# D1.3 State of the art

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## Copyright Statement

# AEON

ADVANCED ENGINE OFF NAVIGATION

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## Abstract

This deliverable discusses the state-of-the-art methodologies for collaborative Human-machine interactions, multi-agent systems and operational research for the management of a fleet of electric towing vehicles. This comprehensive overview serves as a starting point for the activities of WP2 (support algorithms for autonomous and non-autonomous taxiing operations) and WP3 (design and develop a demonstrative supervision interface that actively supports the new taxiing supervision role and the collaboration with current controllers). The suitability of these methodologies for the AEON solution is discussed. Also, research gaps and methodological needs for innovation are also discussed. Last, but not least, a detailed overview of projects that are relevant for AEON is provided. The analysis includes projects funded by the SESAR Programme but it is not limited to them.

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# Executive Summary

AEON project deals with the facilitation of green taxiing techniques operations and proposes a set of dedicated solutions to contribute to reduced fuel consumption and emissions, and increased safety. Such solutions are seen as part of an airport collaborative decision-making tool, with the aim to fluidify the taxiing operations by taking into account the characteristics of each vehicle, and to efficiently manage fleets of tugs and non-autonomous aircraft.

One aspect of this facilitation is to provide the different ground operations actors (ground handlers, airport manager, ATC, airlines operations) with a collaborative tool to share their needs and constraints, propose a solution and eventually implement it. In order to do that, AEON would provide one or several HMIs for collaborative work and supported by two kinds of algorithms:

- Multi-agent path planning to suggest the best routing options for each vehicle, including towing vehicle detachment locations and speed constraints to smooth taxiing operations.
- Operations research for best taxiing technique allocation, and real time re-allocation, based on the daily flights list and available equipment and for towing vehicles fleet management.

As a first step towards developing the AEON solutions, this report identifies the **state-of-the-art methodologies for collaborative human-machine interactions**, multi-agent systems and the management of a fleet of electric towing vehicles. It also includes a review of the current state-of-the-art in the research area of airport ground operations.

Related work focusing on collaborative Human-Machine interactions has been surveyed. The field of **Computer Supported Collaborative Work** is first described and its main dimensions are presented which will be used to analyse existing technologies and approaches relevant for the AEON project. Then existing work on the Situation Awareness (SA) of all stakeholders is introduced so that an appropriate mental image of the situation and cooperate is able to be maintained and the best possible results can be achieved. Also, aspects related to **Distributed Situation Awareness** (DSA) are covered that could be relevant for AEON. Finally, the work focused on **Human-Automation Teaming** (HAT)is introduced and relevant work related to Human and Automation Collaboration is identified.

An important component of any novel concept of airport surface movement operations is path planning of aircraft and other vehicles, taking into account diverse kinematic constraints and interdependencies between moving actors. To this end, **multi-agent path planning techniques** will be used in AEON. Such techniques allow detailed modelling of the environment and different operational components (such as aircraft and towing vehicles) with their variety of structural and behavioural properties, and to perform computationally efficient simulation and optimisation of conflict-free taxiing paths for all the involved actors. In this document, the most prominent state-of-the-art methods and approaches for multi-agent path planning are reviewed, and a set of the most promising from them is identified to be further implemented in the AEON's concept of operation.

Studies on the **assignment of towing vehicles to aircraft**, as well as the availability of these towing vehicles in connection to their need to charge their batteries, are also reviewed. Most papers propose a mixed-integer linear problem for the assignment of towing vehicles to aircraft. This document discusses the objective functions considered, as well as the computational performance of the models. The studies reviewed show that the focus lies on the analysis of the operations are the strategic planning level, while the analysis of the tactical level is identified as a research gap.

A number of projects have already addressed the research area of airport ground operations and provided solutions to contribute to reduced fuel consumption and emissions. In this document we present and discuss a **review of the work carried out in 45 research projects**, both concluded and ongoing, with the purpose of identifying solutions and topics relevant to AEON, to be potentially taken into account while designing the concept of operations and in later stages of the project in general.

These reports conclude with research directions that will be studied during the AEON project such as the clear definition of situation awareness elements, meaningful performance indicators, interaction and path planning challenges that will need to be explored to achieve strong and reliable collaboration required by human and automated agents. Note that some of these directions might lead to unsuccessful results but will still be considered and documented during the project.

# 1 Introduction

## 1.1 Purpose of this document

This report identifies the state-of-the-art methodologies for collaborative Human-machine interactions, multi-agent path finding systems and management of a fleet of electric towing vehicles as well as the state-of-the-art in the research area of airport ground operations.

This is a comprehensive state-of-the-art, which has the purpose of setting the scene of the research activity to be performed in the AEON Project. In particular it is intended to directly feed:

- the definition of the concept of operations carried out in WP1.3
- the development of models and algorithms for the computational support and implementation of the proposed operational concepts for autonomous and non-autonomous taxiing operations, carried out in WP2
- the design and development of a demonstrative supervision interface to support the implementation of roles and working methods envisaged in the concept of operations, carried out in WP3
- the identification of ongoing related projects to be considered while planning communication, dissemination and exploitation activities, as well as collaboration with Advisory Board and related projects, in the framework of WP7.

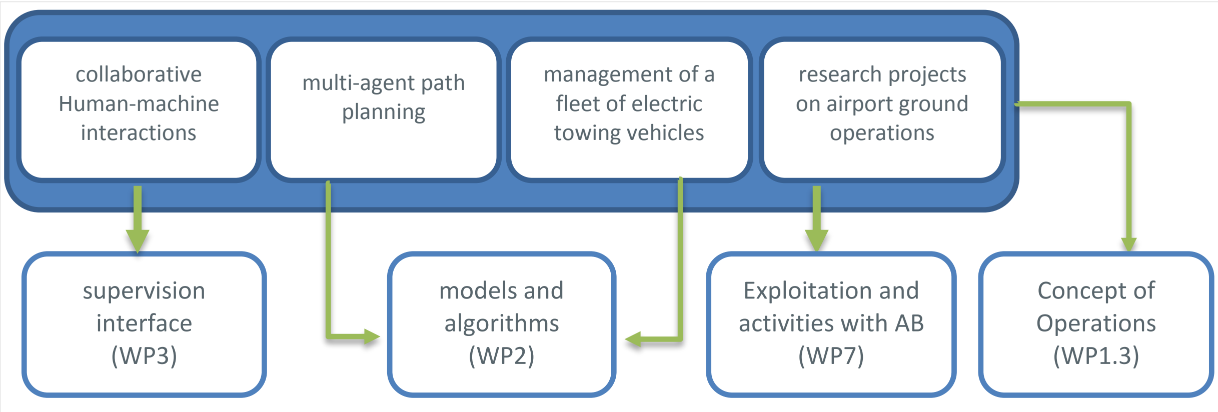


**Figure 1: How the state-of-the-art feeds other project activities**

## 1.2 Scope

The following diagram shows the connections among the 4 state-of-the-art reported in this document and how they are expected to contribute to the definition of the AEON concept of operations and tools being developed and tested during the project. In particular it shows how collaborative HMI, path planning and fleet management constitute the pillars on which the AEON concept of operations and tools ground and how they are internally connected.

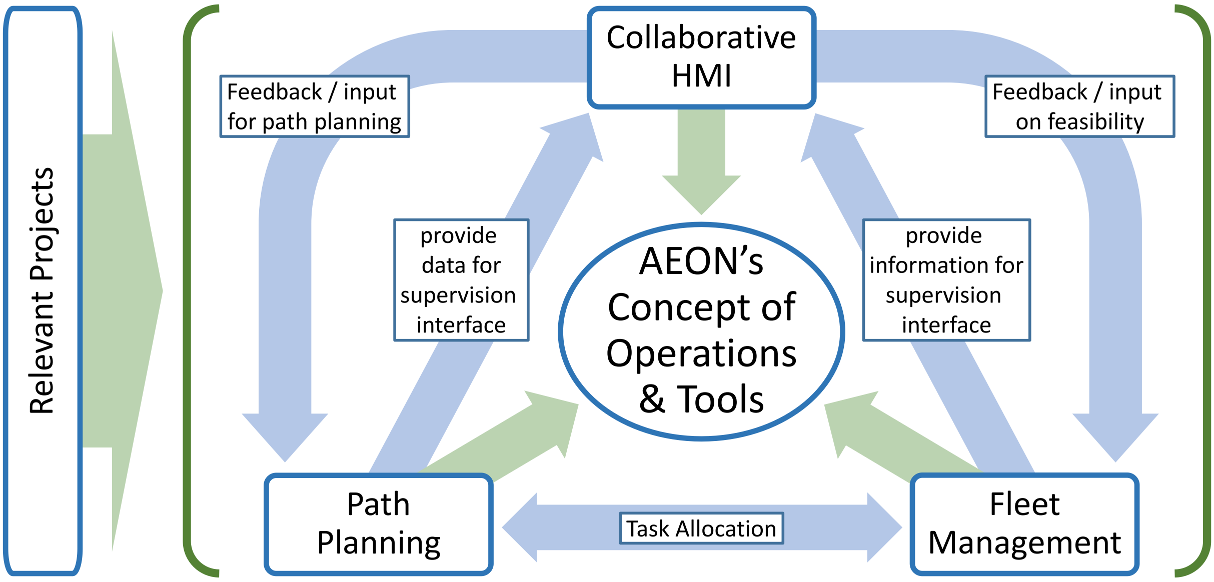


**Figure 2: Scope of AEON and envisioned distributed MAS architecture**

### Collaborative HMI

Airports Ground operations are collaborative distributed activities by nature. They involve several stakeholders (ATCOs, Pilots, Marshallers, Drivers, Airlines) with different roles and tasks. They need to communicate with specific signs or phraseology, be aware of the situation, solve problems and operate the aircrafts and tugs to achieve safe and efficient airports movements. Collaboration is also key to safety and efficiency. For example, ATCOs monitor each other's actions as well as the actions of other ground vehicles. When the controller has devised an incoming flight strategy, the controller needs to give clearances to the pilot at the appropriate moment. Hence, a part of the activity is devoted to remembering which actions to do at present, or in the near future. Furthermore, the resolution of problems depends on the actual execution of orders by pilots. Hence, controllers must monitor that pilots actually follow orders as given.

Introducing green-taxiing services will likely introduce changes for the involved persons with additional roles or tasks among the stakeholders. These new roles or tasks need to be seamlessly integrated in the current workflow to prevent adding workload for existing roles while offering strong environmental benefits. Even though AEON solution could be integrated as part of an airport operation centre, there would still be some actors remotely located, starting with ATCOs in the control tower.

This results in a need to study related work covering Computer Supported Collaborative Work (CSCW), Distributed Situation Awareness (DSA) and Human Automation Teaming (HAT) to cover topics related to the design and evaluation of interactive systems able to support collaborative activities. From this state of the art, methods are identified and design guidelines that should be applicable during the project, to understand users' needs, design new technologies and evaluate them.

In later stages of the project the work on collaborative HMI will constitute an important pillar of the AEON concept of operations and tools and serve as input to both path planning and fleet management.

**Path planning**

In their daily work, air traffic controllers need to plan ground trajectories for every taxiing aircraft and other vehicles, such as tugs. This needs to be done taking into account diverse interdependencies, as well as efficiency, safety, and environmental requirements and constraints. The multi-agent system modelling paradigm is well suited to formally represent, analyse and optimize complex, dynamic, interdependent, collaborative distributed systems with diverse actors. In this document, we review several classes of multi-agent path planning techniques that could be used for existing and novel airport surface movement concepts of operation.

In later stages of the project the work on path planning will constitute an important pillar of the AEON concept of operations and tools and serve as input to both collaborative HMI and fleet management.

**Fleet management**

Together with collaborative monitoring of the operations, and the path finding for taxiing, it is also of interest to investigate how to manage a fleet of electric towing vehicles. The decision to allocate a specific towing vehicle to an aircraft is performed collaboratively by the stakeholders. They based their decision according to the available fleet of towing vehicles and whether these vehicles can operate (have enough battery charge). The AEON solution provides an optimal sizing of the fleet of towing vehicles such that the taxiing operations can be performed efficiently and adapts the allocation of electric vehicles throughout the day of operations. These optimisation models provide feedback to the airport manager and fleet supervisor on the availability of the fleet of towing vehicles.

In later stages of the project the work on fleet management will constitute the third pillar of the AEON concept of operations and tools and serve as input to both collaborative HMI and path planning.

**Relevant projects**

Last but not least the diagram shows also a fourth component of the present state-of-the-art, which focuses on past and present research projects in the area of airport ground operations, whose concepts and solutions could be relevant to AEON to take into account while defining its concept of operations and tools. In particular this state-of-the-art includes a review of the research projects that have addressed the topic so far or are addressing it right now, with the twofold purpose of 1) identifying the solutions that can reveal most relevant to AEON to be taken into account during the definition of the concept of operations, and 1) establishing synergies and collaborations with ongoing initiatives.

Although that is not a pillar for the project as the previous ones, nevertheless it is important to take into account also these aspects as well in a comprehensive state-of-the-art and in the following design of concept of operations and tools. The research carried out in AEON aims in fact to be innovative, while at the same capitalizing on the experience gained in other related projects concerning the research area of sustainable and green airport ground operations.

## 1.3 Structure of the document

The remainder of this deliverable is organized as follows.

In **Section 2** related work focusing on collaborative human-machine interactions is described. Several research fields are presented as well as prior work to derive design guidelines and research directions to be used and investigated during the AEON project.

In **Section 3** several classes of techniques and methods for multi-agent path planning of aircraft and other ground vehicles are discussed. The strength and weaknesses of these techniques are reviewed, and the most promising alternatives to be used in the AEON project are identified.

In **Section 0** existing studies on the management of a fleet of electric towing vehicles are discussed. The main aspects considered in literature are the choice of the size of the fleet when considering acquisition costs, reduction of the emissions, on-time performance of the towed aircraft, as well as the assignment of towing vehicles to aircraft during operations. Relevant studies on the management of fleets of generic, commercial electric vehicles are also considered.

In **Section 6** elaborations are provided on a possible integration of path planning and operations research methods for fleet management to resolve path finding and task assignment at the same time.

In **Section 6** a review of research projects in the area of airport ground operations is presented that for different reasons are considered related to AEON. The review concerns projects funded in the SESAR framework (including SESAR1, SESAR WAVE 1 and SESAR WAVE 2) as well as other projects not belonging to SESAR. A three point scale (High – Medium – Low) is used to classify each of the projects according to their relevance to AEON.

Lastly, in **Section 7**, conclusions and research directions are provided.

## 1.4 Acronyms and terminology

The following table reports the acronyms used in this deliverable.

| Term | Definition |
|---|---|
| ACACIA | Advancing the Science for Aviation and Climate |
| A-CDM | Advanced Collaborative Decision Making |
| ADS-B | Automatic Dependent Surveillance – Broadcast |
| ADS-C | Automatic dependent surveillance - contract |
| ALNS | Adaptive Large Neighbourhood Search |
| AMAN | Arrival manager |
| ANSP | Air navigation service providers |

| | |
|---|---|
| AOP | Airport operation plan |
| APOC | Airport operation center |
| AROT | Arrival runway occupancy time |
| A-SMGCS | Advanced surface management guidance and control system |
| ATC | Air Traffic Control |
| ATCO | Air Traffic Controller |
| ATM | Air traffic management |
| BD/ML | Big data/Machine Learning |
| CATC | Conflicting ATC clearances |
| CBS | Conflict-based Search |
| CBS-TA | CBS with Task Assignment algorithm |
| ClimOp | Climate assessment of innovative mitigation strategies towards operational improvements in aviation |
| CMAC | Conformance monitoring alerts for controllers |
| CO-WHCA* | Conflict orientation WHCA* algorithm |
| CPDLC | Controller-Pilot Data Link Communications |
| CPDLC | Controller-pilot data link communication |
| CPF | Cooperative Path Finding |
| CSCW | Computer Supported Collaborative Work |
| CT | Constraint Tree |
| CTA | Control Area |
| DBL | Deep Blue |
| DLR | German Aerospace Center |
| DMAN | Departure manager |
| DMIT | De-icing management tool |
| DSA | Distributed Situation Awareness |
| D-Taxi | Datalink communication during the taxi phase |
| DYNCAT | Dynamic Configuration Adjustment in the TMA |
| EBS | Emergency Breathing systems |
| ECBS | Enhanced CBS: bounded suboptimal variant of CBS algorithm |
| ECBS-TA | suboptimal version of CBS-TA algorithm |
| ENAC | Ecole Nationale de l'Aviation Civile |
| EOBT | Estimated off block time |
| EVS | Enhanced vision systems |
| FC | Flight Crew |

| | |
|---|---|
| FLDT | Forecasted Landings times |
| FlyATM4Eu | Flying Air Traffic Management for the benefit of environment and climate |
| FTOT | Forecasted take off times |
| GCBS | Greedy-CBS algorithm |
| HASO | Human-Autonomy System Oversight |
| HAT | Human-Automation Teaming |
| HCI | Human Computer Interaction |
| HF | Human Factors |
| HMD | Helmet mounted display |
| HMI | Human Machine Interface |
| ICBS | Improved CBS: variant of (MA-)CBS algorithm |
| ICBS-H4 | variant of ICBS algorithm |
| ICTS | Increasing Cost Tree Search algorithm |
| ID | Independence Detection algorithm |
| iECBS | Improved ECBS algorithm: similar to ECBS with highways (ECBS-HWY) but has a different suboptimality factor |
| ILS | Instrument landing system |
| LCK | Lock Controller |
| LVC | Low visibility Conditions |
| MA-CBS | Meta-Agent CBS algorithm |
| MAMMI | Multi-Actors Man-Machine Interface |
| MAPF | Multi-agent Path Finding |
| MAPP | Multi-agent Path Planning |
| MAS | Multi-agent System |
| MDD | Multi-value Decision Diagram |
| MGS | Maximum Group Size algorithm |
| MILP | Mixed-Integer Linear Problem |
| Mote | Modern Taxiing |
| MRS | Minimum runway separation |
| NM | Network Manager |
| NOP | Network operation plan |
| OA | Optimal Anytime algorithm |
| OA-MSG | Optimal Anytime MSG algorithm |
| OD | Operator Decomposition: state space representation of CPF-problems optimized for A* |
| OD+ID | Independence Detection (ID) algorithm using OD |

| | |
|---|---|
| PBS | Priority-Based Search |
| PIPAA | Fuel Cells for Aerospace Applications |
| R/T | Radio telephony |
| RMAC | Runway monitoring and conflict alerting |
| RMAN | Runway manger |
| ROCAT | Local ROT characterization |
| ROT | Runway occupancy time |
| RWSL | Runway status lights |
| RWY | Runway |
| SA | Situation Awareness |
| SAGAT | Situation Awareness Global Assessment Technique |
| SART | Situation Awareness Rating Technique |
| SA-SWORD | Situation Awareness Subjective Workload Dominance |
| SAT | Situation Awareness-based Agent Transparency |
| SVS | Synthetic vision systems |
| TA | Task Assignment |
| TA+CBS | Algorithm that runs Task Assignment first, then CBS algorithm |
| TaCo | Tack Control |
| TLDTs | Target Landing times |
| TMA | Terminal maneuvering area |
| TOBT | Target off block time |
| TTOTs | Target take off time |
| TUD | Technical University of Delft |
| TWR | Control Tower |
| VSB | Virtual stop bars |
| WHCA* | Windowed Hierarchical Cooperative A* |
| WP | Work Package |
| WYSIWIS | What You See Is What I See |

**Table 1: List of acronyms used in this document.**

# 2 State-of-the-art on collaborative human-machine interactions

In this section, we describe the state-of-the-art regarding collaborative interactions between human operators and automated agents. We start by describing the field of **Computer-Supported Collaborative Work** (CSCW) and presenting its main dimensions that we will use to analyse existing technologies and approaches relevant for the AEON project. We then introduce and discuss the **Situation Awareness** (SA) of all stakeholders so that they can maintain an appropriate mental image of the situation and cooperate to achieve the best possible results. We cover aspects related to **Distributed Situation Awareness** (DSA) that seem particularly relevant given the AEON distributed context to inform our future designs. Finally, in addition to collaboration with humans, operators will rely on partly and fully automated agents such as autonomous tugs, to move aircrafts from parking slots to runways holding points or algorithms, to find optimal solutions. We thus present work focused on **Human-Automation Teaming** (HAT) to identify relevant work related to Human and Automation Collaboration.

## 2.1 CSCW and Groupware

Computer-Supported Collaborative Work (CSCW) is a subdomain of the science of Human-Computer Interaction (HCI) concerned with the support to all activities involving more than one person.

Collaboration is the umbrella word to describe all aspects related to group activities: communication, coordination, production, edition etc. CSCW is concerned with the technical aspects, but also the social aspects: studies and theories on users' practices and their relationships emerging from their use of CSCW technologies.

"Groupware" is a synonym to "CSCW systems". Groupware are "computer-based systems that support groups of people engaged in a common task (or goal) and that provide an interface to a shared environment" [1]. Groupware can involve software, hardware, services and group process support [2]. General groupware examples include e-mail, chat, audio-video conferencing, mailing lists, discussion groups, group agenda, workflow system, shared editors (including in web browsers), wiki website, argumentations tools, roomware, collaborative buildings, source code management or mediaspaces. In ATC, groupware examples include radio/frequency through which controllers and pilots exchange information, telephones, airport operations centre, radar images through which a pair of controllers, collocated or distant, collaborate, and strip boards where they still exist.

Like single-user tools, groupware should provide a high level of usability (efficiency, efficacy and satisfaction [3] for production. But groupware should also provide the users with interactions that make *collaboration* between users usable.

