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Electric towing vehicle assignment with charging requirements

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One of the most promising ways to reduce emissions at airports is by towing aircraft instead of taxiing with their main engines, also known as dispatch towing. One of the airports most involved with this concept is Amsterdam Airport Schiphol (AMS), as it has an emission-free target for 2030. One of the challenges with this concept is to optimize the assignment of Electric Towing Vehicles (ETVs) to maximize the effectiveness. The developed model can assign ETVs to flights and charging moments for the tactical planning phase, minimizing 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 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 25% and 45% for the large fleet, which are similar on both days. On both days, outbound flights are the 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 utilization and computation time can be improved significantly, by implementing costs on time and introducing utilization 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.

I. Introduction

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[2].

Dispatch towing operations utilize 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[1] 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[3].

To fully benefit from dispatch towing operations, the strategy of assigning ETVs to flights is crucial as it impacts choices such as fleet size and number of chargers. Therefore, this research focuses on the assignment of ETVs to

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flights and charging moments at AMS. Specifically, the assignment involves a limited fleet of ETVs, aiming to minimize 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, minimizing fuel consumption, charging cost and the number of chargers required.

II.Methodology

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 consider the modelling of the towing routes, as the realized 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 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 discretize the ferry routes. On the airport, three types of nodes and one type of edge are modelled. 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.

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 (vs) is maintained. On the service roads, it is assumed that the ETVs can drive in both directions and no separation for other traffic is considered. As the model is an assignment model, no sequence of flights to be towed is made and there is no information available during optimization about what flight must 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 as 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.

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.

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[1], 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.

A. 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. 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 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

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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. 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 Airport 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. For the inbound tow, the Actual Landing Time (ALDT) and Actual In-Block Time (AIBT) are used.

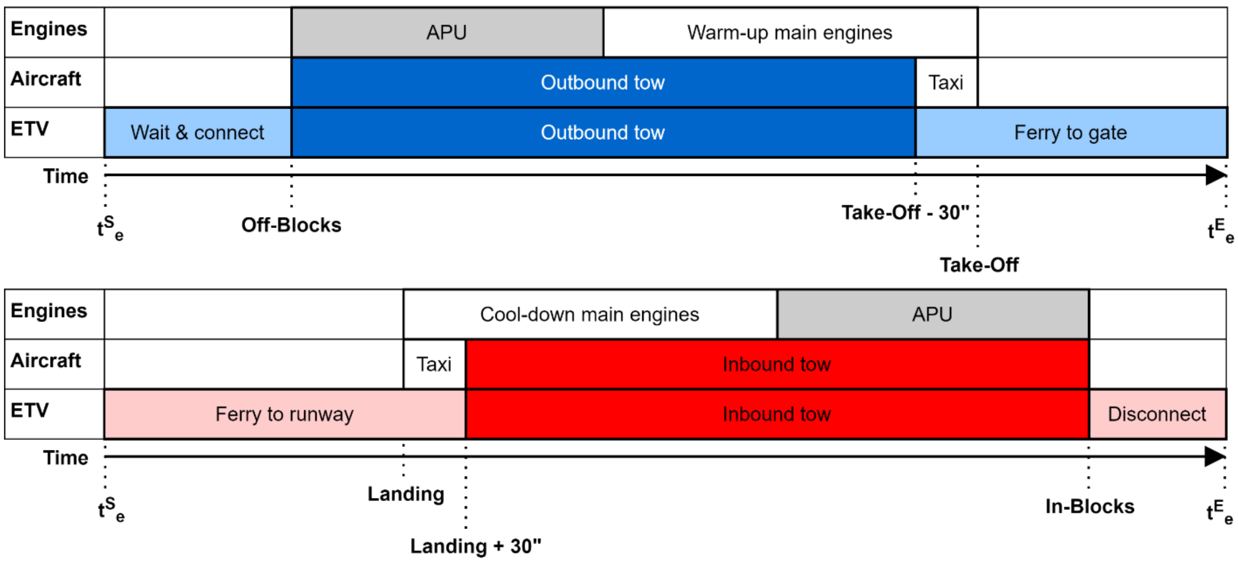

Figure 1: Outbound and inbound towing tasks

B. Balanced charging policy

Throughout a day of operation, the ETV batteries will require a recharge. The approach in this research is to balance the discharging 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 horizons. The balancing policy ensures that the energy an ETV consumes for towing is recharged by a fixed percentage of this consumption. This percentage can be less than 100%, meaning that the charge during the day will decrease and care must be taken that this does not go below the minimum charge level.

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 (W/Wh) of 1C is assumed. Furthermore, as a simplification it is assumed that charging speed remains constant throughout the entire charge. 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) is introduced, so longer charging is more time efficient. In this example, charging blocks start every 5 minutes with two different durations.

