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AEON: TOWARD A CONCEPT OF OPERATION AND TOOLS FOR SUPPORTING ENGINE-OFF NAVIGATION FOR GROUND OPERATIONS

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ABSTRACT

The SESAR Advanced Engine-off Navigation project (AEON) aims at exploring the reduction of ground operations environmental impact based on the use of three classes of greener taxiing solutions: single-engine taxiing solutions, hybrid towing taxiing solutions and electric engine solutions. This approach requires a novel concept of operation and new support tools for sustainable airport ground operations to cope with the additional vehicles on the ground to tow aircraft, discrepancies between aircraft in terms of ground speed according to the taxiing technique and the management of the fleet of towing vehicles. In this paper we first describe the motivation and the context of the project. We then introduce the AEON concept of operation that includes a new role responsible for the supervision of towing vehicles. We also articulate the architecture of our solution and describe three inter-operating support tools: (1) an optimization tool to estimate the number of necessary tugs and assign them to the aircraft before the operations; (2) a multi-agent path planning system providing real-time, conflict-free routes including speed profiles to maximize capacity as well as fuel efficiency. (3) Human-Machine Interfaces for supporting Air Traffic Controllers and the Tug Fleet Manager to control and supervise the whole traffic. Then, we present the validation activities including an evaluation with Air Traffic Controllers using realistic real-time simulations on the Paris Charles de Gaulle airport. Finally, we conclude with a discussion on how this concept could impact on a number of key performance indicators (KPI), such as human performance, safety, capacity, environmental impact and proactive liability allocation in case of an accident.

KEYWORDS

Engine-Off Taxiing, Human-Machine-Interaction, Multi-Agent System, Human Performance, Safety, liability

1. INTRODUCTION

Aircraft jet engines are made for flying, not taxiing. Using main engines for ground operations is inefficient and taxiing phase can represent from 10 to 30% of flight time in Europe [6]. Regarding fuel consumption, Stettler et al. estimated that taxiing to burn 36% of the fuel on a standard Landing and Take Off cycle [21]. They also estimated that the taxi phase accounts for 12% of NO_x, 89% of CO and 91% of HC emissions.

Several alternatives are being developed to reduce fuel consumption and noxious emissions during ground operations [15]. They can be grouped in two categories: autonomous techniques in which the aircraft uses its own equipment such as electric engines in the rear or landing gear; and non-autonomous technique in which external equipment is used such as specifically designed tugs coupled to the aircraft and controlled by the pilot. While each of these solutions can help saving fuel, they all have advantages and drawbacks. Autonomous electric taxiing aircraft have lower dynamic performances (speed and acceleration), non-autonomous solutions add new vehicles to be managed on the taxiways (empty tugs). However, all these techniques share the need for engines warmup and start management for departing aircraft. For this reason, Single Engine Taxiing (SET) is used mainly for taxi-in of arriving aircraft and almost never for departures [10].

In this paper, we present our work during the SESAR AEON project to explore a new concept of operation and dedicated supporting tools for enabling the introduction of engine-off taxiing techniques. More specifically, we worked in close collaboration with multiple stakeholders from two major airports in Europe, Paris CDG (LFPG, France) and Amsterdam Schiphol (EHAM, Netherlands), including ATC officers, pilots, airlines, airport management, and ground handlers to explore and refine our concept and associated tools. We iteratively designed and assessed interconnected solutions to enable an optimized allocation of a fleet of tugs to aircraft, centralized routing providing speed profiles to avoid conflicts, dedicated HMI for Air Traffic Controllers as well as a new role, the Tug Fleet Manager. We describe the main aspects of our concept of operation and the overall architecture of the solution before presenting each component in more details. We then describe the experimental platform we created to perform real-time evaluations of our prototypes on 12x30 minutes long exercises simulating a normal day of traffic at Paris-CDG airport. We conclude with a discussion on how this concept could impact on several key performance indicators (KPI), such as human performance, safety, capacity, environmental impact and proactive liability allocation in case of an accident, and how it could be integrated with existing tools used to manage airport operations such as the Airport Collaborative Decision Making (A-CDM) tool.

2. RELATED WORK

Introducing engine-off taxiing techniques might have a strong impact on the airport capacity and the work of airports' operators due to specific path planning activities and tugs supervision [2].

Electric taxiing and airport ground operations have been modelled extensively in the past years using operations research methods. Prior work modelled the use of a fleet of towing vehicles for parts of the taxiing phases including the optimal allocation of vehicles to aircraft [2, 20], battery charging of vehicles [12], or the sizing of the fleet [11]. Most work focus on fleet management at a strategic level but dedicated optimization models for the management of a fleet of electric towing vehicles are not available for the tactical phase when disruptions impact the usage of the towing vehicles for arrival/departure flights.