### 2.1.1 Group awareness

The main characteristic of CSCW systems is that they should make their users aware that they belong to a group [4]. This need for "group awareness" contrasts with other multi-users systems such as database management systems or distributed operating systems where the goals are rather to hide as much as possible that multiple users access the shared assets at the same time and ensure the integrity of the shared assets. Figure 3 includes categories of information that are important for group awareness, and questions that a user needs to answer when using a groupware. Group Awareness is to be differentiated from Situation Awareness: group awareness is the specific awareness of others' work through the Human-Machine Interface (HMI), while Situation Awareness is a broader concept that encompasses the whole activity.

| Category | Element | Specific questions |
|---|---|---|
| Who | Presence | Is anyone in the workspace? |
| | Identity | Who is participating? Who is that? |
| | Authorship | Who is doing that? |
| What | Action | What are they doing? |
| | Intention | What goal is that action part of? |
| | Artifact | What object are they working on? |
| Where | Location | Where are they working? |
| | Gaze | Where are they looking? |
| | View | Where can they see? |
| | Reach | Where can they reach? |

| Category | Element | Specific questions |
|---|---|---|
| How | Action history | How did that operation happen? |
| | Artifact history | How did this artifact come to be in this state? |
| When | Event history | When did that event happen? |
| Who (past) | Presence history | Who was here, and when? |
| Where (past) | Location history | Where has a person been? |
| What (past) | Action history | What has a person been doing? |

**Figure 3: Elements of workspace awareness relating to the present (left) and to the past (right) (from [4]).**

## 2.1.2 Interactive services and concepts for collaboration

The vocabulary used in CSCW systems reflect the shift of concerns compared to single-user systems: 'users' become 'participants', they enter and leave 'sessions' of collaboration instead of just using a tool, etc. The following is an ontology of CSCW important services and concepts, with examples in general applications and in ATC.

**Group window.** A group window in HMIs is a collection of windows whose instances appear on different display surface.

**Telepointer**. A telepointer is a cursor that appears on more than one display and that can be moved by different users [4], [5]. When it is moved on one display, it moves on all displays. Although seldomly used in ATC systems, presumably because of implementation difficulties, telepointers are an important means to convey information, notably through gestures.

**View**. A view is a visual, or multimedia representation of some portion of a shared context. In the En-route control room, the two radar images are views on the same shared context, with different pan & zoom configuration.

**Synchronous and asynchronous interactions.** In synchronous interactions, such as spoken conversations, people interact in real time. Asynchronous interactions are those in which people interact over an extended period, such as in postal correspondence. In ATC, controllers talk with each other in real-time, and controllers and pilots talk mostly in real-time (depending on the load of the frequency). By contrast, Controller-Pilot Data Link Communications CPDLC enables controllers and pilots to communicate more asynchronously.

**Session**. A session is a period of synchronous interaction supported by a groupware system. Examples include formal meetings and informal work group discussions. A peculiarity of ATC (and some, but not all CSCW systems) is that it is always on, and all users enter and leave an already-running system. New flights constantly enter airspaces and leave them. ATC controllers work during 'shifts' (around 2-hour long sessions) and either leave the session without being replaced (sector closure), or being replaced which implies some coordination with the newly arriving controllers.

**Change**. With an always-on system, users continuously change its content, including while a particular user has left the system. When this user enters the system again (after a few seconds, minutes or hours), s/he might want to be aware and understand the changes brought by other users while s/he was offline [6]. Some visualization allows such a user to see all changes (or the history) [7], [8], or to compare the version s/he knew when s/he left with the new version of the system. The visualization of changes may have different levels of granularity (e.g., for a text editor, a character, a word; it might even be a whole sentence or a paragraph). Visualization of changes can also prove useful in the same session, to remind that a flight got a particular clearance (e.g., level or heading clearance on a strip).

**Comments and annotations.** Besides the artefact being produced, secondary notations such as comments or annotations help users explain, discuss on and coordinate about the evolution of the artefact. In ATC, a service like a 'Warning' on an image radar or a strip is such an annotation, even if it's an annotation for oneself to be reminded in the near future (the oneself of the future can be considered as a teammate for some CSCW services). Such an annotation is also of help for the teammate who is going to replace the ATCO at the end of the shift (e.g., he writing the actual time of usage of a military area in use in some ACCs).

**Conceptual model**. A conceptual model is a set of relevant abstractions and their relationships that help humans use a system and predict its behaviour. With CSCW systems, the relevant abstractions are not only those that concern the content (e.g., a text, a drawing), but also those that concern the changes: a *modification*, a *set of modifications*, a *commit* (which is the act of a user to commit her/his changes on a 'working'/temporary version of the content), a *push/pull* (synchronize her/his commits to a shared version with other users), a *conflict*, a *merge*. Most of ATC systems are synchronous, and do not involve such a conceptual model. However, some of them do: ATCOs may prepare a number of clearances (i.e., a set modifications), and perform/send them later with a CPDLC system (commit + push); on a paper strip, the set of handwritten clearances is a visualization of the history that may prove useful to remind a particular context for a flight [9].

**Implicit and explicit synchronization.** When editing a document, the changes can be implicitly pushed to a shared version, usually as fast as possible to allow other participants to benefit from the most up-to-date version, and thus prevent possible conflicts. However, such a synchronization scheme prevents a participant from preparing (and iterating/designing) a change and committing a final, clean version of the changes. Besides, such synchronization scheme is only available with a living network connection and cannot be performed offline. By contrast, explicit synchronization enables users to decide when their version and the other participants' versions should synchronize. This enables users to change their mind during the preparation, and even for different users to participate to the preparation and the execution of a clearance [10]. However, a user should not forget to explicitly synchronize, and repeating an explicit synchronization interaction can be cumbersome.

**Conflicts, concurrency, consistency, lock**. As users change the same shared content, they might perform conflicting changes. Some systems detect such conflicts and present them to the users to request their resolution. Some systems are able to automatically resolve a conflict and merge two sets of modifications. To prevent conflicts, some systems force users to lock (either implicitly or explicitly) a subpart of the content. These are 'pessimistic' algorithms since they prepare for the worst to happen. The problem is that the lock mechanism increases the amount of latency between the action performed by a user and its effect on the screen, which results in poor usability. By contrast, optimistic algorithms locally perform as fast as possible the action of a user, before trying to synchronize the changes. In the event of a conflict, various algorithms (including automatic undo/redo, composition of actions, operational transforms) can resolve the conflict. Optimistic algorithms rely on the fact that conflicts will be rare: if the system provides an efficient HMI that maximizes group awareness, social protocols between users will take place to avoid conflict, before it's necessary for technical protocols to resolve them. In ATC, procedures and role prerogatives prevent conflicts from occurring on a CWP.

**Role**. A role is a set of privileges and responsibilities attributed to a person, or sometimes to a system module. In ATC, controllers have specific roles and rights. Roles and rights might not be enforced by the system, but rather by established social protocols. By contrast, single-user devices (e.g., a mouse) may raise artificial boundaries eventually leading to rigid roles to enforce an exclusive access to the device. Some systems tentatively break those boundaries, by offering interactions to better distribute micro-tasks among ATCOs [11].

**Participants management**. Since users may enter and leave sessions, and may have different roles and rights, managers of a system might rely on specific services to add users, change their roles and rights, invite or retire them, or regulate their contributions. For example, a manager may rely on a system to manage sectors and distribute controllers on CWPs.

**Feedthrough.** Feedback is the immediate, perceivable response of an interactive application upon a user action. Feedthrough is a word derived from feedback. Where an artefact is shared, that artefact is not only the subject of communication, but it can also become a medium of communication. As one participant acts upon the artefact, the other observes the effects of the action. This observation by the other participants is called feedthrough [12]. Feedthrough and feedback can be similar, but also different: for example, in a graphical editor, the immediate feedback of a rubber rectangle helps a user control the resizing of an image, but a single, static, 'resizing' icon in other participants' views provides information that an image is currently being resized, without the visual disturbance that would occur when the rectangle continuously resizes itself. In ATC, while a previous sector has transferred a flight and the receiving sector is waiting for the pilot to call, in the receiving sector the label of the aircraft changes its colour and blinks. Colour blinking is at the same time a feedthrough that the aircraft has already been transferred from the previous sector and a highlight to quickly identify the aircraft when its pilot calls.

### 2.1.3 Taxonomy of CSCW systems and application to AEON

CSCW systems can be described along several dimensions of analysis. The following identifies several relevant dimensions from related work to understand and elicit AEON requirements.

#### The "clover" model of groupware

Groupware can be analysed according to the type of collaboration services they offer to their users. The "clover" model of groupware [13], [14] (derived from [15]) defines three spaces:

- Coordination: coordinating the production of a shared artefact by multiple users, with respect to time, scheduling, roles, and tasks involved;
- Production: manipulating physical or computerized entities and produce an outcome of the collaboration;

- Communication: exchanging information among users.

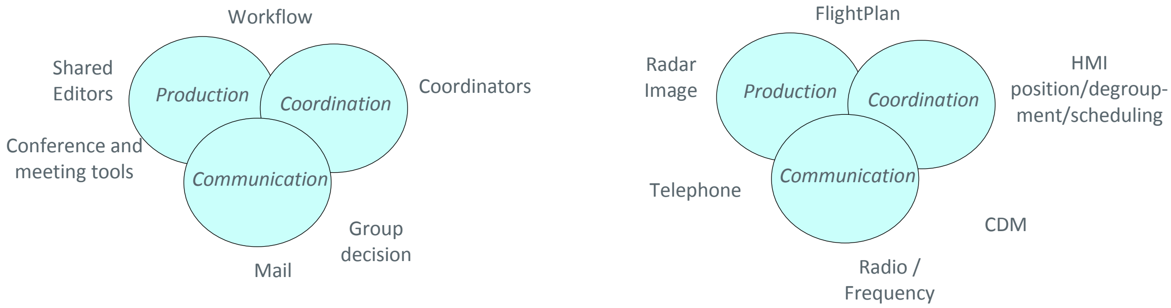


**Figure 4: Clover model of groupware**

A particular groupware participates with varying degrees to each dimension. For example, Email is mostly about Communication, but can contain some coordination aspects (e.g., “I’ll do that, while you do this”) and even production (e.g., sending a paragraph to be integrated in a shared document). A shared text editor is mostly about Production, but can also contain services for Coordination (e.g., reaching an agreement between users using the ‘comment’ service) or even Communication (e.g., a user can perform deictic gestures with a telepointer in a synchronous editor to communicate the part on the document s/he is talking about).

ATC systems contribute to each three types of space (see Figure 2). Within AEON, it is envisioned that services will likely contribute to communication and coordination, but also production e.g., of clearances.

## Space-Time Matrix

Groupware can also be analysed according to the time at which the users interact through the system, and according to their relative physical location [1]. Bringing both dimensions together forms a space-time matrix as presented in Figure 3.

| | Same time | Different time |
|---|---|---|
| Same place | Face-to-face interaction | Asynchronous interaction |
| Different place | Synchronous distributed interaction | Asynchronous distributed interaction |

**Table 2: Space-Time Matrix (from [1])**

| | Same time | Different time |
|---|---|---|
| Same place | TWR position | Shift |
| Different place | Positions TWR/LCK/towing vehicles | Asynchronous distributed interaction |

**Table 3: Space-Time Matrix applied to ATC (from [1])**

ATC systems range into all categories, though very distant one (inter-continent) might not necessitate much interaction per se. For AEON, we expect to design spatially distributed interactions devices/surfaces, at least belonging to different roles or entities. Regarding time, we envision that interactions would be synchronous as when communicating via the radio, or asynchronous while ATCOs or airlines operations crews explore specific solutions on their own or wait for approval before pursuing. It is possible that ATCOs may attempt to plan say, one hour ahead, but there will be a residue of problems, some of which may require action within seconds. The relatively long-term (or upstream) process is often called 'planning' ATC and the short-term (or downstream) process 'tactical' ATC [16]. For AEON, we expect to design for both strategic and tactical tasks.

Even if the space-time matrix informs on the category and the difference between systems (e.g. single display groupware [17] are same-time/same-space system), it is deemed as "not very helpful" [18], as space might not be an issue at all if the collaboration support is adequate. It also misses important details due to its coarse granularity and due to it not taking account dynamicity: some interactions might begin asynchronously, eventually turning synchronous (e.g., a chat exchange turning into a voice call when the matter being discussed necessitates a modality with a higher throughput).

### Communication

| | one | many |
|---|---|---|
| one | ATCO => ATCO, ATCO => 1 pilot | ATCO => pilot**S** |
| many | Pilots => ATCO | |

**Table 4: Communication Matrix applied to ATC (from [1])**

Communication may involve one/many emitters and one/many listeners. In ATC, a single controller is in charge of communicating clearances with each pilot, while a pilot informs the controller on the flight situation. Communication patterns include clearance, request/answer information, or non-requested information by the pilot (e.g., turbulences). The frequency is multiplexed with multiple, short exchanges between different pairs of controller/pilot. Since a frequency is shared by multiple controllers and pilots, exchanges with a particular controller/pilot pair can be listened to by other controllers and pilots and inform on the global situation. In AEON, tugs operators may benefit from this situation awareness.

As discussed earlier, a single 'communication' might use multiple modalities according to the changing needs of the activity. This phenomenon is captured by the Multi-scale communication framework [19], and requires that communication systems should support a variable degree of engagement, smooth transitions between degrees and smooth integration with other media or communication systems.

### Number of participants

The ATC system involves many participants, but for a project such as AEON the total number of participants is less meaningful than the peak number during a day, or than the patterns of collaboration they are involved in. The set of participants and its number evolve with the traffic (pilots leave and leave 'sessions'), the time of the day and the traffic load (more controllers reinforcing teammates), and the weather (more controllers might be involved in case of low-visibility conditions or storms). At the scale of the AEON project, we envision that most direct interactions will involve less than 5 people, far from the hundreds that some systems like source code repositories can manage.

### 2.1.4 Requirements, Design Principles and Evaluation of Groupware

As with any other system, the methodology of HCI system design includes the elicitation of requirements and means to evaluate the product being designed. A peculiarity of HCI system design is the notion of "Design principles" that guide the design to make the product consistent and usable.

#### Requirements for groupware

After a period of discovery and development of new systems, some researchers gathered together a set of requirements for a platform to effectively support collaboration [18]. A CSCW platform should support:

- informal interaction and provide facilities for unrestricted interaction among users in the form of channels of direct communication. (e.g., a conference function)
- information sharing and exchange, and should enable users to:
  - exchange (send and receive copies of) information objects created by any application
  - share an information object, i.e., to make a particular object (e.g., a file) accessible to other users
  - work in close interaction by giving other users access a particular application window
  - fluidly transition between individual and cooperative activities (the user should be able to publish a file, send a message, display a window, etc. to another user just as he or she can print it from an ordinary workstation.)
- decision making
- coordination and control protocols
- domain directories

#### Design Principles for groupware

A number of research projects have tackled the problem of designing a digital system that can be updated, while preserving collaboration. They use design principles that guide the choices and the rationale behind the choices.

#### Use of touch screens

Some research ATC systems rely on the use of one large surface [11] or make use of two touch screens (one per controller) [20]. Their designers argue that touch screens are appropriate tools to support collaboration:

- they increase mutual awareness. Since touch screen-based HMI involve direct manipulation and gestures, seeing what a colleague is doing with his hand (directly or in peripheral vision) on a touch screen provides many cues on his activity.
- unlike mice, touch screens are shareable in a fluid manner: a user can interact on his touch screen as well as on his teammate's.

#### Free layout and close surfaces

The digitalization of paper strips led to HMIs that resemble actual strip boards. However, for the HMIs to actually convey all information conveyed by stripboards, they also have to mimic the ability of actual strip boards to freely lay out the electronic strips. For example, a planning controller may slightly shift or rotate a strip to the left to make it salient for the tactical controller.

As an alternative to replacing paper flight strips with digital systems, paper strips can be augmented with computing functions. Mackay et al describe how augmented paper strips can provide information to the system, while maintaining paper strips' properties and users' habits [21].

As shown in [22], subtleties in settings can greatly improve collaboration. In an experiment for a new control tool [23], experimenters noticed that a pair of controllers collaborated more when the two radar screens were made closer to one another, and oriented slightly towards the other as opposed to strictly facing the two controllers. Though users could interact with the teammate's screen in DigiStrips, the gap between touch screens prevented fluid passing of objects or the emergence of shared territory [24]. By contrast, MAMMI is a system that uses a shared, multi-touch, multi-users surface since shared surfaces make users close together and enable them to interact simultaneously if the interactions were designed appropriately [11].

### Designing Direct Collaboration

The requirements from section 0 were mainly designed for general applications. This has often led to specific tools to support one of the three types of activity described by the clover model. However, clever design might also fulfil some requirements without resorting to explicit tool design.

For example, "direct collaboration" is an HCI design principle to invent smooth and meaningful interactions for collaboration. A direct collaboration system is a "collaborative system in which coordination between users is supported by communication and production tools, and not by dedicated coordination tools" [25]. Three rules might guide the design of direct collaboration system:

- **Integrating Communication Media** - for example avoid a rigid sequence of actions that necessitate to enter a session before editing a document, and rather provide an 'enter session' button on a shared document, or provide a communication channel on the application
- **Integrating Activities** - To avoid unintended disruptions of a task, groupware systems can manage pending tasks and let the choice of when to collaborate to the users. For example, a shared workspace can be associated with each user and receive objects representing pending requests such as a "phone call" button.
- **Production Space as a Medium** - The production space can be used as a channel for conveying social hints in the same way as traditional communication channels. This is possible by introducing interaction styles that support prosody in the same way as voice intonation or gestures accompany oral communications, thus reinforcing coordination hints. For example, the authors designed "shared transfolders" in which ATCOs can drop a reification of a clearance. This allows for some form of prosody: dropping a clearance in a remote corner of the working area will probably mean a low need for synchronization, while one dropped next to the phone icon in the transfolder will be interpreted as a request for a phone call.

Direct manipulation and touch-based ATC systems also rely on the reification of actions into objects [11]. Since objects lie on the table, their manipulation may enable accountability [25]; furthermore, they can be passed around and allow for task reallocation.

### Foster dynamic task allocation by allowing partial accomplishment of actions

A CSCW system should foster dynamic task allocation to increase capacity [11]. Capacity should increase because users will be able to pick up new tasks to be done as soon as they have completed existing tasks (activity preparation and allocation).

Such fostering can be accomplished by carefully subdividing tasks into sub-tasks. For example, an action can be separately prepared, checked and accomplished. Different users can perform each subtask, thus offering seamless workload allocation, as long as the accomplishment status of sub-tasks is visible and as long as the subdivision fulfils operational requirements (especially regulations).

### Provide as much feedthrough as possible

Since activities must be accountable, it is important that appropriate feedback provide an opportunity for teammates to observe one another's actions [11]. Carefully designed feedthrough is one way to provide information.

For example, interactions and graphic rendering techniques such as position remanence in radar images or in traditional cursor-based HMIs , Mnemonic Rendering or Phosphor might provide a sense of the history of teammates' actions. Other group activities may benefit from specific visualizations of social protocols, such as social proxies [29], out-of-screen location indicators such as wedges [1], or specific interactions such as the Telepresence interfaces for Mediaspaces [30].

## Evaluation of groupware

Some researchers sought to provide specific evaluation criteria to assess CSCW systems. They notably defined a set of heuristics to evaluate CSCW systems, tailored to the groupware genre of shared visual workspaces [31]. As always, evaluation and ideation are the two sides of the system design coin, and heuristics for evaluation can also be used as heuristics for ideation.

- **Heuristic 1:** Provide the means for intentional and appropriate verbal communication (chat, audio, video)
- **Heuristic 2:** Provide the means for intentional and appropriate gestural communication (telepointer, avatars, video)
- **Heuristic 3:** Provide consequential communication of an individual's embodiment (capture and transmit both the explicit and subtle dynamics that occur between collaborating participants)
- **Heuristic 4:** Provide consequential communication of shared artefacts (i.e., artefact feedthrough)
- **Heuristic 5:** Provide Protection (access control, concurrency control, undo, version control, and turn-taking)
- **Heuristic 6:** Management of tightly and loosely coupled collaboration (relaxed-WYSIWIS (What You See Is What I See, overviews)
- **Heuristic 7:** Allow people to coordinate their actions
- **Heuristic 8:** Facilitate finding collaborators and establishing contact (Being available, Knowing who is around and available, Establishing contact, Working together)

## Problems in the design and evaluation

Several problems in the design and evaluation of CSCW systems have been identified [32]:

**Problem 1. The disparity between who does the work and who gets the benefit.**

Many CSCW applications will directly benefit certain users, often managers, while requiring additional work from others. A traditional method of coping with such a problem is to create new jobs or "redesign" existing jobs -- in short, to require people to do the additional work.

**Problem 2. The breakdown of « intuitive » decision-making [about designing a CSCW system]**

Decision-makers in a position to commit the resources to application development projects rely heavily on intuition. Not surprisingly, the decision-maker is drawn to applications that selectively benefit one subset of the user population: managers. Managers tend to overlook or underestimate the downside, the extra work that might be required of other users to maintain the application.

**Problem 3. The underestimated difficulty of evaluating CSCW applications.**

Task analysis, design, and evaluation are never easy, but they are considerably more difficult for CSCW applications than for single-user applications.

### 2.1.5 Conclusion on CSCW

CSCW concerns are important for any collaborative activity, all the more for ATC. Collaboration is already known as key to safety and capacity in ATC. In the context of AEON, the quality of the support to collaboration should also foster better optimization of the use of resources and means to fulfil AEON's sustainability goals. AEON introduces more automation and a new role (towing vehicle manager). The main AEON research questions related to CSCW are: what support for collaboration is needed to consider the three envisioned main roles (pilot, controller, towing vehicle manager)? What support for collaboration is needed to consider both humans and automation aspects? These questions are closely related to distributed situation awareness, which is the topic of the next subsection.

## 2.2 Distributed Situation Awareness among participants

In cognitive science, Situation Awareness (SA) describes the ability to "knowing what's happening", during collaborative work. In this section, we describe existing models of SA and in particular Distributed Situation Awareness (DSA) that seems most adequate for the AEON project due to the distributed nature of ground handling tasks. We will also describe existing design requirements for other aviation systems and evaluation methods that could be useful to assess the effectiveness of tools to support SA.

### 2.2.1 Situation Awareness Concepts

Endsley distinguishes the term Situation Awareness, as a state of knowledge, from the processes used to achieve that state, as acquiring or maintaining SA [33]. She defines SA as "*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future*". Figure 5 shows a three-level model of situation awareness. The levels are:

1. Perception (level 1 SA): The basis of SA is formed by the perception of relevant elements in the environment. This involves monitoring or cue detection to enable an awareness of situational elements (objects, events, people, systems…).