C. Fuel savings and energy required

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[4]. The fuel consumption

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during conventional taxiing stems from the main engines, based on the number of engines, the idle fuel flow and the taxi duration.

For every flight f in the flight schedule, the IATA code of the aircraft is looked up in a table[6,7,8]. With the Unique Identification Number (UID) of the engine, the idle fuel flow is looked up in the ICAO Aircraft Engine Emissions Databank[9].

During a towing task, fuel is consumed by the Auxiliary Power Unit (APU) of an aircraft which is used to power the aircraft systems and start the engines. During the engine warm-up time (t_{EWU}) during taxi out and engine cool-down time (t_{ECD}) during taxi in the engines need to be running and thus do consume fuel, while the PAU is assumed to be off.

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. Where the price in dollars per barrel [$/bbl][10], is converted to dollars per kg with conversion 1 barrel = 127.19 kg, and finally this amount in dollars is converted to €1/kg with the currency exchange rate of dollars to euros.

The power (P) required for a tow or ferry movement 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). 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 equal to the power times the taxi duration.

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 [€/kWh][11] 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[12]. Lastly the cost for start time C_{start} and end time C_{end} are described 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.

D. Mathematical Model

The assignment of the fleet of ETVs to flights and charging moments is optimized using an assignment model. The assignment model is classified as a Mixed-Integer Linear Programming (MILP).

Sets

E: Electric Taxi Vehicles (ETVs) indexed by e.
F: Flight operations, indexed by f
H: Horizon time blocks, indexed by h
R: Charging blocks, index by r
T: Time stamps, indexed by t

Subsets are also used. For example, E_f is a subset of ETVs compatible with flight f and F_{eh} are all flight compatible with ETV e and active during horizon h.

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 for 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*

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Variables

x_{ef} : ETV e is assigned to tow flight f, binary

y_f : Flight f taxis conventionally, binary

z_{er} : ETV e is assigned to charging block r, binary

n_c : Number of chargers, integer

t_e^S : Start time of ETV e in minutes

t_e^E : End time of ETV e in minutes

Objective function

$$\text{Min} \sum_{f\in F}\left[\sum_{e\in E_f} C_{tow}x_{ef} + C_{taxi_f}\,y_f\right] + \sum_{e\in E}\left[\sum_{r\in R_e} C_{charging}z_{er} + C_{end}t_e^E - C_{start}t_e^S\right] + C_{charger}n_c \qquad (1)$$

The objective function, shown in Equation 1, minimizes 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 and that taxi conventionally Next, the cost of charging is calculated for all the chosen charging blocks r and 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 maximized. In the fourth term, the number of chargers n_c is minimized.

Constraints

$$\sum_{e\in E_f} x_{ef} + y_f = 1 \qquad \forall f\in F \qquad (2)$$

$$\sum_{f\in F_{et}} x_{ef} + \sum_{r\in R_{et}} z_{er} \le 1 \qquad \forall e\in E, t\in T \qquad (3)$$

$$B_e^C \sum_{f\in F_{eh}} Q_f^T x_{ef} - \sum_{r\in R_{eh}} Q_r^C z_{er} \le 0 \qquad \forall h\in H, e\in E_f \qquad (4)$$

$$n_c - \sum_{e\in E}\sum_{r\in R_{et}} z_{er} \ge 0 \qquad \forall t\in T \qquad (5)$$

$$t_e^S + \left(M - T_f^S\right)x_{ef} \le M \qquad \forall f\in F_e, e\in E_f \qquad (6)$$

$$t_e^E - T_f^E x_{ef} \ge 0 \qquad \forall f\in F_e, e\in E_f \qquad (7)$$

$$t_{e+1}^S - t_e^S \ge 0 \qquad \forall e\in E \qquad (8)$$

Constraint 2 makes each flight f to be towed by one towing vehicle at most or not at all (y_f). Constraint 3 assures that at each time stamp each towing vehicle e can at most either tow a flight (x_{ef}) or be doing a charging cycle r (z_{er}). Constraint 4 forces that for each time horizon h at least a certain fraction B_e^C of the used energy must also be recharged for each vehicle e. Constraint 5 forces the number of chargers to be equal or larger than the maximum simultaneous number of charging cycles over the day. Constraint 6 forces the start time of each vehicle to be at most the starting time of each towing operation it is assigned to. Constraint 7 forces the end time for each towing vehicle to at least equal to each flight it is assigned to. Constraint 8 forces the towing vehicles to be first deployed in the order of their index and aims to limit the amount of symmetry in the model.

