the E-VRP-TW is the introduction of constraints regarding the time window a customer must be visited. Which is very relevant to dispatch towing as flights are constrained by slots from CFMU. Generally, time windows are in place to require a fleet of vehicles to be scheduled to visit a set of customers within a certain time window [68]. This constraint is applied by Hiermann et al. [38], which shows a high resemblance in respect to the complexity of the model to dispatch towing. It should be noted that due to the increased complexity the exact model formulation of Hiermann et al. was not able to solve within realistic computation times. The constraint of time windows should therefore be added only if the model is not overly complex already.

For the possibility of ETVs first performing an outbound tow followed by an inbound tow, another constraint needs to be considered. The EVRP with pick-up and delivery is an extension that allows customers to not only have something delivered, but also allow a pick-up or both. This makes it possible to pick-up a flight for an outbound tow, then drop it of at the uncoupling location and on its way back introduces the possibility to pick-up an inbound tow.

Besides the graphical examples of Figure 3.1, there exist many other possible formulations and layouts. In the layout depicted in the article of Oosterom et al. [68] one of these variations specifically implemented to dispatch towing is shown. Here, various charging stations near the gate are considered. This is a relevant constraint for this study as charging at the gate will be taken in consideration. Charging at the gate would significantly decrease traffic at the apron and possibly increase robustness of the schedule as an early departure can be towed more quickly.

3.5. Concluding remarks

Out of all models discussed, the EVRP is considered to be most relevant for dispatch towing. Not only because it has been implemented before for dispatch towing specifically. But also the extent to which the model can be adapted specifically for the characteristics of ETVs. Another possible model, that was not specifically considered in this literature study but is used in relevant literature, is the vehicle scheduling problem. Moreover, the vehicle scheduling problem share many characteristics with the E-VRP-TW and the discussed EVRP with pick-up and delivery. Also combinations of the vehicle scheduling and routing problem exist. Initially the focus will be put on assigning the ETVs to the flights given the flight schedule (the timetable). Additionally, the routing aspects can be considered.

The GAP and AGM have been studied extensively and frequently used in airport operations. To make these suitable for dispatch towing more adaptations are necessary. However, the various measures to increase robustness, deal with uncertainty and disruptions can be incorporated into the MILP formulation of this thesis.

The model formulation of this thesis will be based on the characteristics of the vehicle scheduling and routing problem. The objective function of minimising the fuel consumption for towed and non-towed aircraft in combination with being robust to uncertainty is considered the most important for this study.

4

Solution methods

When the model for this thesis is defined, a solving algorithm is used to find the solution. Optimisation methods aim to find a solution that maximises or minimises a function with a single or several variables which are subject to constraints [39]. To find an optimal or near-optimal solution to a defined model formulation, different solution algorithms or methods exist. In this chapter, two main solution approaches are discussed. These two solution approaches are exact optimisation methods and (meta)heuristics. First the exact optimisation methods are discussed in section 4.1 after which the (meta)heuristics are discussed in section 4.2. To conclude, the most suitable solution method(s) for this thesis are discussed in section 4.3

4.1. Exact optimisation methods

Exact optimisation methods can guarantee finding an optimal solution. The difficulty in finding an optimal solution often lies in constructing a valid model of the problem. When a model is constructed, it is fairly straightforward to find a solution since implementing an existing exact solution methods provides an optimal solution.

An important property of optimisation problems is its complexity. Complexity classes describe the amount of computational resources necessary to solve an optimisation problem of size n, which is determined by its time and space complexity [56]. Where time complexity describes how many iterations are necessary to solve a problem, resulting in more time necessary for difficult problems. And space complexity describes the amount of space, which is usually computer memory, necessary to solve the problem. Several complexity classes exist which describe a set of computational problems, which are described in detail by Rothlauf [56].

An exact optimisation method is chosen if it can solve an optimisation problem with effort that grows polynomially with the problem size, otherwise known as complexity class P [56]. For problems that are NP-hard, exact optimisation methods need exponential effort. This results in most problem sizes to become intractable. Therefore, heuristics optimisation methods are often used to overcome these problems, which are discussed in the next section.

As discussed in section 2.5, the most commonly employed model formulation in relevant literature is the MILP formulation. The algorithm most frequently used to solve this formulation is the branch-and-bound and branch-and-price algorithm. This method is described in the book of Hillier and Lieberman [39]. The algorithm in the following subsection is explained by summarising this book.

4.1.1. Brand-and-bound

The branch-and-bound technique is used by the Gurobi solver to solve MILP problems [8]. Since the problem size of real-world problems such as dispatch towing are very large, the problem cannot be solved directly in a quick manner. What branch-and-bound essentially does is decomposing (branching) the problem into smaller subproblems. These smaller subproblems are able to be conquered (fathoming). In between the branching and fathoming, the bounding is performed.

Branching involves in choosing a subprobem and dividing it into smaller subproblems. Branching can be performed by different rules, in which solver like Gurobi choose the most efficient one depending on the formulation. The essence of the problem is explained for a formulation with binary variables. In the binary variable example the order of branching is performed in ascending order, so we begin with x_1. In the binary integer problem, the decision variable x_1 is limited to being either $x_1 = 0$ or $x_1 = 1$ which forms the first branch in the branching tree. The branching variable is the variable that is used to perform the branch at any iteration, which in this case is x_1.

Bounding now has to be performed on the branch that was made by x_1. The subproblem that is decomposed by the branching is relaxed, meaning that constraints making the problem difficult to solve are deleted. For the binary case, the binary constraints are relaxed by the widely used LP relaxation. The simplex method is used to solve the relaxation. What results are the bounds for the subproblems.

Fathoming is performed for the solutions that can be dismissed since they are already optimal. The optimal and feasible solution, in case all variables are binary, is named the first incumbent denoted by Z^*. The solution cannot be improved in further branches and therefore this solution can be fathomed. Any new solutions are fathomed when the solution is lower (in case of maximisation) than the incumbent solution or: Bound $\leq$Z*. In case the bound for the second subproblem is higher than the incumbent, a second iteration is performed. Or when all subproblems are found to be not feasible, the solution can be directly fathomed. Iterations that follow, fathom a subproblem if one of the following three tests is agreed:

1. Its bound $\leq$Z*
2. Its LP relaxation has no feasible solution
3. The optimal solution for its LP relaxation is integer

After fathoming, iterations are performed on the remaining subproblem. When no subproblems remain and every subproblem is fathomed, the optimal solution can be found in case an incumbent (feasible) solution exists.

4.2. (Meta-)Heuristics

Heuristics or metaheuristics can be used to solve models that better represent real-world problems. Constructing a model that approaches the real-world more closely is therefore considered simple. As opposed to exact model formulations, the difficulty with heuristics is in finding a high-quality solution. However, heuristics are usually not able to guarantee in solving a problem to an optimal solution.

When dealing with more complex formulations, the computational time of MILP can be too long or even fail to compute a solution at all. Heuristics or metaheuristics can used to improve the computational time to an acceptable amount of time. Heuristics is a solution algorithm that is custom made and can theoretically generate an optimal solution. However, the solution of heuristics are more often at a sub-optimal level. Therefore, heuristics can be used if solving the exact optimisation problem takes too long and is useful for exploring the states of the problem the optimal solution will most likely contain [32].

Similarly to heuristics, metaheuristics can be used if the computational time of the exact formulation is too large or if no solution at all is generated. The advantage of metaheuristics in comparison to heuristics is that they are able to avoid local optima. However, a global optimum cannot be guaranteed. Another drawback of metaheuristics is that they only outperform MILP in computation time when a certain level of complexity is reached.

As identified in section 2.5, various heuristics are applied in literature related to dispatch towing. The one most commonly found in the researched relevant literature was the rolling horizon approach. In general, in the article by Ng et al. it can be seen that the genetic algorithm and tabu search are applied most commonly in airport operations research [52]. The basic concepts of GA and tabu search are explained in the book of Hillier and Lieberman [39] of which the explanation is summarised.

4.2.1. Genetic algorithms

Genetic algorithms are a metaheuristic based on the evolution theory of Darwin. Genetic algorithms therefore involve the process of natural selection which is involved in the notion of survival of the fittest. For any species, the offspring is left with chromosomes of both parents that contain genes that determine the features of the child. Where the likelihood of survival is highest for a child that inherits the better genes. And also it is more likely to pass these genes on to the next generation and so the population has the tendency to improve slowly over time.

A second factor is mutations that randomly occur which change the features of a chromosome. Where some mutations provide desirable changes, it is noted that these desirable mutation contribute to an improved gene pool in the future.

The way in which these ideas are implemented to optimisation problems is quite natural. Feasible solutions correspond to a particular species where the fitness is determined by the objective solution. Therefore, an entire population is processed instead of single possible solutions. Each iteration considers the current population. The youngest members of the population are most likely to become parents and produce children or new trial solutions, sharing some of the genes of the parents. As the genetic algorithm proceeds, there is tendency to improve populations of trial solutions. Also mutations occur, which provides the capability of acquiring new features. Mutations help the genetic algorithm in exploring a new part, perhaps better, of the feasible space. The notion of survival of the fittest eventually leads to a solution that is nearly optimal. Where every algorithm is applied differently, it is a common characteristic of GA that thousands of iterations are needed to reach a stable soution.

4.2.2. Tabu search

The tabu search is a metaheuristic that is able to escape local optima. As a heuristic can be formulated differently for every application, there are some key aspects that are implemented in every tabu search. Every tabu search includes a local search procedure, which commences its search by finding a local optimum. After finding this local optimum, it continues search while allowing non-improving solutions. Once better solutions can be found again, it tries finding a local optimum again. This is referred to as the steepest ascent/mildest descent approach. Implying that, on its way to its search of the global optimum or mountain, it allows for the minimum descent in order to climb to the top again. A tabu list is made to avoid cycling back to the same local optimum. The distinctive feature of this heuristic is its use of memory. The tabu search continues to look for an optimal solution until it is stopped by a specified stopping criterion. Examples of the stopping criterion are a fixed number of iterations (without improvement in the best objective) or computing time. The best solution is accepted at any of the iterations.

4.2.3. Rolling horizon

To model real-time problems an approach called the rolling horizon can be used. In the case of modelling with a flight schedule, the daily flight schedule is divided into smaller time frames. These smaller time frames on the one hand facilitate a smaller problem each time to be optimised, which results in a faster computation. On the other hand, the possibility to introduce feedback into the system is facilitated which is useful to incorporate and compensate for uncertainties in the system [27]. This way of scheduling is also relevant to the tactical way of scheduling, where decisions are made 15 to 30 minutes ahead. Three variants of rolling time horizons for taxi scheduling are discussed in [60], which are summarised:

- Variant 1 - The planning period is divided into set of equal time intervals. Only when aircraft are ready to commence taxiing, for departure and arrivals, they are assigned to an interval. After being assigned to an interval, the assignment stays fixed. Therefore, if the fixed assignment of a previous interval overlaps with the current interval, it will not be considered and only new tasks in that time interval are considered. This is visualised in Figure 4.1. When considering a short time horizon, this will result in many fixed assignments which limits the freedom to optimise. The longer the horizon will be, the more optimal the solution should be theoretically. However, a longer time horizon will impact the computation time.

- Variant 2 - Similar to variant 1, the lengths of the intervals are equal. However, assignments that overlap two or more intervals can be rescheduled. Better schedules are expected with this variant compared to variant 1, due to more freedom. For the problem considered in the paper of Smeltink et al. [60], this allows for a taxi route to be rescheduled with the last node of the previous interval being the constraint. For the problem at hand in this thesis, this type of approach could be applied in scheduling of the charging moments.

- Variant 3 - Sliding window algorithm. In this algorithm, the length of the time window interval is determined on a fixed amount of aircraft. Every time an aircraft is ready to taxi, a new interval starts and the optimisation is made. This algorithm tries to spread the delay more evenly among all aircraft. The drawback of this variant is that the execution time increases significantly, but the quality of the solution is not significantly improved [23].

An implementation of the rolling horizon heuristic applied to dispatch towing is seen in the studies of Kroese [47] and Oosterom et al. [68]. The thesis of Kroese applies a rolling window strategy that fixes the set

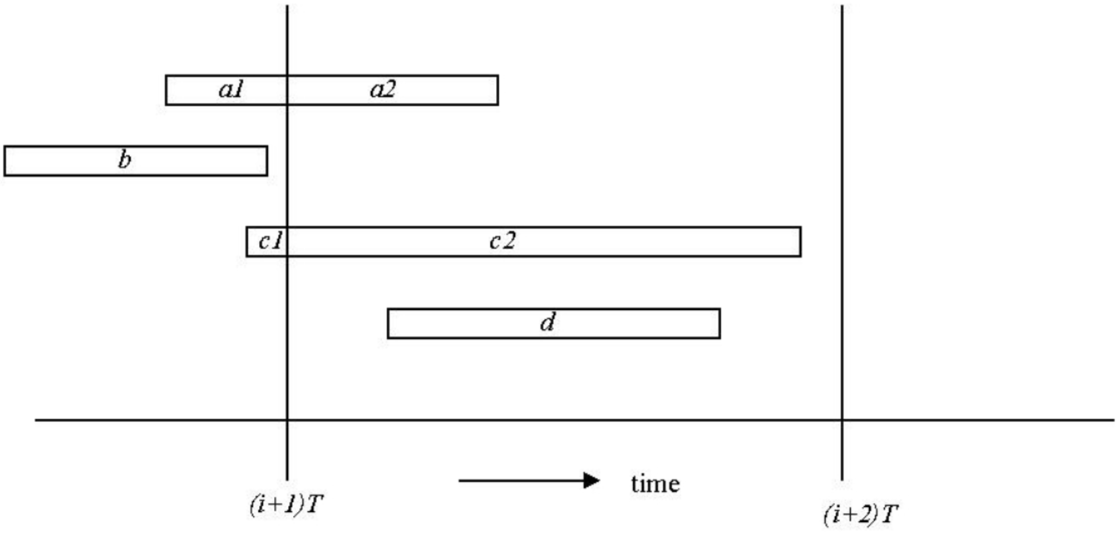


Figure 4.1: Visual example of variant 1 and 2. In variant 1, a2 and c2 are not considered because they are already fixed. For variant 2, a2 and c2 are rescheduled [60].

of towing tasks to be solved. Therefore, it is able to handle both the tasks in peak hours as during off-peak hours as the problem size is the same. This is illustrated in Figure 4.2, where a small problem containing three tasks is considered. The tasks displayed in bold are within the window, tasks outside the window are displayed in grey. The model assigns two ETVs in this case.

