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AEON

ADVANCED ENGINE-OFF NAVIGATION

This assessment report is part of the AEON project that has received funding from the SESAR Joint Undertaking under grant agreement No 892869 under European Union's Horizon 2020 research and innovation programme.

Abstract

AEON aims at fostering the use of environmentally friendly ground operations techniques such as autonomous (i.e., e-taxi), non-autonomous (i.e., TaxiBots) or Single Engine Taxiing (SET). For the non-autonomous method, AEON has developed an allocation algorithm for the scheduling of tugs to make most efficient use of the available resources. In this document, the algorithm is described, illustrated, and it's performance is assessed in a case study at Amsterdam Airport Schiphol.

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1 Introduction

1.1 Purpose of the document

This document provides an adaptive towing vehicle allocation algorithm developed in AEON. Note that this algorithm was developed using a simplified towing vehicle model, in an explorative manner to be implemented as a part of the Tug Fleet Manager Human Machine Interface developed in AEON (see D3.2). The goal of this algorithm is to provide the fleet manager with a vehicle allocation suggestion which maximizes the vehicles utilization.

1.2 Intended readership

The intended audience of this report are mainly the AEON Consortium that will use it to consolidate the AEON CONOPS, and the SJU. However, being a public document, the intended readership includes also:

- the key stakeholders targeted by the solution, in particular ground handlers, airport management, airlines, ATC operators and the industry providing green taxiing solutions, most of which are also represented in the AEON Advisory Board;
- the overall aviation community interested in the document, as it will be publicly available.

1.3 Related documents

The document takes into account most of deliverables already produced by the AEON project, with a particular focus on the following ones:

1. D1.1 Initial Concept of Operations, providing the concept that has been assessed in the validation activities
2. D2.1 Models and Algorithms for Autonomous and Non-autonomous Taxiing Operations
3. D3.2 Supervision HMI

The results included in this report will be used to consolidate the AEON Concept of Operations that will be included in D1.2 Final concept of operations.

1.4 Structure of the document

The document is structured in 5 sections:

- Section 1 is the present introduction
- Section 2 Introduces the adaptive allocation algorithm and its features
- Section 3 Illustrates the algorithm in a case at Amsterdam Airport Schiphol

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- Section 4 contains conclusions and recommendations.
- Section 5 contains references.

1.5 Glossary of terms

Term	Definition	Source of the definition
E-Taxi	Taxi solution that relies on electric motors that are embedded in landing gear or nose wheel gear in order to allow airplanes to push back and taxi without their jet engines running	AEON D1.1
Fleet Manager	New role introduced in the AEON solution, whose purpose is to ensure the best availability of the vehicles fleet by monitoring their status and handling maintenance operations. It is a key role of the AEON concept of operations.	AEON D1.1
Single Engine Taxi	Taxi solution that involves the use of only half the number of engines installed to generate the energy needed for taxiing	AEON D1.1
Tug	Dispatch towing vehicle and system that allows aircraft to taxi for departure to the runway end with engines off. It may also be used for arrival aircraft with some procedure change after the aircraft has left the rapid exit track.	AEON D1.1

Table 1: Glossary of terms

1.6 Acronyms

Term	Definition
AB	Advisory Board
AC	Apron Controller
ACC	Area Control Centre
AEON	Advanced Engine Off Navigation
AMS	Amsterdam Schiphol Airport (IATA code)
ANSP	Air Navigation Service Provider
APOC	Airport Operations Center
APTO	Airport Operator
A-SMGCS	Airport Surface Management Ground Control System

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ATCO	Air Traffic Controller
ATM	Air Traffic Management
ATS	Air Traffic Service
CDG	Paris Charles De Gaulle Airport (IATA Code)
CONOPS	Concept of Operations
DMAN	Departure Manager
EHAM	Amsterdam Schiphol Airport (ICAO code)
E-OCVM	European Operational Concept Validation Methodology
FM	Fleet Manager
GC	Ground Controller
HMI	Human Machine Interface
HP	Human Performance
KPA	Key Performance Area
KPI	Key Performance Indicator
LFPG	Paris Charles De Gaulle Airport (ICAO Code)
OSED	Operational Service and Environment Definition
RMO	Runway Mode-of-Operation
RTS	Real-Time Simulation
SESAR	Single European Sky ATM Research Programme
SET	Single Engine Taxi
TD	TaxiBot Driver
TFM	Tug Fleet Manager
TRL	Technology Readiness Level
UC	Use Case
WP	Work Package

Table 2: Acronyms and terminology

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2 Description of the fleet management algorithm

The tug fleet manager is supported in his role by tug fleet allocation algorithms, which schedule the tugs throughout the day. During the day, tugs can tow aircraft on the taxiway, drive around the service roads, or recharge their battery. While charging, the tugs are unavailable for towing. The schedule of the tugs may also need to change throughout the day as flight delays occur or the tug fleet manager makes manual adjustments.