III.Case study

The airport where the case study of this research focuses on is Amsterdam Airport Schiphol. One of the most important reason that AMS is relevant to analyze for dispatch towing operations is its size. Both in being one of the busiest European airports[13] and its surface area with long taxiing distances and six different runways. Because of the amount and type of traffic, there is a large range of aircraft types, which makes it relevant to study assigning different types of ETVs. For this study the number of different ETVs was limited to two; One for narrowbody aircraft (NB) and one for widebody aircraft (WB), described in table 1. 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 different stands. The network is shown in Figure 2, which was created with the use of Google Earth Pro[14].

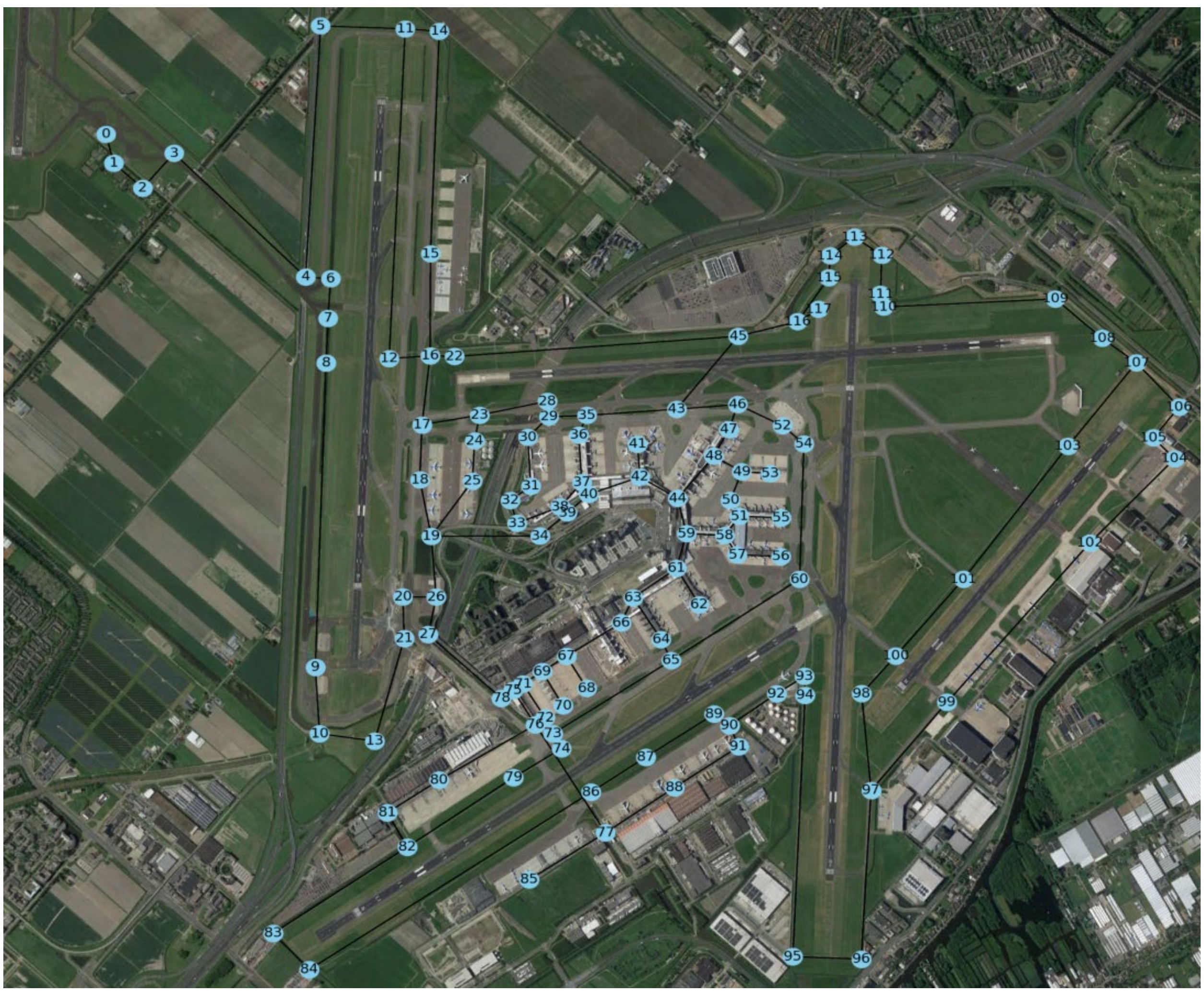

Figure 2: Amsterdam airport Schiphol with serice roads indicated

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[15]. As runway 9-27 is not in operation in the flight schedule of this research, it also

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does not interfere with flights departing and arriving from that runway. For the tunnel crossing under runway 06-24, it is assumed that it is accessible for ETVs in both directions.