Several path algorithms have been introduced over the years using multi-agent systems (MAS)[60]. The success of these algorithms is highly dependent on the environment and constraints that are imposed [7]. Centralized global optimization methods suffer from scalability and computational complexity issues, as the state space and time grow exponentially with the increase of the number of aircraft [19, 23]. Multi Agent Path Finding (MAPF) and Multi Agent Path Planning (MAPP) [9, 13, 16] is a class of decentralized, multiagent planning and scheduling techniques that can address this issue as they scale polynomially and allow for high flexibility and robustness of plans that can be generated and modified in real time. Such techniques would also allow for more efficient, multiagent, anticipatory identification and resolution of conflicts in polynomial time. Effective conflict identification and resolution mechanisms are essential for safety and allow for efficient and smooth traffic flow with the minimum number of stops. Considering a control of the speed profiles of aircraft also enable to eliminate stops and reduce fuel consumption [1].

To support Air Traffic Controllers (ATCOs), Advanced-Surface Management Ground Control Systems (A-SMGCS) routing service must provide path planning decision support [14]. Prior work investigated interaction to help ATCOs validating recommended routes or editing them [5] but did not considered having a variety of taxiing techniques with different speeds capabilities. Using speed profiles have been investigated specific displays to guide pilots following speed targets [4]. To build an effective distributed system, both human and automated agents such as path planning algorithms will require various inputs to operate and dedicated mechanisms to share their solutions or alternatives to other agents. The Human-Automation Teaming [3] will require providing dedicated Situation Awareness [8, 18] elements that are required by each stakeholder, including algorithms, to operate efficiently.

Our goal is to build upon research operations, multi-agent path planning and Human-Automation teaming work to explore a new concept of operation with adequate supporting tools enabling the use of engine off navigation techniques on ground.

3. AEON REQUIREMENTS, SOLUTIONS AND HYPOTHESES

We started by conducting several workshops and interviews with professional stakeholders to better understand the current contexts, the challenges and to identify needs to inform our concept of operation. Based on the results, we elicited requirements covering three aspects of the ground operations, airport management; air traffic control and piloting as detailed in Table 1.

Table 1: Elicited requirements from field work

Ground operation aspects	Requirements
Airport management and ground handling	<ul style="list-style-type: none"> • Defining and sharing the taxiing technique choices for all scheduled aircraft • Supporting the allocation of the tugs to aircrafts and their reallocation
Air Traffic Control	<ul style="list-style-type: none"> • Enhancing situation awareness of the taxiing technique for each aircraft. • Supporting routing decision with conflict free routes
Piloting	<ul style="list-style-type: none"> • Providing speed profiles to avoid stops during taxiing phases • Providing remaining taxi time to anticipate engines start-up

3.1 Overview of the solutions

The AEON concept of operations introduces solutions for using green taxiing techniques at strategic and tactical levels. The overall framework of our solution is presented in Figure 1.

In the strategic phase, *i.e.*, up to 1 hour before the flight is scheduled, we integrate with the airport-collaborative decision making (A-CDM) platform to support discussion and negotiation of the desired taxi technique for the aircraft between the stakeholders. This choice will have an impact on the taxi speed and hence on the flight’s in-block or off-block time. In addition, it also has an impact on the organization of ground handling activities (the tugs, marshallers... need to be available). Given these choices and tug availability, a first set of support algorithm computes an initial tug allocation plan.

In the tactical phase, *i.e.*, during the operations, we introduce a multiagent system suggesting optimal routes for tugs and aircraft. The multi agent system uses flight plan and surveillance data to compute routes and speed profiles to avoid conflicts as well as stop and go at intersections. The path and speed information can be distributed to pilots and tug drivers via the Electronic Flight Bag. We also designed a radar image providing additional situation awareness elements to the ATCOs about the taxiing techniques and supporting the interaction with the optimal route suggestion algorithm. Finally, we designed a moving map for tug drivers and pilots to use the path and speed information.