2. Comprehension (level 2 SA): A synthesis of the elements through pattern recognition, interpretation and evaluation forms the comprehension of the current situation which is compared to the operators' goals

3. Projection (level 3 SA): The last level is the ability to project future states of the environment to determine how it will affect future states of the operational environments. This level is particularly important for decision making.

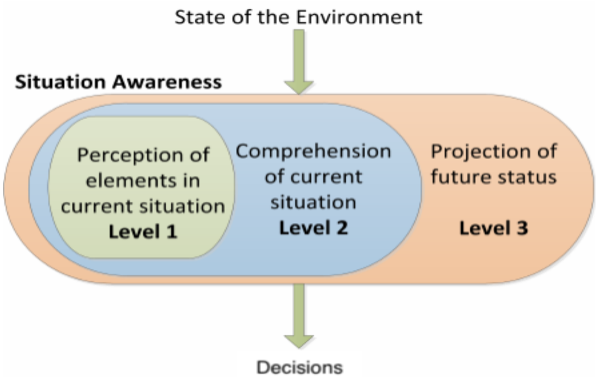


**Figure 5: Three levels of situation awareness**

For Air Traffic Control, Ruitenberg defines SA elements for en-route ATCOs [34] as presented in Figure 6. In the scope of the AEON project, we will need to investigate whether these elements are relevant for ground controllers and possibly propose an updated version. We will also need to consider the other stakeholders involved such as airlines crew, pilots, tug drivers and airport teams.

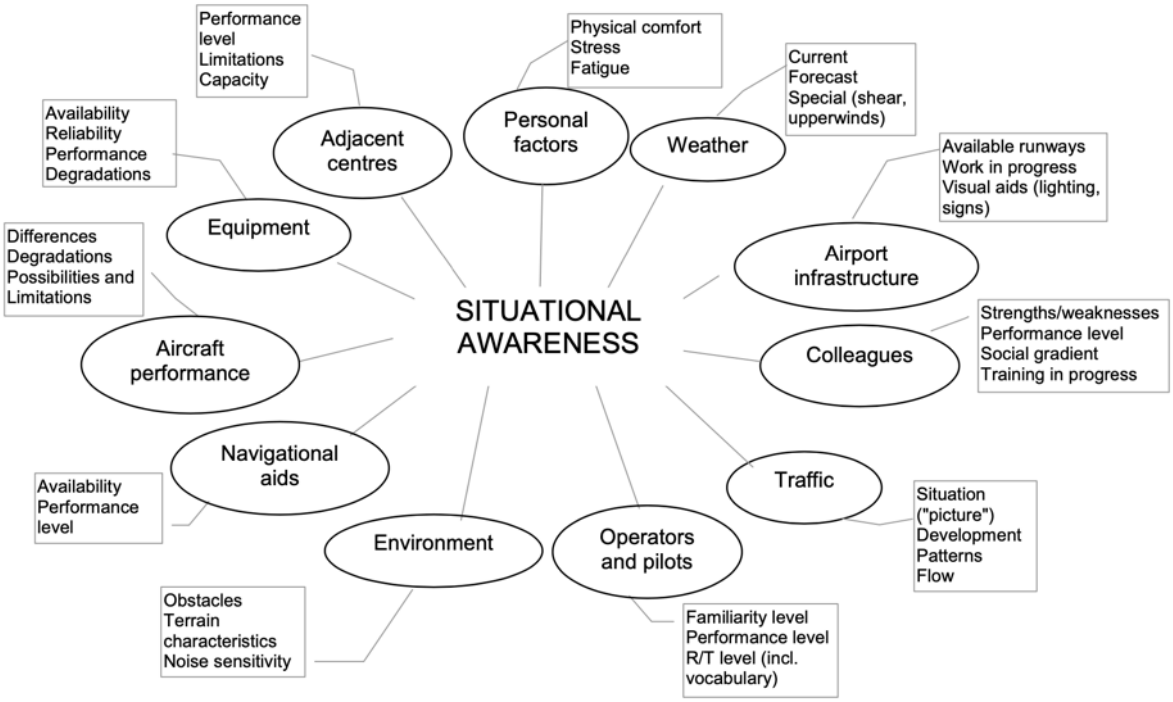


**Figure 7: Elements of SA for ATCOs (from [34]).**

In many organizational environments, especially complicated ones, a team of individuals takes charge of the operational tasks [35]. The traditional and dominant view emphasizes Team SA on a shared understanding of the situation, that is, the team members should have a common picture. Endsley raised a Team SA model, in which a set of circles overlaps with each other [33] (see Figure 7 left). Each circle represents a team member's SA elements related to his or her specific role. The overlaps of the circles represent shared SA, and the union of the circles represents Team SA. Team SA is defined as "*the degree to which every team member possesses the SA required for his or her responsibilities*" [33]. According to this model, the success or failure of a team depends on the

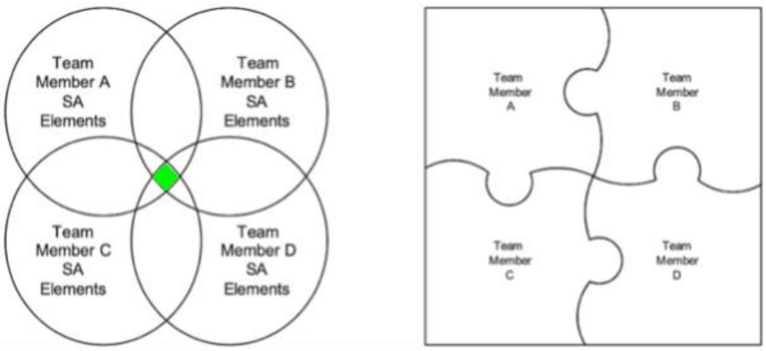


**Figure 6: Shared Situation Awareness (left). Compatible Situation Awareness (right) (figure from [36])**

success or failure of each of its team members.

Another approach considers Compatible Situation Awareness instead of Shared SA [36]. Compatible SA is based on the notion that no individual working within a collaborative system will hold exactly the same perspective on a situation. Compatible SA therefore suggests that, due to factors such as individual roles, goals, tasks, experience, training and schema, each member of a collaborative system has a unique level of SA that is required to satisfy their particular goals. Each team member does not need to know everything, rather they possess the SA that they need for their specific task but are also aware of what other team members need to and do know as illustrated in Figure 7 (right). Although different team members may have access to the same information, their resultant awareness of it is not shared, since the team members often have different goals, roles, experience and tasks (and thus different schema) and so view the situation differently based on these factors. We believe that the AEON project falls within the Compatible SA approach as most stakeholders (ATCOs, pilots, truck drivers or marshallers) will likely have some shared elements but different goals, experiences and tasks.

### Distributed Situation Awareness

Building upon the Compatible SA that we identify as most relevant for the AEON project, Stanton et al [30] propose that SA is distributed amongst the humans and non-human artefacts in the socio-technical system. In their view of Distributed Situation Awareness (DSA), SA no longer exists solely in the individuals, but is an emergent property of the system. A system analysis cannot be accounted for by summing independent individual analyses. The basis of their theory is described in the six following propositions [36]:

- *SA is held by human and non-human agents. Automated agents as well as human operators have some level of SA in the sense that they are holders of contextually relevant information. For instance, automated tugs do have SA thought their sensors.*
- *Different agents have different views on the same scene. This emphasizes the role of past experience, memory, training and perspective. Also, autonomous and automated technology may be able to learn about their environment and evolve over time.*
- *Whether or not one agent's SA overlaps with that of another depends on their respective goals. Different agents could actually be representing different aspects of SA.*
- *Transactions between agents may be verbal and non-verbal behavior, customs and practice. Technologies transact through sounds, signs, symbols via the HMIs.*
- *SA holds loosely coupled systems together. It is argued that without this coupling the systems performance may collapse. Dynamical changes in system coupling may lead to associated changes in DSA.*
- *One agent may compensate for degradation in SA in another agent. This represents an aspect of the emergent behavior associated with complex systems*.

Stanton et al. [36] reports that the application of Distributed SA has led to encouraging results. It promotes higher performance in teams than shared SA. Distributed SA theory offers explanations of the behaviours of complex socio-technical systems in a wide range of domains such as energy distribution or digital mission planning for military operations.

Figure 8 illustrates the models of DSA with a compatible SA model at the center made of Agents and Artefacts. The human and non-human agents and the artefacts exchange situational data via SA transactions.

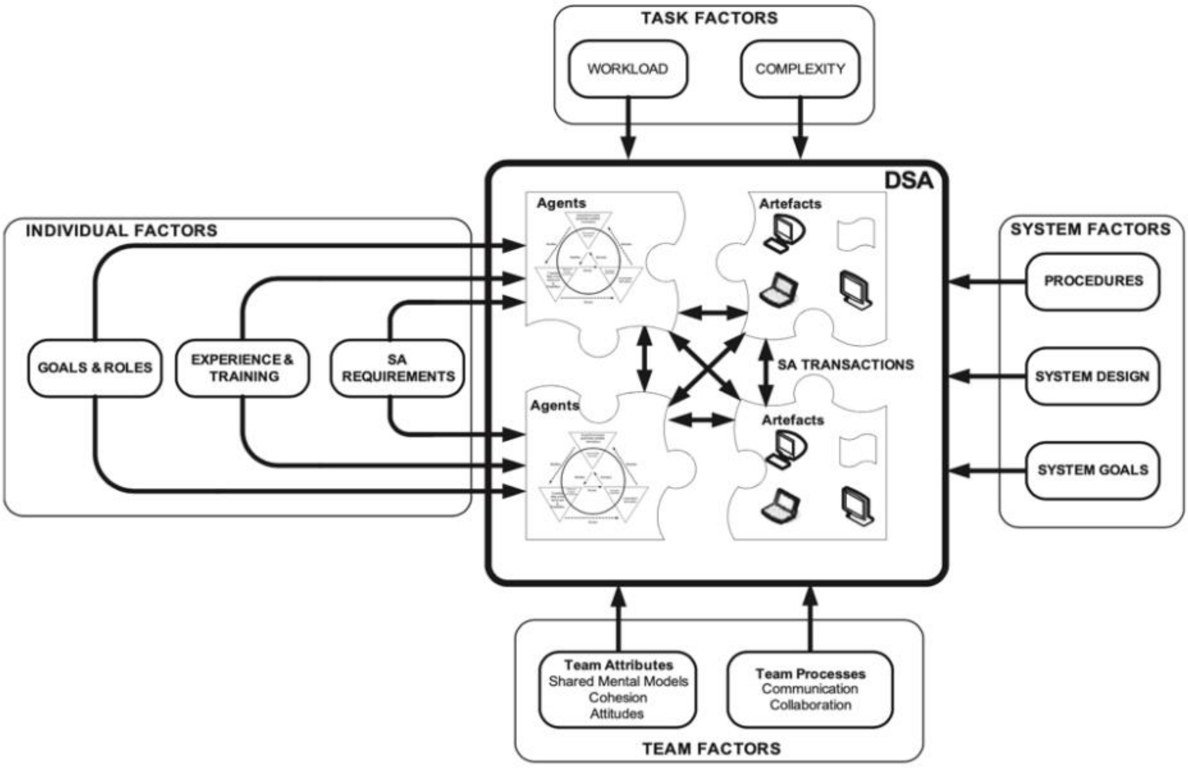


**Figure 8: Distributed Situation Awareness Model (from [36])**

Within the AEON project, multiple users will collaborate through various systems to achieve their respective goals, i.e., handling outbound and inbound aircrafts. This implies that all stakeholders must build a distributed SA to maximize the effectiveness of the system and maintain both safety and capacity. A design challenge is to offer support for maintaining distributed situation awareness during the operations. In addition to current elements, we will also have to maintain an ecological performance of the whole system. In the next section, we will review the Affecting factors described in this model and relevant design guidelines to support SA in such a distributed system.

## Affecting factors

According to Salmon et al. [36] , numerous factors affect and influence SA according to task, individual, system and team factors as presented in Figure 8. We describe below some of their components and give details with respect to the specific challenges we may face within the scope of the AEON project. Then, we build upon existing work to describe specific factors related to ATCOs SA.

**Task factors** concerns the characteristics of the tasks being performed by teams that can either facilitate or inhibit team performance. Factors such as task design, complexity, workload, time pressure, task allocation and familiarity with the task can all potentially affect the DSA acquired during performance of the task in question [37]. For example, the level of workload experienced by team members is a key element in the safety, reliability and efficiency of complex sociotechnical systems such as ATC [38]. Inappropriate levels of workload (either too high or too low) are likely to lead to reduced levels of DSA. Endsley points out that a major factor creating a challenge for operator SA is the increasing complexity of many systems and suggests that complexity can negatively affect SA via factors such as increased system components, the degree of interaction between components and the dynamics or rate of change of the components.

**Individual factors** concern mostly factors related to how an agent's goals and roles within the system, its experience and training as well as the availability of required data, are adequate to the entire system. AEON will likely introduce minimizing fuel consumption as a new goal for each role and will introduce needs for accessing relevant data to inform decisions.

**System factors** are related with the design of the system to support development and maintenance of the SA. For instance, if the system fails at presenting the appropriate information to the operator who requires it because it is incomplete or erroneous. The structure of the network of agents involved and the communications channels that are available to the different agents comprising the system are also likely to have an impact on the quality of the system's DSA. Communication links are one of the critical factors in the acquisition and maintenance of DSA and it is important that the appropriate communication links are present within a system and are maintained throughout task performance. In the case of AEON, an important effort will concern the design of communication mechanisms, whether they are explicit (radio, text messages) or implicit (noise of important activity, emotions). Procedures that enforce the communication of critical DSA-related information, such as instructions, work progress and situational updates are particularly important. Stone and Posey [39], for example, suggest that each member's awareness of the current situation could be significantly reduced if communication is not appropriate among members. One approach typically adopted by distributed teams is closed loop communication [38], which involves the initiation of communication by a sender, acknowledgement of receipt of the information by the receiver and then a follow up by the sender to check that the message was interpreted as intended.

**Team Factors** concerns team attributes and processes. For example, according to Salas et al. [40], there are five main processes: leadership, mutual performance monitoring, back up behavior, adaptability and team orientation, that are necessary for improved team performance. Lack of shared mental models between team members can lead to confusion regarding who held the information to update the situation awareness. Similarly, lack of communication between agents can lead to an out-of-date DSA of the system. Since AEON may introduce a new role in the existing operations workflow, supporting the new Team organization and these five processes need to be considered.

Jeannot [41] offers very interesting results in terms of factors leading to loss of SA and strategies used to recover SA for en-route ATCO as presented in Figure 9 . During AEON, we will keep these factors in mind and explore interaction supporting users in recovering SA if required.

| Factors leading to loss of SA | Strategies used to recover SA |
|---|---|
| • Time pressure<br>• Focusing on non-pertinent, or less pertinent information<br>• Focusing on a subset of relevant information but missing the evolution of other information<br>• Becoming reactive rather than proactive<br>• Reduction in room to manoeuvre,<br>• Increased occurrence of non-safe situations<br>• Noise/distraction other people<br>• Mental and/or physical fatigue<br>• Volume of traffic; unexpected and sudden variation of traffic load<br>• Number of phone calls<br>• Lack of strip information at the right time<br>• Lack of adequate feedback<br>• Too much happening and having to process too much information<br>• Traffic building up<br>• Unusual or unexpected events (e.g. aircraft calling in too early) | • Increase in delay between pilot calls and controller answer<br>• Check consistency between strips and radar<br>• Force themselves to speak slowly and precisely, return to strict phraseology<br>• Request help: ask for sector splitting, if possible, to decrease load<br>• Analyse closely all the strip<br>• Force themselves not to spend too much time on a single problem<br>• Change principle of strip classification, re- organise strips according to new criteria (e.g. by entry or exit point)<br>• Physically manipulate the strips (i.e. re-positioning the strips aids concentration)<br>• Prioritise work and “forget” less important tasks<br>• Disregard the strips of ‘hello-goodbye’ a/c (in the case of too many strips)<br>• Always prioritise new strips |

**Figure 9: SA factors for ATCOs from [41]**

Another contribution from the same work concerns indicators of good and reduced SA as presented in Figure 10. Some of the indicators of reduced or impaired SA such as delay between pilot calls and controller answer or the need to check the same information several times can be monitored and represented by the AEON solution to alert a specific operator as well as the others on possible risk of reduced SA. Using indicators as the use of exclusive language such as 'but' and 'except', and the use of second person pronouns has been used to automatically assess viable team interactions for classrooms [42] and could be adapted to the AEON project.

| Indicators of good SA | Indicators of reduced/impaired SA |
|---|---|
| • Anticipating events<br>• Being able to predict next a/c call<br>• Managing resources (technical system , internal, team …)<br>• Managing time<br>• Feeling of being in control; able to implement elegant solutions<br>• Taking the right decision at the best moment, managing traffic in a safe and expeditious way<br>• Detecting mismatches | • Increase in delay between pilot calls and controller answer<br>• Inconsistency in communication with pilots, colleagues, adjacent sectors or centre<br>• Sudden and unexpected variation of workload<br>• Confusion<br>• Need to check same information several times |

**Figure 10: Indicators of good or reduced SA from [41]**

### Measuring SA

Several techniques exist to measure situation awareness of individual members as well as Distributed Situation Awareness as reviewed in [36]. The most popular technique is the Situation Awareness Global Assessment Technique (SAGAT) that consists in interrupting simulation at random times and asks the crew to state their assessment of the current situation based on Endsley's three levels model. There is a specific version of the SAGAT for Air Traffic Control that could be relevant to use within the AEON project. Other tools such as Situation Awareness Rating Technique (SART) or Situation Awareness Subjective Workload Dominance (SA-SWORD) are also used. These techniques are often used for assessing pilot's situation awareness, but some work also studied more collaborative contexts and ATC contexts.

For instance, the Situation Present Assessment Method [44] is a real-time probe technique that was developed to asses air traffic controllers' awareness. The technique was improved and used by Eurocontrol with SASHA [41] for the assessment of air traffic controller SA in automated systems. SASHA comprises two techniques, SASHA_L (real-time probe technique) and SASHA_Q (post-trial questionnaire). SASHA_L is based on the Situation Present Assessment Method [44] and involves probing the participant on-line using real-time SA related queries. The response content and response time is recorded. Once the trial is completed, the participant completes the SASHA_Q questionnaire, which consists of 10 questions designed to elicit subjective participant ratings of SA. This technique might be used to assess the SA support of the AEON solution. However, question will need to be adapted to ground controllers as most of the existing work focused on en-route Air Traffic Control and did not consider other operators in the loop. In our case, we might need to assess SA of each such as airlines operations, or airport management.

### Design guidelines

In this section, we review some related work that offers guidelines for designing collaborative systems able to support Situation Awareness. As pointed out, traditional Human Factor design guidelines are inadequate for achieving the SA required in complex systems [33]. Stanton et al. [36] built upon several project to offer the following guidelines. We describe some of them that seemed the most important within the scope of AEON.

**Clearly define and specify SA requirements**: The collaborative system design process should begin with a clear definition and specification of the DSA requirements of the overall system and of the different operators working in the system in question.

**Design to support compatible SA requirements:** Rather than present everything to everyone, or use common operational picture displays, collaborative systems should be designed so that users are not presented with information, tools and functionality that they do not explicitly require. Systems should therefore be designed to support the roles, goals and SA requirements of each of the different users involved in the process in question. This might involve the provision of different displays, tools and functions for the different roles and tasks involved, or might involve the use of customisable interfaces and displays.

**Design to support SA transactions:** SA transactions are means by which DSA is developed and maintained during collaborative tasks by the agents. Systems and interfaces that present information to team members should therefore be designed so that they support SA transactions where possible. This might involve presenting incoming SA transaction information in conjunction with other relevant information (i.e. information that the incoming information is related to and is to be combined with) and also providing users with clear and efficient communications links with other team members. Similarly, procedures can be used to support SA transactions; this might involve incorporating certain pieces of information into procedural communications between team members in order to support SA transactions.

**Use multiple interlinked systems for multiple roles and goals:** role specific systems might be more appropriate to support DSA development and maintenance. When a team is divided into distinct roles, team members have very different goals and informational requirements; it may therefore be pertinent to offer separate (but linked) support systems.

**Ensure that the information presented to users is accurate at all times:** The information presented by any collaborative system should therefore be highly accurate and system designers need to ensure that the information presented by all aspects of the system is accurate at all times.

**Ensure information is presented to users in a timely fashion and that the timeliness of key information is represented:** SA-related information should therefore be presented to users in a timely manner, without any delay, at all times. Further, the timeliness of information should be represented on interfaces and displays, allowing users to determine the latency of information.

**Use procedures to facilitate DSA:** procedures are an effective means of facilitating DSA acquisition and maintenance through SA transactions. It is therefore recommended that procedures should be used to support SA transactions via encouraging the continual communication of DSA-related information around collaborative systems and also by structuring communications so that related information is communicated together.

## Conclusion on Distributed Situation Awareness

DSA gives interesting direction to design groupware systems able to support operators understanding their current environment and making informed decisions. Building from work presented in this section, we will involve participants from the early design phases to gather SA requirements for ground ATCOs and supervisors of the towing vehicles. We will also explore interactions to achieve efficient and effective SA transactions. We will try to assess the DSA status of the operators during the design and experimental phases of the project.

## 2.3 Human Automation Teaming

Human Automation Teaming (HAT) can be defined as a group of human and autonomous agents, performing activities and achieving outcomes together towards a common goal. In particular in HAT, the autonomous agents work alongside humans performing essential tasks and teamwork functions that a human would [45]. This new teamwork configuration is partially shifting the role of human agents to supervisors, adding new tasks to their workload. These tasks include assessing situations for taking decisions, correcting agents' errors or even managing agents' failures. However as autonomous systems become more and more reliable, operators tend to detach from automation making the ability to takeover autonomous control challenging. Therefore, it is necessary to keep human operators attentive to autonomous agents' activities and actions. This is highly relevant to AEON as autonomous solutions for taxiing have already started to be deployed in airports around the globe. In this section, we discuss the challenges to support collaboration between human and autonomous agents, and to design reliable and efficient HAT interactions which will allow AEON's stakeholders to perform their activity in an optimal way.