Table 1: ETV parameters

ETV type	Compatible aircraft	M_e [Mg]	P_e^C [kW]	Q_e^C [kW]	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	23

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[13]. 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. In total over the day:

- 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.

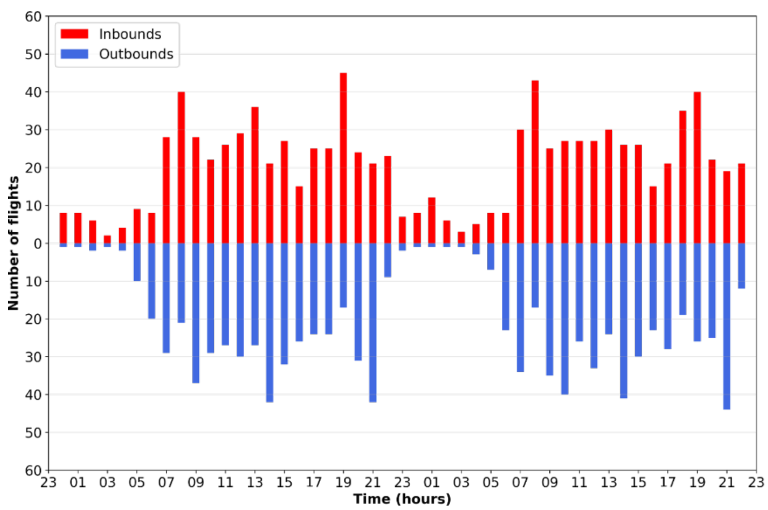

Figure 3: Distribution of towable inbound (red) and outbound (blue) flights on 17 and 18 July 2019 at AMS.

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, runways used are mainly 36L, 36C, 36R and 06. 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 most of the time, indicating a southbound runway operation.

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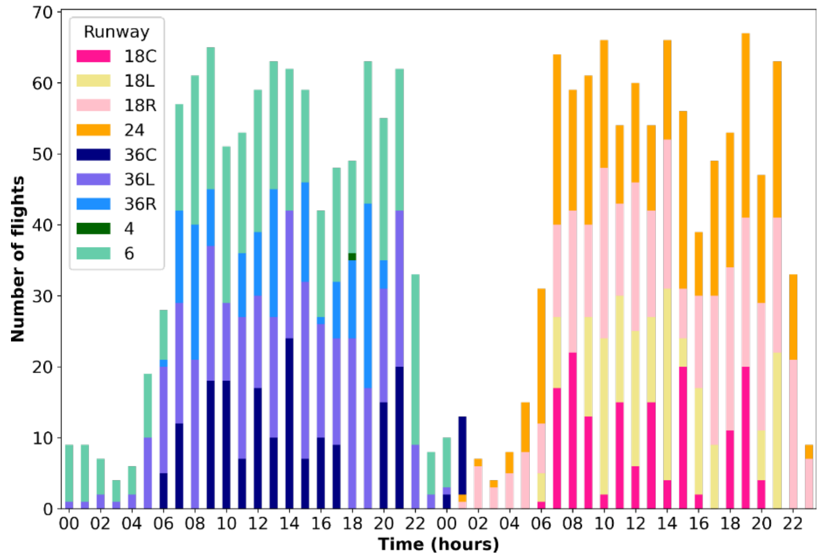

Figure 4 Distribution of runways between 17 and 18 July 2019 at AMS.

Besides the ETVs specifications, other parameters that have been used in the model are shown in Table 2. 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 vs is stated. Lastly, the model parameters of t_p, t_h, R, $t_{horizon}$, $t_{overlap}$ remain constant for all case studies.

Table 2: 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	$t_{process}$	[min]	1
Handling time	t_{handle}	[min]	2
Charging blocks	R	[min]	[35,40,45,50,55,60,65,70]
Horizon duration	t_h	[h]	3
Horizon overlap	$t_{overlap}$	[h]	2
Start time cost	C_{start}	[€/min]	0
End time cost	C_{end}	[€/min]	0

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 analyzing 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 analyze these.

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IV. Results

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 number of simultaneous operations and charging. For the NB flights, there are a maximum of 44 simultaneous operations 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.