2.1 Algorithm context

An overview of the setting of the fleet management algorithm can be found in Figure 1. The algorithm takes as input information about the airport, the tugs, and the day of operations. A single-agent path planning algorithm (from AEON deliverable 2.2) is used to estimate traveling times. It uses this information to create a fleet schedule which maximizes the utilization of the tugs and returns this information as a tug to flight assignment and a tug charging schedule. This information is provided to the TFM, who may decide upon manual changes to this schedule. If the schedule is modified, the algorithm is run again to check feasibility. If a feasible schedule is found, it is given to the path planning algorithm, which determines the routes the tugs and (towed) aircraft take on the airport road network in order to avoid congestion and collisions.

Throughout the day, information on the setting may be updated: the flight schedule may change (delays), the tug availability may alter (possible breakdowns), or the airport layout adapts (due to a runway mode-of-operations switch). Because of this, the tug schedule may need to be updated by the algorithm. For this, a dynamic rolling horizon approach has been incorporated into the fleet management, which is able to account for all the above-mentioned situation changes.

Hereafter, we shall discuss the details of the algorithm. We start with describing the input, second we describe the initial planning algorithm, and last we will outline the rolling horizon approach.

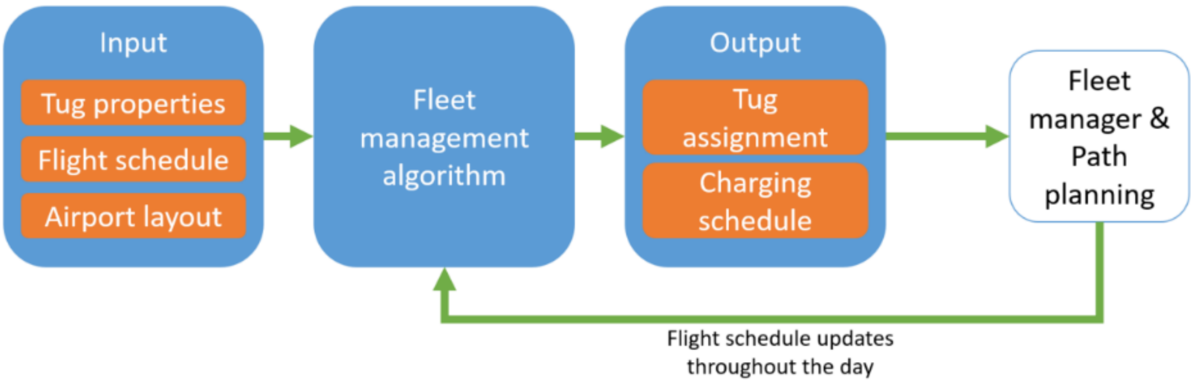

Figure 1 Towing fleet allocation algorithm overview and interaction with the fleet manager and path planner

2.2 Input of the fleet management algorithm

As shown in Figure 1, the fleet management algorithm uses three different types of input, we shall describe them below.

Airport road networks We consider an airport map. This is the same one used for the multi-agent routing algorithm from AEON deliverable 2.1. On this airport, the runways, gates, and tug-charging stations are connected by the taxiway network. The taxiways connect the gates to the runways, the places where aircraft are picked-up and dropped-off. For each runway, a default pick-up and drop-off point is defined. Each road in this network is characterized by a distance and by the maximum allowed taxiing velocity. Information on the time it takes to traverse the airport using the different networks is used as input for the allocation algorithm. An example of an airport road network can be seen in Figure 2.

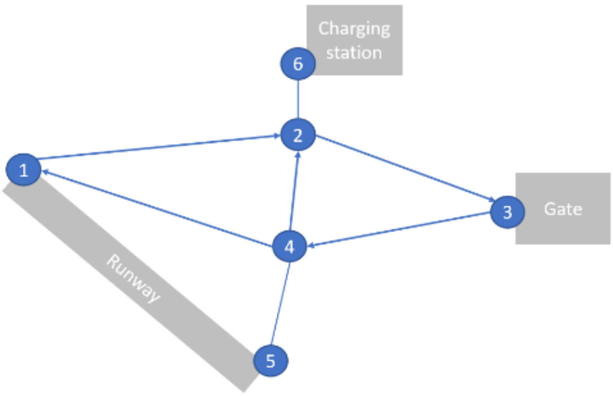

Figure 2: Mock airport road network. The taxiway network, connects the gates, runways, and tug charging stations with each other.

Flight schedule During a day of operations starting at $t = 0$ and ending at $t = 24$ hours, a set of flights A arrives and departs at the airport which are designated to be towed in the A-CDM (conform the AEON concept of operations), all other flights arriving and departing at the airport are not part of the algorithm input data. This set is partitioned in medium A_M, heavy A_H, and ultra-heavy A_U aircraft. An aircraft from $a \in A_t$ can be picked up by a tug at time, needs to be dropped off by another time, and takes a certain energy to be towed by a tug. The drop-off time is calculated using a single-agent version of the path planning algorithm detailed in Deliverable 2.1. In order to account for delays due to the resolution of separation distance conflicts, a buffer time of 3 minutes is added to the drop-off time of each tow.