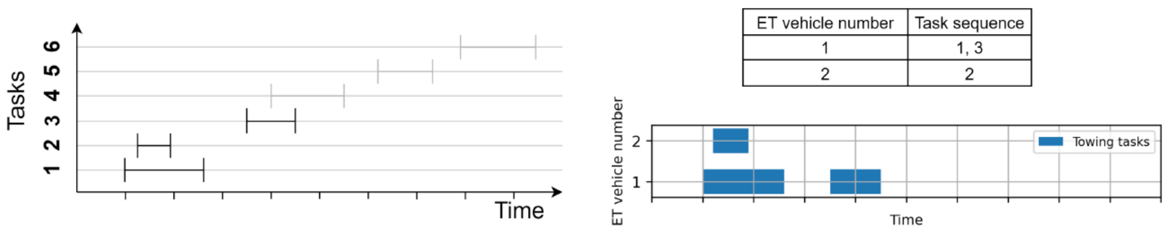


Figure 4.2: First window considered, containing three tasks [47].

After the first window is solved the first three tasks are frozen and some inputs for the next window are used. The last task performed by each ETV is used as constraint in the next window. Therefore, overlapping tasks are accounted for and also the batteries can be charged in between two tasks within one or multiple windows. The ending time of the first tasks are depicted in bold as are the three new tasks, which is shown in Figure 4.3. The information of the ending time of the last task, the end node of the last task and battery level are regarded from the first window. It is also seen that battery recharging is performed.

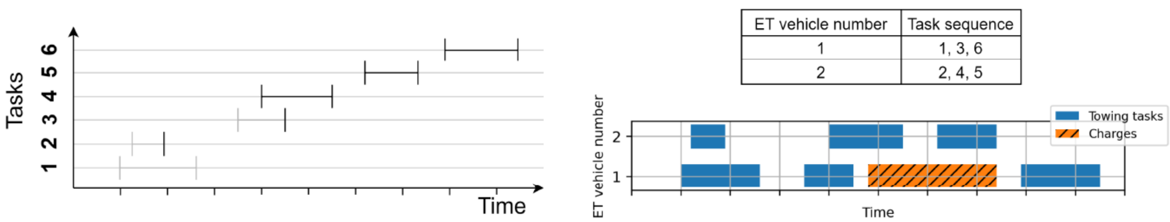


Figure 4.3: Second window considered, containing three tasks again [47].

Lastly, the evolution for a full day of operations with one ETV is shown in Figure 4.4, from the article of Oosterom et al. This study showed that the optimality gap with the exact MILP formulation was 1.4% on average considering multiple flight schedules.

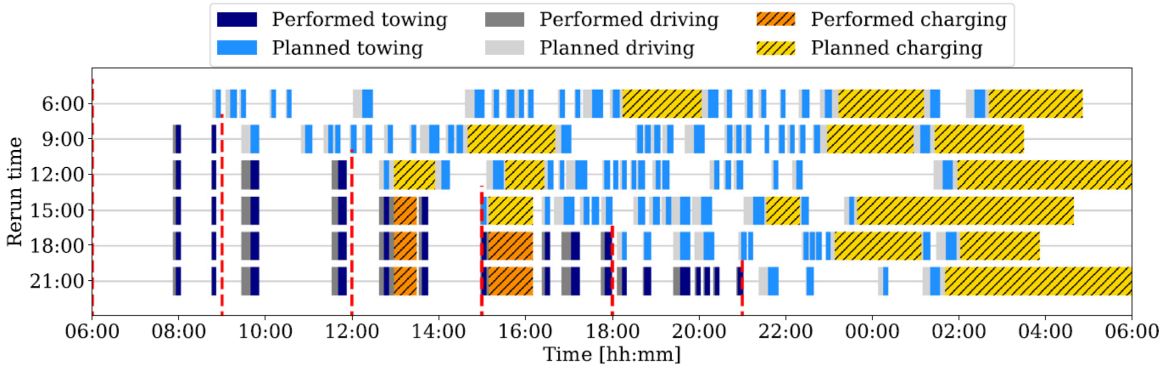


Figure 4.4: The evolution of one ETV during a day of operations. Reevaluated schedules every 3 hours starting from 6:00 until 21:00 are shown. On each row/line, both the scheduled as the actual flight arrival/departure times are used [68].

4.3. Conclusion on solution methods

The aim of this thesis is to solve the problem to optimality. Therefore an exact formulation using MILP with the characteristics of the vehicle scheduling problem and routing problem is considered first. For the model to deal with a deterministic flight schedule, the computation time does not have to be very realistic. But within the bounds of several hours. When posed not too complex but also realistically, an exact optimisation will be the method to point out the full potential of dispatch towing with ETVs.

However, as uncertainties are introduced with real-time planning a trade-off has to be made between a realistic computation time and an optimal solution. It is expected that an exact solution method will not suffice to compute within update times of 15 to 30 minutes. Therefore, a (meta)heuristic is deemed necessary. The rolling horizon approach seems especially suitable for handling disruptions to a predefined schedule and solving them within a realistic amount of time whilst the optimality is not largely impacted.

5
Research proposal

In this chapter the research proposal is described. First, section 5.1 describes the research objective and section 5.2 the research questions. The research framework explaining the methodology and the scope of the project are described in section 5.3, together with the project planning.

5.1. Research objective

The research objective is stated as follows:

> To develop an approach that assigns a limited set of electric towing vehicles to aircraft for real-time dispatch towing operations at AMS, while accounting for uncertainties in the operation by using optimisation methods.

5.2. Research questions

To accomplish the research objective of this thesis a main research question is formed:

> How can the real-time assignment of dispatch towing operations with a limited fleet of electric vehicles at AMS be described by an adapted version of the vehicle scheduling problem?

The question is divided into the following sub questions:

1. How is the assignment of dispatch towing modelled?
2. What are the objectives for assigning the ETVs to flights?
3. How is the assignment modelled for handling real-time dispatch towing operations?
4. What are the objectives for the real-time assignment?
5. How are the number of ETVs determined?
6. What is the recharging policy?
7. What scenarios are used to evaluate the performance of the system?
8. How is the performance measured and what key performance indicators are relevant?

5.3. Research framework

In this research framework the steps that are needed to answer the research question are explained in subsection 5.3.1. Assumptions and choices made considering the scope of the project are discussed in subsection 5.3.2. Lastly, the research plan giving an estimate on the duration per step and planning for the thesis, are discussed in subsection 5.3.3.

5.3.1. Methodology

In the thesis, that will commence after this literature study, a methodology will be followed described by the following steps.

1. **Orientation**: to find an answer on the first question, an orientation on modelling choices and formulations will be performed.
2. **Baseline model**: a baseline model is developed that is able to assign a limited fleet of ETVs with a deterministic flight schedule. Initially, a MILP is formulated for the baseline model. The choices of how the assignment is made are incorporated and focus will be on determining the objectives most relevant to assigning the vehicles of which a first outline was drawn in chapter 3. The recharging policy is determined and added to the baseline model. Next, focus is put on finding objectives for the real-time assignment and the exact rolling horizon approach is determined.
3. **Model extension**: when the baseline model is up and running, extensions can be made on the model. First, focus is put on improving the baseline model. Next, the disruptions are further looked into to improve the incorporation of real-time operations. Additionally to the assignment the routing of the vehicles can be included. Lastly, calculating the environmental impact in the sense of fuel consumption or emissions reduction can be added to the model.
4. **Analysis**: the last step before the report can be finished is the analysis of the scenarios and results. Focus is on answering research questions 6-8. The results will also be analysed statistically.

5.3.2. Scope

To define what assumptions are made of what is going to be done and what will specifically not be considered, a project scope is discussed here. Also, the scope aims to supports in safeguarding the available time and resources for the thesis.

- Type of research: the schedule that will be developed accounting for operational factors of influence only.
- Human factors: ETVs will be driven by humans and they are assumed to perfectly execute without failure the times set for the ETV processes such as (un-)coupling and outbound tow. Furthermore, enough trained personnel is assumed to be available to perform all assigned tows.
- ETVs: initially only the NB type ETV is assumed to be operative. Furthermore, it is assumed that all ETVs will operate perfectly and will always be available except for recharging. Also, the return movement of an ETV will not conflict with or delay other taxiing traffic.
- Flights: only flights of which disruptions data with respect to A-CDM milestones, are scheduled.
- Weather conditions: different operating characteristics of the ETV due to weather conidtions will not be taken into account.
- Recharging stations: it is assumed that recharging stations at the gate is possible, are installed and available.
- (Un-)Coupling locations: it is assumed that every (un)coupling location is situated in such a way that it does not conflict with conventional taxiing traffic.
- Environmental impact: an aircraft type is assumed to have one type of engine and fuel use.
- Gate allocation: is assumed to be known.
- Active runways: are assumed to be known throughout the day.
- Runway scheduling: is not taken into account.
- Engine warm up/cool down: all aircraft will have the same engine warm up time and the same engine cool down time. Additionally, it is assumed that the engine warm up can be performed during the outbound tow and will be completed at the end of the tow. The engine cool down is assumed to be finished for the inbound tow when the aircraft is coupled.
- Traffic: effects of congestion or delays on the apron or taxiway network whilst towing are not considered.

5.3.3. Thesis planning

In this thesis planning, the methodological steps and duration of each are outlined in a planning, shown in Table 5.1.

Table 5.1: Planning of the thesis phase

Project phase	**Description**	**Duration (weeks)**
Orientation	-Make detailed planning -Inform on the different model choices and formulations	2
Baseline model	-Explore the objectives that can be implemented in the model -Develop the recharging policy -Develop the model formulation that is able to assign etvs	8
Analysis	-Development and analysis of test scenarios -Validate and verify the baseline model -Prepare mid-term meeting and concise report	3
Mid-term meeting	Asses progress & project management	-
Orientation	Incorporate mid-term meeting feedback on model and report	1
Operational model	-Develop further scenarios and case study -Develop model extensions	7
Analysis	Validate and verify extended models	3
Draft report	-Write draft thesis -Prepare Green Light Meeting (GLM)	4
GLM	Present final results	-
Finish thesis	-Incorporate feedback of draft thesis into final thesis report -Prepare graduation presentation	4

Bibliography

[1] CPLEX Optimizer | IBM. URL https://www.ibm.com/analytics/cplex-optimizer.

[2] Feasibility Study Sustainable Taxiing at Schiphol Version 1.0. Technical report.

[3] Gurobi Software - Gurobi Optimization. URL https://www.gurobi.com/downloads/gurobi-software/.

[4] Historical Highlights of the GSE Industry | Aviation Pros. URL https://www.aviationpros.com/gse/article/21265092/historical-highlights-of-the-gse-industry.

[5] How Have Aircraft Tugs Evolved Over Time? URL https://simpleflying.com/airport-tugs-evolution/.

[6] IAI's Airplane TaxiBot is the Safer and Greener Solution. URL https://www.iai.co.il/p/taxibot.

[7] ISO 20683-1:2016(en), Aircraft ground equipment Nose gear towbarless towing vehicle (TLTV) Design, testing and maintenance requirements Part 1: Main line aircraft. URL https://www.iso.org/obp/ui/#iso:std:iso:20683:-1:ed-2:v1:en.

[8] Mixed-Integer Programming (MIP) A Primer on the Basics - Gurobi Optimization. URL https://www.gurobi.com/resources/mixed-integer-programming-mip-a-primer-on-the-basics/.

[9] Push back to the future - Airside International. URL https://www.airsideint.com/issue-article/push-back-to-the-future/.

[10] Schiphol | Aircraft stand allocation, . URL https://www.schiphol.nl/en/operations/page/allocation-aircraft-stands/.

[11] Schiphol | Manuals Business Area Aviation, . URL https://www.schiphol.nl/en/operations/page/manuals-business-area-aviation/.

[12] Schiphol | Expected runway usage forecast, . URL https://www.schiphol.nl/en/you-and-schiphol/page/gebruiksprognose-alles-wat-je-maar-wilt-weten/.

[13] Schiphol | Aircraft process maps, . URL https://www.schiphol.nl/en/operations/page/maps/.

[14] Schiphol Tomorrow | Completing the dual taxiway system, . URL https://www.schiphol.nl/en/projects/page/completing-schiphols-dual-taxiway-system/.

[15] Schiphol | The benefits of sustainable taxiing, . URL https://www.schiphol.nl/en/innovation/blog/the-benefits-of-sustainable-taxiing/.