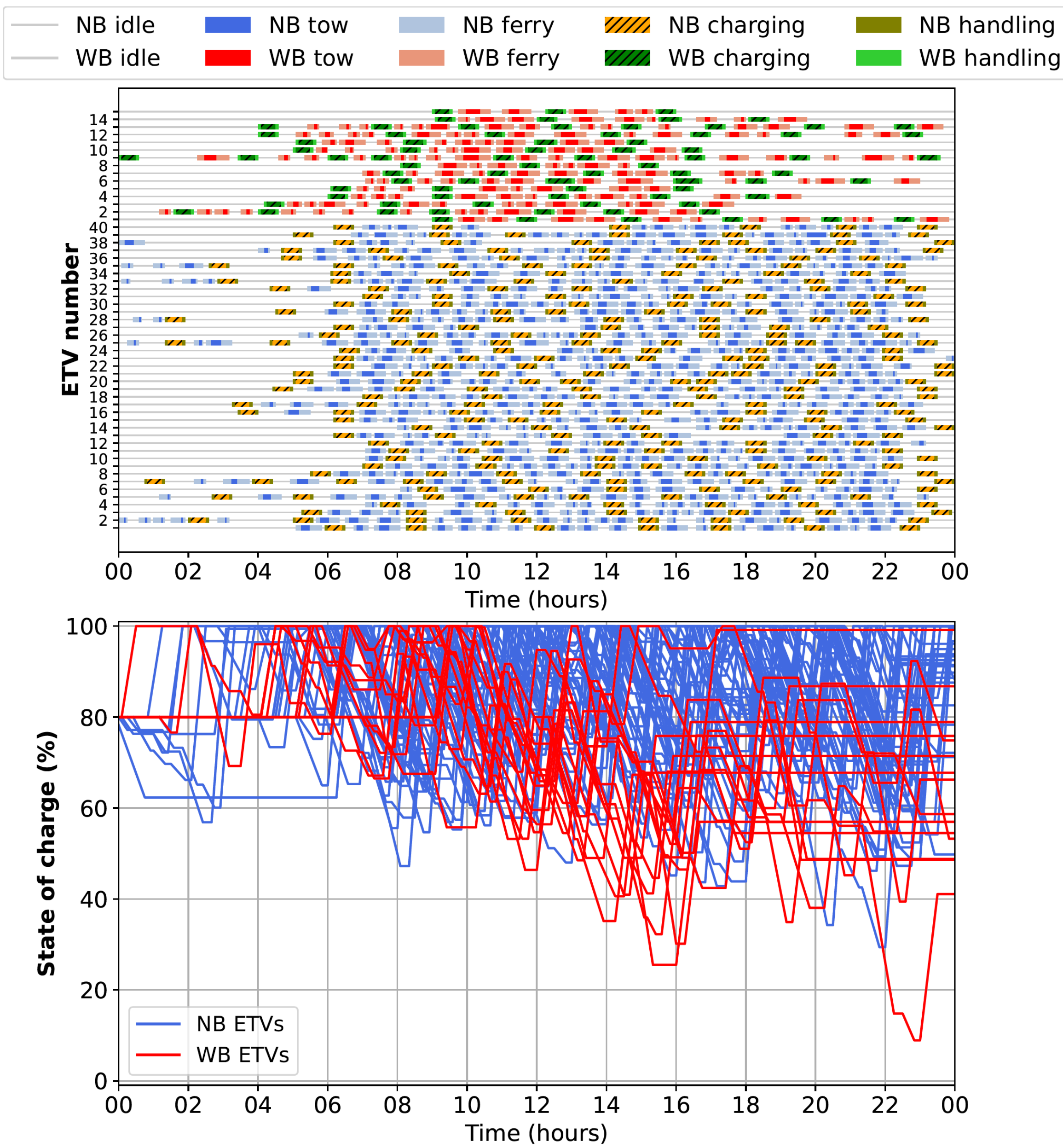

Figure 5: ETV assignment schedule and battery state-of-charge for the large fleet on 17 July.

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The distribution of flights that are towed by both fleets and the resulting total fuel cost savings, are summarized in Table 3. 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 3: Flights towed vs taxiing

Fleet	Day	Flights towed	Flights self-taxiing	Fuel cost savings
Small fleet:	17 July 2019	14% NB, 5% WB	81 %	25%
10 NB, 5 WB	18 July 2019	17% NB, 5% WB	78%	23%
Large fleet:	17 July 2019	46% NB, 11% WB	43%	45%
40 NB, 15 WB	18 July 2019	50% NB, 11% WB	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. 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 fewer gaps.

Not all ETVs are utilized optimally, having long idle times between towing and/or charging tasks in Figure 5. This difference of utilization 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 visualized. The utilization 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 utilization 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.