The AEON concept also introduces a new role at the airport, the tug fleet manager (TFM), which is envisioned to be responsible for operating and maintaining the tugs. Throughout the day, the TFM ensures the best availability of the vehicle fleet by assigning tugs to arriving/departing aircraft, by monitoring their status (the state-of-charge of the battery, the availability of the tug to perform a towing task) and by handling operational delays of arriving/departing aircraft. The TFM will oversee the towing vehicles being on time to pick-up arriving/departing aircraft and tow these aircraft to the gates/runways. The TFM is also expected to assign towing vehicles to the specific aircraft. These assignments are supported by the dedicated algorithms for allocating vehicles to aircraft and for identifying efficient routes to follow. Once a towing mission is assigned, it becomes the joint responsibility of the TFM and ATCO to reach the aircraft to be towed on time for smooth operations.

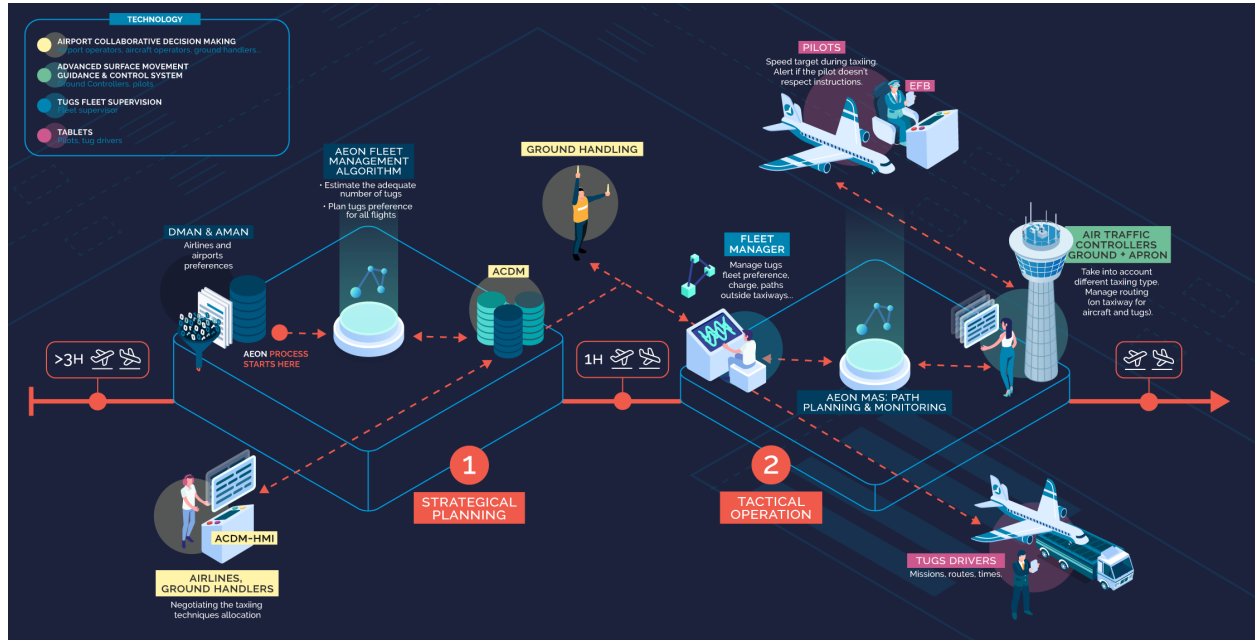


Figure 1: AEON concept image highlighting the actors, technologies, and operational phases taken into account.

3.2 Hypotheses

Concerning the non-autonomous taxiing technique, it has been considered that the tugs would only move on the taxiways network, even when not towing any aircraft. The use of service roads would have been too complex since they are also used by a wide variety of other vehicles and the route planning would have impeded. In addition, the aircraft loading and unloading processes were only possible at dedicated areas, namely the deicing pads that are close to the runway entry and exit (respectively for departure and arrival aircraft). Finally, no assumptions were made concerning the economic model for the non-autonomous taxiing technique (whether the service would be provided by the airport, the ground handler, or the airline). Actually, this choice has no impact on the operations that are proposed and evaluated in AEON project.

In the setup put in place for the concept validation, the ground ATCO and TFM were in separated rooms (tower and apron ATCOs were simulated). Both had a radar image view of the airport and the TFM had a dedicated HMI for tugs allocations. The ATCO could talk to the aircraft' pilots directly over radio on a given frequency and the TFM talked to tug drivers only on another frequency. Finally, 3 people acted as pseudo pilots and tug drivers, responding to ATCO and TFM requests and manipulating the simulation engine accordingly.

4. INTER-OPERATING SUPPORTING TOOLS

In this section we describe the tools that were developed during the project that include an allocation tool for optimizing the fleet of vehicles operations, a multi-agent path planning tools providing conflict free routes and speed targets for aircrafts, and interfaces and interactions for ground controllers and the tug fleet manager to carry out their tasks with the support of the algorithms.