[16] TaxiBot. URL https://www.taxibot-international.com/.

[17] US8544792B2 - Towbarless airplane tug - Google Patents. URL https://patents.google.com/patent/US8544792B2/en?q=turret&assignee=Israel+aerospace+industries&oq=Israel+aerospace+industries+turret&sort=old.

[18] Conventional or Towbarless Tractors? | Aviation Pros, 10 2008. URL https://www.aviationpros.com/gse/article/10375718/conventional-or-towbarless-tractors.

[19] Schiphol Airport CDM Operations Manual Welcome to Amsterdam Airport. Technical report, 9 2019.

[20] AEON Project - D1.3 State of the art. Technical report, 4 2021. URL https://www.aeon-project.eu/avada_portfolio/d1-3-state-of-the-art/?portfolioCats=58.

[21] AEON Project - Advanced Engine-Off Taxiing Operations, 2021. URL https://www.aeon-project.eu/.

[22] Jason A D Atkin, Edmund K Burke, John S Greenwood, and Dale Reeson. On-line decision support for take-off runway scheduling withăuncertain taxi times atăLondon Heathrowăairport. *Journal of Scheduling*, 11(5):323–346, 2008. ISSN 1099-1425. doi: 10.1007/s10951-008-0065-9. URL https://doi.org/10.1007/s10951-008-0065-9.

[23] Jason A D Atkin, Edmund K Burke, and Stefan Ravizza. The Airport Ground Movement Problem: Past and Current Research and Future Directions. In *4th International Conference on Research in Air Transportation*, pages 131–138, Budapest, 6 2010. ISBN 9781450714686.

[24] Dirk Bresser and Simon Prent. Schiphol | Single-Engine Taxiing; wouldn't it be better? URL https://www.schiphol.nl/en/innovation/blog/single-engine-taxiing/.

[25] Julia M Brevoord. *Electric Vehicle Routing Problems: The operations of electric towing trucks at an airport under uncertain arrivals and departures*. PhD thesis, 4 2021. URL http://essay.utwente.nl/86091/.

[26] Robert Camilleri and Aman Batra. Assessing the environmental impact of aircraft taxiing technologies. 9 2021. URL https://www.researchgate.net/publication/354948224_Assessing_the_environmental_impact_of_aircraft_taxiing_technologies.

[27] Gillian Clare and Arthur G. Richards. Optimization of Taxiway Routing and Runway Scheduling. *IEEE Transactions on Intelligent Transportation Systems*, 12(4):1000–1013, 12 2011. ISSN 1524-9050. doi: 10.1109/TITS.2011.2131650. URL http://ieeexplore.ieee.org/document/5752242/.

[28] Indira Deonandan and Hamsa Balakrishnan. Evaluation of Strategies for Reducing Taxi-out Emissions at Airports. 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, 2010.

[29] Ulrich Dorndorf, Andreas Drexl, Yury Nikulin, and Erwin Pesch. Flight gate scheduling: State-of-the-art and recent developments. *Omega*, 35(3):326–334, 6 2007. ISSN 03050483. doi: 10.1016/j.omega.2005.07.001.

[30] Jia Yan Du, Jens O. Brunner, and Rainer Kolisch. Obtaining the optimal fleet mix: A case study about towing tractors at airports. *Omega*, 64:102–114, 10 2016. ISSN 03050483. doi: 10.1016/j.omega.2015.11.005. URL https://linkinghub.elsevier.com/retrieve/pii/S0305048315002492.

[31] EUROCONTROL Airport CDM Team. Airport CDM Implementation Manual. Technical report, EUROCONTROL, 3 2017.

[32] C. Evertse and H.G. Visser. Real-time airport surface movement planning: Minimizing aircraft emissions. *Transportation Research Part C: Emerging Technologies*, 79:224–241, 6 2017. ISSN 0968090X. doi: 10.1016/j.trc.2017.03.018. URL https://linkinghub.elsevier.com/retrieve/pii/S0968090X1730102X.

[33] Goldhofer. Phoenix AST-2E, 2019. URL https://www.goldhofer.com/en/towbarless-tractors/ast-2e-phoenix.

[34] Goldhofer. A second żPHOENIXń E added to the Lufthansa LEOS GSE fleet, 2022. URL https://www.goldhofer.com/en/press/current-news/a-second-phoenix-e-added-to-the-lufthansa-leos-gse-fleet.

[35] Jean-Baptiste Gotteland, Nicolas Durand, and Jean-Marc Alliot. Handling CFMU slots in busy airports. 1 2003.

[36] Merlijn Groot and Paul Roling. The Potential Impact of Electric Aircraft Taxiing: A Probabilistic Analysis and Fleet Assignment Optimization. In *AIAA AVIATION 2022 Forum*. American Institute of Aeronautics and Astronautics Inc, AIAA, 2022. ISBN 9781624106354. doi: 10.2514/6.2022-3919.

[37] Xue Han, Peixin Zhao, Qingchun Meng, Shengnan Yin, and Di Wan. Optimal scheduling of airport ferry vehicles based on capacity network. *Annals of Operations Research*, 295(1):163–182, 12 2020. ISSN 0254-5330. doi: 10.1007/s10479-020-03743-0. URL https://link.springer.com/10.1007/s10479-020-03743-0.

[38] Gerhard Hiermann, Jakob Puchinger, Stefan Ropke, and Richard F. Hartl. The Electric Fleet Size and Mix Vehicle Routing Problem with Time Windows and Recharging Stations. *European Journal of Operational Research*, 252(3):995–1018, 8 2016. ISSN 03772217. doi: 10.1016/j.ejor.2016.01.038. URL https://linkinghub.elsevier.com/retrieve/pii/S0377221716000837.

[39] Frederick S. Hillier and Gerald J. Lieberman. *Introduction to Operations Research*. McGraw-Hill Education, New York, NY, 11 edition, 2021.

[40] Jakub Hospodka. Electric taxiing Taxibot system. *MAD - Magazine of Aviation Development*, 2(10):17, 7 2014. doi: 10.14311/MAD.2014.10.03.

[41] IATA. Net zero 2050: operational and infrastructure improvements Fact sheet. 10 2021. URL www.iata.org/flynetzero.

[42] ICAO. Doc 4444 - Procedures for air navigation and air traffic management. Technical report, International Civil Aviation Organization, Montréal, 11 2016.

[43] Mi Ithnan, T Selderbeek, Wwa Beelaerts van Blokland, and G Lodewijks. Aircraft Taxiing Strategy Optimization. Technical report, 2013.

[44] Danuta Kaller. *Robust model for operational stand and gate planning Schiphol*. PhD thesis, TU Delft, Delft, 3 2019.

[45] Harshad Khadilkar and Hamsa Balakrishnan. Estimation of Aircraft Taxi-out Fuel Burn using Flight Data Recorder Archives. In *AIAA Guidance, Navigation, and Control Conference*, Reston, Virigina, 8 2011. American Institute of Aeronautics and Astronautics. ISBN 978-1-60086-952-5. doi: 10.2514/6.2011-6383. URL https://arc.aiaa.org/doi/10.2514/6.2011-6383.

[46] Laura Khammash, Luca Mantecchini, and Vasco Reis. Micro-simulation of airport taxiing procedures to improve operation sustainability: Application of semi-robotic towing tractor. *5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems, MT-ITS 2017 - Proceedings*, pages 616–621, 8 2017. doi: 10.1109/MTITS.2017.8005587.

[47] Jurjen Kroese. *Electric taxiing: an optimisation study on the future of airport operations*. PhD thesis, 2021. URL https://repository.tudelft.nl/islandora/object/uuid%3A26ce37f6-367a-4cd1-862d-af25b39f5be2.

[48] Jane Lin, Wei Zhou, and Ouri Wolfson. Electric Vehicle Routing Problem. *Transportation Research Procedia*, 12:508–521, 1 2016. ISSN 2352-1465. doi: 10.1016/J.TRPRO.2016.02.007.

[49] Milos Lukic, Paolo Giangrande, Ahmed Hebala, Stefano Nuzzo, and Michael Galea. Review, Challenges, and Future Developments of Electric Taxiing Systems. *IEEE Transactions on Transportation Electrification*, 5(4):1441–1457, 12 2019. ISSN 2332-7782. doi: 10.1109/TTE.2019.2956862.

[50] Angel Marín and Esteve Codina. Network design: taxi planning. *Annals of Operations Research*, 157(1): 135–151, 10 2007. ISSN 0254-5330. doi: 10.1007/s10479-007-0194-0.

[51] Paola Di Mascio, Maria Vittoria Corazza, Nicolò Rocco Rosa, and Laura Moretti. Optimization of Aircraft Taxiing Strategies to Reduce the Impacts of Landing and Take-Off Cycle at Airports. *Sustainability 2022, Vol. 14, Page 9692*, 14(15):9692, 8 2022. ISSN 2071-1050. doi: 10.3390/SU14159692. URL https://www.mdpi.com/2071-1050/14/15/9692/htmhttps://www.mdpi.com/2071-1050/14/15/9692.

[52] K.K.H. Ng, C.K.M. Lee, Felix T.S. Chan, and Yaqiong Lv. Review on meta-heuristics approaches for airside operation research. *Applied Soft Computing*, 66:104–133, 5 2018. ISSN 15684946. doi: 10.1016/j.asoc.2018.02.013.

[53] Nikolai Okuniek and Dustin Beckmann. Towards higher level of A-SMGCS: Handshake of electric taxi and trajectory-based taxi operations. *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*, 2017-September, 11 2017. ISSN 21557209. doi: 10.1109/DASC.2017.8102047.

[54] Hannah Ritchie. Climate change and flying: what share of global CO2 emissions come from aviation? - Our World in Data, 10 2020. URL https://ourworldindata.org/co2-emissions-from-aviation.

[55] P. C. Roling and H. G. Visser. Optimal Airport Surface Traffic Planning Using Mixed-Integer Linear Programming. *International Journal of Aerospace Engineering*, 2008:1–11, 2008. ISSN 1687-5966. doi: 10.1155/2008/732828.

[56] Franz Rothlauf. Optimization Methods. pages 45–102. 2011. doi: 10.1007/978-3-540-72962-4{_}3.

[57] Maximilian Schiffer and Grit Walther. The electric location routing problem with time windows and partial recharging. *European Journal of Operational Research*, 260(3):995–1013, 8 2017. ISSN 03772217. doi: 10.1016/j.ejor.2017.01.011. URL https://linkinghub.elsevier.com/retrieve/pii/S0377221717300346.

[58] Megan Segeren. *Potential Impact of Operational Towing on Aircraft Emissions*. PhD thesis, TU Delft, Delft, 11 2022.

[59] Smart Airport Systems. Schiphol game changer! How to change the paving of the road from good intentions to concrete actions | Enhanced Reader. URL www.smart-airport-systems.com.

[60] J W Smeltink, Maarten Soomer, Peter de Waal, and Rob Mei. An Optimisation Model for Airport Taxi Scheduling. *Informs Journal on Computing - INFORMS*, 9 2004.

[61] Sabine Soepnel and Paul C. Roling. Impact of Electric Taxi Systems on Airport Apron Operations and Gate Congestion. In *17th AIAA Aviation Technology, Integration, and Operations Conference*, Reston, Virginia, 6 2017. American Institute of Aeronautics and Astronautics. ISBN 978-1-62410-508-1. doi: 10.2514/6.2017-4391. URL https://arc.aiaa.org/doi/10.2514/6.2017-4391.

[62] Mojdeh Soltani, Sobhan Ahmadi, Ali Akgunduz, and Nadia Bhuiyan. An eco-friendly aircraft taxiing approach with collision and conflict avoidance. *Transportation Research Part C: Emerging Technologies*, 121:102872, 12 2020. ISSN 0968090X. doi: 10.1016/j.trc.2020.102872. URL https://linkinghub.elsevier.com/retrieve/pii/S0968090X20307725.

[63] Gerald N. Steuart. Gate Position Requirements at Metropolitan Airports. *Transportation Science*, 8(2): 169–189, 5 1974. ISSN 0041-1655. doi: 10.1287/trsc.8.2.169.

[64] TaxiBot. TaxiBot concept, 2022. URL https://www.taxibot-international.com/concept.

[65] United Nations. Historic net-zero international flight goal agreed at UN conference | UN News, 10 2022. URL https://news.un.org/en/story/2022/10/1129367.

[66] E V M Van Baaren. *The feasibility of a fully electric aircraft towing system Master Thesis*. PhD thesis, 2019. URL http://repository.tudelft.nl/.

[67] Edzard van Baaren and Paul Roling. Design of a zero emission aircraft towing system. In *AIAA Aviation 2019 Forum*. American Institute of Aeronautics and Astronautics Inc, AIAA, 2019. ISBN 9781624105890. doi: 10.2514/6.2019-2932.

[68] Simon van Oosterom, Mihaela Mitici, and Jacco Hoekstra. Dispatching a fleet of electric towing vehicles for aircraft taxiing with conflict avoidance and efficient battery charging. *Transportation Research Part C: Emerging Technologies*, 147:103995, 2 2023. ISSN 0968-090X. doi: 10.1016/J.TRC.2022.103995.

[69] M.A.R. Van Velthuizen. Taxi planning optimization using mixed integer programming. *Delft University of Technology, Faculty of Aerospace Engineering, memorandum m-799*, 1997. URL https://repository.tudelft.nl/islandora/object/uuid%3A03e0de23-eb13-4d9f-8ad8-7262e4feae9c.