Tugs The aircraft are towed using a set of tugs T, partitioned in medium T_M, heavy T_H, and ultra-heavy T_U tugs, which tow their respective weight class aircraft. Each class has a battery of a specific size. Each tug has to start and end its day of operations at the depot and with a full battery. Recharging the battery can be done at a charging station for a minimum time of $t_c^{min} = 1$ hour.

2.2.1 Bootstrapping the pick-up / drop-off events

As we have discussed in last subsection, the output of the tug fleet management algorithm is used as input for the multi-agent path planning algorithm, as this algorithm requires to know which towing method is assigned to which flight. However, the fleet management algorithm also requires information about the towing paths as an input. From it, it requires (1) the runway pick-up/drop-off location, (2) the pick-up/drop-off times, and (3) the energy used while towing. Hence, there is a problem of which algorithm to run first in order to provide input for the second. In the AEON solution, we have used a bootstrap approach to solve this problem.

This approach rests on adding buffers to the input of the algorithm. The runway pick-up/drop-off point, which the path-planning algorithm chooses in order to obtain a maximum system throughput, is substituted by a default location for each runway heading. The pick-up time for arriving aircraft is estimated by adding a constant 2 minute buffer to the touch-down time.

Using these values, a single agent path planning algorithm is used to determine an estimation for the time of arrival at the drop-off location. In order to account for the fact that other aircraft need to be avoided on route, a constant 3 minute buffer time is added to obtain the drop-off time. Last, we assume that the required energy use does not change as a result of taxiway-conflict avoidance.

2.3 Fleet management Algorithm

The tug fleet management algorithm creates a tug schedule and suggests this to the tug fleet manager. This schedule contains: which aircraft from A_t are to be towed, which tug from T tows which aircraft, and when (and where) the tugs are going to recharge. The algorithm aims to maximize the environmental impact of the tugs and uses a greedy search approach to determine which flights are towed. After this, the multi-agent path planning algorithm will route the aircraft for minimum travelling time. In this subsection we shall describe how the initial schedule is created, in the next, we shall describe the rolling horizon approach which describes how the schedule is adapted to events throughout the day.

Algorithm: Greedy tug to flight assignment and charging schedule creation

Data: A set of flights from weight class x: A_x, which can be towed; a fleet of tugs T_x; an airport service road and taxiway network.
Result: An assignment of the tugs to the aircraft and a tug charging schedule
Initialization: Fleet of tugs starting at $t = 0$ at the depot n_d with a full battery
While there is a tug available to tow flights:
Select the first available tug
Determine the set of all flights A_s in A_x which this tug can tow next such that:

1. The flights have not yet been assigned to a tug
2. The tug does not run out of battery life;
3. There is enough time after towing to recharge the tug to full battery before the end of the day.;
4. The earliest flight which meets (1)-(3) is in A_s ;
5. Two flights from A_s cannot be towed consecutively by this tug.

If $A_s \neq \emptyset$:
Let $\hat{a} \in A_s$ be the flight with the highest reduced emissions if it is towed instead of taxis by itself
Assign $\hat{a}$ to this tug

Recharge the tug between the two towed flights for as long as possible, if the available time is longer then t_c^{min}

Else:

Send this tug to the depot for recharging, it is no longer available to tow aircraft

End

End

Post-process the charging schedule to ensure the tugs use as few charging cycles as possible.

The algorithm initializes the fleet at the start of the day at the depot with a full battery. To allocate the tugs, the algorithm iterates in time. During each iteration, the next available tug is assigned to a flight, or is sent to the depot to recharge for the end of the day. The flight which is assigned to the tug is the flight $\hat{a}$ from a subset $A_s \subset A_x$ with the highest marginal emission savings. The set A_s confirms to (1) its flights have not been assigned to tugs (yet) , (2) the flights from it can be towed by the tug without running into battery life problems, (3) the tug can tow any flight from A_s and still be at the depot with a full battery by the end of the day, (4) the flight with the earliest arrival/departure time which conforms to these three conditions is in A_s, and (5) no pair of flights from A_s can be towed consecutively by this tug. By enforcing (3), we ensure that tugs can start towing immediately the next day. Finally, if after a number of iterations all tugs are at the depot by the end of the day, the algorithm terminates the loop and post-processes the charging schedule using the algorithm by van der Klauw et al. (from [3]).

The algorithm is run for only one type type of tugs, but can be extended to multiple types (e.g. one tug type for medium / heavy / ultra heavy aircraft).