4.1. Allocation of tugs to aircrafts

During the strategic planning phase, the AEON fleet management algorithm helps estimate the adequate number of tugs to operate a given airport in a given period, considering its specific traffic. Taking into account the arrival and departure sequences, plus the operational constraints of the tugs fleet, the AEON fleet management algorithm sizes the fleet of tugs needed and at the tactical level can reallocate the fleet depending on operational events.

Algorithm inputs

The tug scheduling algorithm uses three inputs:

- The airport road networks, including their types and the time it takes to traverse the airport using the different networks.
- The flight schedule during a day of operation to estimate the drop-off time and corresponding energy based on a single-agent version of the path planning algorithm detailed in Section 4.2.
- A list of tugs present at the airport that has to start and end their day of operations at the depot and with a full battery. Charging the battery can be done at a station for a minimum time of $t_c^{min} = 1$ hour.

Allocation algorithm

From those input parameters, the tug fleet management algorithm creates a tug schedule. This schedule contains: which aircraft are to be towed, which tug 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. We first compute an initial schedule and later use a rolling horizon approach to adapt the tugs schedule to events throughout the day.

The algorithm is run for each weight class of the aircraft (medium/heavy/ultra-heavy). 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. 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 from van der Klauw et al. [22].

Rolling horizon approach for unplanned events

To cope with a number of events that may occur such as flight delays, tug breakdowns, or changes to the schedule because of manual preferences by the tug fleet manager. A rolling horizon approach is used to adapt the schedule. When an event occurs, the input information is updated and we reuse the allocation algorithm to re-optimize the tug schedule for the remainder of the day.

In the case that the TFM assigns a flight to a specific tug, this is considered as a fixed point in the day for this tug and the algorithm ensures that this flight is always in the tug schedule. In case a flight is manually unassigned from a tug, it is always left out of the set A_s for this tug. Figure 2 illustrates an initial schedule and an example of the rolling horizon approach. A fleet of five tugs for aircraft class medium tows flights from 6 AM to 6 AM (the next day). At 2 PM, tug 5 breaks down, and the schedule is re-optimized for the remaining tugs. At 4 PM tug 5 is repaired and enters service again, and serves the remainder of the day.

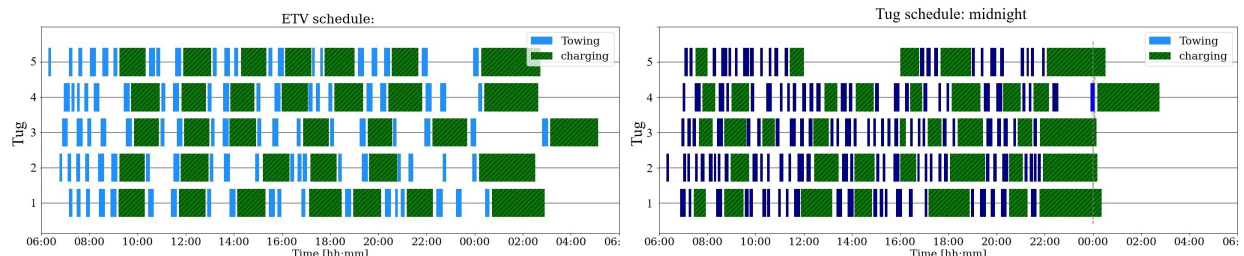


Figure 2: Right: Tug schedule at the start of the day of operations. Left: Tug schedule after 4 PM, tug 5 has been repaired and remains in service.

4.2. Path Planning

The hybrid multi-agent system (MAS) computes conflict-free paths and monitors the subsequent plan execution of all aircraft and tugs moving over the airport surface concurrently. It comprises a distributed-hierarchical structure of both centralized and distributed agents as illustrated in Figure 3.

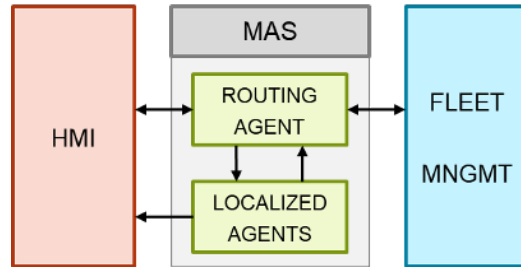


Figure 3: Multi-agent system and interaction with HMI and fleet management algorithm.