[70] WheelTug. WheelTug website, 2022. URL https://www.wheeltug.com/.

[71] Stefano Zaninotto, Jason Gauci, and Brian Zammit. A Testbed for Performance Analysis of Algorithms for Engineless Taxiing with Autonomous Tow Trucks. *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*, 2021-October, 2021. ISSN 21557209. doi: 10.1109/DASC52595.2021.9594411.

[72] P. X. Zhao, W. Q. Gao, X. Han, and W. H. Luo. Bi-Objective Collaborative Scheduling Optimization of Airport Ferry Vehicle and Tractor. *International Journal of Simulation Modelling*, 18(2):355–365, 6 2019. ISSN 17264529. doi: 10.2507/IJSIMM18(2)CO9. URL http://www.ijsimm.com/Full_Papers/Fulltext2019/text18-2_355-365.pdf.

III

Appendices

A

Appendix A: Additional results of the small fleet assignment on 17 July

This appendix shows all the results of assigning the small fleet on 17 July for reference purposes, that were not shown in the paper. Two new Figures are introduced, of which the first, Figure A.2, visualises a pie chart with all flights where the grey slice represent non-compatible flights, the pink coloured slice represents towable flights that no ETV has been assigned to and lastly the flights that are towed. From the towed flights slice, the bar enlargement shows the ratio of towed NB versus WB flights. And Figure A.3, presents the hourly ratio of towed NB and WB flights compared to the NB/WB flights taxiing towing during that hour.

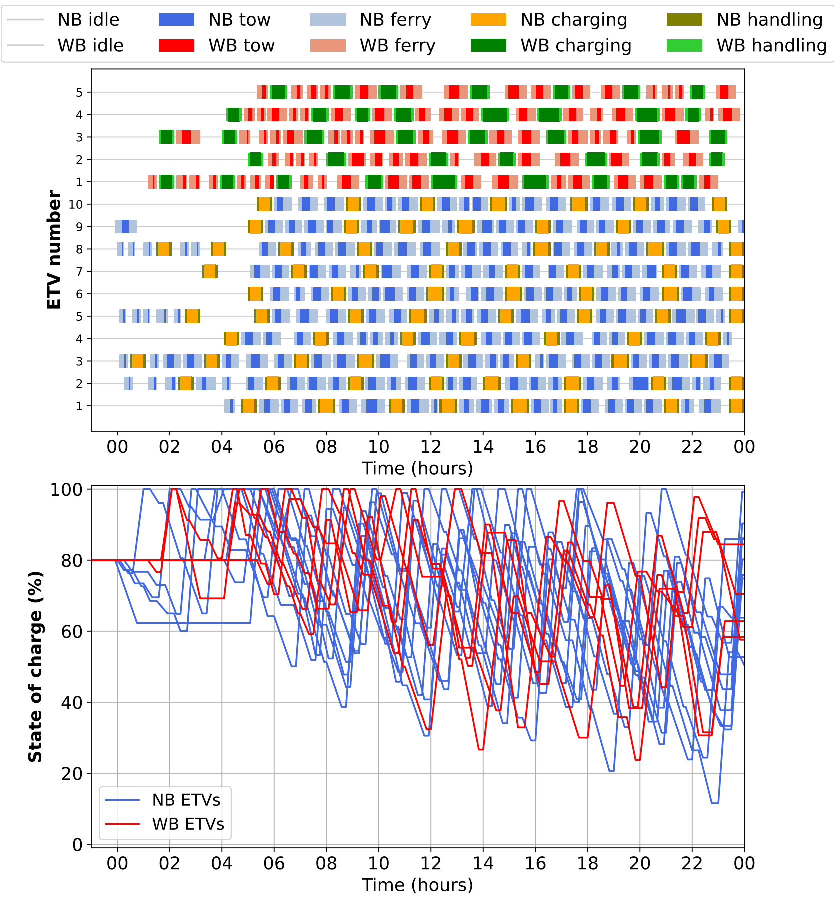


Figure A.1: ETV assignment schedule and battery state-of-charge for the small fleet on 17 July.

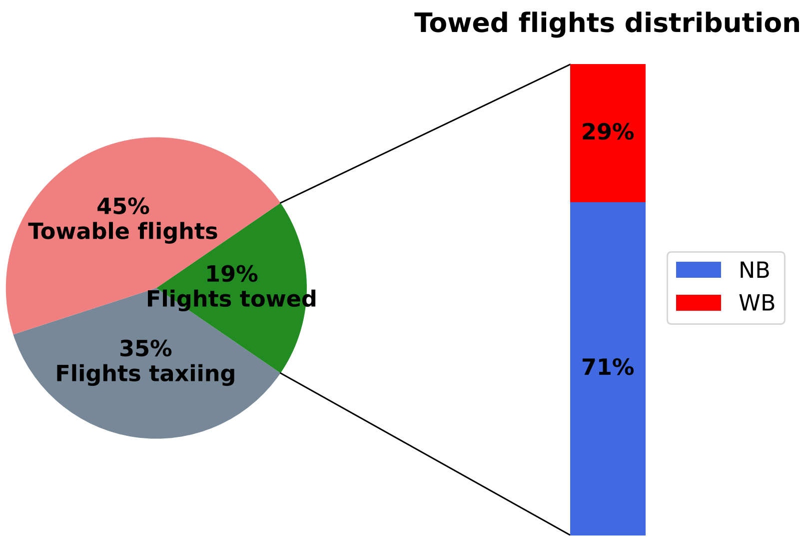
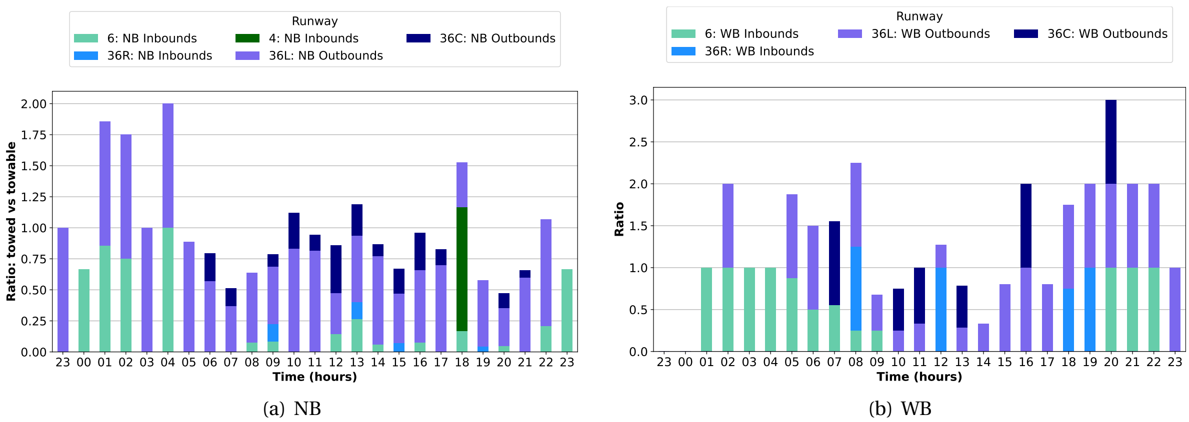


Figure A.2: Distribution of towed flights versus flights taxiing for the small fleet on 17 July.



(a) NB (b) WB

Figure A.3: Runway distributions of NB flights and WB flights for the small fleet on 17 July.

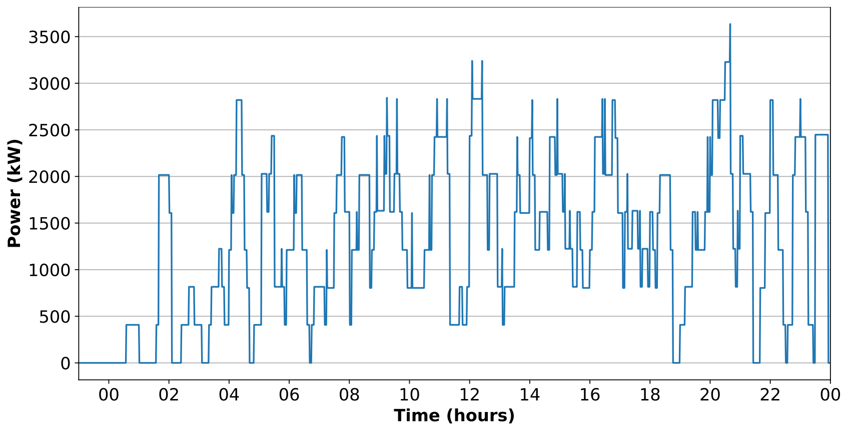


Figure A.4: Cumulative charging power per timestamp of all chargers throughout the day on 17 July, for the small fleet.

B

Appendix B: Additional results of the large fleet assignment on 17 July

This appendix shows all the results of assigning the large fleet on 17 July for reference purposes, that were not shown in the paper. Two new Figures are introduced, of which the first, Figure B.1, visualises a pie chart with all flights where the grey slice represent non-compatible flights, the pink coloured slice represents towable flights that no ETV has been assigned to and lastly the flights that are towed. From the towed flights slice, the bar enlargement shows the ratio of towed NB versus WB flights. And Figure B.4, presents the hourly ratio of towed NB and WB flights compared to the NB/WB flights taxiing towing during that hour.

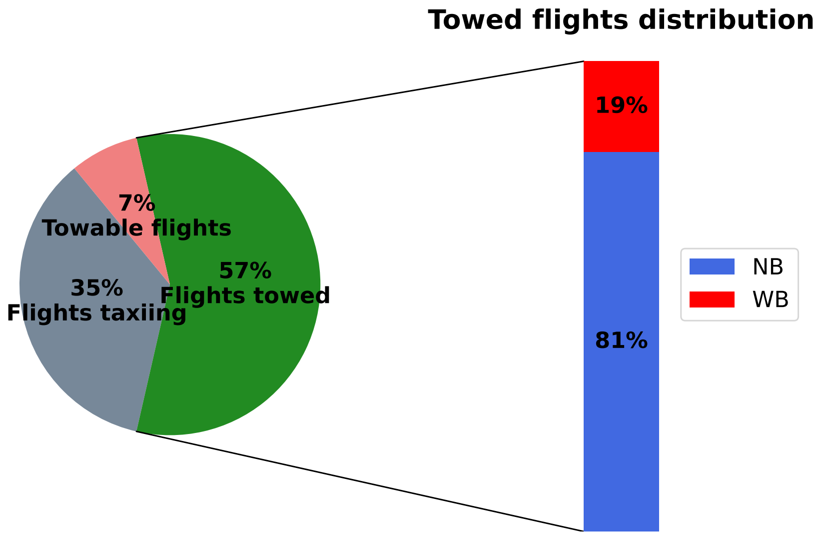


Figure B.1: Distribution of towed flights versus flights taxiing for the large fleet on 17 July.

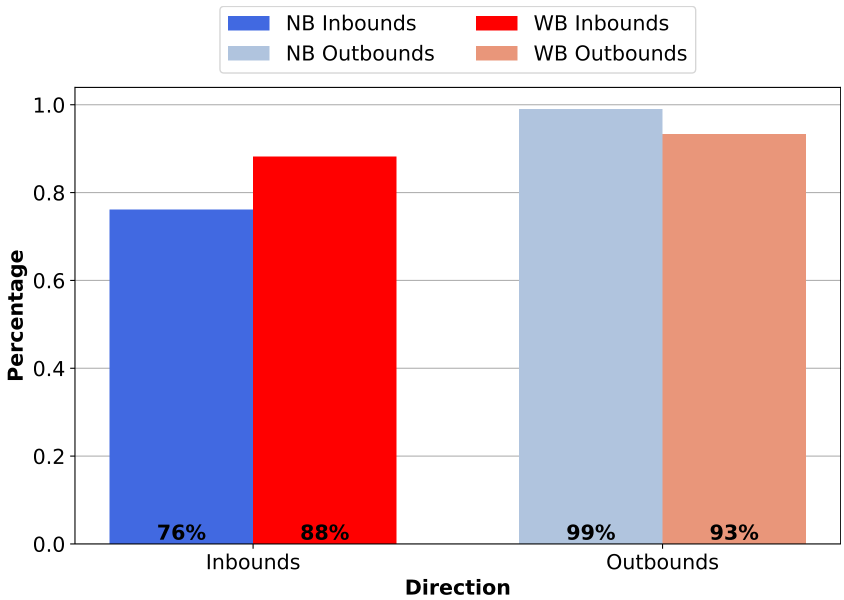
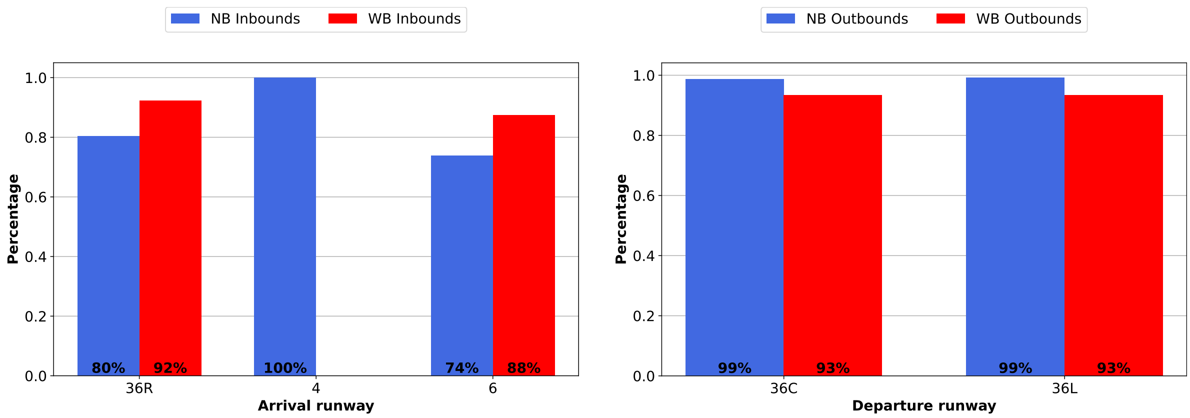
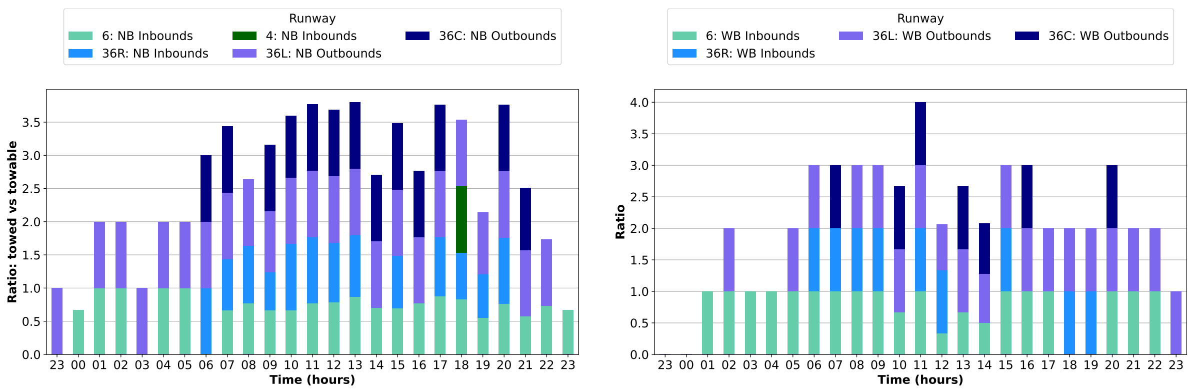