2.4 Dynamically adjusting the schedule of the tugs using a rolling horizon approach

Throughout the day, a number of events may occur which distort the schedule created by algorithm 1. A rolling horizon approach is used to adapt the schedule, which uses algorithm 1 as a subroutine. We have accounted for the following events:

Sudden tug (un)availability Throughout the day, a tug may become unavailable for a number of reasons (e.g. a breakdown, a crew scheduling problem). In this case, it cannot tow any of the flights it was assigned to later on this day. In this case, the fleet management algorithm is rerun from the moment of the breakdown with the following constraints: (1) all flights which are towed at the moment are delivered to their drop-off point, (2) all flights which are waiting to be towed are also assigned a tug in the new schedule, and (3) besides these flights, all others may be reassigned to a new tug of may be ask to taxi by another method. The algorithm is performed again to ensure that the maximum utilization of the remaining tugs is obtained. The new schedule is given to the TFM for review.

Similarly, if a tug enters into service throughout the day, a new assignment is obtained for all other tugs as well.

Flight delay In the case that a flight, which is assigned to a tug is delayed, and an infeasibility in that tugs schedule is caused, the schedule will be revaluated for the rest of the day using the assignment algorithm. This is subject to the same conditions as mentioned before in the case of a tug unavailability.

RMO change In the case that the runway mode of operations changes, some parts of the taxiway and service road systems may become (un)available to the tugs and towed aircraft. In this case, it may take longer (or shorter) to traverse the airport for certain routes. If this results in an unfeasible schedule, it is recomputed for the rest of the day using the fleet management algorithm, with the same conditions as mentioned before.

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3 Fleet management algorithm illustration at EHAM

3.1 Input data

In order to illustrate the features of the fleet management algorithm, we provide an illustrative case at EHAM airport. The following input data is used

Airport road network EHAM comprises six runways and nine piers with gates, a taxiway and a service road network, which are visualised in Figure 3 (from [4]). The runways and piers are displayed in blue, the taxiway in solid lines, and the service road network in dashed lines. Black circles indicated junctions, vertically hatched circles indicate gate/runway access points, and red circles indicate possible charging station locations. The tug depot is located at C5.

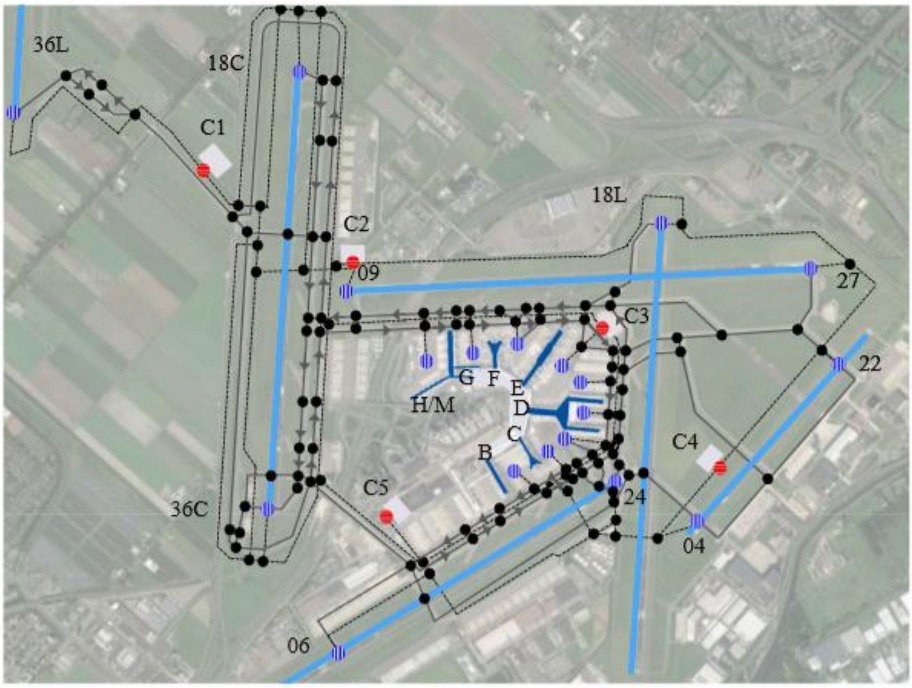

Figure 3 EHAM road network. The runways and piers are displayed in blue, the taxiway in solid lines, and the service road network in dashed lines. Black circles indicated junctions, vertically hatched circles indicate gate/runway access points, and red circles indicate possible charging station locations. The tug depot is located at C5.

Tugs We consider a fleet of five tugs which are able to tow narrow body aircraft. The tugs have a battery with a capacity of 300 kWh. They are able to tow aircraft at a maximum velocity of 40 km/hour and traverse the service road at 30 km/hour. They can be recharged at a rate of 100 kWh. Connecting and disconnecting the tugs from the aircraft is assumed to take two minutes.