The centralized Routing Agent computes conflict-free routes for all vehicles that are scheduled to be taxiing within a predefined planning window and is repeated at least once per replanning period. To compute paths, the airport layout is represented as graph $G = (V, E)$ with nodes V as junction points or end points such as gates, and edges E as center lines of taxiways and service roads. We use motion planning to account for vehicle kinematics in planning since heavy vehicles such as aircraft entail finite acceleration and deceleration. To ensure conflict-free paths, we deploy a two-level search based on Priority-Based Search (PBS) [16] with an augmented version of the Safe Interval Path Planning (SIPP) algorithm [17], which will be outlined in the next sections. Once a route is cleared by ATC, the Localized Agents, in their current form conceptualized to be positioned at every junction, monitor the execution of the cleared route, and trigger central replanning if the deviation exceeds time thresholds.

The MAS can be utilized by the fleet allocation algorithm (4.1) to obtain estimates for time and distance of paths. Furthermore, the MAS interacts with the human-machine interface to facilitate co-design of the vehicle routes. For that, the Routing Agent takes constraints of the ATCOs into account during path planning and poses route suggestions to them. Additionally, the vehicle-specific objective functions can be adjusted to influence the path planning. These are currently based on a linear combination of taxi time and distance but may later be extended with other cost-parts. Besides that, the estimated arrival time and remaining distance per vehicle as well as the deviations during plan execution computed by the Localized Agents can be visualized in the HMI to keep stakeholders up to date.

Single Agent Motion Planning based on SIPP

In the low-level search, we plan separately for each vehicle using SIPP. In contrast to classical path finding algorithms such as Dijkstra or A^* , SIPP uses time intervals to specify the time dimension in its state definition. This reduces the number of possible states and makes SIPP efficient to use for motion planning with vehicle kinematics. We adapted the successor-generation of SIPP to account for constraints, vehicle-specific kinematics, and an activity sequence. The latter is used to include the various possible taxiing phases in the same planning, modelled as one of three activities: go-to activities such as regular taxiing have both a path and speed degree of freedom. Follow activities such as pushback operations have a predefined path associated to it, so that speed is the only remaining degree of freedom for these route segments. Wait activities such as coupling to or decoupling from a tug are fixed time periods at a set of given locations (nodes) that have to be accounted for in planning. During the search, constraints and ATCO preferences for taxiway-directionality are taken into account. While constraints limit the possible set of edges and are used to represent blocked taxiway-segments such as a crossing of an active runway, ATCO preferences influence the chosen path by assigning weights to the cost of traversing an edge. The possible motions along an edge are bound by the type-specific vehicle kinematic values for maximal speed, speed limit in turns, and fixed acceleration/deceleration rates.

Multi-Agent coordination using PBS

To compute collision-free paths for all vehicles, we utilize the Priority-Based Search algorithm. Using a depth-first search, PBS creates a binary search tree that establishes a priority order between conflicting vehicles. The vehicle dimensions are converted into circular shapes and used to compute unsafe time intervals of the vehicle motion over each edge. This set of edges includes their path as well as the swiped adjacent edges. Two vehicles are in conflict if their unsafe intervals on any edge overlap. PBS then creates two child nodes, giving priority to one of the two conflicting vehicles in each. SIPP is called again to account for the newly set unsafe intervals of the prioritized vehicle while determining a new path for the deprioritized one. PBS continues the conflict detection and resolution with the child node that has the lowest overall sum-of-cost of all paths. The path planning terminates once all conflicts have been detected and resolved successfully.

Path co-design, clearing and replanning

ATCOs can co-design the routes by specifying certain locations that must be passed. These are added as via-nodes to the activity sequence of a vehicle. Once satisfied with the computed path, ATCOs can clear the vehicle route in the HMI. During replanning, only the speed profile over a cleared path will be adapted to resolve a conflict between two vehicles. The updated speed profiles are reported back to the HMI for further use as outlined in the next section.

4.3. User Interfaces and Interaction

We designed interfaces and interaction to support three types of users with their tasks: the new role of TFM that must supervise the tug fleet allocation plan and update it according to operational events; the ground ATCOs that must control aircraft with various taxiing techniques and additional towing vehicles that will have to attach and detach from aircraft; and the pilots that will have to follow speed targets and to turn on their engines at the most appropriate time. The envisioned position of the TFM is composed of a supervision HMI to monitor on the tugs' status and their allocation as well as a radar image which allows the spatial monitoring of all the vehicles on the apron and the taxiways, similarly to the tool used by ground ATCOs.