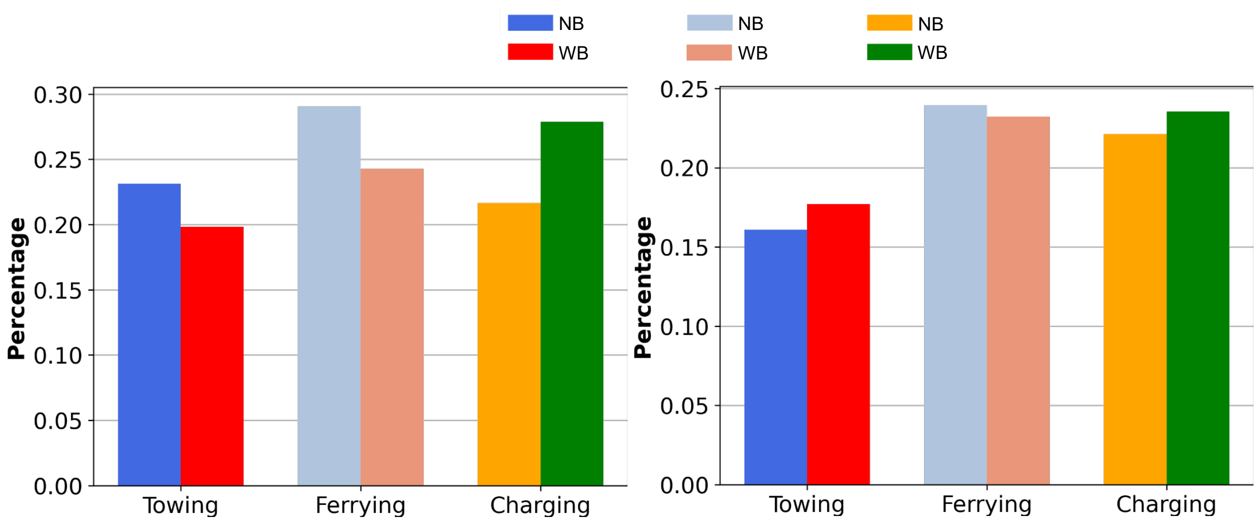

Figure 6: ETV Utilization distribution on 17 July (small fleet left, large fleet right)

Inbound vs Outbound towing

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. For NB flights, 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.

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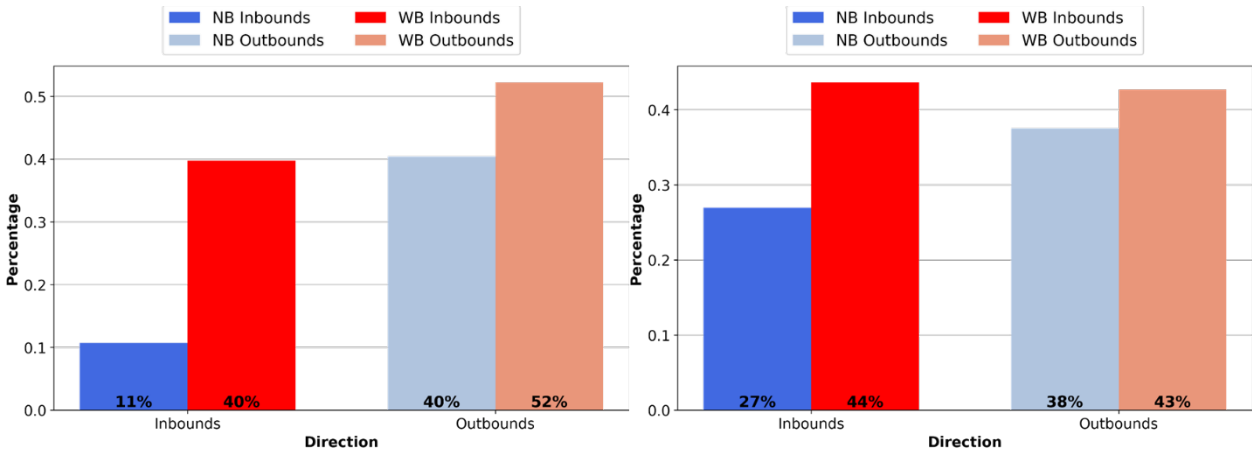

Figure 7: Distribution of towed NB/WB inbounds versus outbounds (Northbound left, Southbound right)

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.

The higher amount of NB flights towed on the day of the southbound operation, 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 are 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 06 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 utilization during nighttime.