Flight schedule The flight schedule used is comprised of historical data from the 14th of December, 2019. In total, 913 flight arrived and departed at EHAM that day, and the distribution of these can be seen in Figure 4.

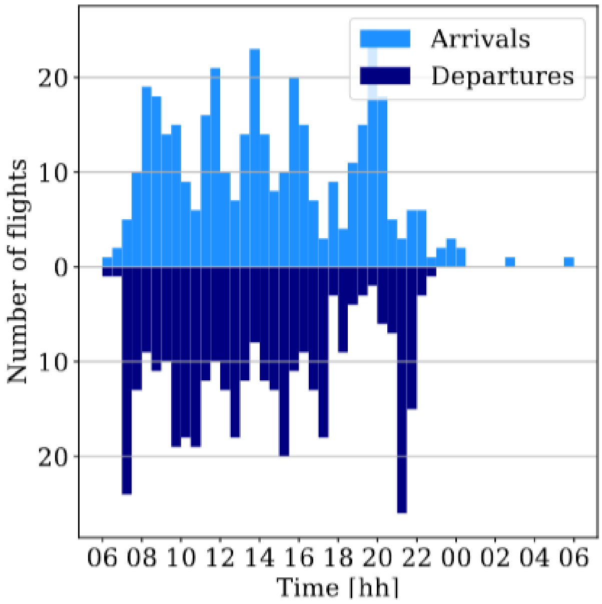

Figure 4: Landing/take-off time distribution of the flights arriving/departing at EHAM on the day of operations of December 14th, 2019.

3.2 Scenarios

We consider two different scenarios: a tug breakdown and a manual flight-to-tug assignment by the TFM.

3.2.1 Tug breakdown

First, let's consider a case where, for some reason, a tug breaks down during the day, needs to be sent to maintenance for inspection, and joins the fleet later this day.

- At 6:00 the day of operations start with five tugs. At this moment, an initial tug allocation is created and accepted by the tug fleet manager, this schedule can be found in Figure 5.
- At 14:00, tug 5 is recharging its battery and an error occurs, it needs to be inspected and cannot tow flights any longer. At this moment, all flights that tug 5 was supposed to tow are unassigned from this vehicle and some of them are reassigned to other tugs. This new schedule can be found in Figure 6.
- At 16:00, the error is found and resolved, tug 5 enters into service again. Again, a new schedule is created, where some flights are assigned to tug 5. This schedule can be found in Figure 7.
- At midnight, the day of operations is almost finished. The schedule is performed without further alterations, and the situation can be found in Figure 8.