Figure B.2: Distribution of towed NB/WB inbounds versus outbounds for the large fleet on 17 July.



(a) Inbounds (b) Outbounds

Figure B.3: Runway distributions of towed inbounds and outbounds for the large fleet on 17 July.



(a) NB (b) WB

Figure B.4: Runway distributions of NB flights and WB flights for the large fleet on 17 July.

C

Appendix C: Additional results of the small fleet assignment on 18 July

This appendix shows all the results of assigning the small fleet on 18 July for reference purposes, that were not shown in the paper. Two new Figures are introduced, of which the first, Figure D.2, visualises a pie chart with all flights where the grey slice represent non-compatible flights, the pink coloured slice represents towable flights that no ETV has been assigned to and lastly the flights that are towed. From the towed flights slice, the bar enlargement shows the ratio of towed NB versus WB flights. And Figure D.6, presents the hourly ratio of towed NB and WB flights compared to the NB/WB flights taxiing towing during that hour.

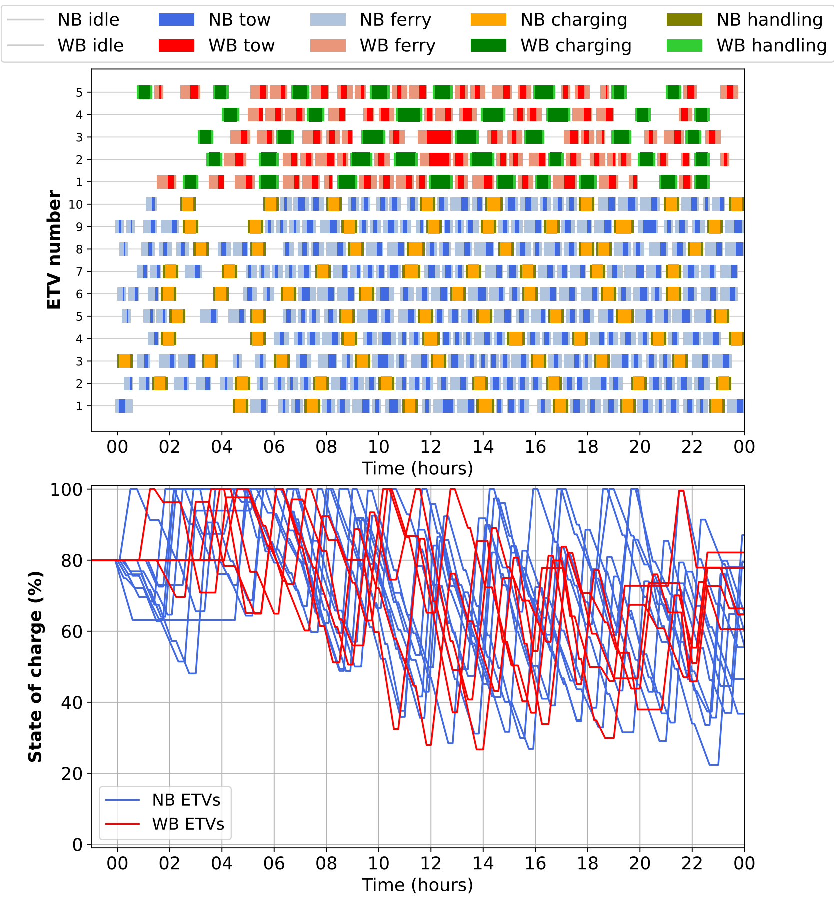


Figure C.1: ETV assignment schedule and battery state-of-charge for the small fleet on 18 July.

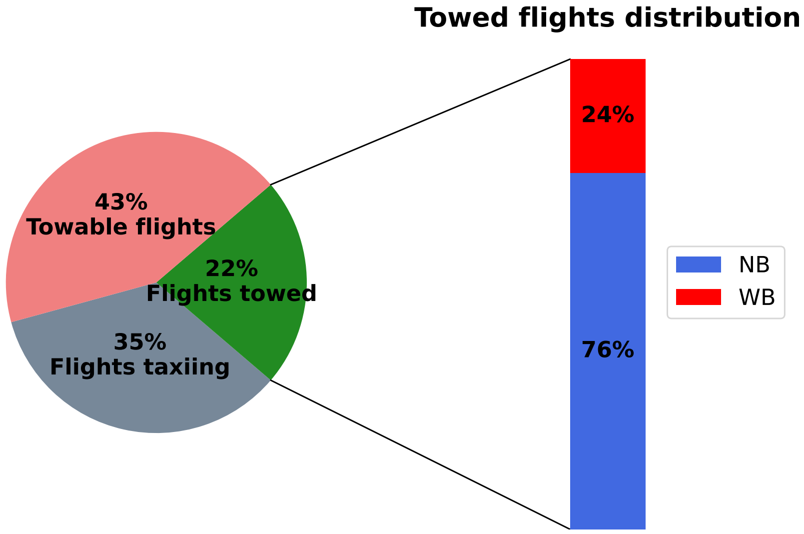


Figure C.2: Distribution of towed flights versus flights taxiing for the small fleet on 18 July.

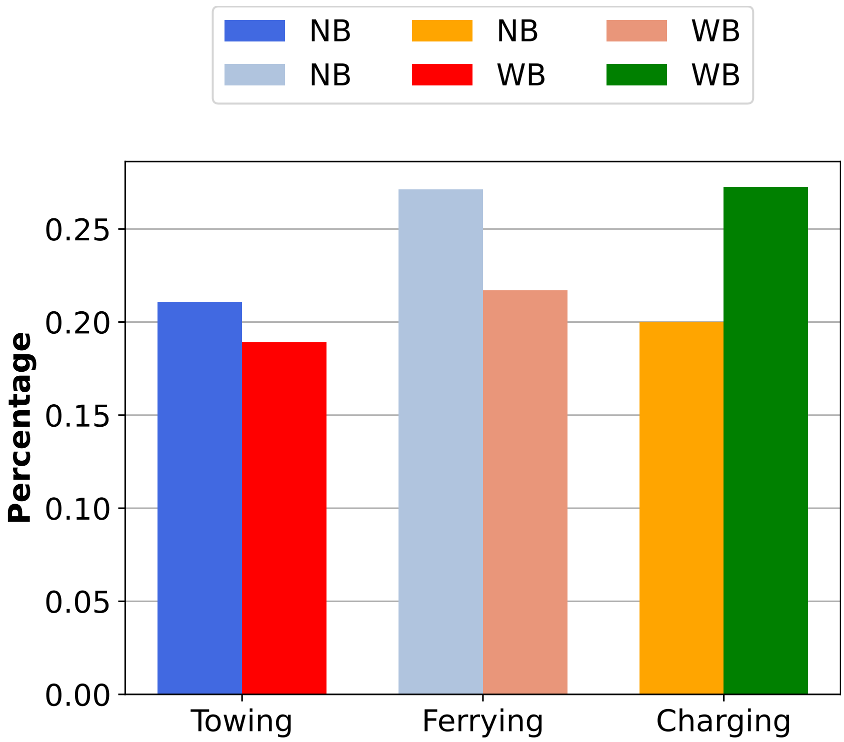


Figure C.3: ETV utilisation distribution for the small fleet on 18 July.

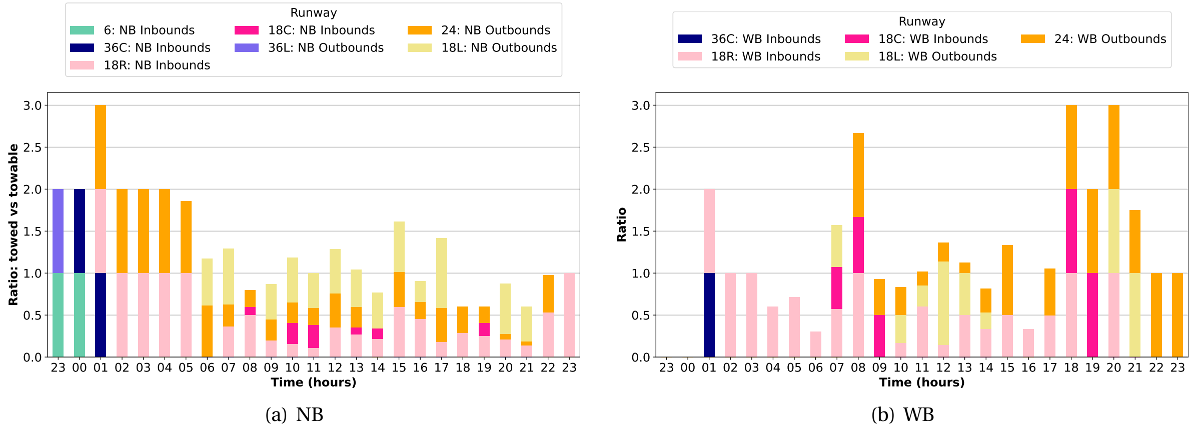


Figure C.4: Runway distributions of NB flights and WB flights for the small fleet on 18 July.

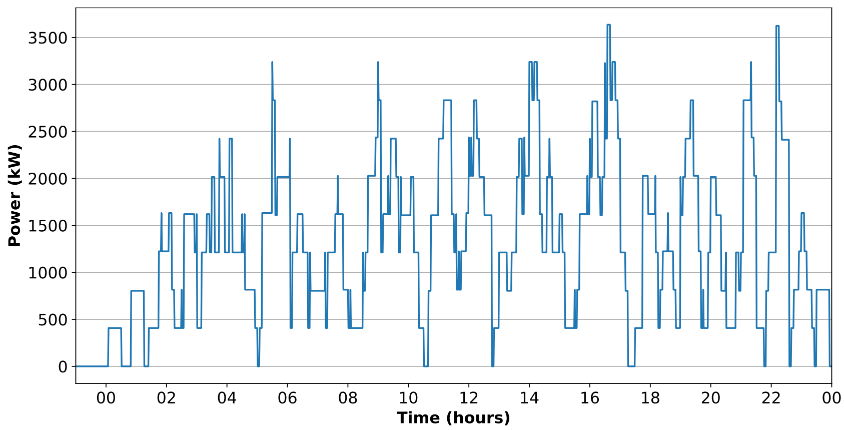


Figure C.5: Cumulative charging power per timestamp of all chargers throughout the day on 18 July, for the small fleet.

D

Appendix D: Additional results of the large fleet assignment on 18 July

This appendix shows all the results of assigning the large fleet on 18 July for reference purposes, that were not shown in the paper. Two new Figures are introduced, of which the first, Figure D.2, visualises a pie chart with all flights where the grey slice represent non-compatible flights, the pink coloured slice represents towable flights that no ETV has been assigned to and lastly the flights that are towed. From the towed flights slice, the bar enlargement shows the ratio of towed NB versus WB flights. And Figure D.6, presents the hourly ratio of towed NB and WB flights compared to the NB/WB flights taxiing towing during that hour.