Charging power

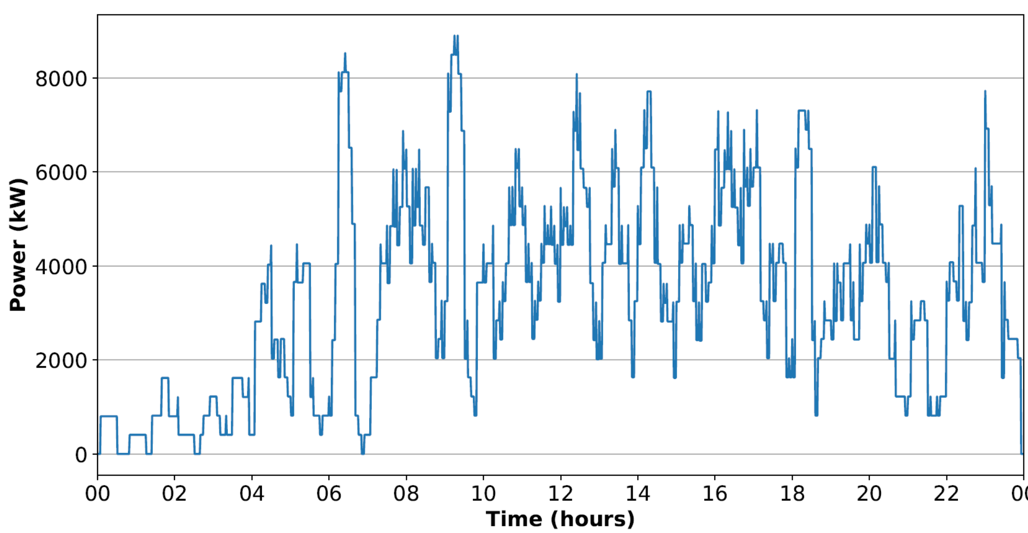

Figure 8: Charging power per timestamp on 17 July for the large fleet

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 minimize the total value of the peaks by minimizing the number of chargers. The average and maximum peak power for the different fleet sizes is shown in Table 4.

Table 4: Charging power

Fleet	Day	Number of chargers	Average power [kW]	Maximum power [kW]
Small fleet:	17 July 2019	7	1339	3636
10 NB, 5 WB	18 July 2019	19	3294	8904
Large fleet:	17 July 2019	7	1343	3636
40 NB, 15 WB	18 July 2019	23	3603	10128

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

Two fleets sizes have been analyzed on the characteristics of utilization, runway distribution and charging power. However, as the model objective is the minimization of fuel consumption and number of chargers, this is analyzed 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 9.

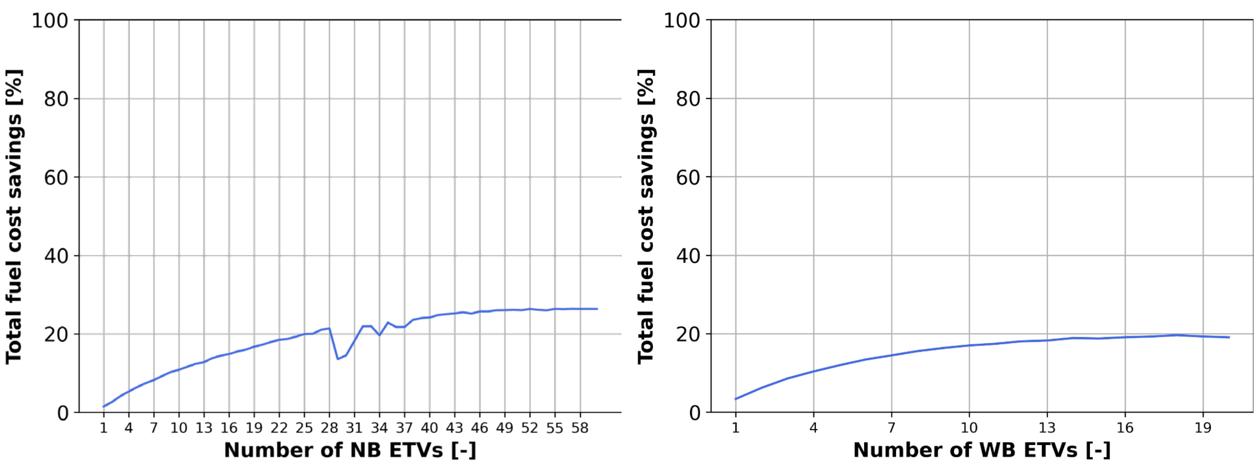

Figure 9: Fuel cost of a range of NB and WB ETVs

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 as possible to have the highest savings amount for the whole day. When adding ETVs to the fleet, the amount saved per ETV decreases as the number 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 utilization. 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.

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The number of chargers required for a specific fleet size is shown in Figure 10. 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 the minimum required number of chargers can be explained due to the utilization of ETVs dropping for a larger fleet size.