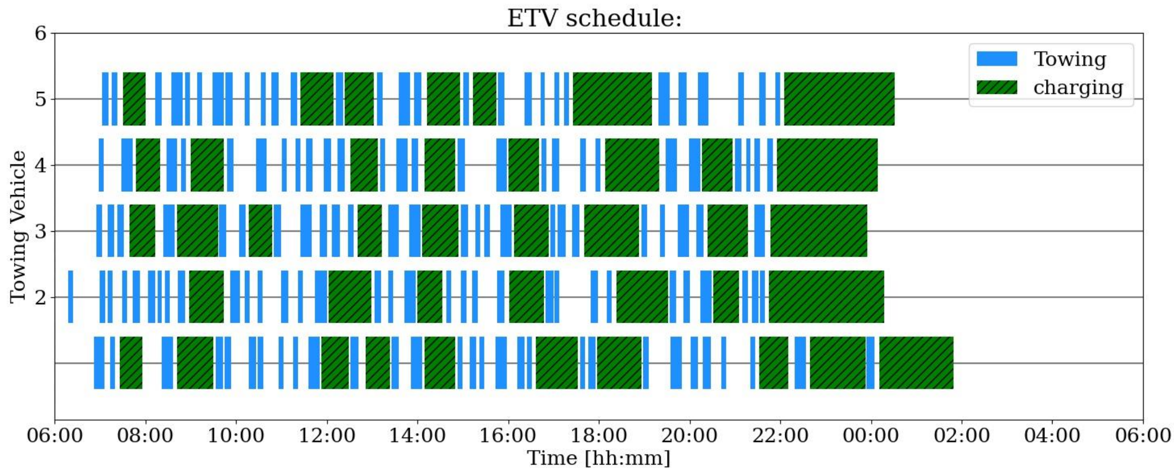

Figure 5: Initial tug allocation at 6:00

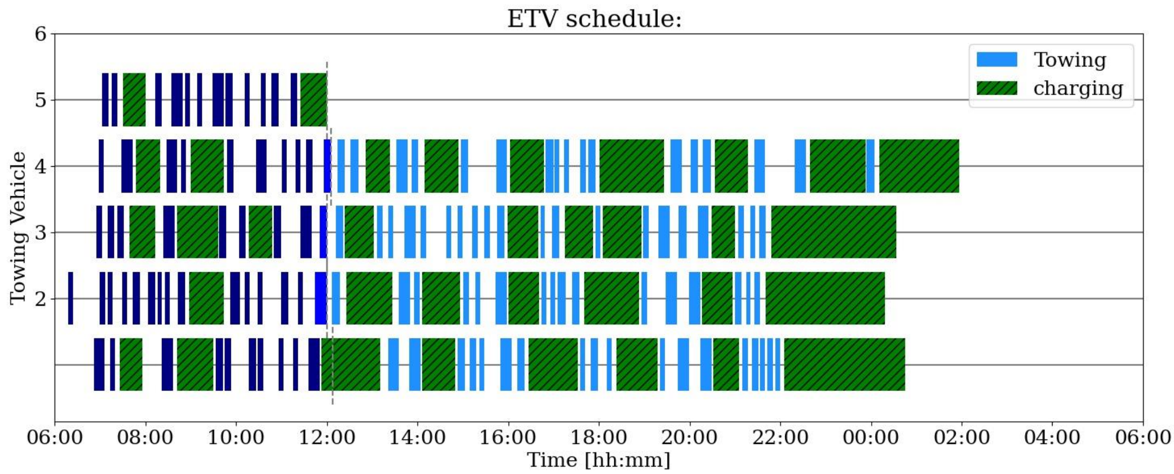

Figure 6: tug allocation at 2 PM, after tug 5 has been sent to maintenance

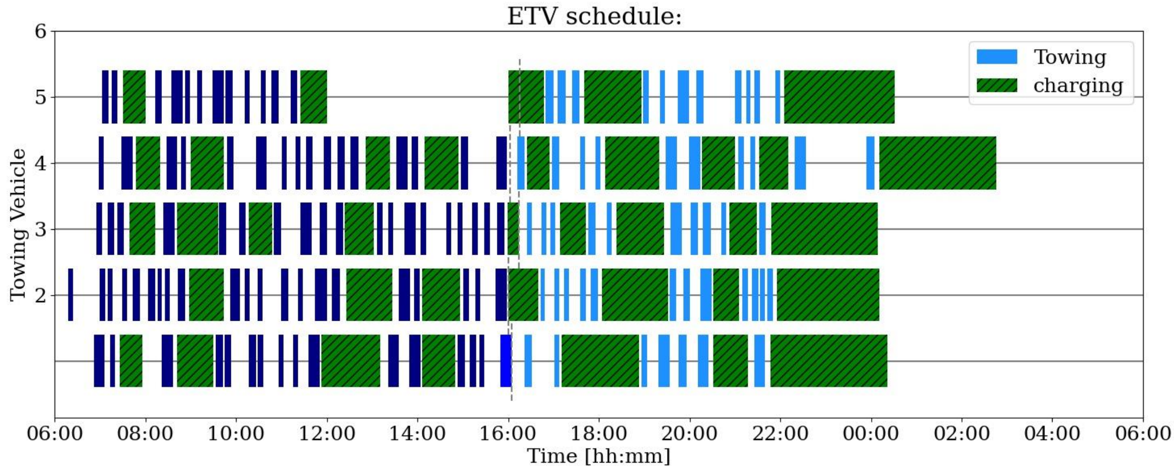

Figure 7: Tug schedule at 16:00, after tug 5 has been repaired and is ready for re-entry into service

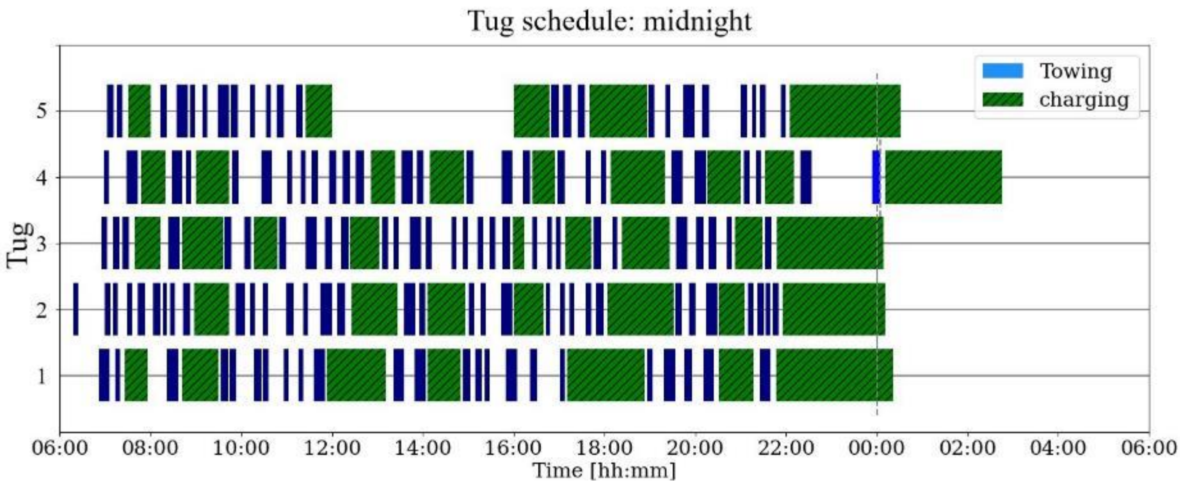

Figure 8: Tug schedule at midnight, after almost all of the schedule has been completed

3.2.2 Manual flight assignment

As we have discussed before, the TFM may decide to make manual alterations to the tug schedule. An example of this can be found in Figures 9 and 10.