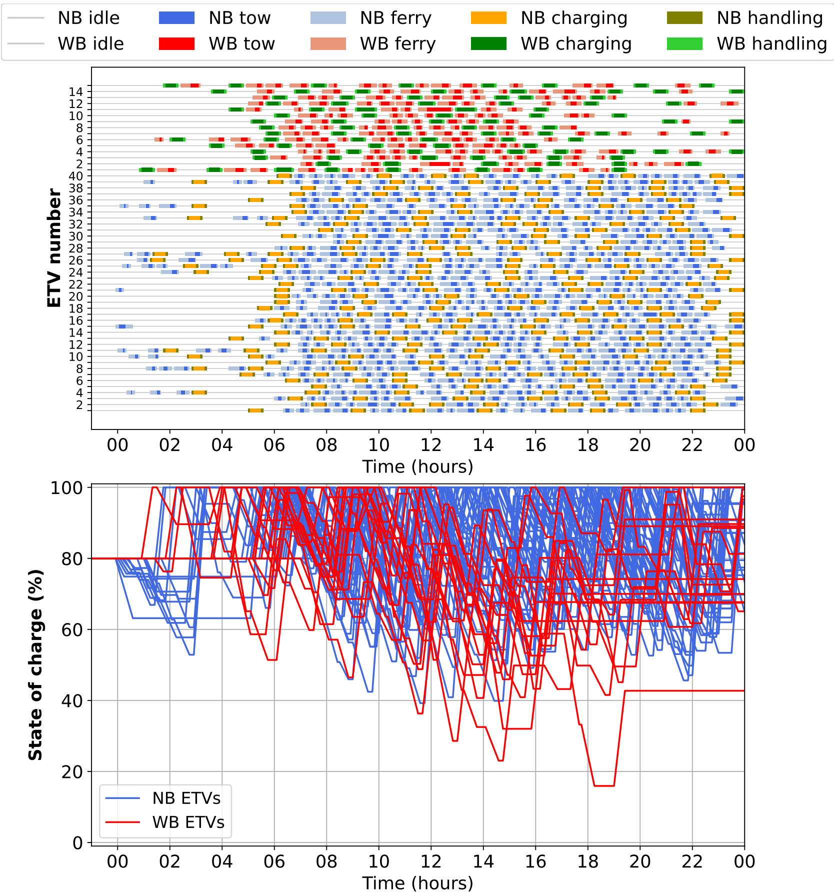


Figure D.1: ETV assignment schedule and battery state-of-charge for the large fleet on 18 July.

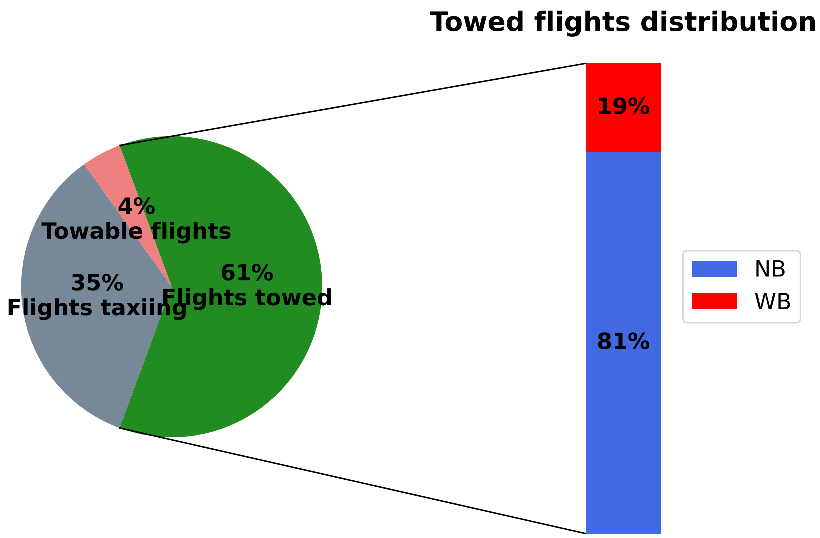


Figure D.2: Distribution of towed flights versus flights taxiing for the large fleet on 18 July.

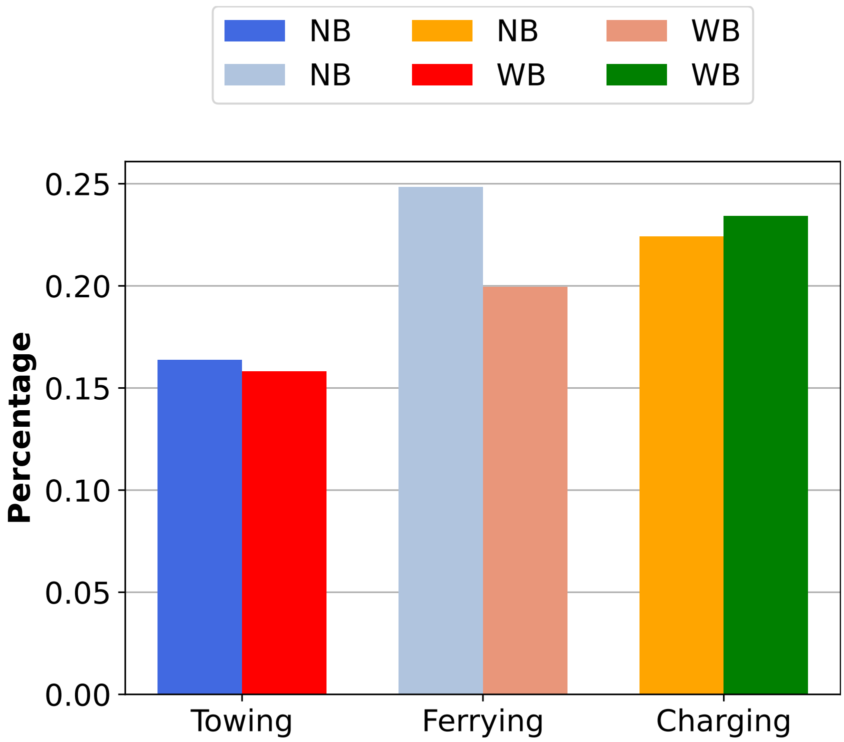


Figure D.3: ETV utilisation distribution for the large fleet on 18 July.

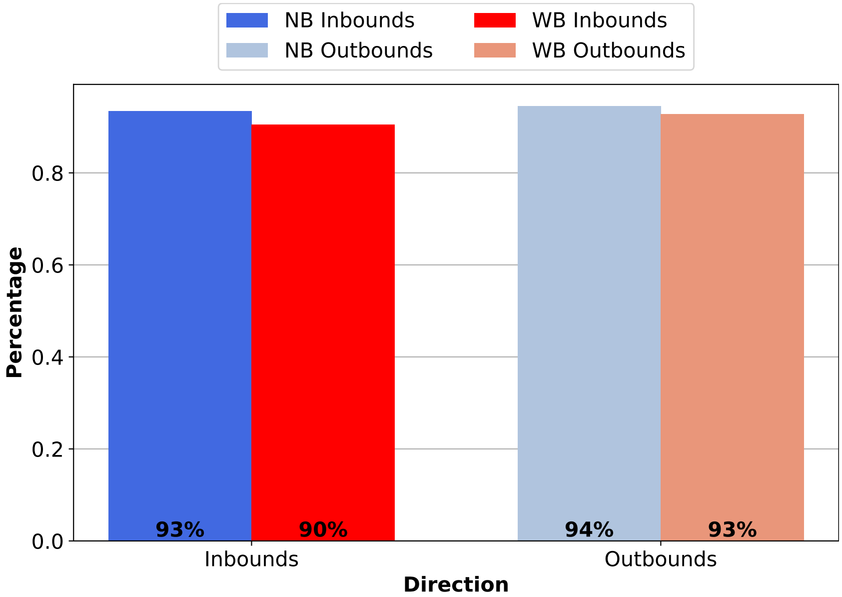
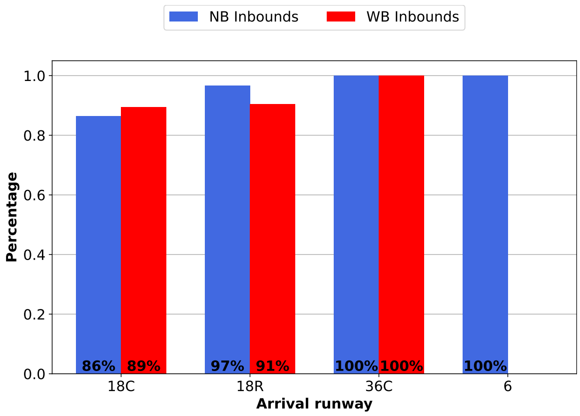
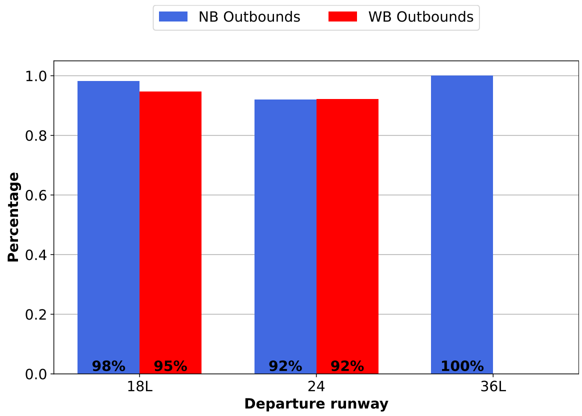


Figure D.4: Distribution of towed NB/WB inbounds versus outbounds for the large fleet on 18 July.

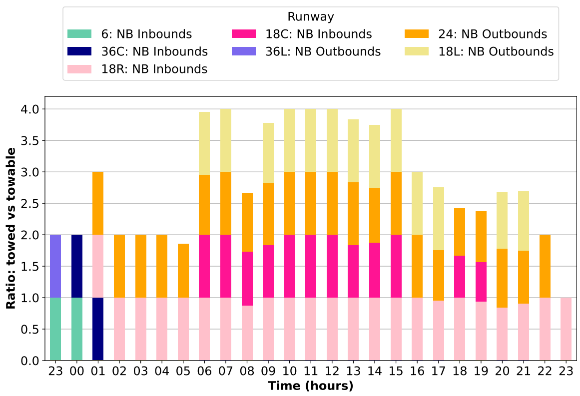


(a) Inbounds

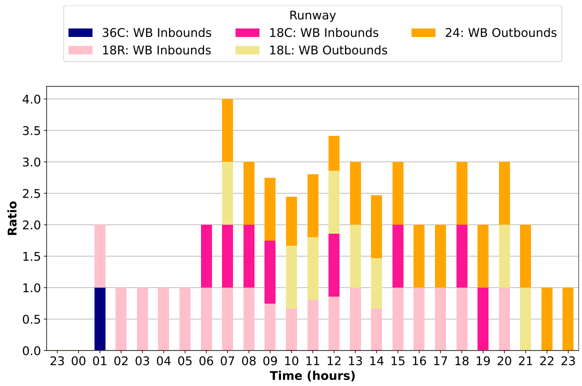


(b) Outbounds

Figure D.5: Runway distributions of towed inbounds and outbounds for the large fleet on 18 July.



(a) NB



(b) WB

Figure D.6: Runway distributions of NB flights and WB flights for the large fleet on 18 July.

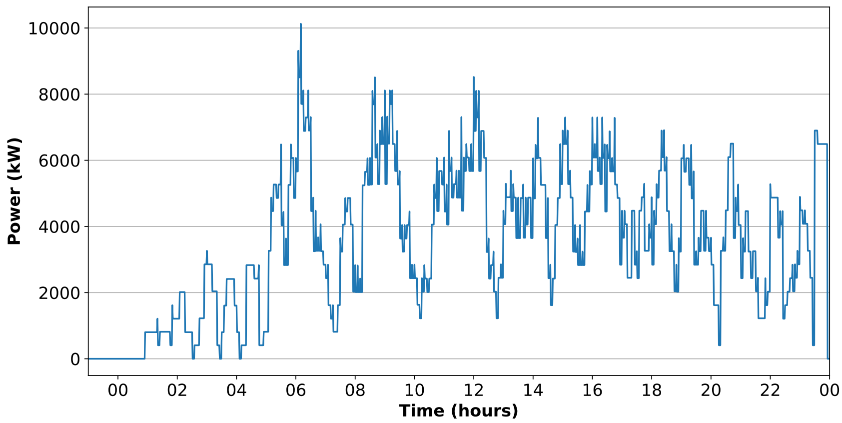
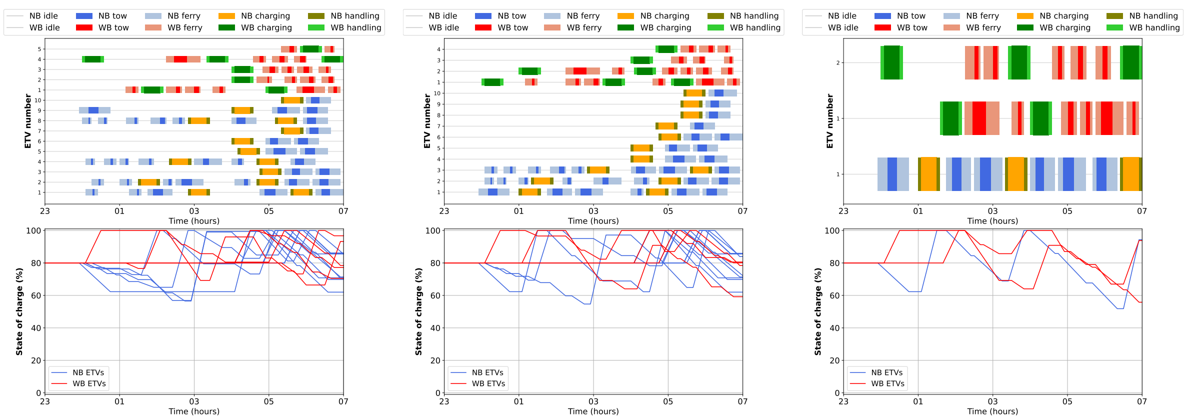


Figure D.7: Cumulative charging power per timestamp of all chargers throughout the day on 18 July, for the large fleet.