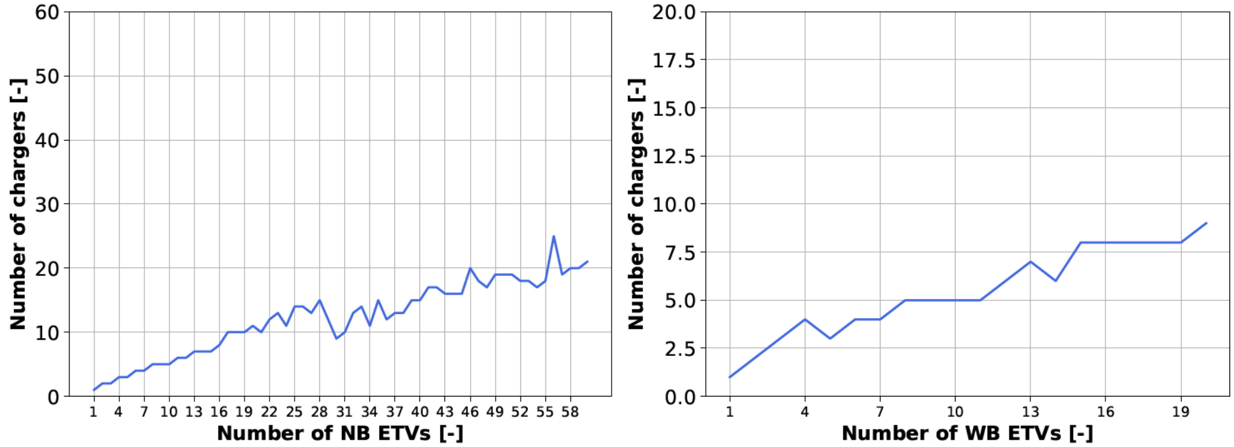

Figure 10: Number of chargers required for a range of NB and WB ETVs.

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 must charge slightly longer than 1.5 hours to get a full charge. In Figure 11, 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.

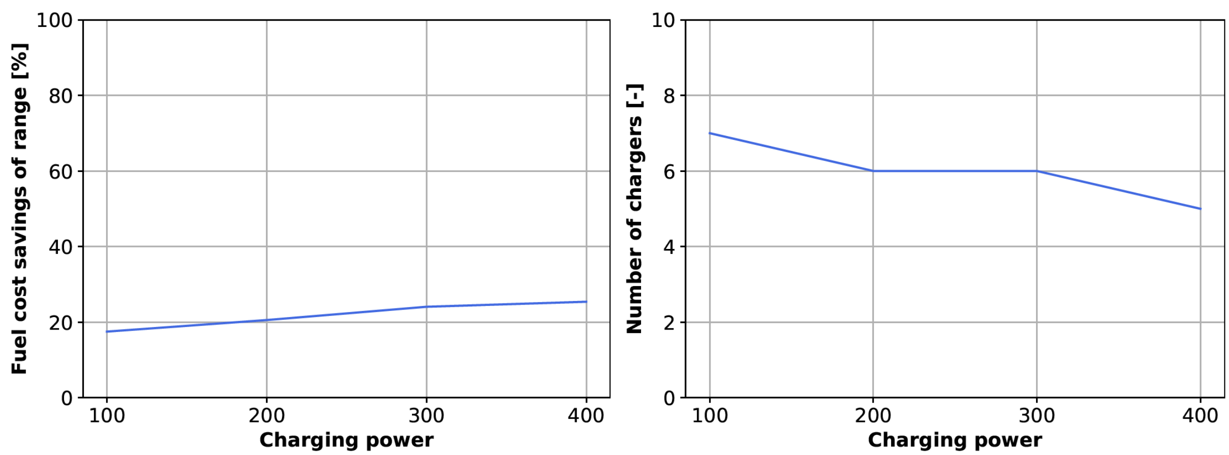

Figure 11: Impact of charging power on savings and number of chargers

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 utilization which reduces fuel cost savings.

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 required.

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V.Conclusions

The fuel cost savings of a given fleet remain similar on days with similar traffic amounts. A different runway configuration does not impact these savings significantly. A relatively 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. It can therefore be considered that implementing dispatch towing at AMS is attractive.

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 utilization is high since there are many flights with high savings available to few ETVs. The higher the ETV towing utilization, the more energy is consumed requiring a high balancing percentage. However, for a large fleet of ETVs the towing utilization decreases. As for a large fleet, more flights can be towed by the higher number 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 returning the investment more quickly.

VI.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 for 24 hours. Whilst capturing the effects to be expected on peak days at a busy airport, this impacts the computation time significantly. Implementing a rolling horizon approach provides for reduced computation times as the solution space is smaller. Furthermore, this approach would be especially suitable for analyzing the assignment during a more real-time operation.

The balancing recharging policy limits the potential fuel savings. If the model can track battery level, choosing the moments for recharging and durations causes 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. This does require a more complex vehicle scheduling model which is likely much more difficult to solve. A similar issue concerns the ferrying times which could be made more accurately with a scheduling model.

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

An 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 on 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 always ensure safety. Furthermore, it is assumed that there is a constant warm-up/cool-down time which varies per aircraft and weather conditions to begin with.

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