The original proposition by the fleet management algorithm can be found in Figure 9. The fleet manager decides to retire tug 1 earlier this day, and does so by reassigning the last flight assigned to this tug to tug 2. As can be seen, this does not only change the schedule of tug 1, but because of battery constraints, also that of tug 2.

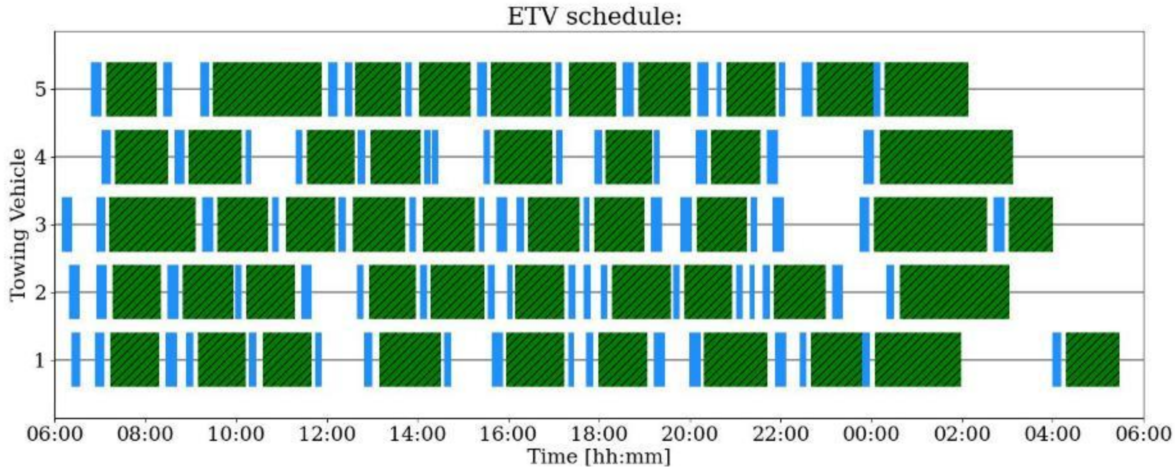

Figure 9: Initial tug allocation at 6 AM

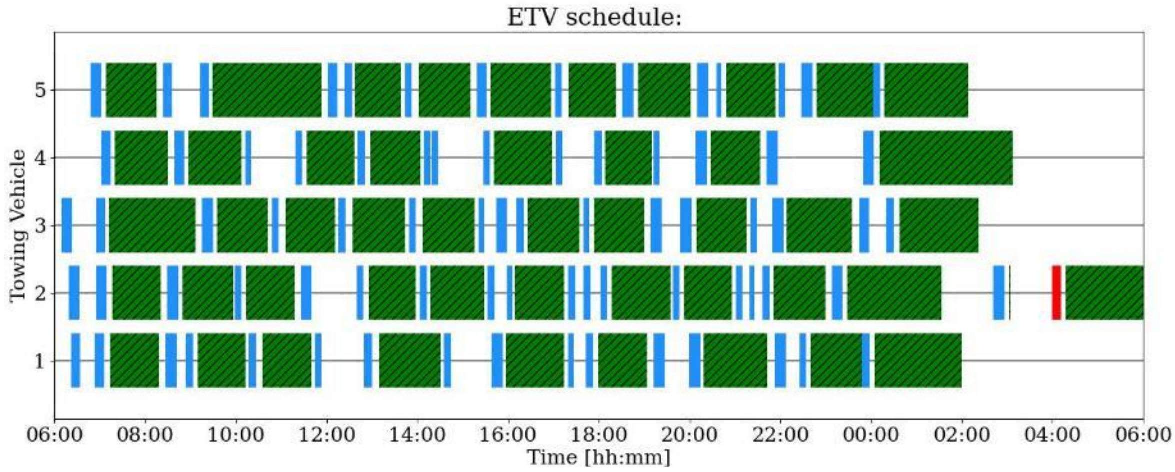

Figure 10: Tug allocation after a manual flight reassignment by the TFM (in red).

4 Verification and Validation

Verification and validation of the allocation model were performed. During implementation, continuous verification was performed. The model was developed in different modules, allowing for the independent testing of the building blocks. Gannt charts of the resulting schedules were generated to verify the correctness of the model's results (such as Figures 5 through 10). These were presented to experts from Amsterdam Airport Schiphol to verify schedule feasibility. Using these tools, it was ensured that valid schedules were generated using the allocation algorithm.