Human-automation is not new. Its genesis can be dated to the early 70s with research on conversational agents [46]. In his research, Carbonnel introduced SCHOLAR a novel type of computer assisted instruction system capable of reviewing the knowledge of a student in a given context [46]. In this system, students are prompted by the agent which can communicate students' request statuses, detect misspelling, answer students' questions with acceptable English or generate test questions and evaluate students' test answers. SCHOLAR was the first system to propose and maintain a mixed-initiative man computer dialog. Mixed-initiative interaction is defined as a flexible interaction strategy in which each agent (human or computer) contributes to what it is best suited at the most appropriate time [47]. Horvitz describes mixed initiative support as an efficient, natural interleaving of contributions by users and automated services aimed at converging on solutions to problems [47]. In his vision, not only these systems take advantage of combining the power of direct manipulation and potentially valuable automated reasoning, but they also facilitate collaboration between users and intelligent services to achieve their goal.

The last decades have seen the rapid development of sensors and computational power. Autonomous agents can now perform sophisticated functions with no or little intervention of humans [48]. Depending on the function performance, reliability and importance, different levels of autonomy can be applied. However, higher level of autonomy contributes to better team performance by increasing communication efficiency, improving coordination and reducing workload [49].

In HATs, autonomous agents perform complex tasks which require to engage with other teammates to achieve team objectives. Previous research has established that task difficulty has an effect on team performance, especially the tasks switching frequency and the workload increasing with the difficulty [50], [51]. As the difficulty increases, more effort and time are needed to deal with the tasks, causing the communication and engagement between agents to reduce [50].

Teams composed of humans alone tend to outperform teams with autonomous agents [52]. While autonomous agents are able to manage workload better, human operators can adapt to new situations better [53], thanks to the way human agents communicate to each other. Mc Neese et al. have shown that humans provide more status updates and request less information between them than when collaborating with autonomous agents [45]. Therefore, in order to support the supervising role of human agents in HATs, communication is key. In fact, the more reliable and robust the automation is, the less likely human operators will be aware of critical information and will take manual control when needed [54]. This is very relevant to AEON as any taxi failure will critically impact the airport runways schedules.

In a recent effort to summarise the research on level of automation and situation awareness, Endsley has proposed a Human-Autonomy System Oversight (HASO) model that takes into consideration the impact of the level of automation on human performance and cognition for automation task stages. These stages include monitoring and information presentation, generation of options, decision making and implementation of actions [54]. The specificity of HASO is the implementation of strategies to reduce workload and improve human engagement towards automation through level of automation, adaptive automation and grain of automation control. As a result, a list of guidelines to support operator situation awareness and autonomy oversight has been proposed (Table 5).

These guidelines, which complete previous guidelines on situation awareness (see section 0. Design guidelines), ensure that (1) the designed interfaces will provide a high level of transparency promoting understandability and predictability of the system, (2) will communicate agent's reliability or robustness to the operator at all times, and (3) will allow the operators to develop a mental model of the autonomy and perform the appropriate actions to keep the system in line with their goals.

| ***Guidelines*** | ***Summary*** |
|---|---|
| Automate only if necessary and avoid operators to detach from automation as much as possible | Automation should be avoided unless its assistance is really needed as it can lead to significant problems such as lack of understanding, system complexity, decision biasing and out-of-the-loop performance issues. |
| Use automated assistance for carrying out routine tasks rather than higher-level cognitive functions | Automation that carries out the action in a routine task is highly beneficial for reducing manual workload, however decisional automation should be avoided as it can create out-of-the-loop problems. |
| Provide system awareness support rather than decisions | Systems that provide situation awareness through well designed information presentation to operators, integration and projection yield better performances and robustness. |
| Keep the operator in control and in the loop | Increasing operator involvement and control will improve engagement in task performance. Ensure that the operator maintains control over the automation, and design strategies that include human decision in the task flow. |
| Avoid the proliferation of automated modes | Keeping autonomy modes low will help operators to develop a good mental model of how the system works and will facilitate the autonomy mode tracking and |

| | |
|---|---|
| | learning. |
| Make modes and system states salient | The current mode of automation should be made salient to the operator (including mode transitions back to manual operation). The current state of the automation should be salient so that any violation of operator expectations will be readily apparent. |
| Enforce automation consistency | Consistency in the terminology, information placement, and functionality of the system between modes should be enforced to minimize errors in working with system autonomy. |
| Avoid advanced queuing of tasks | Approaches that maintain operator involvement in the decisions associated with execution of tasks will avoid potential failures with no immediate support that could interrupt the task flow. |
| Avoid the use of information cuing | Automatic highlighting of information should be avoided in favour of approaches that allow people to use their own senses more effectively. Providing strategies to declutter unwanted information or improving picture clarity are preferable. |
| Use methods of decision to support that create human/system symbiosis | Encourage people to consider multiple possibilities and perform contingency planning that can help project future states and provide systems that support humans to consider alternate interpretation of the data. |
| Provide automation transparency | Make clearly apparent what the system is currently doing, why it is doing it and what it will do next to improve transparency and observability of the system. |
| Ensure logical consistency across features and modes | Differences in operational logic, information presentation and sequences of input not necessary for the operation should be reduced to limit system complexity. |
| Minimize logic branches | Reduce linkages and conditional operations in the autonomy and modes as much as possible to minimize system complexity. |
| Map system functions to goals and mental models of users | Use a clear mapping between user goal and system functions to limit the degree to which operators need to understand the underlying software or hardware linkages to operate or oversee the autonomy. |
| Minimize task complexity | Limit the number of actions needed to perform desired tasks to reduce the sequence errors and cognitive load in interacting with the autonomy. |

**Table 5: Guidelines for supporting human understanding of autonomous systems and the reduction of complexity in autonomous system (from [54])**

Transparency of autonomous agents is critical to maintain situation awareness and to allow reliable supervision by human operators. Building upon [33], Chen et al. have proposed the *Situation Awareness-based Agent Transparency* (SAT) model to identify the information autonomous agents need to provide to ensure a clear communication with human operators [55]. Matching Endsley's situation awareness levels [33] (Section 2), they have proposed 3 levels of information that should be accessible to operators for effective supervision control. While the first level provides basic information about the current agent's state and goals, intentions and plans, the second level informs about the agent's reasoning process and all the considerations when planning its actions. Finally, the third level communicates future states, predicted results and consequences, and uncertainties about projections. A summary of the model is provided in Figure 11. In AEON, stakeholders may have to collaborate with autonomous taxiing agents. Therefore, we will identify the relevant information at

**Situation Awareness-based Agent Transparency**

**Level 1: Goals & Actions**

*Agent's current status/actions/plans*

- Purpose: Desire (Goal selection)
- Process: Intentions (Planning/Execution); Progress
- Performance
- Perception (Environment/Teammates)

**Level 2: Reasoning**

*Agent's reasoning process*

- Reasoning process (Belief/Purpose)
- Motivations
  - Environmental & other constraints/affordances

**Level 3: Projections**

*Agent's projections/predictions; uncertainty*

- Projection of future outcomes
- Uncertainty and potential limitations; Likelihood of success/failure
- History of Performance

**Figure 11: The situation awareness-based agent transparency model (from [55])**

all SAT levels required by each stakeholder for a reliable and efficient collaboration.

Although avoiding errors in automation is crucial, not all errors can be prevented. Automation errors such as missed and false alarms or misdiagnoses can be defined as events that make "the automation behaves in a manner that is inconsistent with the true state of the world" [56]. In the context of AEON, these errors, which can yield severe consequences, could create disruptions in airport ground operations resulting in queuing delays on airport runaways. Furthermore, external and unexpected challenges may degrade the condition in which human operators need to perform their tasks, and affect the performance of the automation [57]. To mitigate the detrimental consequences of imperfect automation, it will be essential to provide operators with control that allows flexibility and resilience of the automation [57], such as in adaptable systems where human operators are involved in the decision of what and when to automate [58].

High level of automation, low human engagement and teaming will require elaborated human-machine interfaces that support shared awareness between human and the autonomy to coordinate actions towards shared goals. The guidelines introduced in this section will serve as a design frame to elaborate novel and compelling interaction techniques that will ensure safe and efficient oversee of autonomous systems within AEON. However, the research on designing effective shared situation awareness in HAT is still young. The research and interaction design in AEON will contribute to establish novel shared situation awareness representations to enable effective collaboration between AEON stakeholders, and between humans and autonomy.

## 2.4 Summary and research directions

This section offered a comprehensive set of definitions, examples, guidelines and techniques to support the design of collaborative HMIs with the AEON project. We started by reviewing GroupWare and CSCW concepts, tools and examples in Air Traffic Control. We then investigated Situation Awareness and Distributed Situation Awareness to cover how information needs to be exchanged and maintained between all participants so that the teamwork is effective. We concluded with a review of Human Automation Teaming as the collaboration in AEON will involve not only humans but also intelligent agents such as planning algorithms or autonomous towing vehicles. Such context introduces subtle changes and provide additional guidelines to support the design of an effective solution. Below we summarize several Research Directions that we need to explore during the AEON project.

### Research Directions:

In order to provide efficient and reliable interaction techniques that will support collaboration between humans and autonomous agents optimally, the research related to Human-Machine collaboration aspects in AEON will be twofold.

The first research axis will aim at understanding the role and the contribution of each stakeholder in taxiing operations at airports. Alongside with identifying and documenting all the tasks performed by the operators, a specific focus will be given to investigate all the explicit and tacit communication processes that come into play to support situation awareness and limit workload for each operator. We will also examine the effect of plane towing automation on operators' activities in order to identify the mechanisms linking the input and the output that will change for each operator, and the new issues that will need to be addressed in the future of airports ground operations.

The second research axis will aim at providing usable interaction techniques and interactive systems that will support distributed situation awareness in human-automation teaming and facilitate rapid decision and tactical collaboration. This state-of-the art will provide us with a framework to emphasise situation awareness support between all the human and autonomous workers in our design approach. In addition, we will tailor our approach to the specific context of AEON through user-centred design in order to create and evaluate innovative and efficient representations of information and interactive controls in stakeholders' digital monitoring tools that will take advantage of human senses and humans' ability to understand complex situation rapidly through multimodal and feedback. This will allow operators to maximise taxiing operations flow and manage fleet of taxis and aircrafts.

# 3 State-of-the-art on Multi-agent Path Finding

Airports can be characterized as complex, dynamic, and unpredictable environments. Multiple users such as aircraft and ground vehicles have to reach their individual goals while sharing a limited amount of resources such as runways, taxiways, and gates. Some of these goals might even be in conflict with each other. To reach all individual goals in a safe and efficient manner, it is important that the activities of all users are well planned and coordinated with each other. This is especially true for a distributed system aimed at providing conflict free and efficient paths along the airport's surface. The field of multi-agent systems (MAS) which deals with this problem is called multi-agent planning and scheduling [59]. Several algorithms have been introduced over the years. It is known that the success of these is highly dependent on the environment and constraints that are imposed and that the applicability of every planning mechanism has its limits [60].

In this section, an overview and comparison of multi-agent path planning and related techniques will be provided. In section 4.1 the problem of multi-agent planning and its special case multi-agent path planning (MAPP) is introduced. In section 4.2 the family of A*-based multi-agent planning approaches will be provided. Rule-based planning approaches are reviewed in section 4.3. Reduction-based approaches are considered in section 4.4. Two level path planning approaches are reviewed in section 4.5. In section 4.6, the reviewed families of approaches are compared, and promising techniques will be identified to be considered in this project.

## 3.1 Multi-agent Planning and its special case Multi-agent Path Planning

An agent is an autonomous entity that is able to make decisions and interact with the environment and other agents. A *multi-agent system* consists of a set of agents, interacting and coordinating with each other to achieve goals that a single agent is not capable of achieving.

Multi-agent coordination is defined as the managing of interdependencies between agent activities [61]. An interdependency is defined as the relationship between a local and a non-local task where carrying out one task affects the performance of the other [61]. In a typical coordination problem, the agents must decide on an appropriate set of actions to achieve their goals, in the presence of other agents' goals, distribute the limited resources available between them and execute their actions. Weerdt et al. [59] define the multi-agent planning problem as follows:

*Given a description of the initial state, a set of global goals, a set of (at least two) agents, and for each agent a set of its capabilities and its private goals, find a plan for each agent that achieves its private goals, such that these plans together are coordinated and the global goals are met as well.*

Based on a study performed by Durfee [60], Weerdt et al. [59] identified the following phases towards solving a multi-agent planning problem:

1. **Global task refinement**: Global goals and tasks are refined to the point where subtasks remain which can be assigned to individual agents.
2. **Task allocation**: Allocating of these subtasks to the agents.
3. **Coordination before planning**: Defining rules or constraints for the individual agents which prevents them from producing conflicting plans.
4. **Individual planning**: Making a plan for each agent individually so that it reaches its goals.
5. **Coordination after planning**: Coordinating the individual plans of the agents.
6. **Plan execution**: Execution of the plans and generation of results.

Additionally, the authors stress that not all phases need to be completed in order for multi-agent planning to be realized. For example, phases 1 and 2 can be skipped if there is no common goal between the agents.

According to Durfee [60], three fundamental strategies in multi-agent planning problems are coordination before planning, coordination after planning and coordination during planning (i.e phases 4 and 5 run simultaneously). Coordination before planning aims at resolving all possible conflicts between agents before their local plans are constructed. This can be achieved in either of the three following ways:

1. Defining a set of rules that specify the allowed actions of the agents at specific scenario (social laws).
2. Assigning tasks to agents that will not interfere with the goals of other agents (task assignment).
3. Adding constraints on the task assignment so that the resulting action will be conflict-free (coordination by design).

In coordination after planning the idea is to merge all local plans and schedules by taking into consideration all possible combinations and orderings and subsequently use coordination mechanisms to resolve the found conflicts, if any. The revised plans are then communicated to the agents. This approach yields in a somewhat centralized way of planning as a dedicated agent is responsible of gathering the plans of other agents and executing the coordination mechanism. The Conflict-based Search (CBS) algorithm used by Fines [62] belongs in this category. Lastly, coordination during planning entails the sharing of plans between the agents and the continuous re-planning of activities when conflicts are found. The continuous exchange of information between agents can be done at different levels of hierarchy:

1. **Centralized planning for decentralized plans**: Plans are created in a centralized way (i.e. one agent creates sub-plans for each agents and monitors the progress). An example is the Partial Order Planning algorithm [63].
2. **Distributed planning for centralized plans**: Cooperative agents each contribute a part of their plan such that a global plan can be formed.
3. **Distributed planning for decentralized plans**: Agents have partial representation of other agents' plans and use this information to update their plans in view of improving the global plan. An example framework of this is the Generalized Partial Global Planning [64].

**Multi-agent Path Planning (MAPP)** is a sub-field of multi-agent planning which deals specifically with the planning of non-conflicting paths. Applications can be found in various fields such as robotics

[65], computer games, and transportation [66]. The literature on MAPP contains a wide body of algorithms with varying performance and complexity. Some of these algorithms are explicitly designed to solve for path finding (PF) problems, which are a subset of MAPP. The following MAPP problems are found in the literature: Cooperative path finding (CPF) [67]–[70], Multi-agent path finding (MAPF) [71]–[74], Multi-agent path planning (MAPP) [75], [76] and Multi-robot path planning (MRPP) [77]–[79]. Generally speaking, these approaches trade solution quality, completeness and scalability [76]. A commonly made distinction is between decoupled (or distributed) and coupled (or centralized) approaches [80]. In the former case, the planning task is decomposed into independent problems for each agent and agents plan separately for their path. It is a fast and scalable approach, but leads to non-optimal solutions and in most cases incomplete. Decoupled approaches usually solve the MAPP problem in three phases [75]. First, individual plans are computed with respect to static obstacles and without considering the paths of other agents. In the second phase, agents are prioritized with respect to when their plans are to be revised. In the last phase, the individual plans are revised based on the priority list defined in phase two. In a centralized setting, all agents are planned together. This can result in complete and optimal solutions at the expense of computational power, because finding a solution becomes exponentially hard with increasing number of agents.

In the following sections we review a number of classical path planning approaches which were used in the context of multi-agent path planning.

## 3.2 A*-based multi-agent planning approaches

Multi-agent path planning approaches which are based on the A* algorithm and its extensions are discussed in this section.

### 3.2.1 Cooperative A* search

In Cooperative A* (CA*) algorithm [69], first A* searches for every single agent are performed. After the path of each agent is determined, the states along the path are written in a three-dimensional reservation table such that they are avoided in subsequent searches made by other agents. According to Silver, CA* is not able to solve certain classes of problems. The problem arises when a greedy solution of one agent prevents finding a solution for another agent. A variation of CA* is the hierarchical CA* (HCA*). This algorithm is similar to the CA* but uses the abstract distance heuristic to perform the A* searches. This algorithm executes a modified A* search in a reversed fashion. After a path is found, the algorithm reserves the series of points of the path in the reservation table. Conflicts are thus avoided by disallowing agents to use paths already reserved by previous agents. The order by which agents reserve paths in the reservation table is chosen randomly [72]. The latter presents an issue in which the algorithm may not be able to find a solution for a given prioritization scheme. This makes HCA* incomplete.

Both CA* and HCA* compute paths before plan execution using a full depth cooperative search. In a scenario where the state space is large, their usability is limited. Silver introduced an online variant called windowed HCA* (WHCA*) to shorten the global search and to limit the prioritization issue of

HCA*. Within that window a partial path is calculated for each agent and filled in the ⍰-sized reservation table. Agents start following their partial paths and after a time interval, the window is shifted forward and a new cycle of partial paths is calculated. WHCA* returns less optimal solutions than the HCA* but is more applicable to real-time applications, since agents plan for the next ⍰ steps, which significantly reduces the size of the reservation table. A downside of WHCA* is that it does not consider conflicts that might occur between agents. An agent might reserve ⍰ points without knowing whether these points are required by another agent or not. Like HCA*, WHCA* also suffers from incompleteness [72].

Bnaya and Felner [72] continued the work of Silver and introduced a variant of the WHCA* which takes conflicts into account (conflict orientation WHCA* (CO-WHCA*)). CO-WHCA* has more flexibility in placing the window where the paths of the agents are reserved. This allows agents to be at most ⍰/2 steps away from the conflict and agents who are not allowed to use the conflicting path have enough time to find an alternative. This is in contrast to WHCA* where agents have to plan right before the conflict occurs. The authors also presented a version of CO-WHCA* that uses a prioritization scheme (CO-WHCA*P) which prioritizes the agents that use the reservation table.

This algorithm showed higher performance than WHCA* in terms of success rate and solution cost. CO-WHCA*P had the highest execution time since it needed to consider all possible combinations of agent prioritizations.

### 3.2.2 Standley's improvements

Standley [70] introduced two improvements to the standard A* algorithm for solving the cooperative path finding problem. Operator decomposition (OD) considers a representation of the state space in which each timestep is divided into the number of agents, so that each agent is considered one at a time. This distributed approach allows the A* search to reduce the amount of surplus nodes generated. The method is able to achieve up to an exponential reduction in computing costs while determining conflict free paths, but the technique is still exponential in the number of agents. Furthermore, Standley argues that A* with OD is also admissible and complete.

The second technique aims at improving the performance of the OD. Independence Detection (ID) works as follows. The algorithm first assigns each agent in a group and finds a path, using OD, for each agent independently. The found paths are then simulated. If a conflict is found during the simulation, a new path is determined for one of the conflicting agents which should not conflict with the original agent. If the process of finding a new path fails, it is repeated for the other conflicting agent. In case both searches fail, the agents are merged into a group and a path is planned for this group. All new paths are found using a conflict detection table. The approach achieves an exponential reduction in computation costs.

Although both approaches reduce the computing costs, the resulting optimal OD+ID algorithm, as Standley notes, has still a computing time that is expensive for real-time applications. The algorithm is able to increase the performance of the standard A* algorithm by a considerable amount. However HCA* performs better than OD+ID on average in terms of both success rate and computational costs.

### 3.2.3 Approximate and optimal anytime algorithms

Standley and Korf [81] proposed a complete algorithm, called Maximum Group Size (MGS) that deals with OD+ID's drawback of high runtimes. By dynamically removing constraints in the original OD+ID specification which make it optimal, the algorithm is able to trade optimality for computing time. In an experiment with 150 agents, MSG with agent group of size equal to one, solved 99.92% of the problem instances in less than a second, while HCA* only 47.01%. The OD+ID was not able to solve any instance.

Later, MGS was adapted to an optimal anytime algorithm (OA-MGS) which is more suitable for real-time applications. The anytime algorithm can be terminated at any time and the best computed solution up to that point can be retrieved. This is performed via a method called Iterative Deepening. The method uses information computed in past iterations for calculations for subsequent iterations which results in lower runtimes. The optimal anytime algorithm can achieve a performance similar to the OD+ID, and return a good quality solution even when terminated earlier.

## 3.3 Rule-based planning approaches

Rule-based approaches use rules that define the properties of the agents, their environment and/or the interaction between them. Unlike the algorithms in the previous section, rule-based approaches usually do not involve an A* search to expand nodes in the search space. Typically, these methods find a solution relatively fast but often it is suboptimal.

### 3.3.1 Push and Swap algorithm

Luna and Bekris [68] introduced a suboptimal algorithm for solving the cooperative path finding problem and named it Push and Swap (PS). The algorithm can be applied to problems with □ − 2 agents in a graph with □ vertices. Two operations are used in the algorithm. During a □□□□ operation, an agent forces other agents to move away from its shortest path (by "pushing" them) and then proceeds with following that path. Certain scenarios are harder to solve and only pushing will not suffice. Such scenarios require agents to switch positions, and this is accomplished with the □□□□ operation. □□□□ brings the two agents in a location of the graph which contains two empty vertices so that the swap can take place. While doing so, other agents might have to move to other locations and then return to their original positions after the swapping has taken place. Although the algorithm was initially shown to be complete on problems with two unoccupied vertices, De Wilde et al. [82] showed that its completeness cannot be guaranteed in certain scenarios. The algorithm was compared with Silvers's WHCA* [69] (with window sizes of 8 and 16) on a number of scenarios including a randomly populated grid with 20% obstacles. PS resulted in a higher success rate and lower computation times.