E

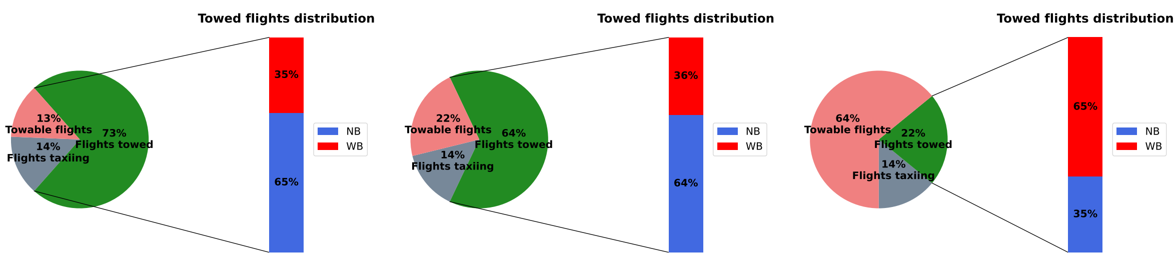
Appendix E: Additional results for utilisation and symmetry analysis

This appendix shows all the results of assigning the large fleet on 18 July for reference purposes, that were not shown in the paper. In principal, the figures are shown side-by-side from no costs to high costs, with the exception of Figures E.5-E.10.Two new Figures are introduced, of which the first, Figure E.2, visualises a pie chart with all flights where the grey slice represent non-compatible flights, the pink coloured slice represents towable flights that no ETV has been assigned to and lastly the flights that are towed. From the towed flights slice, the bar enlargement shows the ratio of towed NB versus WB flights. And Figures E.8-E.10, present the hourly ratio of towed NB and WB flights compared to the NB/WB flights taxiing towing during that hour.



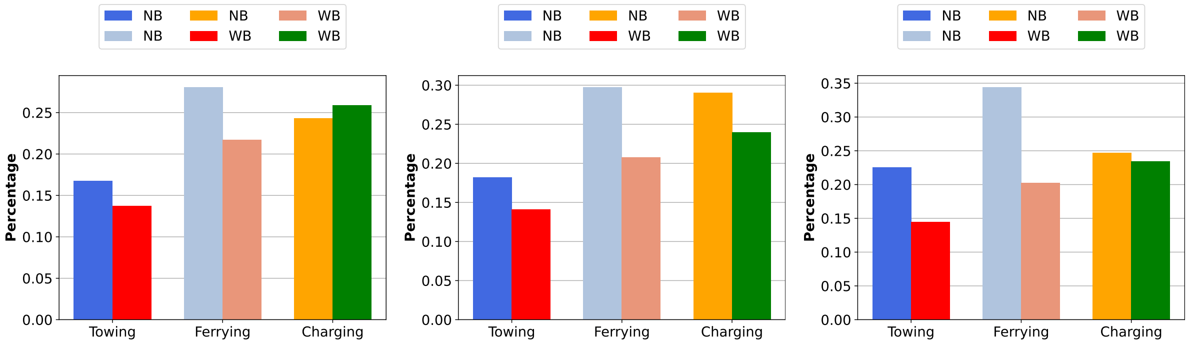
(a) No costs (b) Low costs (c) High costs

Figure E.1: ETV assignment schedules and states-of-charge for for different costs on start and end time on 17 July.



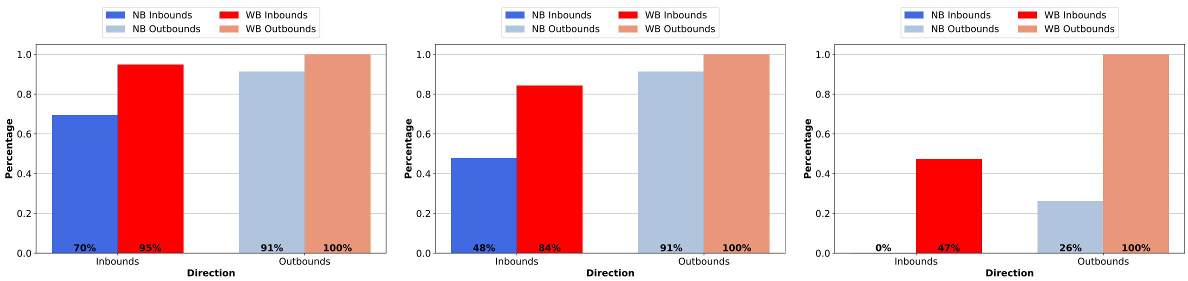
(a) No costs (b) Low costs (c) High costs

Figure E.2: Distribution of towed flights versus flights taxiing for different costs on start and end time on 17 July.



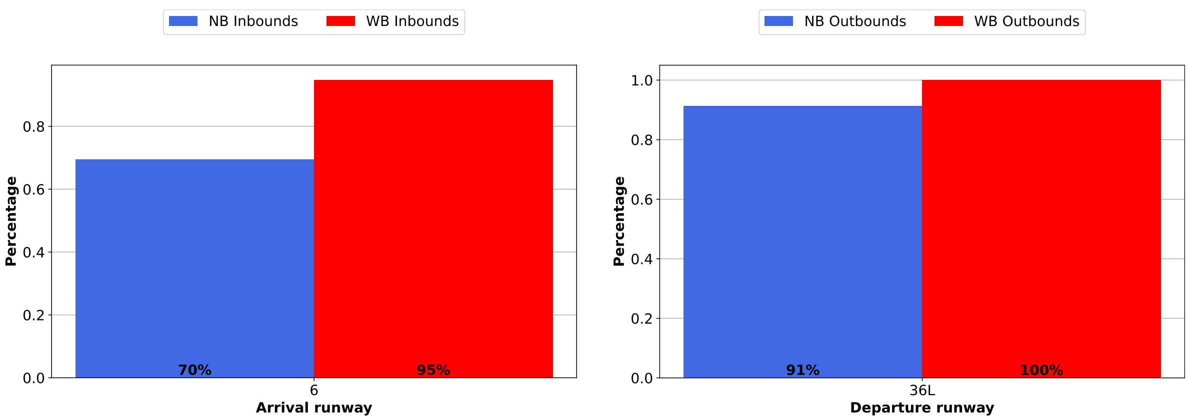
(a) No costs (b) Low costs (c) High costs

Figure E.3: ETV utilisation distribution for different costs on start and end time on 17 July.



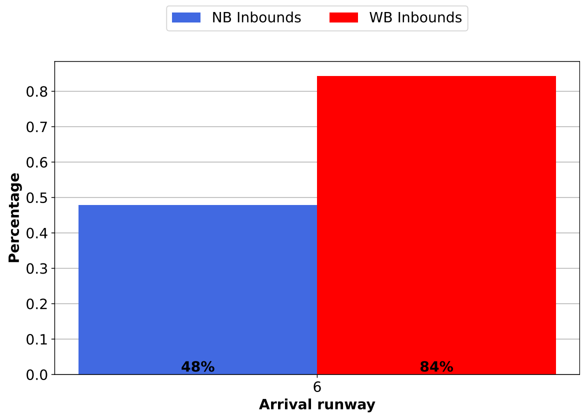
(a) No costs (b) Low costs (c) High costs

Figure E.4: Distribution of towed NB/WB inbounds versus outbounds for different costs on start and end time on 17 July.

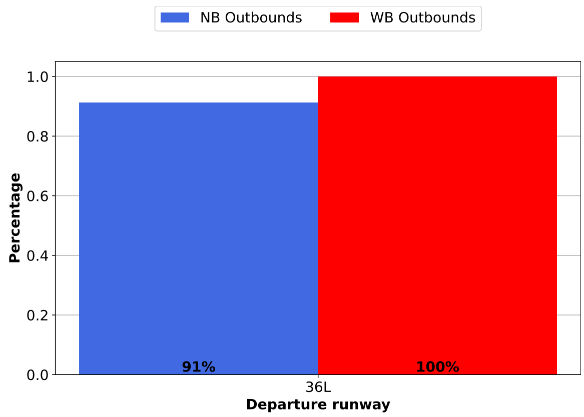


(a) Inbounds (b) Outbounds

Figure E.5: Runway distributions of towed inbounds and outbounds for no costs on start and end time on 17 July.

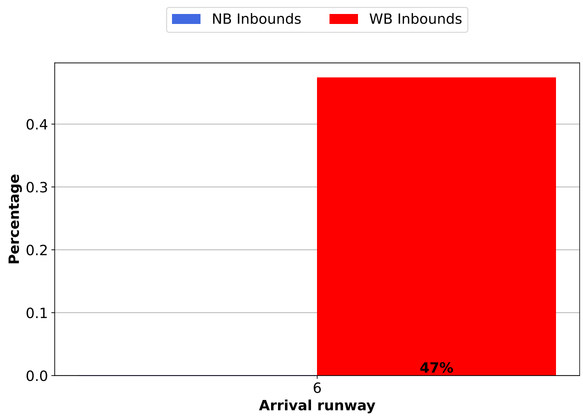


(a) Inbounds

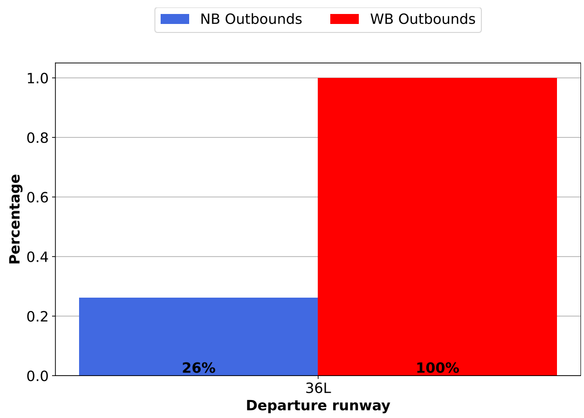


(b) Outbounds

Figure E.6: Runway distributions of towed inbounds and outbounds for low costs on start and end time on 17 July.

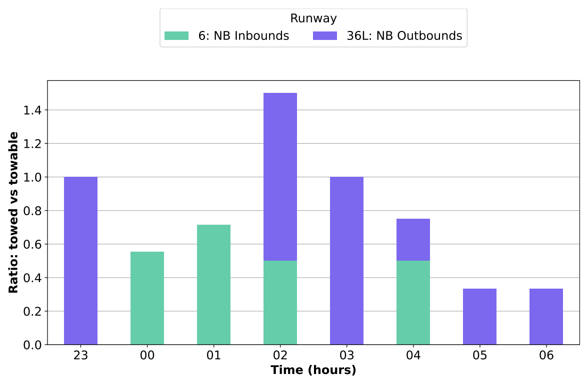


(a) Inbounds

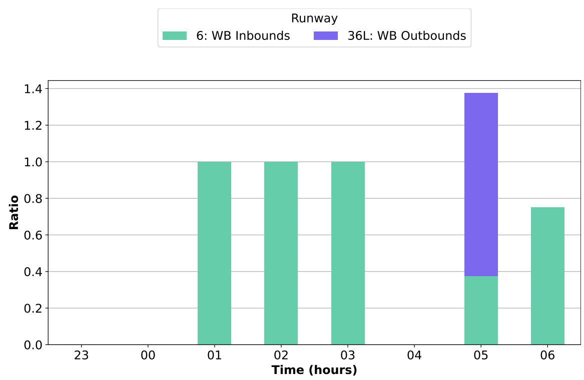


(b) Outbounds

Figure E.7: Runway distributions of towed inbounds and outbounds for high costs on start and end time on 17 July.

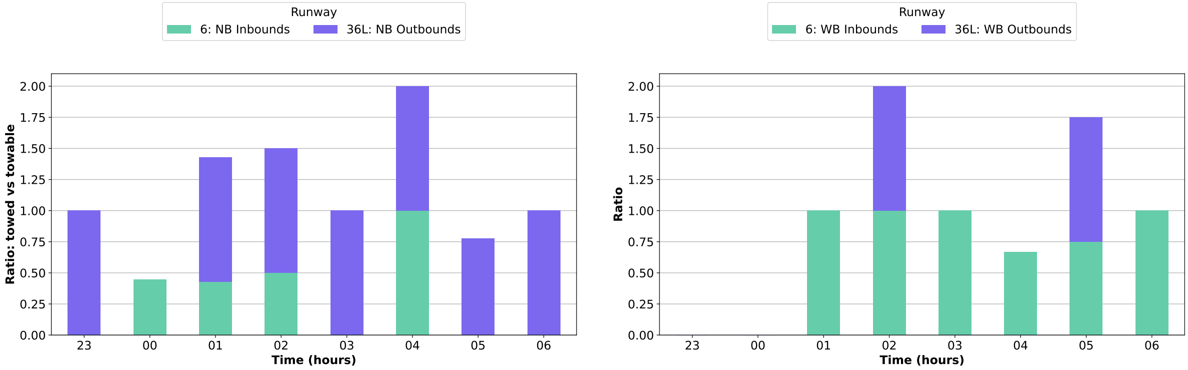


(a) NB



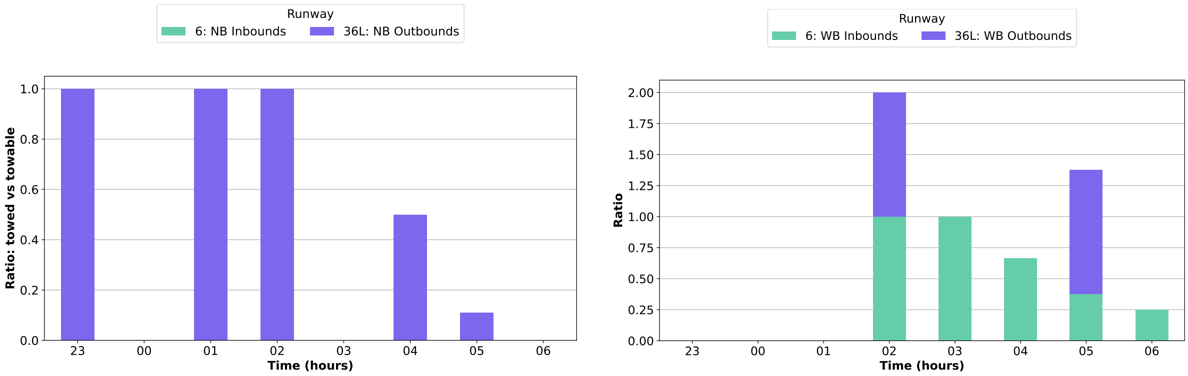
(b) WB

Figure E.8: Runway distributions of NB flights and WB flights for no costs on start and end time on 17 July.