The performance of the greedy allocation model has been assessed by comparing it to an optimal allocation generated using a mixed-integer linear programming formulation of the problem. The number of vehicles required to tow all eligible flights has been computed using both methods, the results can be found in Figure 11. The results generated by the AEON solution remain within 3% of the lower bound, ensuring that the algorithm performs as required.

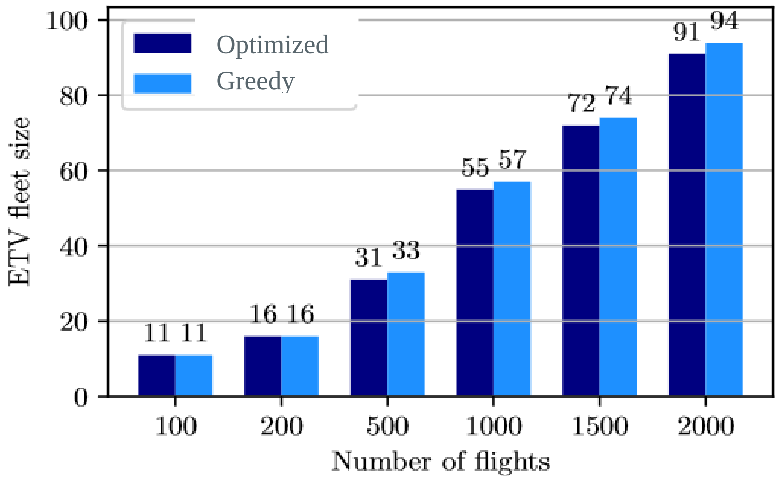

Figure 11: Number of vehicles required to tow all aircraft using the greedy AEON solution and a linear programming formulation.

Furthermore we have compared the performance of the AEON charging strategy, where vehicles are allowed to recharge throughout the day for at least an hour and can leave after that at any time, with two other possible charging strategies. These represent a simpler mode of operation which would also be feasible, but is was found that using them has a large impact on the required fleet size. The two other charging strategies are 1) *night-charging* and 2) *charging up to full capacity.* We have used a schedule with 1000 flights at EHAM, the fleet sizes can be found in figure 12. Further analysis can be found in a study by van Oosterom and Mitici [4].

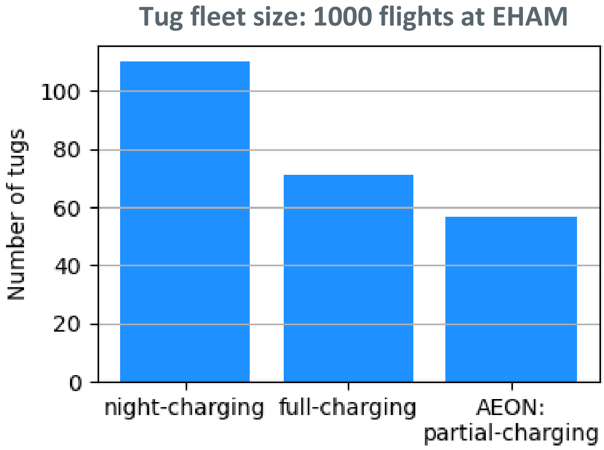

Figure 12: Required fleet sizes using different charging protocols [4].

Validation was performed with operational experts from Amsterdam Airport Schiphol and in a real-time simulation of Paris Charles-de-Gaulle with air-traffic controllers as tug fleet managers. It was found that the algorithm can be run online throughout the day to adapt to the manual adjustments made by the TFM.

Furthermore, the algorithm was found to be able to be leveraged for long term decision support in tree areas: tug fleet sizing, charging strategy optimization, and maintenance planning. In order to optimize the required tug fleet size at an airport, different flight-schedules and expected RMOs can be used to simulate the fleet performance throughout the year. As we have seen, different charging strategies can be compared. Finally, by forecasting the fleet schedule for the next days, the impact of different maintenance decisions can be assessed and the most effective one can be implemented.

5 References

[1] AEON D1.1 – *Concept of Operations Initial version* (2021). AEON Consortium

[2] AEON D2.1 -- *Models and Algorithms for Autonomous and Non-autonomous Taxiing Operations* (2022)

[3] Thijs van der Klauw, Johann Hurink and Gerard Smit (2016), *Scheduling of Electricity Storage for Peak Shaving with Minimal Device Wear.* Energies 2016, 9, 465, doi:10.3390/en9060465

[4] Simon van Oosterom and Mihaela Mitici (2022), *Analyzing the impact of battery capacity and charging protocols on the dispatchment of electric towing vehicles at a large airport*. AIAA AIVATION 2022, doi:10.2514/6.2022-3920

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