### 3.3.2 Tree-based agent swapping strategy

Khorshid et al. [83] introduced a tree-based approach for solving MAPF problems called the tree-based agent swapping strategy (TASS). It is a rule-based centralized algorithm which is shown to be complete only for tree graphs. TASS guarantees finding a solution in polynomial time but suboptimal in nature. The approach shares some similarities with the PS algorithm explained above. Firstly, both of them perform a swapping operation, secondly they can solve only for certain graph topologies, and thirdly they find sequential paths where one agents is moved at a time.

### 3.3.3 Push and Swap variants

A PS variant which returns solutions in which agents are moved in parallel was introduced by Sajid et al. [84]. Parallel Push and Swap (PPS) was shown to find solutions as fast as PS and of quality similar to the optimal anytime algorithm of Standley and Korf [81]. In a later research, DeWilde et al. [85] proposed Push and Rotate, a PS variant which deals with the drawbacks of the PS as presented in [82] and guarantees completeness in graphs with at least 2 unoccupied vertices. In the pre-processing phase of the algorithm, the graph is divided into subgraphs to which agents are allocated. Agents allocated to the same subgraph are allowed to perform swapping operations with each other. In the last step, agents are assigned a priority based on which they are planned. During the movement phase, a shortest path is computed for the agent first in the priority list and subsequently the agent is moved towards that path. At the event in which an agent is blocking the moving agent's path and the blocking agent has a lower priority, the latter is pushed to an empty vertex. Otherwise, a swapping operation is performed. The algorithm is also able to detect and solve instances in polygons something which PS failed to do. It does so using a rotate operation.

An important point to notice is that these algorithms assume that the agents are flexible to move in every direction. For example, in order to perform a swap operation agent must change their direction of movement within one step. This in turn makes their applicability to airport surface movement operations challenging. The infrastructure at a given airport might pose certain constraints in the movements that aircraft are allowed to do. A swap operation would require aircraft to be able to perform U-turns which is only possible in certain locations on the airport's surface. Reaching those locations would potentially increase the total travel distances and times, resulting in less efficient overall operations. The ruled based approaches are not as flexible as other approaches presented in this chapter and will therefore not be considered in the trade-off later on.

## 3.4 Reduction-based approaches

Approaches that aim to reduce the MAPF problem into a simpler problem, which is then solved using other more classical techniques, are called reduction-based approaches.

### 3.4.1 Constraint Satisfaction Problem-based methods

Real world maps usually have underlying structures. For example, in airports long taxiway segments are normally placed parallel to the runways, and intersections are found in locations close to the terminals.

This motivated Ryan to propose a technique for reducing the size of search using domain information [77], [86]. His method is based on exploiting the structure of a given problem and decomposing it in subgraphs such as stacks, cliques, halls and rings. A search using these subgraphs allows for a more informed pruning of the search space without sacrificing completeness. Subsequently, this new knowledge is encoded as a constraint satisfaction problem. Basically, the problem is encoded in integer variables over finite domains, and constraints which describe the relations between the variables that need to be satisfied. A prioritization in the variable assignment can also be incorporated. This allows for more constrained variables to be dealt earlier in the search thus limiting the amount of backtracking when the assignments fail to satisfy the constraints. A variable assignment which satisfies all constraints presents a complete plan.

Ryan tested his approach and concluded the following: First of all, the problem decomposition into subgraphs combined with the informed search resulted in the highest rates of success. Note, however, that for easy problems the planner which considers map abstractions is 20-30 times slower than the planner without any abstractions. For harder problems, the abstract planner takes 0.25-0.30 of the time of the planner without abstractions. A prioritized variable assignment always yields a higher success rate but costs more to compute.

This approach can be considered suitable to be applied in airports as their lay-outs can easily be decomposed into subgraphs. However, it has not been compared with other path planning algorithms; therefore, it is difficult to draw conclusions about this algorithm.

### 3.4.2 SAT solvers

Surynek [87], [88] introduced a different approach for solving the cooperative path finding problem. His approach is based on reducing the cooperative path finding problem into a Boolean (or propositional) satisfiability problem (SAT). In such problems, the goal is to determine whether an interpretation that satisfies a given Boolean formula exists. If it exists, it means that replacing the variables in the Boolean formula by TRUE and FALSE will result evaluating the formula as TRUE. Such a problem is called satisfiable. Once the Boolean formula is constructed, a SAT solver is used to find the solution. The challenging part is how to effectively encode a given collaborative path finding problem to a Boolean formula. Surynek's work aims to answer this question by investigating several types of encodings. To create a propositional representation of an agent's trajectory over time, Surynek uses Time Expansion Graphs (TEG). Put simply, a TEG is a graph representation of a temporal trace that captures all possible movements of agents over a graph, at all timesteps, up until a goal is reached. Finding the solution means searching for non-overlapping vertex disjoint paths in a TEG consisting. Reduction based algorithms such as SAT, typically suffer from high running times.

In a later research, Surynek et al. [87] presented a method for reducing the computing time of SAT based approaches. Their adapted SAT based approach, called MDD-SAT, focused on solving MAPF problems with respect to the sum of costs objective. MDD stands for Multi-value Decision Diagram

(MDD), a type of data structure which was used to reduce the size of the TEGs. Instead of considering all states for all timesteps as done in the TEGs, only the vertices and edges which result into valid paths are considered in the MDDs. According to the authors, this can lead to a reduction of variables in the model of up to two orders of magnitude. The approach was tested on different maps against other optimal methods such as the EPEA*, ICTS and ICBS. On one of the maps which has similar properties to an airport's taxiway environment such as corridors and bottlenecks, MDD-SAT still suffered from large overheads when compared to ICTS and ICBS.

Continuing in this research line, Surynek et al. [89] later proposed two suboptimal variants of the MDD-SAT, namely uMDD-SAT and eMDD-SAT. The former is the unbounded and the latter the bounded variant. The bounded variant returns a solution with cost less than or equal to $(1-\epsilon)\,C*$, where $C*$ is the optimal solution and $\epsilon$ is a user defined parameter which specifies the degree of suboptimality.

eMDD-SAT was tested against the suboptimal Push and Swap [68] and ECBS [71] algorithms. ECBS is a bounded suboptimal variant of Conflict Based Search, a two-level MAPF solver presented in the next section. In tests on a map, which has structural similarities with airports, it was found that ECBS performed the best in terms of both solution quality and execution time.

## 3.5 Two-level-based multi-agent planning approaches

In this section algorithms with two-level-reasoning will be discussed. Usually, at the top level a global search is performed and at the lower level the search is further refined. Algorithms from the M* and the CBS families belong in these categories and a discussion of these follows.

### 3.5.1 M* algorithm

Wanger and Choset [79] proposed M*, an algorithm which combines the properties of both coupled and decoupled approaches. On the top-level decoupled planning is used to compute single agent paths using the A* algorithm. For the paths which are found to conflict, at a later time point, a joint state space search (coupled planning) is performed again using the A* but for the conflicting agents only. So unlike A*, M* does not consider the regions of the spate space which have no conflicts. Furthermore, M* expands less nodes from the OPEN list than A*. Similarly to A*, however, its computational cost increases exponentially with the number of colliding agents. The authors also show that M* is both optimal and complete. Following the idea of trading optimality for runtime, one can inflate the cost heuristic used in the M* by a value $\epsilon > 1$ and end up with the so called Inflated-M*. Recursive M* (rM*) is an optimal variant which improves M*'s performance when dealing with physically separated, but simultaneously coupled sets of agents, resulting in a computational cost which is exponential not in the number of colliding agents but in the size of the largest set of mutually colliding agents. It does so by splitting the agent collision set maintained in the original M* into independent subsets for which planning is performed separately. The method is similar to the ID framework discussed above but it does not keep the robots in the same set after a collision is resolved as is done in the ID. Running experiments on a grid with a density of 104 cells per agent and each cell having a 35% probability of being an obstacle, it was shown that inflated-recursive M* has the best performance in terms of success rate, runtime and scalability.

In Wanger [90] the author presented the ODM* and EPEM* by replacing the A* with M* in the OD and EPEA* algorithms. When tested on a 32x32 grid with a maximum of 60 agents, the ODM* and EPEA* scored better in terms of success rate and runtime than A*, OD, M* and EPEA*. Their recursive variants ODrM* and EPErM* scored even better with the two of them having a very similar performance. Their suboptimal variants i-ODrM* and i-EPErM* showed an even more promising performance yielding higher success rates and runtimes. In terms of implementation i-ODrM* can be considered more straightforward to implement as opposed to i-EPErM* which is built on the EPEA* and requires the definition of a domain specific operator selection function (OSF).

### 3.5.2 Increasing cost tree search method

Sharon et al. [91] developed a centralized two level framework called Increasing Cost Tree Search (ICTS) which solves MAPF optimally. Every node $s$ in a cost tree consists of a $k$-vector of individual agent costs ($k$ is the number of agents). The root (1st level) of the cost tree consists of the optimal costs of the agents' paths which are computed assuming that no other agents exist. The second level of the tree consists of nodes (child nodes) in which a unit cost is added to the cost of one agent.

A node in which there is a complete non-conflicting solution for all agents is considered a goal node. The top level searches the cost tree in a breadth-first manner. The low-level checks whether a node $s$ is a goal node. This is accomplished by storing all individual agent paths in a data structure called multi-value decision diagram (MDD). The cross product of the MDDs returns $k$ non-conflicting paths for the agents. The ICTS was found to outperform Standley's OD+ID framework based on A* in terms of both success rate and runtime when tested on maps similar to airport maps. The authors also presented a number of pruning techniques aimed at removing non-goal nodes already from the high level so that the activation of the low-level search is avoided. These techniques outperformed the basic ICTS in terms of runtime [91].

### 3.5.3 CBS family

A state of the art algorithm for MAPF called conflict based search (CBS) was proposed by Sharon et al. [78], [90]. CBS can be considered as both a coupled and decoupled approach. It guarantees finding an optimal solution while the pathfinding is done via single agent searches just like in the other decoupled approaches. Plan coordination in this context is performed through the merging of the individual plans of the agents.

CBS works on two levels. The high level searches the nodes of a constraint tree (CT) for conflicts via a best first search. A constraint tree consists of a set of constraints which prevent an agent from occupying a vertex at a specific time point, a solution which consists of all individual agent paths and a total cost which sums all individual agent path costs. If a conflict is determined at the high level, the node is declared as a non-goal node and is split into two child nodes, each having their own constraints. The nodes are then processed by the low level which tries to find paths for individual agent that are consistent with the newly assigned constraints. This is also done in a best first search manner.

The new paths aim to avoid the conflict point either by making the agent move to an adjacent node or by making it wait at a current node. The authors used the A* algorithm to perform the single agent searches. After the node has been processed by the low level, a high-level search is run again in order to validate the node. If after the validation no conflicts are found, the node is declared as a goal node and the solution is found.

The authors tested the CBS on a number of maps against other optimal algorithms. They concluded that the performance of the CBS depends on the structure of the environment. More specifically on maps similar to airports, CBS was found to outperform both ODA* and ICTS with pruning (ICTS+3E).

### 3.5.4 Meta-Agent CBS

A CBS-based framework was introduced by Sharon et al. [80] as a first step towards dynamically adapting algorithms. The authors note that the high-level search of CBS is exponential with the number of conflicts encountered as opposed to the number of agents in A*-based approaches. This makes CBS to perform poorly in highly coupled environments. Meta-agent CBS (MA-CBS) aims at improving this behaviour by automatically identifying agents which are strongly coupled and merging them into a single agent instead of performing a split action. Once the merging is performed, the low-level search is run for this meta-agent using any optimal MAPF solver. The decision to merge or split is defined as the merging policy. The authors use the number of conflicts parameter B to do this. If, for example, two agents have the number of conflicts greater than a conflict bound, then these agents are merged into a meta-agent. If the conflict bound is set to 0, then algorithm behaves similar to Standley's ID framework described above. If on the other hand the number of conflicts is equal to infinity, the algorithm behaves like the basic CBS.

MA-CBS was tested under the same conditions as those in which CBS was tested. The algorithm showed the most improvement for the maps with open spaces. In airport like maps the MA-CBS had a slightly superior performance than the basic CBS.

### 3.5.5 Extensions of CBS

Boyarski et al. (2015) presented a variant of (MA-)CBS called Improved CBS (ICBS) by introducing three new improvements to the basic implementation:

- Merge and restart (MR): When a merge decision is made for a set of agents inside a CT node, the CT node is discarded and the search is restarted from the root node. In the new search however the agents are merged from the beginning. This results in computational savings.
- Prioritizing conflicts (PC): The conflicts are classified in cardinal, semi-cardinal and non-cardinal and are hierarchically solved based on their class.
- Bypassing conflicts (BP): The split action is not immediately performed on the conflict node. It is be possible that the path of one of the agents is modified and therefore would bypass the conflict.

This reduces the size of the CT and saves a significant amount of search from being performed.

The authors tested ICBS on different maps against other optimal algorithms like Sharon et al. [80], [92] did in their own work. For the airport-like maps ICBS performs somewhat similar to the other approaches. The benefit of the three improvements is well seen when examining the runtime performances. It takes less than 5 seconds in the worst case of having 80 agents for the algorithm to return a solution, outperforming by almost a factor of 3 the next best performing algorithm.

In a more recent study, Felner et al. (2018) introduced ICBS-$h$, an enhanced version of ICBS. At the high level of CBS a best-first search on the CT is performed where the nodes are ordered by their costs. Nodes to be expanded and processed by the low-level are therefore prioritized based on their costs. The authors wanted to add admissible heuristics to the priority of the best-first search in order to make it more informed. Out of the four heuristics introduced, the ICBS-$h$ was found to perform the best. When tested on airport-like maps against the basic ICBS, both resulted in a similar performance in terms of success rate. The former, however, had up to 2-3 times better performance in terms of runtime and number of nodes expanded.

Hang Ma et al [93] proposed a method to incorporate prioritization in CBS, called Priority-Based Search (PBS). PBS performs a depth-first search in a Priority Tree, rather than a best-first search in a conflict tree. This means that the algorithm of PBS constructs a priority order, rather than a tree of constraints to find a solution. The other principles of CBS remain largely unchanged, meaning that the nodes of the search tree still maintain a set of plans and a cost value. In the lower-level of PBS, the priority order is, just like in the CA* algorithm, used to plan consecutively conflict free paths.

### 3.5.6 Suboptimal variants based on CBS

Barer et al. [71] introduced a number of suboptimal CBS variants. Optimality in CBS is guaranteed by running optimal best-first searches at both high and low levels. The high-level searches for the CT goal-node with the lowest cost, and the low-level searches for an optimal single agent path that satisfies the agent’s constraints. Nodes which have solutions very close to the optimal but not optimal are disregarded. This causes scalability and runtimes issues when the number of agents is high (> 50).

Greedy-CBS (GCBS) is an unbounded suboptimal variant in which the high- and/or low-level searches are relaxed, favouring the expansion of nodes which yield valid solutions fast. The degree of suboptimality is not specified, hence the term ’unbounded’. The high-level search is relaxed by prioritizing CT nodes that seem closer to the goal node. To do so the authors developed a number of conflict heuristics which allow the high-level search to select first less conflicting nodes. Although the authors experimented with different heuristics, results were only provided for the number of pairs heuristic which counts the number of pairs of agents that have at least one conflict between them. To relax the low-level search, a similar method was used. In the basic CBS, the low-level search finds the shortest individual path that satisfies the agent’s constraints. The authors adapted the low-level search by using a best-first search instead, A* in this case, that prioritizes paths based on the value of the conflict heuristic.

Three variants of GCBS were tested, namely GCBS-H which uses the conflict heuristic on the high level and standard A* on the low level, GCBS-L where CT nodes are prioritized according to their cost in the high level and the conflict heuristic is used at the low level and GCBS-LH which uses the conflict heuristic for both levels. The GCBS-LH was shown to perform the best with solutions within 5% of optimal. No results in terms of its runtime performance were provided.

In addition, two complete bounded suboptimal variants were introduced, namely Bounded-CBS (BCBS) and Enhanced-CBS (ECBS). Both algorithms use focal searches to return bounded suboptimal solutions. A focal search contains two lists of nodes: OPEN which the regular OPEN list of A* and FOCAL which contains a subset of nodes from OPEN. The FOCAL list uses two functions to determine the nodes in FOCAL.

In BCBS focal searches are used at both levels of CBS. The authors prove that BCBS is able to find a solution with the cost at most $w \cdot C^*$, where C* is the cost of the optimal solution. The ECBS deals with the issue of how to find the best value for w. ECBS is a $w$-suboptimal variant of CBS whose both levels use also focal searches. The advantage of ECBS over BCBS is its additional flexibility in the high-level search, once the low level finds low cost solutions. When compared to other bounded suboptimal CBS versions on airport-like maps, ECBS was able to maintain a success rate of 100% even with 70 agents while CBS could not solve any of the tested instances. This shows that relaxing the optimality of CBS and bounding it with a certain factor and additionally incorporating focal searches, significant improvements in success rates can be obtained. ECBS was also compared to previously introduced bounded suboptimal path finding algorithms, including M* variants and A*-based approaches. Results showed that ECBS with a suboptimality factor of 1.1 outperformed all algorithms. The authors did not provide any figures related to their respective runtimes but made the following conclusion in terms of the GCBS and ECBS. If the goal is to achieve solutions as fast as possible which can potentially be of high cost then GCBS is an ideal candidate. If on the other hand stability, reliability and solutions guaranteed to be bounded are of importance then ECBS is a more appropriate candidate. For surface movement operations where global goals include the reduction of the environmental footprint and taxiing delays, solutions not far from optimal are preferred.

Cohen et al. [94], [95] introduced a variant of ECBS with highways (ECBS+HWY). Using an inflated heuristic in the low-level search, the planning is biased towards paths that contain links from the user-defined set of highways. In experiments performed with 150 agents in grid-like environments, ECBS+HWY outperformed ECBS in terms of both runtime and solution cost. In a later paper Cohen et al. [95] developed iECBS. Similar to ECBS+ HWY it uses a focal search with a highway heuristic but has only one parameter which makes tuning easier. When compared to ECBS in a grid-like environment with the same suboptimality factor, iECBS was found to have lower runtimes. In addition, two algorithms for automatically generating highways were introduced.

In analogy to the windowed approach used in WHCA* and its variant CO-WHCA*, Li et al. [96] describe the necessary alterations to different regular MAPF solvers to incorporate this method. For Bounded-Horizon (E)CBS, only the high-level search needs to be adapted. Additionally to that, the low-level search of PBS is adapted to be like Bounded-Horizon CA*, which is identical to WHCA*. In all adapted versions, conflict resolution is done only up to a pre-defined time horizon $w$, while conflicts beyond that limit are ignored. This decreases the search space and therefore results in a lower runtime of the path finding algorithm. Moreover, the authors use this approach in their

Rolling-Horizon Collision Resolution (RHCR) framework, which they apply to an automated warehouse environment with repeatedly new goal locations assigned to the agents. Besides the bounded-horizon parameter $w$, the authors introduce the pre-defined replanning period $h$ in RHCR, which specifies the amount of timesteps before the paths are replanned. In contrast to replanning every timestep, running the MAPF solver once every $h$ timesteps further reduces its runtime. Despite that, $w \geq h$ must be ensured to avoid unsolvable conflicts. Furthermore, to avoid idle agents, enough goal locations must be pre-assigned so that each agent's total planned traversal time exceeds $h$. Based on empirical results, the authors were able to show that RHCR produces high-quality solutions up to a very high number of agents, greatly outperforming other algorithms. More specifically, the authors concluded that RHCR using bounded-horizon PBS generates significant faster solutions than bounded-horizon CBS, ECBS and CA*, for the same number of agents and search window length. The method has improved scalability, and performs only little more worse in terms suboptimality compared to bounded-horizon CBS and ECBS. However, RHCR has not been tested on airport-like maps. A key difference to their use case is that in airport-like environments new agents may appear during the replanning period $h$. With an $h$-value greater one timestep, this could lead to non-anticipated collisions with existing agents. Nonetheless, using a windowed (E)CBS or PBS approach is a promising way towards enabling a more real-time applicability of the path planning also for a complex environment like airports.

### 3.5.7 Sampling based approaches

Sampling based algorithms are a class of motion planning algorithms that find conflict-free paths by sampling points from a state space. Their ability of finding solutions quickly in high-dimensional motion planning problems has made them quite popular in the motion planning community. Among the most famous sampling based algorithms are algorithms based on rapidly exploring random trees (RRTs) [97].

The RRT algorithm iteratively builds a tree of states by randomly sampling states from the state space. When a new state is sampled, an attempt is made to connect the newly sampled state to the nearest vertex of the tree. If such connection is not possible, a new state is then randomly sampled. The algorithm runs until the goal vertex is reached. Once it is reached, the edges of the tree are backtracked and the path from start state to goal state is returned. RRTs have been proven to be probabilistically complete, meaning that the probability of not finding a solution tends to zero as the number of samples increases. A disadvantage of RRTs is that they do not make any guarantees regarding the optimality of the solutions.

The problem was addressed by Karaman and Frazzoli [98] by introducing RRT*, an adapted anytime version of RRT which instead is proved converge to optimal solutions. The main difference with the RRT* is that when a solution is found, the algorithm does not stop but continues to draw new samples from the state space. The tree is therefore extended, new regions of the state space are explored and new low-cost paths are discovered.