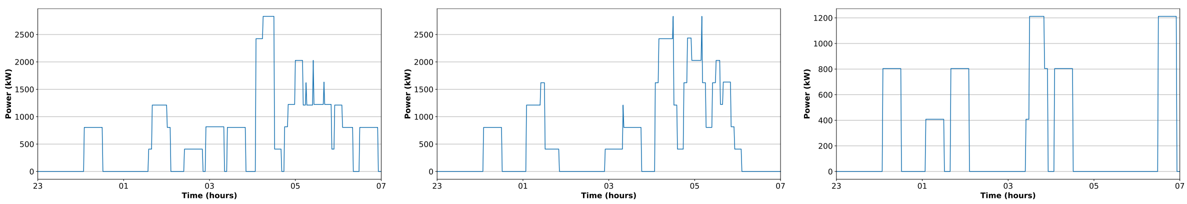
(a) NB (b) WB

Figure E.9: Runway distributions of NB flights and WB flights for low costs on start and end time on 17 July.



(a) NB (b) WB

Figure E.10: Runway distributions of NB flights and WB flights for high costs on start and end time on 17 July.



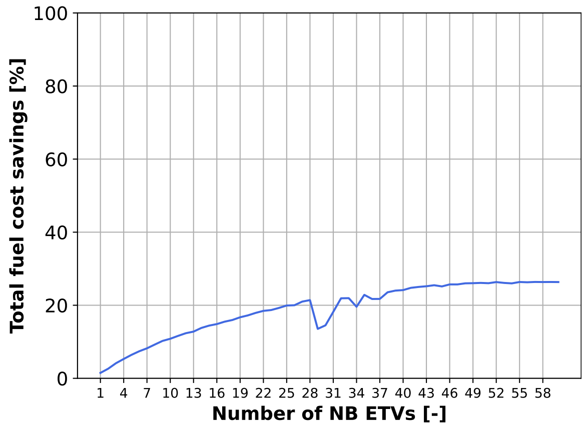
(a) No costs (b) Low costs (c) High costs

Figure E.11: Cumulative charging power per timestamp on 17 July, for different costs on start and end time.

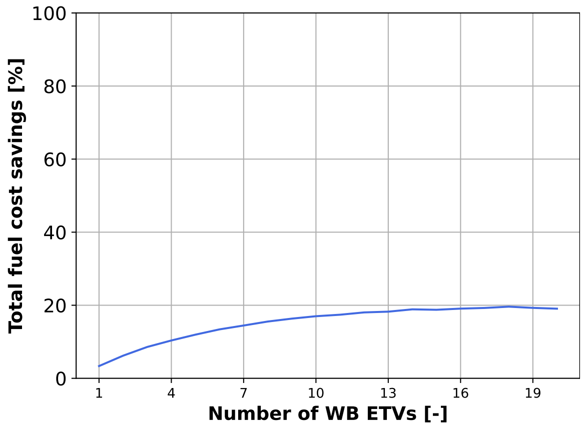
F

Appendix F: Additional results of ETV fleet impact on fuel savings and number of chargers

This appendix shows the total fuel cost savings for a range of NB ETVs and WB ETVs in Figures F.1(a) and F.1(b) respectively. Here the savings made by the ETVs towing flights are compared to the total fuel costs of all flights.



(a) NB



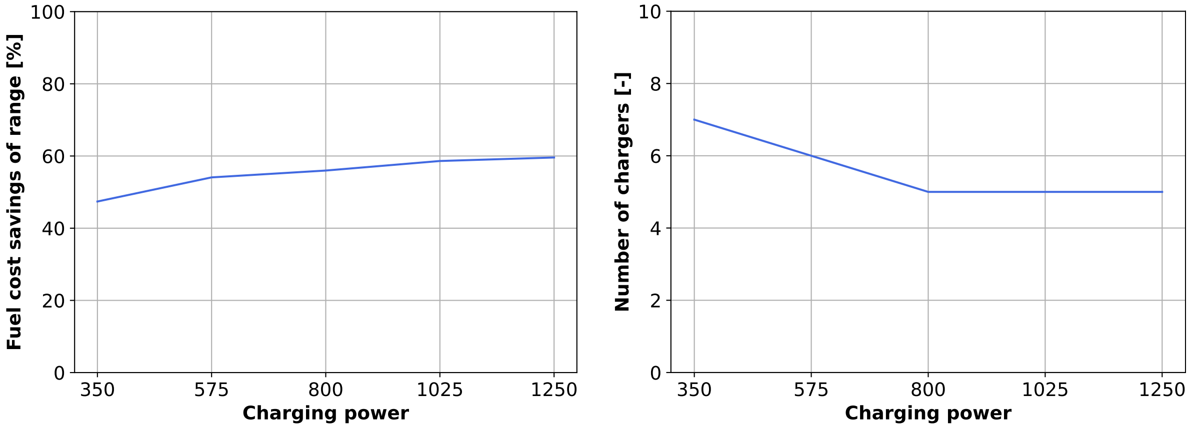
(b) WB

Figure F.1: Fuel cost of a range of NB and WB ETVs compared to the total fuel cost of all flights taxiing.

G

Appendix G: Additional results for sensitivity analysis of charging power

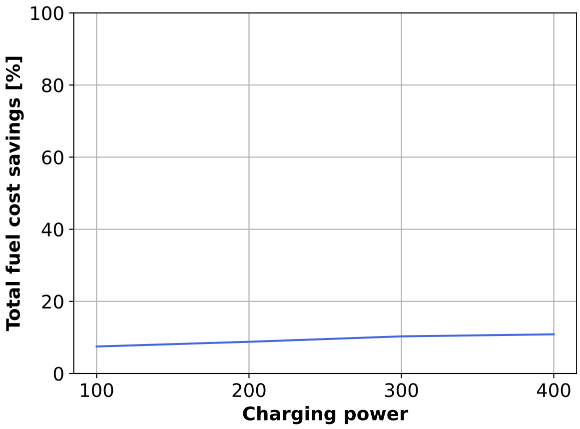
This appendix shows the sensitivity analysis for the WB range in Figure G.1, which shows similar characteristics to the NB charging power analysis. Additionally, the fuel savings of both the NB and WB charging power analyses are compared to the total fuel costs in Figure G.2.



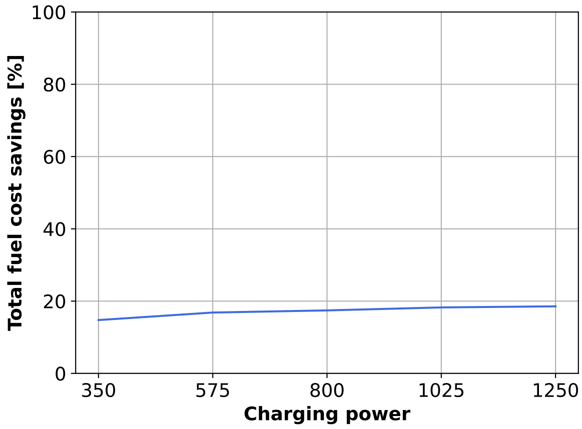
(a) WB Fuel cost savings

(b) WB Number of chargers

Figure G.1: Impact of WB charging power on savings and number of chargers.



(a) NB charging power



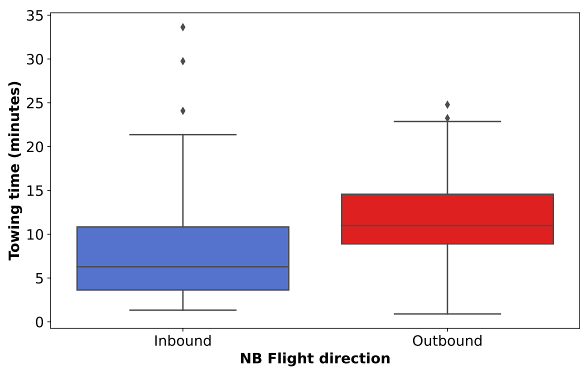
(b) WB charging power

Figure G.2: Total fuel savings for both the NB and WB charging power sensitivity analyses.

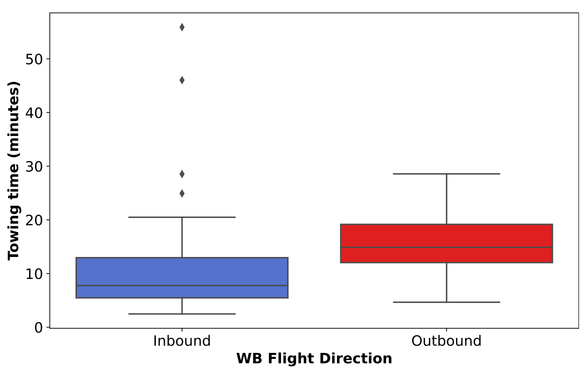
H

Appendix H: Towing time distributions

This appendix show all the towing time distributions separately, first for both days in Figure H.1, then 17 July Figure H.2 and lastly 18 July Figure H.3.

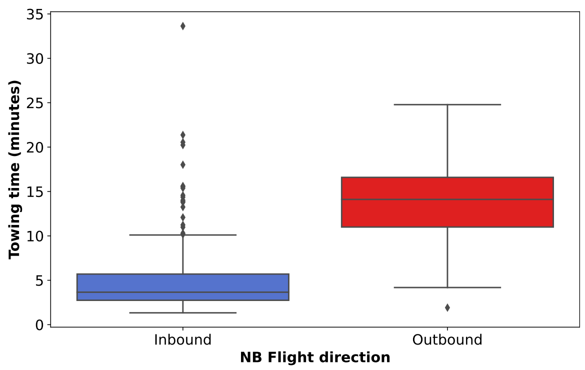


(a) NB Towing time distribution

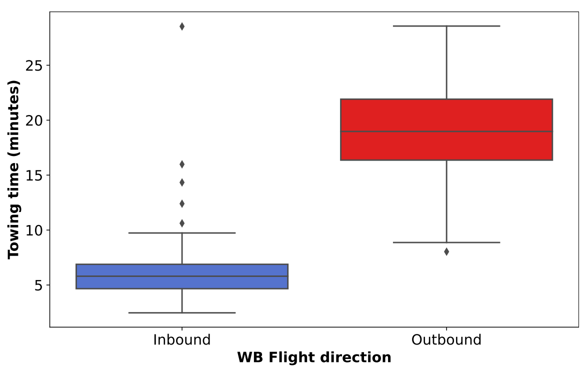


(b) WB Towing times distribution

Figure H.1: Towing time distribution of towable NB/WB flights on 17 and 18 July.

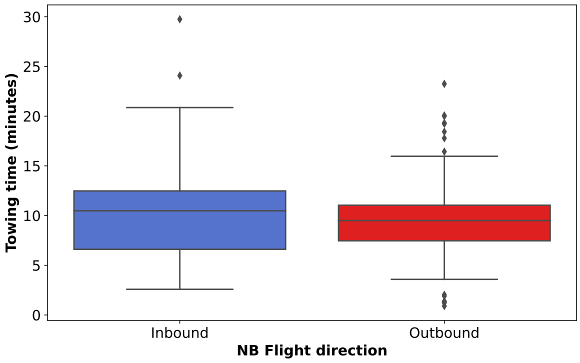


(a) NB Towing time distribution

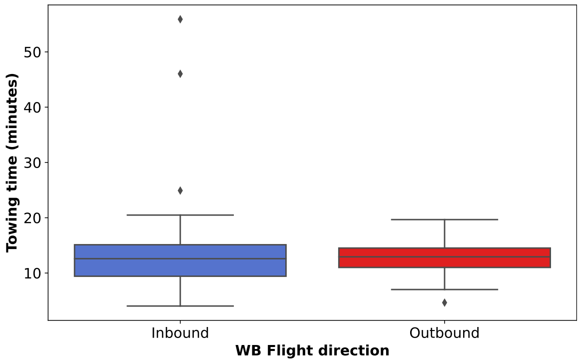


(b) WB Towing times distribution

Figure H.2: Towing time distribution of towable NB/WB flights on 17 July.



(a) NB Towing time distribution



(b) WB Towing times distribution

Figure H.3: Towing time distribution of towable NB/WB flights on 18 July.