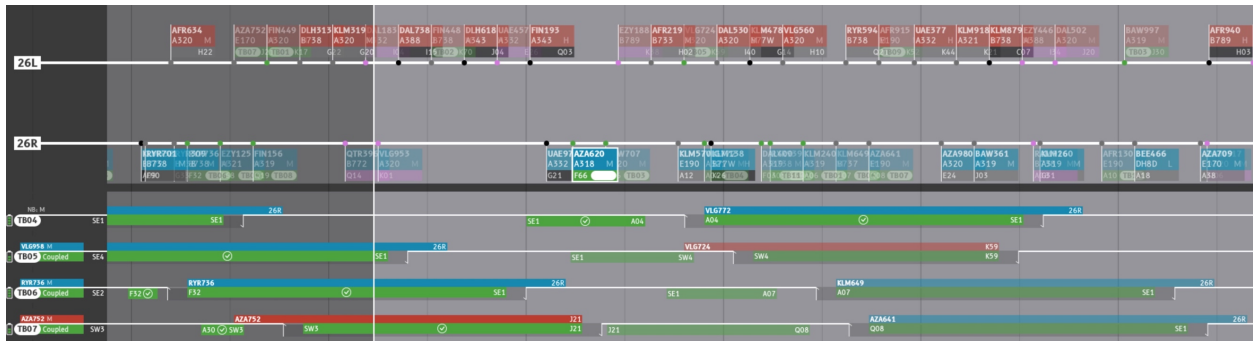


Figure 4: Supervision HMI with arriving and departing aircraft on the top and the tugs underneath with allocations.

Tug Fleet Management HMI

The supervision HMI present a synoptic view of the status of fleet of tugs and their planned allocation to departing and arriving aircraft as presented in Figure 4. The HMI presents the data through a horizontal timeline with two main panels. The top panel provides inbound and outbound flights schedule information and their expected TMO for each runway. The top area uses horizontal ribbons to present the planned departures and arrivals for each runway. All the departures and arrival items also display the taxi mode of the aircraft and in particular any tug request. The bottom panel displays allocations for each tug available to the operator. For each tug, the callsign and the battery status are displayed. Each tug is associated to a line which represents it schedule throughout the day. On each line, aircraft and tugs allocations, expected journeys and tug unavailability duration are shown. Although most of the allocations are computed and set by AEON algorithms using data from the A-CDM, the operator can made change via the interface to amend or cancel allocations.

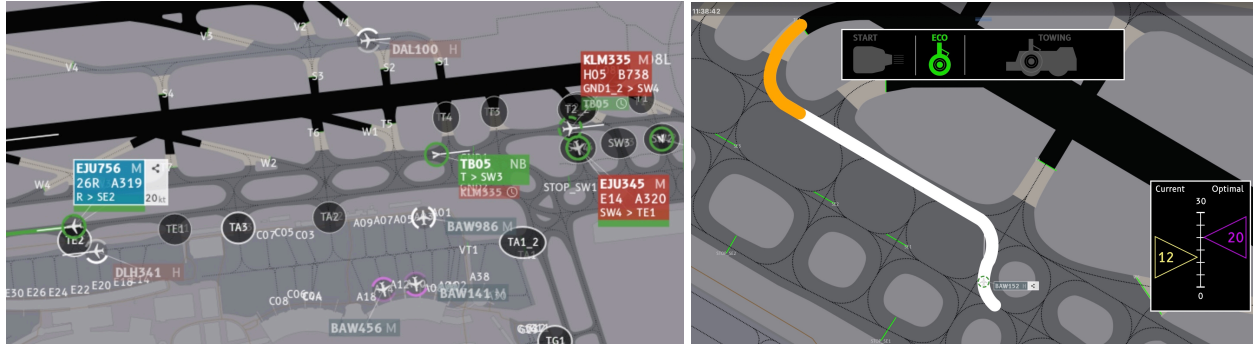


Figure 5: Left: Portion of the radar image representing aircraft, their taxiing techniques and the towing vehicles. Right: Moving map representing the route, a speed indicator and indications for engine start-up. engines

Radar image

We designed a radar image presented in Figure 5 right for both ATCOs and TFM. It provides situation awareness on aircraft's status, trajectory, and traffic on the airport taxiways. It also provides several vehicles' characteristics and status information that are either textual or iconographic, and suggests paths which are computed depending on the taxi technology used by each aircraft. The flights are represented by an aircraft icon and tugs are depicted with a triangle shape surrounded by a green circle. To facilitate the identification of each tug and aircraft on the airport taxiways, information such as callsign, aircraft type, bound type, origin, and destination locations are provided on each vehicle tag. While inbound flights' tag is colored in blue, outbound flights' is colored in red and tugs' tag is colored in green. These colors were inspired by the current radar color coding used at Paris-CDG airport. For each aircraft, the Taxi Mode of Operation (TMO) is presented as follows:

- Aircraft using all their engines are represented by 2 white semi-circles on both sides of the aircraft icon. For single SET, only a single semi-circle is visible indicating that half of the engines are off.
- Autonomous taxiing with electric engine is represented by highlighting in purple one of the 2 semi-circles at the front and rear of the aircraft icon. When the aircraft uses the eTaxi or Wheeltug technologies, the semi-circle at the front or the back is highlighted, respectively;
- Non autonomous taxiing, which necessitates aircraft to be tugged, is represented by a green dashed circle around the aircraft icon.