Cáp et al. [99] introduced the multi-agent version of RRT* (MA-RRT*) which is able to solve cooperative path finding problems. MA-RRT* builds on top of Graph-RRT*, a modified version of RRT* suitable for motion graphs on which agents move. MA-RRT* samples the agents' joint state space in a uniform manner. The authors note that for sparse instances of cooperative path finding problems, the global solutions consist of paths which are usually similar to the optimal paths of the individual agents. To further increase the performance of MA-RRT* they proposed the informed-sampling MA-RTT* (isMA-RRT*) algorithm in which the sampling strategy is biased towards regions of the agents' state space which are close to the optimal single-agent paths. The isMA-RRT* algorithm works as follows: Single agent paths are first found using Graph-RRT*. Once the paths are found, MA-RRT* is run using a sampling function which draws samples from the Gaussian neighborhood of these single-agent paths. The performance of MA-RRT* and isMA-RRT* was compared with A* and Standley's OA algorithm. Tests were performed for varying grid sizes and numbers of agents. For these experiments, a runtime limit of 5 seconds was set. The results indicated that MA-RRT* versions did not only solve instances quicker but were able to solve far more instances than the A* and OA algorithms. In particular, isMA-RRT* was able to solve 77% of the instances. The authors also looked at the suboptimality of the first valid solutions and best valid solutions, for the instances were either A* or OA found solutions. It was observed that when the algorithms were left to run, the best solutions converged to suboptimality factors very close to the OA.

Sampling based approaches form an alternative to the traditional search-based approaches introduced earlier. isMA-RRT* in particular was demonstrated to perform well on grid-like maps when compared to the basic A* and Standley's OA. However, its performance is not yet quantified on maps which resemble an airport's environment nor has it been compared to other state of the art algorithms for multi-agent path-finding.

## 3.6 Comparison of the multi-agent planning approaches

The comparison of the approaches is based on results related to their performance which were found in the literature. Note that not all approaches were directly compared to each other in the literature. The following criteria, relevant for AEON project, were used for the comparison:

- **Success rate**: The ratio of agents for which the algorithm was able to find valid, conflict-free paths.
- **Runtime**: The computational time it took for the algorithm to produce a valid solution. Algorithms with low runtimes are more suitable for real-time applications such as airport applications.
- **Solution cost**: Relates to how close the solution of a given algorithm is to the optimum.
- **Scalability**: Relates to how well the algorithms scale in terms of the success rate and runtime with increasing number of agents.

The best performing A* based approaches - CO-WHCA* and GIPP - produce suboptimal solutions. The former is a distributed online algorithm, while the latter is centralized. Although these two approaches were not directly compared in the literature, CO-WHCA* is considered to be more suitable since distributed methods scale better than centralized approaches. In addition, GIPP is more complex, since an optimization mechanism is applied after a solution to the path finding problem has been found.

The performance of two-level planning approaches ICTS with ICBS is similar [88]. In [73], however, ICBS scored higher than both ICTS and MA-CBS. However, ICBS scored lower than its most recent variant ICBS-H4 when tested on the same map. Taking these facts into account, the most promising multi-agent planning approaches are compared in the table below.

It can be seen that the three suboptimal variants of CBS, ECBS, iECBS and Bounded-horizon PBS have the best performance among the compared algorithms. iECBS is a better choice if it is applied to grid-like environments with highways. ECBS and Bounded-horizon PBS algorithms are more applicable to airport-like environments.

| Approach | Advantages | Limitations |
|---|---|---|
| **CO-WHCA*** | - Scalability | - Not complete<br><br>- Worse performance than GCBS and ECBS |
| **OA-MSG** | - Optimal<br><br>- Higher success rate than GCBS | - Tested only on grid-like maps |
| **GCBS** | - Low runtimes<br><br>- Always finds a solution | - Unbounded suboptimal |
| **ECBS** | - Good success rate up to 100 agents on airport-like maps<br><br>- Degree of suboptimality can be specified | - Runs faster than CBS but no exact figures are available |
| **iECBS** | - Runs faster than ECBS in grid-like environments<br><br>- Same suboptimality factor as in ECBS | - More applicable to grid-like environments |
| **ICBS-H4** | - Low runtimes (120-380 ms for 100 agents) on airport-like maps<br><br>- Better memory requirements than for CBS | - Has a lower success rate for 60 agents on airport-like maps than ECBS |
| **Bounded-horizon PBS** | - Explicit representation of priorities of agents<br><br>- Runs faster than ECBS and CA* | - A bit worse performance in terms of suboptimality than ECBS |

**Table 6: Comparison of the most promising multi-agent path finding methods**

# 4 State-of-the-art on operations research for the management of a fleet of towing vehicles

Electric taxiing and airport ground operations have been modelled extensively in the past years using operations research methods. A mixed-integer linear programming (MILP) is commonly used to model operations, while heuristics are proposed in case the computational time required to solve a MILP is high. Formally, a MILP problem is stated as:

$$\begin{gathered} max/\min c^T \cdot x \\ subject\ to\ A \cdot x \leq B \\ l \leq x \leq u \end{gathered}$$

where $c^T$ is a vector of costs, $x$ is a vector of decision variables, $A$ and $B$ are a matrix and a vector of coefficients, $l$ and $u$ are a lower and an upper bound respectively. Below we review several papers that have used operations research methods to model and analyse electric taxiing and airport ground operations.

In a recent study, Soltani et al [100] proposes a hybrid taxiing solution to reduce the airports' impact on Greenhouse gas emissions where part of the taxiing operations is handled by tow trucks powered by renewable energy, while the rest of the aircraft continue using their engines to complete taxiing. A MILP model is proposed for hybrid taxi operations of arriving and departing aircraft, with the objective to minimize fuel consumption and the total aircraft delays. A total of 205 aircraft are considered for the case study. The output of the model is the assignment of taxi vehicles, set of taxiways, pick-up time, and drop-off time. The main contribution is the incorporation of collision and conflict avoidance constraints. Different scenarios are demonstrated: no-towing, 100% towing, and hybrid towing (71% towed by tow trucks). Hybrid towing is deemed the best solution, considering the total cost and emissions (a 95% reduction in CO2 emissions is estimated). The models proposed, however, do not consider an optimal sizing of the fleet of towing vehicles. In fact, the size of the fleet of electric towing vehicles is expected to impact the on-time performance of the aircraft. In AEON we plan to determine optimal towing-vehicle fleet sizes. Moreover, this study does not consider the unavailability of towing vehicles due to charging, which we will address in AEON.

Du et al [101] addresses the composition of a fleet of towing vehicles at a strategic phase. An optimisation model, together with a Column generation approach, is proposed to determine an optimal towing-vehicle fleet size and mix, as well as to determine the time of buying, overhauling and selling vehicles. Several scenarios are considered for a fleet of 10, 25, 50, 75 and 100 aircraft considering several flight schedules. In contrast with the previous study, the authors do not consider the routing of the towing vehicles, but only the long-term strategic perspective. While this analysis provides insights into the volume of investment needed to introduce towing vehicles at a large European airport, the actual operation of the fleet of towing vehicles, charging needs and potential delays are not considered. In AEON, we aim to include the routing of the towing vehicles, which impacts the assignment of the towing vehicles to aircraft, which in turn impacts the size of the towing vehicles.

Han et al [102] proposes a MIP model to solve the ferry vehicle scheduling problem with the objective of minimizing the number of ferry vehicles. It also proposes a vehicle-sharing network. The problem of the minimum number of ferry vehicles is transformed into the minimum node-disjoint path cover problem of the ferry vehicle-sharing network and is eventually transformed into a network maximum flow problem to be solved. A case study for Beijing Capital International Airport (PEK) has been carried out to validate the model. Similar to this study, we also aim to build our optimisation models for a fleet of towing vehicles based on a network of taxiing ways, that connects the gates of the airport with the runways. With this, the problem of minimum number of towing vehicles is addressed.

Zhao et al [103] propose a bi-objective MIP model to minimize the number of towing trucks, while balancing the usage of these towing trucks during a day of operations. Only departing aircraft are considered. To solve this problem, the authors propose two algorithms that are based on standard particle swarm optimization: the lexicographic method, and the Pareto method. This methodology is evaluated in a case study for Beijing Capital International Airport (PEK). The results show that the lexicographic method was deemed the most suitable for this case. Also for this study, the authors aim to obtain an optimal routing of towing vehicles at the strategic level, whereas in AEON our goal is to assess the assignment of towing vehicles both at the strategic and tactical level, considering potential disturbances to the schedule.

Schiffer and Walther [104] propose a MILP model to optimized both the routing of a fleet of generic, commercial electric vehicles, as well as the battery charging moments and locations of the charging. These requirements are also relevant for electric towing vehicles. The objective is to minimize travel distances, the total number of vehicles used, the number of charging stations, and the total cost of using electric vehicles. Both partial battery charging, as well as charging at remote sites, are considered. This integrated approach of sizing the fleet of electric and specification of the battery charging moments are particularly relevant for electric towing vehicles. Similarly, in AEON we aim to consider the charging of the electric towing vehicles. During charging, the towing vehicles are unavailable for operations, leading to a need to have a large fleet of such towing vehicles.

Hiermann et al. [105] introduces the Electric Fleet Size and Mix Vehicle Routing Problem with Time Windows and Recharging Stations. This problem models the need for generic electric vehicles to charge, hence charging time and power constraints are added to the problem. The choice of charging stations is also included. To solve the problem for large instances, the authors propose a metaheuristic approach based on Adaptive Large Neighbourhood Search (ALNS) with embedded local search and labelling procedures. Although the proposed method does not solve the problem to optimality, the proposed hybrid heuristic is computationally efficient (ALNS with a limit of 2000 iterations reaches a solution in approximative 25min with the reported computers considered). In fact, for small problem instances (5-15 vehicles), the ALNS is able to find optimal solutions. Given that for AEON we consider large European airports such as Schiphol, we expect that when considering a realistic amount of taxiing operations, heuristics may be needed to obtain a towing vehicle-to-aircraft assignment. Such hybrid heuristics as introduced by Hiermann are identified as suitable for our approach in AEON.

Roling and Visser [106] propose an optimisation model for the routing and scheduling of airport surface traffic, which is based on a MILP model. The objective of the model is to minimize delays and the total taxi times, while de-conflicting the surface traffic. The model is able to adapt to uncertainties and perturbations. The taxi planning involves the management of arrival traffic on the taxiway system from landing runway to the apron, as well as the management of departure traffic from push-back to take-off. The proposed time-based taxi-planning concept assumes that guidance and control systems are available to provide aircraft with high-precision taxi capability. As for most of the previous studies, this paper does not consider the unavailability of towing vehicles due to charging. Rather, this paper focuses on the management of the flow of aircraft.

Baaren and Roling [107] propose a MILP vehicle routing problem to determine, from a set of arriving and departing flights, which of them is optimal to tow using an electric towing vehicles such that the total aircraft fuel consumption, energy consumption and emissions are minimized. Case studies for Rotterdam the Hague (RTM) and Amsterdam Airport Schiphol (AMS) have been conducted. The results show that the total fuel consumption per day can be reduced by at least 65% (1,548 kg), while at Amsterdam Airport Schiphol, the total fuel consumption per day can be reduced by at least 82% (192,600 kg) when efficiently managing the fleet of electric towing vehicles. The results show that the largest fuel reduction potential at Schiphol is by towing the medium category aircraft. By towing all the medium category flights, 60% less fuel will be consumed at Schiphol. These results provide insights for the case studies we consider for AEON, i.e., the medium-sized type of aircraft seems to be the most beneficial to tow at large airports where a mix of types of aircraft (small, medium, heavy) are expected to operate.

In general, the studies above address the problem of electric fleet management at the strategic level, i.e., the authors assume that the flight schedules are known, and that the aircraft adhere to these flight schedules. In some cases, such as [108] and [106], the authors indicate the suitability of their models for tactical modelling, where aircraft are subject to arrival/departure delays in real-time. However, to the best of our knowledge, 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. Our review also identified promising heuristics to be used for large case studies, as well as the type of aircraft (small, medium, heavy) it is most beneficial to consider for electric towing.

# 5 Integration of path finding and operations research methods for fleet management

To resolve both problems of task assignment and path planning at the same time, CBS with Task Assignment (CBS-TA) extension of CBS was proposed in [109]. The two key ideas of CBS-TA are: (1) to perform search in a forest instead of a tree, and (2) to create that forest on demand, i.e. not expanding all possible task assignments. CBS-TA is shown to be complete and optimal and, furthermore, the authors have implemented ECBS-TA, its suboptimal version. In comparison with CBS, CBS-TA only needs to adapt the high level search phase.

CBS-TA starts with a single root node that uses the best task assignment, while ignoring possible conflicting agents. Every time a root node is expanded, a new root node is created with the next best task assignment. The idea of the next best task calculation is based on [92] but instead of calculating a set of best assignments, the solution is calculated on demand. The idea of the algorithm is that some assignments are prevented to be included and other are forcefully being included. Consider the

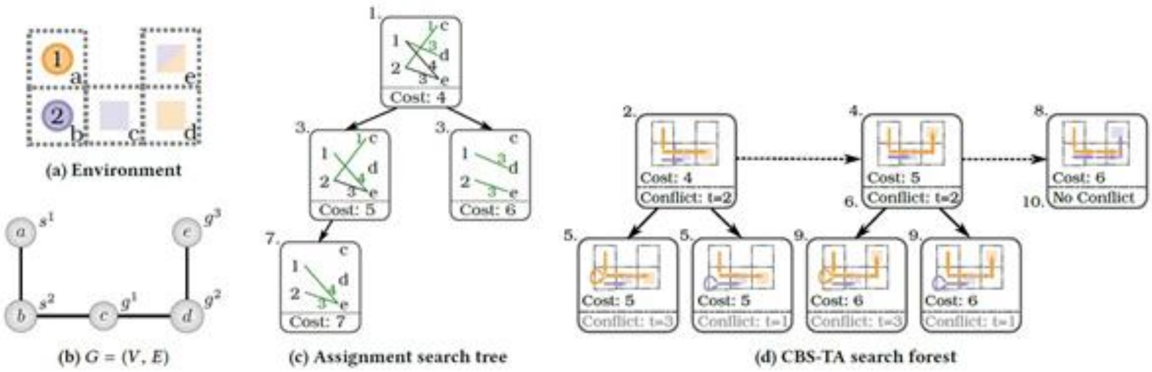


**Figure 12: Elaboration of the CBS-TA example**

$$C = \begin{array}{c} \\ 1 \\ 2 \end{array} \begin{array}{c} \begin{matrix} c & d & e \end{matrix} \\ \begin{pmatrix} \infty & 3 & 4 \\ 1 & \infty & 3 \end{pmatrix} \end{array}$$

**Figure 13: Cost matrix for the example in Figure 12**

following example from [109]:

Figure 14 (a) shows the example environment where agents 1 and 2 are located at nodes a and b respectively with task locations c, d and e. The same figure shows (in accordance with the colours) that agent 1 can be assigned to d or e and agent 2 to c or e. The corresponding graph is shown in (b) with nodes a and b being start nodes and c, d and e being goal nodes. A cost matrix can then be created which displays the path lengths from each start node to each goal node as can be seen in

Figure 15. Given this cost matrix, any assignment algorithm (I.e, OR assignment problem) can be used to obtain an optimal task assignment.

In the example, (1) the first task assignment sends agent 1 to d and agent 2 to c (costs 3 and 1 respectively) as displayed in Figure 17 (c). The latter corresponds to the first root node in Figure 18 (d) but the path validation (2) returns a conflict between the two agents at the second timestep. Whenever a root node is expanded, a next best assignment and a new root node have to be added. (3) The first new assignment expansion prevents 1-d from happening and the second prevents 2-c from happening and enforces 1-d. (4) The shortest path is again calculated following the new task assignment, again leading to a conflict in timestep 2. At this point (5) the first conflict is tried to be resolved by imposing constraints on when each agent is allowed to be at position c. A new root node has to be expanded. (6) The process starts again by expanding the assignment tree, (7) adding a new root node (8) and trying to resolve the previous conflict (9) obtained in (4). Since the third root node

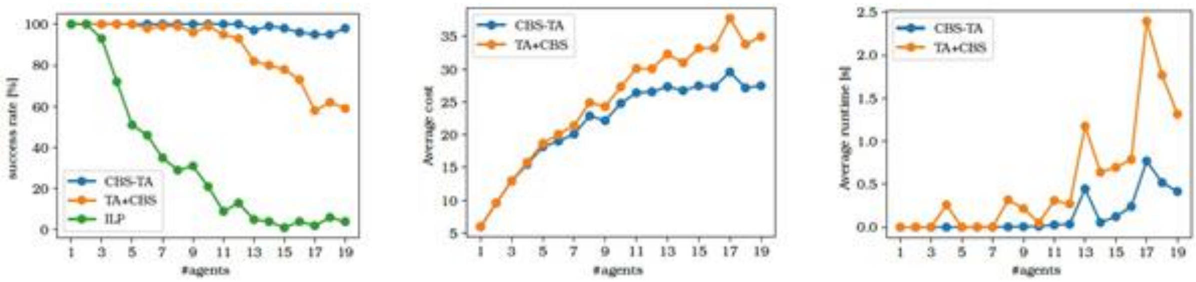


**Figure 16: Performance of CBS-TA w.r.t. TA+CBS with respect to success rate (left), average solution cost (middle) and average runtime (right) for different numbers of agents [104].**

does not contain conflicts (10), this solution is returned.

The performance of CBS-TA is compared to solving task assignment and path finding separately, task assignment before CBS (TA+CBS). In Figure 19 one can observe that until a certain point, the curves CBS-TA and TA+CBS stay close to each other but when more and more agents are added, the performance of TA+CBS seems to degrade. CBS-TA behaves particularly well in dense areas, where task assignment and path finding are tightly coupled [109].

# 6 State-of-the-art on related projects

When looking at an advanced and innovative concept of taxiing operations it is important to consider the current state of the art in the research area of airport ground operations and the solutions that already exist or are being developed in this framework, with the twofold purpose of avoiding duplications and discovering and exploiting synergies and opportunities for collaboration.

With this aim, this section provides an overview of the improvements on which the research has been focusing in the recent period in order to increase airport capacity through improving traffic predictability, while maintaining high safety levels. In this state-of-the-art a total of 46 projects/solutions are reported and analysed, that in different ways and for different reasons could be worth referring to and taking into account in later research stages of the AEON project. They mainly refer to research activities conducted in the framework of the SESAR Industrial projects, but the list includes also other projects funded as SESAR Exploratory Research projects and not funded by SESAR.

In order to follow the chronological order of the research project presented and show their relation with the SESAR Programme, the results taken into account in this state-of-the-art overview are distinguished and organized in four categories:

- SESAR1 Solutions
- WAVE1 SESAR2020
- WAVE2 SESAR2020
- Other related projects, not belonging to SESAR Industrial

The first group consists of solutions from the "High performing airport operations" of the SESAR 1 Solutions Catalogue published in 2019. The second set is from the "Wave 1" of the SESAR 2020 solutions, while the third group derives from the "Wave 2". Finally, the fourth class consists of projects related to AEON, because interested in improving airport ground operations by means of innovative and sustainable solutions and procedures. In this forth category we find projects that have already published their final results as well as projects that are still ongoing.

In the following sections we describe the solutions taken into account for each group and highlight the aspects that can be relevant to AEON, as well as the overall relevance of each project to AEON. The relevance can be High (H), Medium (M) or Low (L).

- **High (H)** refers to results that are considered highly relevant for the project. For example, it includes the solutions capable of reducing ATC workload and improving airport efficiency while keeping high levels of safety.
- **Medium (M)** refers to solutions that investigate aspects that, although relevant, are not pivotal in the AEON project. It is the case for instance of solutions that reduce surface incursions but that could create stop and go, or all those that might have a positive impact on safety but a not so significant effect in terms of airport efficiency.

- **Low (L)** refers to solutions that are worth knowing as part of the overall ecosystems of projects addressing the research topic of airport ground operations, but at the moment do not seem to be directly related to AEON; the main purpose of providing low relevant solutions is to present a complete archive of what is being addressed in the research area.

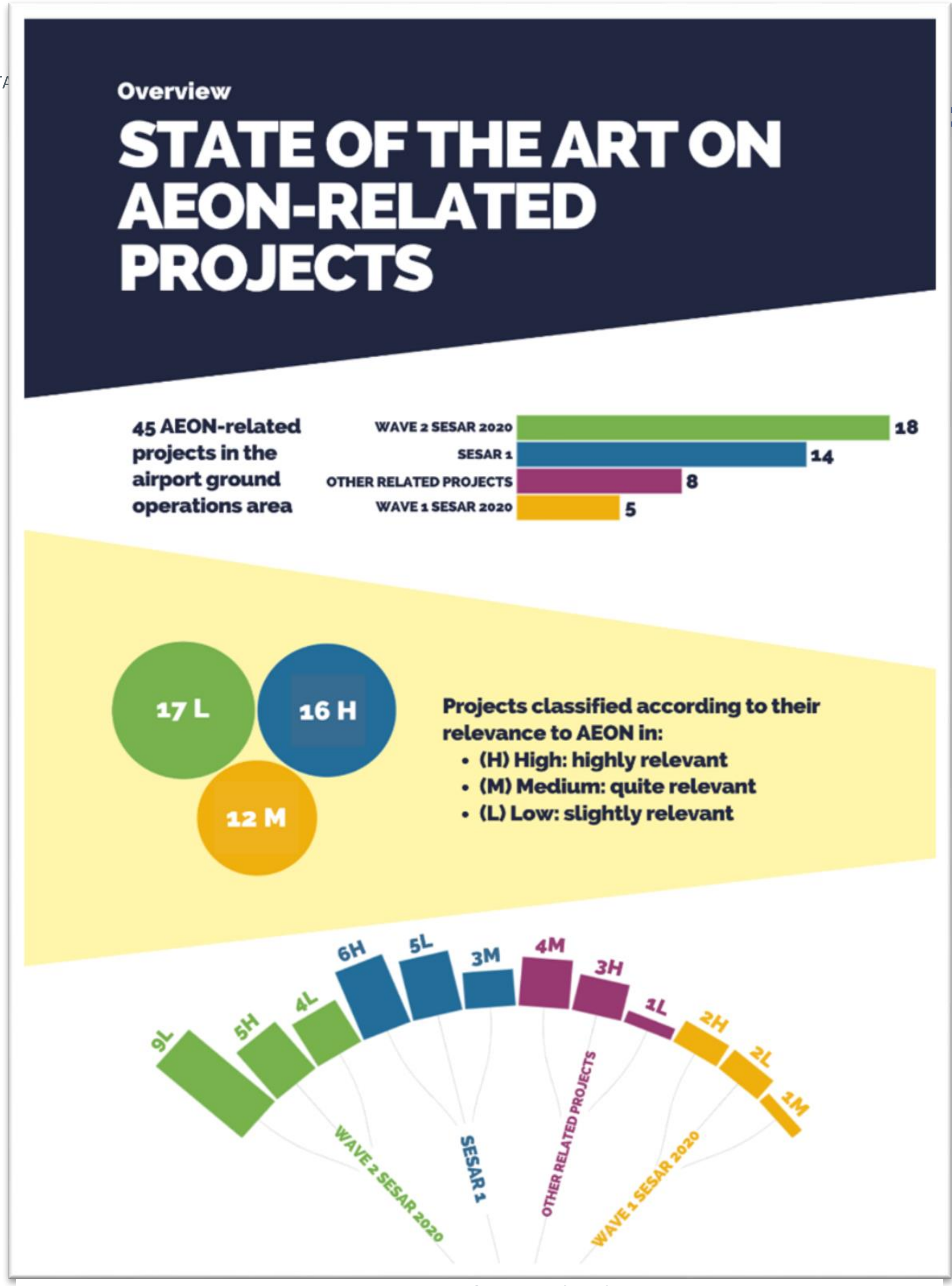


Figure 20: Overview of AEON related projects

Figure 21: Overview of AEON related projects

Figure 22: Overview of AEON related projects

Figure 23: Overview of AEON related projects



Figure 24: Overview of AEON related projects

Figure 25: Overview of AEON related projects

## 6.1 SESAR 1 – Solutions

This section presents and analyses 14 solutions from the "High-performing airport operations" chapter of the SESAR 1 Solution catalogue. These solutions aim to enhance capacity and safety at airports through collaborative decision making (CDM) for enhancing the runway throughput, integrating the surface management and through airport safety nets.

### 6.1.1 #22 Release 5 - Efficient planning around the airport

The SESAR surface route planning function automatically generates taxi routes which are then displayed on the controller working position. The software uses flight plans and current operational data to calculate the optimum route for each aircraft. It also computes the taxi time, which can then be used for departure planning purposes. The controller can graphically edit the route before relaying it to the pilot by voice, or where possible by datalink. The software employed by this solution increases predictability and capacity, while the taxi route optimization reduces taxi times and fuel burn.

Input and relevance to AEON:

The most relevant aspects to AEON concern how the software works and how it can be combined with guidance assistance tools such as airport moving maps and airfield ground lighting. Although the ENAC ground radar prototype already includes this solution, it will be important to properly define its usage in the framework of the AEON Concept of Operations. Relevance: High (H).

### 6.1.2 #23 Release 5 - Improved Communications thanks to datalink

Controller–pilot data link communications (CPDLC) is employed to reduce radio transmissions when exchanging routine and non-critical messages, especially during periods of busy traffic. Radio remains available on first contact with the controller for radio check and for safety or time critical clearances. The delivery by datalink of info and clearances during the taxi phase is known as D-TAXI. The solution allows to provide reliable and repeatable message sets for non-safety critical exchanges, increasing safety at busy airports by freeing up congested radio channels and delivering instructions more effectively. As a result, the pilot and controller can focus on other operational issues.

Input and relevance to AEON:

Solution #23 can be considered as a means to ease the information exchange between controllers and pilots during taxiing operations. The ENAC ground radar prototype already includes this solution and could be used during the AEON simulations, provided that the use of this solution is included in the Concept of Operations of Advanced Engine Off Navigation. Relevance: Medium (M).

### 6.1.3 #26 Release 5 - Taxi route display for pilots

A graphical display of the taxi route on the airport moving map increases the flight crew's situational awareness, notably in low-visibility conditions or an airport with which they are not familiar. This solution employs an electronic route planning system, to select the optimal taxi route, and controller pilot data link communication, to relay the route to the cockpit. Airport moving maps results in enhanced safety, predictability and efficiency levels, particularly due to the electronic route planning system. Trials also showed that this solution reduce fuel burn and emissions.

Input and relevance to AEON:

The electronic route planning system reduces delays by increasing pilots' visibility. Since AEON will mainly focus on the controller's side rather than looking at the cockpit, the solution is considered not so relevant to be taken into account in later stages of the project. Furthermore, recent aircraft already feature moving maps. Relevance: Low (L)

### 6.1.4 #47 Release 5 – Follow the greens

This solution integrates taxi route management with the airfield ground lighting, in order to provide flight crew and vehicle drivers with supplementary means of guidance. Lights are automatically and progressively switched on (in segment or individually) as the aircraft moves along the assigned route. This solution also relies on the surface movement guidance and control system to provide accurate aircraft position data.

Input and relevance to AEON:

The solution reduces runway incursions, taxi route deviations and holding position overruns. The fewer speed changes also result in lower fuel consumption. As taxi speeds are globally increased, apron throughput is improved. ENAC tower simulator could implement this solution from the controller perspective, even though it is not high priority. Anyway, it is beneficial from the pilot side, and in the framework of AEON it could be replaced by adequate speed targets to electric engines aircraft or tug vehicles. Relevance: Low (L)

### 6.1.5 #48 Release 5 - Enhancing safety with virtual bars

In low-visibility situations, virtual stop bars support the ground controller in providing surface movement guidance. Virtual stop bars alert controllers of any kind of unauthorized movement by aircraft or vehicles in the area of the runway. As a result, safety is enhanced thanks to an improved predictability of surface movements.

Input and relevance to AEON:

The solution reduces runway incursions and taxi route deviations. The fewer speed changes also result in lower fuel consumption. As taxi speeds are globally increased, apron throughput is improved. On the other hand, when virtual stop bars are used to stop aircrafts at intersections if they are not cleared to go further, they could create stop and go resulting in enhanced taxi times. The actual benefits of integrating this solution in the AEON concept of operations have not been explored yet and will be taken into account while designing the Concept of Operations. Relevance: Medium (M)

### 6.1.6 #02 Release 5 - Enhancing safety at busy airports

This solution detects conflicts much sooner than current safety nets for runway operations which rely only on surveillance data to trigger an alarm. The automatic conflicting ATC clearances (CATC) alert system can be configured to detect non-conformance to ATC instructions or procedures anywhere in the movement area. Controllers employing this solution have higher situational awareness, performing better during busy hours. Safety results increased.

Input and relevance to AEON:

The solutions can improve safety during taxiing operations, and it can be useful to determine speed targets ahead of time. Relevance: Medium (M)

### 6.1.7 #70 Release 3 - Surface safety in all weather conditions

This solution develops further the Automatic Dependent Surveillance – Broadcast (ADS-B) applications to improve ground surveillance systems in terms of safety, performance, interoperability and security. It provides the controller with the position and automatic identity of all relevant aircraft and vehicles in the movement area. In low visibility conditions the controllers employing this solution show higher situational awareness levels. The automatic generation of real alerts enhances safety, while operational acceptance is benefited.

Input and relevance to AEON:

The information related to aircraft and vehicles positions in the movement area could be used by AEON to support controllers deciding the optimal routes to allocate each taxiing technique. Relevance: Medium (M)

### 6.1.8 #01 Release 5 - Visual signals to safeguard runway users

The runway status lights (RWSL) offer visual signs about the status of a runway. They alert the pilot or the vehicle driver the instant the runway is unsafe due to the detection of mobile behaviour by the advanced surface movement guidance and control system (A-SMGCS). As a result, runway safety and situational awareness in pilots are increased.

Input and relevance to AEON:

Even though this solution is already implemented in one of the airports considered within this project (Paris Charles de Gaulle), AEON is looking at the controllers’ side rather than the pilots and thus the solution is not considered relevant in the current framework of the project. Relevance: Low (L)

### 6.1.9 #04 Release 5 - Providing vehicle drivers with enhanced visual tools

A screen in the airport vehicle allows drivers to access an airport moving map, information regarding surrounding traffic and receive alerts if a dangerous situation arises. Warnings include possible collisions, infringements of a runway, or closed / restricted area. Airport vehicle drivers show higher situational awareness levels and safety is increased in airport operations.

Input and relevance to AEON:

This solution could guide tow vehicles going to fetch an aircraft to be towed. Relevance: High (H).

### 6.1.10#106 Release 1 – A baseline for on-time departure

Departure Manager (DMAN) lends itself to tactical scheduling by calculating optimum pre-departure sequences based on information provided by airport, airline and air traffic control sources (A-CDM processes). SESAR developed a baseline DMAN to reduce delays by enabling controllers to establish pre-departure sequences by using DMAN in conjunction with airport collaborative decision-making procedures involving local airport and airline partners. The baseline improves predictability and stability of departure sequence, start-up approval time and off-time blocks. Moreover, positive effects on runway delays, waiting and taxi times are recorded. Runway tactical scheduling is increased, while fuel consumption and $CO_2$ emissions are decreased.

Input and relevance to AEON:

DMAN sequence must be a strong input to AEON algorithm as the AEON solution must ensure that the sequence is fulfilled. The DMAN calculation shall be adapted to different taxi times according to taxiing techniques. Relevance: High (H).

### 6.1.11#53 Release 4 – Improving on-time departure

Accuracy in taxi time forecast can be improved if the Departure Manager (DMAN) takes into consideration data provided by the advanced surface movement guidance and control system (A-SMGCS). The solution accounts for where aircrafts are parked, taxi route length and tactical adjustments such as temporary restrictions. It reduces waiting time at the runway holding point, which saves fuel and allows air navigation service efficiency. Furthermore, accuracy of taxi time-out predication and hence take-off time predictability are increased, allowing the aircrafts to adhere to their target take-off time (TTOT).

Input and relevance to AEON:

DMAN synchronized with pre-departure sequencing could be a pivotal input to AEON algorithm as the AEON solution must ensure that the sequence is fulfilled. The DMAN calculation shall be adapted to different taxi times according to taxiing techniques. Relevance: High (H).

### 6.1.12#54 Release 4 – Extending the planning horizon

By integrating the activities of arrival manager (AMAN) and the departure manager (DMAN) tools, an optimisation algorithm can calculate the ideal traffic flow that takes into account both arriving and departing aircraft. Arrival and departure flows to the same runway (or for dependent runways) are integrated by setting up a fixed arrival-departure pattern for defined periods. The solution is an enabler for accurate runway sequencing and facilitates long-range planning such as extended arrival management. Increased predictability results in increased runway throughput and reduced fuel burn.

Input and relevance to AEON:

Understanding how the optimisation algorithm works and how the activities of AMAN and DMAN tools are integrated to set up the fixed arrival-departure pattern. Relevance: High (H).

### 6.1.13#21 Release 5 – Airports are the nodes of the network

The solution focuses on integrating airport operations plan (AOP) with the network operations plan (NOP) to extend the planning activities including air traffic demand and improved target time coordination. The solution aims to maintain airport performance in all operating conditions, and to share information with the wider network. Two main services are provided by this solution: to establish appropriate performance goals and to monitor the performance during the execution time frame.

Input and relevance to AEON:

Although it is likely that AEON will increase predictability through a better collaboration, hence improving the quality of information shared with Network Manager (NM), this is not the main objective of the project. Relevance: Low (L).

### 6.1.14#116 Release 5 – Improved winter weather forecasting for de-icing operations

SESAR de-icing management tool (DMIT) refers to a system capable of improving the predictability of aircraft de-icing operations at European airports by taking data inputs from meteorological service providers and involving the relevant airport stakeholders. The solution increases the accuracy of information related to when the procedure is going to take place, how long it will take and when the aircraft will be ready to taxi for departure, which is currently calculated by predetermined estimates. The solution means that air traffic controllers no longer need to work without situational awareness of de-icing activities and needing to make their own estimates of when aircraft are ready for departure.

Input and relevance to AEON:

This solution could help AEON to understand what types of meteorological information are collected and the potential impact of de-icing operations. However, considering adverse weather conditions is not a central aspect of our project. Relevance: Low (L).

## 6.2 WAVE 1 SESAR 2020 – Industrial Research

The five results presented in this section are from industrial research projects funded by the SESAR Joint Undertaking and concluded in 2020. Some of the solutions presented here intend to increase airport capacity through proposing a more efficient runway usage, while others – considered less relevant to AEON - try to enhance pilots' human performance with augmented visual operations and on-board systems that detect traffic alerts.

### 6.2.1 PJ.02-08-01 – Trajectory based Integrated Runway Sequence (V3 Maturity level)

The main goal for the Integrated runway Sequence function is to establish an integrated arrival and departure sequence by providing accurate Target Take off Times (TTOTs) and Target Landing Times (TLDTs), including dynamic balancing of arrivals and departures while optimising the runway throughput. The look ahead Time Horizon is the time at which flights become eligible for the integrated sequence. The Stable Sequence Time Horizon is the time horizon within which no automatic swapping of flights in the sequence will occur, but landing and departure time will still be updated. The value of these time horizons is determined by the local implementation and they are not necessarily the same for arrivals and departures. The solution reduces air and ground queuing time, resulting in reduced fuel consumption and increased airport capacity. Further, the integrated RWY sequence function is applicable for all airport layouts.

Input and relevance to AEON:

The arrival and departure dynamic planning could provide target times and a forecasted arrival, but also a departure path to fulfil. Taxiing techniques could be allocated accordingly with the Stable Sequence Time Horizon. Relevance: High (H).

### 6.2.2 PJ.02-08-02 – Optimised use of runway configuration for multiple runway airports

The solution supports the Tower Supervisor to determine the optimal runway configuration and distribution of demand according to capacity and local constraints. During the Medium/Short term Planning Phase, the Runway Management (RMAN) tool checks the intentional demand versus the available capacity and is capable of forecasting imbalances, raising alarms and alerts based on the indicators provided. In the Execution Phase, the RMAN tool monitors departure, arrival and overall delay and punctuality, in addition to the capacity shortage proposing changes if necessary. Since the demand is continuously evolving, the RMAN continuously computes the optimal runway configuration and the associated Forecasted Landing (FLDT) and Take Off (FTOT) Times of arrival and departures flights that maximises the runway throughput. As a result, flight time and delays are reduced.

Input and relevance to AEON:

This solution could provide inputs to the design of the AEON algorithm in order to determine the best fit between taxiing allocations and forecasted landing and take-off times. Relevance: High (H).

### 6.2.3 PJ.02-08-03 – Increased Runway Throughput based on local ROT characterization (ROCAT)

The Increased Runway Throughput based on local ROT characterization (ROCAT) is a concept that intends to reduce the in-trail separation on final approach with the aim of increasing runway throughput by taking into account the Runway Occupancy Time (ROT). The most constraining factor for the reduction of the separation is, together with the wake turbulence, the ROT; and therefore, a new separation minimum could be computed based on the prediction of the ROT, the minimum runway separation (MRS) and the wake categorization separation. ROCAT defines separation sub-categories based on runway occupancy time, wake minima from RECAT and reduced radar separation based on ICAO approved minima. The controller workload is reduced, while arrival runway throughput rises by 10-14%

Input and relevance to AEON:

Decreased ROTs should be taken into account in AEON as a means to reduce the time to deploy a particular taxiing technique. Relevance: Medium (M).

### 6.2.4 PJ.03a-04 – Enhanced Visual Operations

Enhanced Visual Operations refers to enhanced vision systems (EVS) and synthetic vision systems (SVS), which will be developed to enable more efficient taxi, take-off and landing operations in Low Visibility Conditions (LVC). This is applicable to all platforms. Even if main airline platforms have auto-land capabilities to facilitate approaches in LVC, they have no capability to facilitate taxi and take-off in order to maintain airport capacity.

Input and relevance to AEON:

In taxi operations, the Helmet Mounted Display (HMD) displayed taxi guidance information improving awareness specifically in a large airport environment. Relevance: Low (L).

### 6.2.5 PJ.03b-05 – Traffic Alerts for Pilots for Airport Operations

Traffic Alerts for pilots for airports operations refer to enhancing on-board systems in order to detect risks of collision with other traffic during runway and taxiway operations. In all cases the flight crew are provided with appropriate alerts. Safety in airport operations result as increased.

Input and relevance to AEON:

The alert system used in this solution might increase safety and situational awareness in pilots during airports operations, though our main focus in AEON is on the controllers' side. Relevance: Low (L).

## 6.3 WAVE 2 SESAR 2020 – Industrial Research

The wave 2 of SESAR 2020 solutions consists of industrial research projects that produced partial results during the last year, but that are not concluded yet. Within SESAR2 we selected 19 solutions that are worth considering as a framework for the development of AEON's operational concept, however they will not be taken into account as pivotal into our analysis because their maturity level should be increased further to be exploitable into AEON's analysis.

### 6.3.1 PJ.02-W2-17.1 – Improved Capacity and Safety of Runway Operations at Secondary Airports in Low Visibility Conditions

There are new methods for surveillance of aircraft and vehicles that enable operations in meteorological conditions below Instrument Landing System Category 1 (ILS CAT1) at secondary airports that are operated either remotely or stationary. This solution addresses the need to evaluate the required level of infrastructure, services and procedures to benefit from the new capabilities, considering the new technologies involved, and the particular context of secondary airports with limited demand. As a result, runway safety and capacity at the secondary (small / medium) airports is improved in the meteo conditions below ILS CAT 1 thanks to use of alternative ground surveillance. The solution improves predictability, capacity and safety in adverse weather conditions on less equipped airports, thanks to cost-efficiency technologies with improved performances, supported by adapted procedures.

Input and relevance to AEON:

This solution is not relevant for our project as it mainly focuses on secondary airports operating in low-weather conditions, aspects that are not pivotal in AEON. Relevance: Low (L).

### 6.3.2 PJ.02-W2-17.2 – Improved Approach procedures into Secondary Airports in Low Visibility Conditions

This solution focuses on means of lowering the decision height through development and validation of LPV-100 capabilities. Procedures shall be supported by systems that do not involve major airport and ANSP capital investments, while at the same time, comply with performance requirements related to Low Visibility Operations. Access availability of secondary (small/medium) airports is more resilient in low visibility conditions thanks to the new airborne features as well as infrastructure, services or procedures that enable safe and cost-effective approach in meteo conditions below CAT I minima (CR 04044 Create PJ.02-W2-17.2). It improves accessibility/resilience to adverse weather conditions on less equipped airports, thanks to adapted procedures supported by cost-efficiency technologies with improved performances.

Input and relevance to AEON:

As this solution aims to improve approach procedures in secondary airports, the AEON project is not going to include it in its preliminary operational concept. Relevance: Low (L).

### 6.3.3 PJ.02-W2-17.3 – Airport Safety Nets for Controllers at Secondary Airports

This solution focuses on the need to have a ground safety net at secondary (small/medium) airports with different prerequisites (e.g. no A-SMGCS surveillance, no RMCA [Runway Monitoring and Conflict Alerting], no routing or no EFS [Electronic Flight Strips] - to be clarified as R&D progresses) compared to the airport safety net at the main airports with A-SMGCS Surveillance. As a result, airport Safety is improved at Secondary Airports thanks to detection of potential and actual conflicting situations and incursions, involving mobiles and stationary traffic on runways, taxiways in the apron/stand/gate areas at the secondary (small/medium) airports, adjusted to the available infrastructure (alternative ground surveillance e.g. video camera, ADS-B only, etc.) and operational environment. As a result, safety and human performance are improved on less equipped airports, thanks to safety nets supported by cost-efficiency technologies.

Input and relevance to AEON:

Safety nets are already taken into consideration in the solution PJ.02-W2-21.1, which focuses on larger airports, where solutions such as the tug vehicles are more likely to be part of the airport thug-fleet. Relevance: Low (L).

### 6.3.4 PJ.02-W2-21.1 – Extended Airport Safety Nets for Controllers at A-SMGCS Airports

This solution updates and extends the Airport Safety Net concepts Conflicting ATC Clearances (CATC) and Conformance Monitoring Alerts for Controllers (CMAC) to cover the entire airport surface. Based on airport surveillance data and electronic environment integrating ATC clearances, taxi-routes and local procedures, the Safety Support Tools for controllers upgrade the Advanced Surface Movement Guidance and Control System (A-SMGCS) to detect potential and actual conflicting situations, incursions and non-conformance to procedures or ATC clearances, involving mobiles (and stationary traffic) on runways, taxiways and in the apron/stand/gate area as well as unauthorised/unidentified traffic. The solution targets traffic safety on the movement area and during take-off and landing. Appropriate predictive indications and alerts are provided to controllers, increasing situational awareness and giving automated support in order to avoid hazardous situations. Extended safety nets for controllers maintain or increase the level of safety with increasing traffic. ATC Human Performance benefits by increased situational awareness and automated decision support.

Input and relevance to AEON:

The Safety Support Tools could integrate the AEON algorithms to enhance safety levels, improving situational awareness in controllers and easing their decision-making process for a better allocation of each taxiing technique. Relevance: High (H).

### 6.3.5 PJ.02-W2-21.2 – Enhanced Guidance Assistance to Airport Vehicle Driver Combined with Routing

The scope includes the development and validation of a system providing to Vehicle Drivers the display of dynamic traffic context information including status of runway and taxiways, obstacles and route by application of an airport moving map. This is a needed improvement to enhance guidance assistance to vehicle drivers operating on the airport manoeuvring area under low visibility conditions. Guidance assistance information is automatically shown on a dedicated display in the vehicle as a graphical path to be followed. The efficiency of surface operations is increased when using enhanced guidance assistant for Vehicle Drivers to exchange routing information between Vehicle Drivers and Tower Controllers. The control of airport vehicles is optimised in both the apron and manoeuvring area. Safety will benefit from the reduction of misunderstanding of clearances and information given only by voice.