To help the ATCO to visualize the optimized routes computed by algorithms, we display the corresponding route when a flight or a tug is selected. This is meant to help ATCOs identifying possible conflicts with the vehicles on other tracks. The route suggestions use the same colors than for TMO: white for classic and SET, purple for electric and green for towing. In addition, information such as suggested coupling positions for an inbound flights or decoupling position for outbound flights are displayed. These suggestions are computed by the path planning algorithm and can be refined by the TFM. The final decision remains to the ATCO who can change a suggested route if needed before validation and clearance.

Moving map

The moving map tool, illustrated in Figure 5 left, displays information on routes, speeds and traffic awareness. It can be used inside the cockpit. The map centered on the aircraft helps pilots following the ATCO's cleared taxi route and the target taxiing speed as well as monitoring their TMO or other aircraft on the taxiways. The speed monitor instrument was designed according to Bernatzky et al. [4] recommendations on speed guidance interface for trajectory based-dispatch towing. It allows pilot to optimize their speed according to the optimal traffic configuration computed in real time by the planning algorithms, to mitigate untimely stops, gas emission and delays and to fluidify the entire airport traffic. The moving map also provides the coupling and decoupling locations and assists pilots with the engines' warmup procedure. On the cleared route, an orange segment informs the pilot where (and when) the engine should be started. This is supplemented with a starting timer which is displayed on the moving map dashboard at the relevant time. The length of the segment, and therefore the duration, is computed according to the waiting time for the runway access.

5. VALIDATION METHODOLOGY

The AEON solution was validated using an iterative, participative, and multi-layered assessment approach that involved the Consortium and its stakeholders since the earliest phases of the project.

A three-step iterative process was adopted, which included three validation sessions: the initial validation session carried out with selected aviation stakeholders, the intermediate validation session in which the concept was discussed with personnel from Schiphol Amsterdam Airport and Paris Charles De Gaulle Airport, and the final validation session in which the AEON concept and tools were tested in real-time simulation (RTS) by 6 pairs of ATCOs as visible in Figure 6. During this overall process, the project explored the impact of the proposed solution on several interconnected Key Performance Areas (KPA), namely: 1) Human Performance, 2) Liability, 3) Safety, 4) Cost-Benefit, 5) Capacity, 6) Efficiency, and 6) Environment. Each KPA was then further detailed in specific objectives and criteria.



Figure 6: Experimental setup of the final assessment. Left: ATCO with the radar HMI and a realistic Paris-CDG tower simulation. Center: TFM with the supervision HMI and the radar HMI. Right: Pseudo pilots positions.

6. VALIDATION RESULTS

The several validation activities allowed us to improve the concept of operation and the supporting tools. In the final validation, we were able to evaluate most of the tools altogether in a realistic scenario except the algorithms that were not integrated in the platform used for the real time simulation, although their logic were evaluated during debriefings with the involved ATCOs. We detail and discuss the results according to some of the KPI of the project.

Safety

One of the important identified safety issues was that pilots, air traffic controllers or other actors involved in ground operations may consider a taxiing aircraft-tug combination to be a lower priority towed aircraft. This would lead to false expectations about the behavior of this actor, which could result into reduced safety margins. One more important safety hazard stems from the fact that a tug connected in front of an aircraft is not visible from the aircraft's cockpit. This lack of visibility could result in unintended runway incursion, when the aircraft would stop too late at the runway holding point and the tug would appear at the protected area of the runway. Furthermore, it was evident from the preliminary safety analysis that operations at tug coupling/de-coupling locations needs to be studied in more detail, as they could present risks to both people (tug drivers) and equipment. These risks need to be quantified in a follow-up study. Also the location of such points on the airport surface should be considered from the safety point of view.