Input and relevance to AEON:

As per solution #04 from SESAR 1, this solution could guide tow vehicle going to fetch an aircraft to be towed. Relevance: High (H)

### 6.3.6 PJ.02-W2-21.3 – Management and Control of Vehicle Operations via Datalink

Datalink is a compound of processes and technologies offering streamlined and error-proof digital means for performing traffic separation at the airport and for constantly keeping status and awareness of all dialogues currently open between ATCOs and mobiles. The solution exploits the extension of datalink operations to vehicles management. Like for aircraft operations, datalink removes possible misunderstandings and ambiguities in the exchange of clearances and requests between ATCOs and Vehicle Drivers. Vehicle datalink management is a fundamental additional support to ATC in challenging operating environments such as large airports with complex layouts on peak hours and/or low visibility conditions. Also, it allows Vehicle Drivers to have constant visual access to all the clearances in a digital format. Airport operations efficiency will benefit from an improved smoothness of vehicle traffic flows and a reduction of potential misunderstandings between ATCOs and Vehicle Drivers. The level of safety with increasing traffic is maintained or increased thanks to improved controller’s and vehicle driver’s situational awareness and reduced controller’s workload.

Input and relevance to AEON:

The digital format for clearances could be integrated into the AEON algorithm to increase safety, situational awareness and human performance of vehicle drivers. Moreover, it provides support to ATC dealing with complex situations such as in large airports during peak hours. Relevance: High (H).

### 6.3.7 PJ.02-W2-21.4 Full Guidance Assistance to mobiles using 'Follow the Greens' procedures based on Airfield Ground Lighting (aprons/taxiways/runways)

This solution intends to automate the prioritization of mobiles along their cleared route on the whole movement area. The Guidance Service takes into account other traffic to guide the mobile as it progresses along its assigned route and at the holding points. It allocates priorities between mobiles based on local operating rules (e.g. runway exit versus parallel taxiways, aircraft versus vehicle, aircraft converging or crossing at intersections and taxiways passing close to push back routes or other taxiways where insufficient wingtip separation exists) as well as known constraints from the surface management system. Automatic Guidance will be provided using the “Follow the Green” concept on the Airfield Ground Lighting infrastructure. Benefits are expected in increased safety performance in all weather conditions, improved predictability through guidance and reduced workload and stress for ATCOs and vehicle drivers.

Input and relevance to AEON:

As per solution #47, this solution reduces runway incursions, taxi route deviations and holding position overruns. The fewer speed changes also result in lower fuel consumption. As taxi speeds are globally increased, apron throughput is improved. ENAC tower simulator could implement this solution from the controller perspective, even though it is not high priority. Anyway, it is beneficial from the pilot side, and in the framework of AEON it could be replaced by adequate speed targets to electric engines aircraft or tow vehicle. Relevance: Low (L)

### 6.3.8 PJ.02-W2-21.5 – Enhanced Safety in LVP through use of Dynamic Virtual Block Control

The solution makes use of real stop bars and Virtual Stop Bars (VSB) appropriately placed in the manoeuvring and movement areas, for example at any operationally relevant positions, to reduce the size of control blocks while ensuring a safe longitudinal spacing is guaranteed between taxiing aircraft or taxiing aircraft and vehicles in low visibility conditions (when ATC is in charge of providing a safe longitudinal spacing among taxiing traffic). Tower Controllers select the clearance limit at a VSB position for an aircraft under control and communicate the clearance via R/T. Guidance information towards the cleared VSB position is sent by means of an appropriate CPDLC message. The assigned VSB position and the guidance information become active when cleared by the controller. The solution targets high traffic operations in low visibility condition and applies to very large, large and possibly medium airports. Flight and airport operations efficiency will benefit from a reduction of speed changes, an improved smoothness of surface traffic flows and a reduction of potential misunderstandings. The level of safety with increasing traffic is maintained or enhanced thanks to improved pilot's situational awareness and reduced pilot's and controller's workload.

Input and relevance to AEON:

As per solution #48, this solution reduces runway incursions and taxi route deviations. The fewer speed changes also result in lower fuel consumption. As taxi speeds are globally increased, apron throughput is improved. On the other hand, when virtual stop bars are used to stop aircrafts at intersections if they are not cleared to go further, they could create stop and go resulting in enhanced taxi times. The actual benefits of integrating this solution in the AEON concept of operations have not been explored yet and will be taken into account while designing the Concept of Operations. Relevance: Medium (M)

### 6.3.9 PJ.02-W2-21.6 – Surface Route Planning and Management operations

The solution aims at researching and validating enhanced capabilities at the Airport ANSP to obtain most suitable ground routes for all mobiles on the movement area (runways, taxiways and aprons) taking into account user's preferences and known constraints (such as taxiway closures, aircraft types, etc.). The capabilities provide the ANSP with assistance in the short term planning phase (some minutes before the estimated off block time (EOBT) and the control area (CTA), or before the mission start time for vehicles), and in the execution phase, e.g. for re-routing. Benefits are expected mainly in ATCO Human Performance aspects (e.g. reduced workload) and a positive impact on predictability.

Input and relevance to AEON:

In the future, this solution could provide a pivotal input to the AEON algorithm in order to choose the taxiing techniques for each aircraft and comply with airlines preferences. Relevance: High (H).

### 6.3.10PJ.02-W2-14.10 - Dynamic Pairwise Runway Separations based on ground-computed arrival ROT (D-PWS-AROT)

This solution addresses Big Data/Machine Learning (BD/ML) techniques used to develop more accurate predictions of Arrival Runway Occupancy Time (AROT) and runway exit based on aircraft characteristics such as aircraft type, weight, equipment (EBS/non-EBS) and weather. The BD/ML techniques will lead to an improvement of post-operations offline analysis, together with continuous monitoring and improvement of the quality of AROT predictions during operations. Overall, the Dynamic Separations for Arrivals solution will bring benefit in terms of increased runway throughput capacity and resilience due to the reduced, optimised separation/spacing on the final approach and runway (with potential positive impact on safety).

Input and relevance to AEON:

In the future, this solution could help AEON's supporting tools on evaluating the taxiing time based on aircraft characteristics. Relevance: Medium (M).

### 6.3.11 PJ.02-W2-14.11 – Dynamic Pairwise Runway Separations for Arrivals (based on A/G data exchange)

This Solution introduces the downlink of Arrival Runway Occupancy Time (AROT) airborne predictions (based on aircraft performance, selected runway exit, atmospheric and runway conditions, aircraft weight) to Air Traffic Control (ATC) for a more-efficient runway separation delivery. The solution targets capacity constrained runways during high intensity runway operations and applies to very large, large and possibly medium airports. Increase in runway throughput thanks to a reduction in approach separation, due to a more accurate prediction of the runway occupancy time (reduction of ROT dispersion for equipped aircraft).

Input and relevance to AEON:

Decreasing approach separation could negatively influence the ATC giving them less time to allocate any taxiing techniques and increasing their workload. Relevance: Medium (M).

### 6.3.12 PJ18-W2-53B – Improved Ground Trajectory Predictions enabling future automation tools V3 Stream

This solution will provide the (Planner or Tactical) controller, Conflict Detection and Resolution tools using more accurate parameter settings and based on enhanced ground predicted trajectory through the use of improved and/or additional relevant data (e.g. Aircraft trajectory data downlinked via ADS-C, more recent weather information). Improved and/or additional relevant trajectory data may be made available via air/ground datalink exchanges (e.g. using real recorded downlinked ADS-C information). Controller's efficiency is increased due to the workload reduction, better trajectory prediction precision increases airport capacity and traffic prediction.

Input and relevance to AEON:

Knowing trajectory conflict and resolution in advance might optimize taxiing techniques allocation and taxiing time. Relevance: High (H).

### 6.3.13 PJ18-W2-56 – Air/Ground Trajectory Synchronisation via lateral and vertical complex CPDLC clearances to support TBO

This solution will research enhanced operational procedures with a more efficient use of CPDLC with lateral and vertical data link clearances. The proposed work will improve the alignment of the airborne trajectory with the trajectory that the ground actors plan to execute by sending complex clearances more and more in advance. The airborne trajectory will become more useful on the ground as it will integrate the impact of future ground actors' instructions, allowing decisions that are more efficient. With the proper automation, this will decrease both ATCO and Flight Crew (FC) workload leading also to a better Air Traffic Control (ATC) and FC resources management. CPDLC clearances sent in advance can modify a larger portion of the trajectory and therefore allow for its more strategic management, reducing workload to issue tactical instructions. The new procedures will also allow increased predictability, improved safety awareness thanks to 2D / 3D air to ground synchronization enabled by advanced use of on-board trajectory data and automation support for solving inconsistency.

Input and relevance to AEON:

This solution should be considered for enhancing the decision-making of operators by increasing their awareness of the mismatch existing between airborne trajectory and the trajectory expected by ground actors, resulting in a better taxiing time and a better allocation of the taxiing techniques. Relevance: High (H).

### 6.3.14 PJ.04-W2-28.2 – Regional Airport(s) Collaborative Management

This solution, devoted to regional airports, considers the benefit of creating a single joint AOP combining information from a wider group of airports (too small to have their own individual AOP) with similar operational needs. As a result, this solution enhance predictability, thanks to an ensured common situation awareness, improve cooperation and information sharing through innovative approaches to an Airport operation center (APOC) deployment, and improve performance management for regional airports through a cost-efficient solution.

Input and relevance to AEON:

AEON results might introduce variations in the AOP, although this is not the goal of the project. Relevance: Low (L)

### 6.3.15 PJ.04-W2-28.3 – Connected Large Airports

This solution, devoted to the connection of large airports to the network, both in "normal" operation and in severe disruption scenarios where the influence of major hubs on the network is bigger, notably intends to finalise the data exchange standard. The scope of the solution is to end developing the OIs AO-0801-B "Collaborative Airport Planning Interface (AOP fully integrated with NOP & local business rules)". Connected large airports improve punctuality and turnaround predictability in a way that the interests of Airports and Airspace Users are taken into account as well as satisfying the NM needs (balancing network). This solution will lead to the mitigation of reactionary delays through the allocation of optimized TTAs, which will allow to reduce the impact on key departure legs. Resilience is increased thanks to a more accurate D-1 AOP information, and a better management of TTAs, both contributing to the reduction of the negative impact on airport capacity, when a Demand Capacity imbalance happens.

Input and relevance to AEON:

As for the previous solution, AEON results might introduce variations in the AOP, although this is not the goal of the project. Relevance: Low (L)

### 6.3.16PJ.04-W2-29.1 – Airside/Landside Performance Management

This solution aims at enhancing the information sharing and collaborative decision making between the airside and the landside processes in an airport. On one hand this solution will consider the airside processes enhancement with the inclusion of landside (passenger and baggage flow) process outputs (shared in the AOP via the Target Off Block Time (TOBT) update) that can affect ATM Performance. On the other, it provides detailed monitoring of the different processes relating to the turnaround. Predictability and punctuality are increased by enhancing the information sharing and collaborative decision making between the airside and the landside processes in an airport and improving the management of the turnaround process. Efficiency and resilience are enhanced too, thanks to tools, such as 'what-if' functionality or enhanced prediction functionality through techniques such as business intelligence / machine learning.

Input and relevance to AEON:

This solution doesn't address any particular aspects related with AEON. Relevance: Low (L)

### 6.3.17PJ.04-W2-29.2 – MET Performance Management

This solution aims at increasing the resilience to meteorological events through anticipated and proactive management of their impacts on the AOP. Enhance predictability thanks to pro-actively managed meteorological impacts on the AOP. Airport resilience is enhanced by minimising airport operation disruption caused by meteorological events. Decision support functionalities increase efficiency by assessing the impact of key meteorological conditions on airport performance and propose pre-defined solution scenarios.

Input and relevance to AEON:

At the current state the AOP is not pivotal for the scope of the research conducted in AEON. Relevance: Low (L)

### 6.3.18PJ.04-W2-29.3 – ENV Performance Management

This solution aims at integrating environmental considerations into the overall airport operations management process. The ENV performance management improves environment efficiency by exploiting environmental parameters at airports in support of strategic or tactical decision-making.

Input and relevance to AEON:

Environmental parameters don't seem to have such a large impact on the deployment of the techniques studied within AEON, hence they might be considered in a later stage. Relevance: Low (L)

## 6.4 Other related projects

This section presents other projects, not belonging to SESAR Industrial present or past solutions, which are considered potentially relevant to AEON and with which – as far as possible and feasible - AEON intends to collaborate in order to exchange relevant information and create synergies to maximize the individual impact of each project. The Consortium has already started making contact with five of these projects (those that are still ongoing) and, in the next months, it will continue to collaborate with them. These projects have been chosen because they were covering aspects similar to the ones studied in AEON, or due to the presence of beneficial overlaps.

### 6.4.1 ACACIA

ACACIA (Advancing the Science for Aviation and Climate) is an EU-H2020 project aiming at assessing the climate impact of non-CO2 aviation's emissions. The project, led by the German Aerospace Centre (DLR), lasts 3.5 years, from January 2020 to June 2023. It shares with AEON the aim of fostering knowledge development for a greener aviation and to provide knowledge basis and strategic guidance for future implementation of mitigation options. Nevertheless, apart from this high level common intention, the purpose of the project is widely focused on environmental aspects, rather than on operational ones and do not focus specifically on airport ground operations. The relevance to AEON is limited, but considering the high-level common goal, it is considered worth being taken into account. Relevance: Low (L)

### 6.4.2 ALBATROSS

ALBATROSS is a wide scale initiative of major European aviation stakeholder groups to demonstrate how the technical and operational R&D achievements of the past years can transform the current fuel intensive aviation to an environment-friendly industry sector. The project, led by the AIRBUS Operation SAS, lasts 2 years, from December 2020 to November 2022. The SJU ALBATROSS project will explore and then demonstrate in real conditions the feasibility of implementing the most fuel-efficient flights through a series of gate-to-gate live trials across Europe and by integrating the most recent technical and operational innovations.

Input and relevance to AEON:

Along with several aviation technical and operational improvements, ALBATROSS tests in real conditions the efficiency of taxiing operations such as single-engine taxiing and tug vehicles.

Relevance: High (H)

### 6.4.3 ClimOp

The EU-funded ClimOP (Climate assessment of innovative mitigation strategies towards operational improvements in aviation) project detect, evaluate, develop and propose to aviation stakeholders and policymakers a set of most promising and integrated mitigation strategies aiming to restrict the aviation sector's climate impact. ClimOp, led by Deep Blue (DBL), lasts 3.5 years, from January 2020 to June 2023.

Input and relevance to AEON:

ClimOP focuses on operational and infrastructural improvements at ground level such as efficient taxiing, electrification of ground equipment, and renewable energy production. During the project, these operations will be assessed considering their impact on climate and the aviation stakeholders.

Relevance: Medium (M)

### 6.4.4 DYNCAT

DYNCAT (Dynamic Configuration Adjustment in the TMA) is an SJU funded project that aims at enabling more environmentally friendly and more predictable flight profiles in the airport vicinity, namely on approach, by supporting the pilots in configuration management. The project, led by the German aerospace center (DLR), lasts from June 2020 to November 2022.

Input and relevance to AEON:

DYNCAT identifies the impact of current (approach) ATM operations in the TMA on environmental pollution, cost effectiveness and safety and to quantify the potential for environmental impact (noise, CO2 emission) reduction through better communication between ATC and the flight deck.

Relevance: Medium (M)

### 6.4.5 FlyATM4Eu

FlyATM4Eu (Flying Air Traffic Management for the benefit of environment and climate) is an SJU founded project aiming at expand approved climate-assessment methods and optimization of aircraft trajectories in order to identify promising mitigation options suitable to solve the task of reducing overall climate impact of aircraft operations. The project, led by the German Aerospace Center (DLR), lasts from June 2020 to November 2022.

Input and relevance to AEON:

Their climate assessment methods might be useful to consider the impact each taxiing technique has on climate change. Another aspect could be whether the trajectories they are going to propose might have an impact on the arrival procedures.

Relevance: Medium (M)

### 6.4.6 MoTa

MoTa (Modern Taxiing) studied the impact of future taxiing technologies such as Datalink and autonomous taxiing tugs on airport taxiing operations and air traffic controller workload. Seven air traffic controllers were asked to manage ground traffic in two scenarios that imposed medium and high levels of workload with three different degrees of automated technology assistance: paper strips; Datalink and path suggestion; Datalink, path suggestion, and tugs. Initial results indicate that participants were able to manage more traffic when using either just the interface or interface and tugs, but the inclusion of tugs also resulted in an increase in self-reported workload. Participants were divided on technology acceptance with no one rejecting completely the new technology.

Input and relevance to AEON:

The ground radar image can be used for tugs fleet management and ATC clearances, including speed targets. The usage of digital assistance such as path suggestion and datalink on ground should also alleviate additional workload in AEON.

Relevance: High (H)

### 6.4.7 TaCo

The TaCo (Take Control) is a European Union's H2020 Research and Innovation project aiming to define an automated system supporting ground and tower controllers' tasks in non-nominal conditions. The project, led by Deep Blue (DBL), has ended its activities in June 2018.

One objective of the TaCo project is to give the ability to the ground ATCO to decide and adjust a global strategy for taxiing. Since the taxiing strategy has a strong impact on the work of the tower ATCO, especially on the construction of the departure sequence, the tools prototyped in TaCo should be shared between the ground and tower control positions. A list of parameters that can be tuned has been defined and the implementation of a configurable departure manager seemed a good automation algorithm to fit most of these strategy criteria.

Input and relevance to AEON:

This project developed two results interesting for the AEON's purpose: a definition of operational needs for automation support in the tower, performed together with ATCOs; a prototype of automated tools to support air traffic controllers in the tower.

Relevance: High (H)

### 6.4.8 PIPAA

The PIPAA project (Fuel Cells for Aerospace Applications), which is part of the HyPort initiative, a meta-project of the french Occitanie region which aims to make Toulouse Blagnac airport the first zero-emission airport in the world thanks to hydrogen energy. Safran Power Units, one of the world's leading manufacturers of power systems for the aerospace industry, is leading this project, in which Tronico, Ad Venta and Easyjet are also involved, contributing to on-board testing of the systems developed. The industrial partners will rely on the technical skills of the French Atomic Energy Commission (CEA), the National Polytechnic Institute of Toulouse (INPT) and the National Civil Aviation School (ENAC).

PIPAA's ambition is to develop an autonomous on-board electrical generation system for medium-haul aircraft and business jets, and to validate the entire hydrogen distribution and refuelling chain for aircraft on an airport platform. Compact and light, these electrical generation systems combining fuel cells and hydrogen tanks will make it possible to supply specific aircraft loads, both on the ground and in flight, thus significantly reducing the ecological footprint of aircraft.

ENAC ACHIL team participates in this project with fast time simulations of e-taxi equipped aircraft on ground. Standard day has been registered and is replayed with different e-taxi deployment use cases:

- 30%, 50% and 100% of eligible aircraft (Airbus A320 family)
- 50 kVa or 70 kVa power engines
- Deployment per airline or per parking zones...

For each simulation the impact on taxi times, fuel consumption and noxious emissions is evaluated.

Input and relevance to AEON: The results could be used for AEON cost benefits analysis and relevant use cases definition.

Relevance: Medium (M)

### 6.4.9 The 2050+ airport

The 2050+ airport project was an R&D project aiming to prepare airports for 2050 and beyond by creating a concept development methodology (CDM) that to ultimately:

- Enable 90% of European travellers to complete their intra-European door-to-door journeys within 4 hours
- Promote cost effectiveness through low operating costs and optimal revenue
- Develop climate neutral operations and low sound pollution

The project, led by the Royal Netherlands Aerospace Centre (NLR), lasted for 3.5 years, from September 2011 to February 2014.

Input and relevance to AEON:

This project delivered a set of recommendations for airport managers that could be of potential interest for the AEON Consortium.

Relevance: Medium (M)

The results of this state-of-the-art research and analysis will be then taken into account in later stages of the project, particularly when defining the AEON concept of operations and tools.

From the research conducted it emerges clearly that the topic being addressed by AEON is rather new and innovative. Although different projects have already addressed solutions to improve the efficiency of ground airport operations, exploring also in some cases the operational improvements that can derive from the adoption of engine off, single engine and electric engine systems, AEON seems to be the first attempt to create a consistent and unique operational concept of operation and tool for their combined use both at strategical and tactical level to improve the effectiveness of the ground operations of a big airport.

# 7 Conclusions and research directions

**The purpose of AEON is to offer a set of dedicated solutions, such as supervision interfaces, path finding and fleet management algorithms, to support autonomous and non-autonomous engine-off taxiing operations at airports, and thus contributing to reduce fuel consumption and emissions, and increasing safety.** Such solutions are seen as part of an airport collaborative decision-making tool, having the aim of improving the taxiing operations fluidity by taking into account the characteristics of each vehicle, and by efficiently managing fleets of tugs and non-autonomous aircraft.

This deliverable presents the results of a comprehensive study on the state-of-the-art methodologies for collaborative Human-machine interactions, multi-agent systems and operational research for the management of a fleet of electric tow vehicles and an overview of the work carried out in a number of projects that, for different reasons, could be considered relevant to AEON.

Based on this state-of-art, some research directions have been identified to be explored during the AEON project that integrate the different aspects discussed in this document.

**Integrated approach to human and automated agents**

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. We will focus our efforts on characterizing what inputs and Situation Awareness elements are required by each stakeholder, including algorithms, to operate efficiently. For instance, we need to specify the interactions between path planning algorithms and air traffic controllers by means of providing constraints (on kinematics, priorities, temporal-spatial, arrival/departure time) and cost functions to optimize such as minimize fuel consumption or on-time performance runway occupancy. Another aspect will be to define when operators need to be provided multiple alternatives or 'real-time' solutions to the problem at hand. The expected results related to these challenges will feed work on proposing dedicated and efficient algorithms as well as guidance to specify the different level of information and collaboration support needed by each agent.

**Fleet management and supervision**

Regarding the management of a fleet of electric towing vehicles, we have reviewed several papers on optimisation models for towing vehicle allocation and fleet sizing. However, several challenges remain regarding the availability of the towing vehicles. For instance, we might need to create tools enabling fleet supervisors to make suggestions to algorithm with respect to the availability of towing vehicles, anticipate a possible lack of towing vehicle and adjust the current plan. This will have implications for algorithms and HMIs.

**Non nominal situations**

Finally, we also need to explore non nominal situations that will require agents to re-plan their actions to achieve safe and efficient operations. These constraints will help us devise algorithms able to give very fast results to agents when needed and also to explore handover interactions for human operators when automation is not able to cope with the constraints. For instance, being able to present even sub-optimal solutions might prove useful to recover from degraded situations.

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