Human Performance

Several considerations arose from the results produced in the final evaluation. Although all the roles implied with taxiing operations appeared to be considered, the description of the tug fleet manager (TFM) need to be further detailed and improved to ensure the support of Ground ATCOs. Ground ATCO's performance appeared to benefit from situation awareness concerning the TFM activity and familiarity with the designed operations. The exchange of communication between these two roles was not adequate and caused ATCOs to manage the tug vehicles even though it was not her/his responsibility. In this light, the TFM and Ground ATCO shall be considered as a team. Two additional roles concerned by the AEON operational

concept are the pilot and ground handling (GH) companies, since the e-taxi and tug vehicles usage will modify pushback and taxiing operations. Pilots will require new skills to take-over tug drivers when driving e-taxi-equipped aircraft. Similarly, tug drivers will need new competencies to operate the tug vehicles and manage the coupling and uncoupling of the aircraft. Staffing levels for Ground ATCOs will increase to accommodate the higher demand for TFM. The same will happen for GH companies which will need to increase their staffing levels to provide more tug drivers, but on the other hand, will see a decrease in demand for towing vehicle drivers.

Cost-Benefits

The cost benefits analysis shows that for 13 larger European airports there is a reasonable business case to implement towing, assuming each towing vehicle needs to offset an average of 1000 kg of fuel on a peak day. Further analysis for Amsterdam Airport Schiphol (AMS) and Paris CDG shows that towing all heavy and medium sized aircraft vehicles would most probably make sense on a 2018 year basis. For smaller, regional aircraft, utilization would be relatively low, limiting the business case if all aircraft were towed. It would make sense to only operate a few of these sized vehicles. For eTaxi without any engines on, the business model shows net savings if installed on all aircraft. If we would need at least 1000kg of fuel saved per day to offset the installations costs, only around 10% of the fleet would be equipped. Sensitivity analysis shows that the weight added must also be very limited, which could be a challenge. The business model thus seems a lot more limited than that for towing, especially as towing aircraft equipped with eTaxi would completely negate the benefit of the eTaxi system, as the main benefits in terms of on ground fuel consumption is largely at the same large airports as towing would be deployed. For towing the most important unknown is the operating cost of a towing vehicle, which can only be quantified by the manufacturer and the operator. To limit the operational costs, it would be beneficial to make the towing vehicles autonomous and not require a driver on board.

Liability

The liability assessment shows how developing and deploying new technological solutions within well-consolidated procedures may have a relevant impact on the responsibility regimes of the operators involved. The analysis of the AEON solution reveals how the TFM, as a connection between strategic and tactical operations, needs to have an adequate understanding of the work of ATCOs, despite playing different roles. Otherwise, the liability risk exposure of ANSPs and their operators would increase until becoming unbearable. The linear design of the communication flow and the consistent deployment of the related means represent an essential precondition for minimizing risks related to carelessness due to poor situational awareness. Eventually, innovation of roles and procedures should be coupled with a dedicated review of internal policies, rescoping general and specific licenses according to the new skills required.

7. CONCLUSION AND DISCUSSION

We described the work carried on during the SESAR AEON project to explore a new concept of operation and dedicated supporting tools for enabling the introduction of engine-off taxiing techniques. We described the initially envisioned concept of operation and the set of supporting tools enabling it. These tools include an optimized allocation of a fleet of tugs to aircraft, centralized routing providing speed profiles to avoid conflicts and dedicated HMI for Air Traffic Controllers as well as a new role, the Tug Fleet Manager. We described the main aspects of our concept of operation and the overall architecture of the solution before presenting each component in more details. We described our validation activities and detailed the main results regarding safety, human performance, liability and cost benefit KPI.

The introduction of the TFM role posed specific challenges regarding the collaboration with the ground ATCOs and the liability aspects. Further research is required to offer adequate tools and define precisely the responsibilities and training of the TFM. Regarding the allocation algorithm, we were not able to integrate it in the validation platform and assess the quality of the allocation for realistic operations. However, based on the feedback from airport managers, we will explore its use as a decision support tool to identify best charging location or runs simulations on coming days to find the best day for planning maintenance on tugs. Regarding the path planning algorithms, we use a simpler version on our simulation

because the computing time were too high to make it usable by ATCOs. We are currently improving the performances to be able to integrate it. The path planning tool currently respects the routing used by air traffic controllers. This make the results in line with ATCOs' current expectations but possibly less optimal. We are interested in running several simulation with different level of constraints and its impact on performances.

We are currently pursuing the analysis of the results from our validation activities to investigate the impact on capacity and environmental impact of our solution. Based on these additional results, we will articulate an updated version of the concept of operation. Future efforts will consider the use of autonomous vehicles for towing aircraft and improvements on the allocation, planning and HMI tools based on our validation results.

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