EXPLORATORY RESEARCH

D5.6 Thematic challenge briefing notes (1st and 2nd releases)

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Copyright Statement

Engage

THE SESAR KNOWLEDGE TRANSFER NETWORK

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Abstract

Engage identified four thematic challenges to address research topics not contemporaneously (sufficiently) addressed by SESAR. This deliverable serves primarily as a record of the two sets of released thematic challenge briefing notes.

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1 Introduction

1.1 Objectives of this document

Engage identified four thematic challenges to address research topics not contemporaneously (sufficiently) addressed by SESAR. A separate document describing each challenge was prepared by the Engage consortium as an input for the thematic workshops, these briefing notes, along with an updated second series were published on the Engage website [2]. This deliverable documents the two sets of thematic challenge (TC) briefing notes.

1.2 Four thematic challenges

In summary, the selection process for the thematic challenges began with an open call between January and March 2018, with 54 proposals received by Engage. Six priority themes were identified, from which the top four were selected and the two remaining themes are maintained as candidate future themes. The selection process of these challenges was reported in D3.4 [4].

The four thematic challenges are:

- TC1: Vulnerabilities and global security of the CNS/ATM system
- TC2: Data-driven trajectory prediction
- TC3: Efficient provision and use of meteorological information in ATM
- TC4: Novel and more effective allocation markets in ATM

The Engage consortium prepared a briefing note for each thematic challenge, to summarise the key concepts (with references), publishing the initial editions on the Engage website [2] in August 2018. The TCs were further fine-tuned through the first series of workshops (described in D2.5 [3]), resulting in the Edition 2.0 briefing notes. These were prepared as inputs for the *first Call for catalyst funding*.

Edition 2.0 of the **first set of briefing notes** were published in November 2018 (TC3 published in December 2018). Each thematic challenge was also presented at the SESAR Innovation Days 2018.

Further updates were made to the briefing notes to consolidate the conclusions from the next round of TC workshops. In December 2019 the **second set of briefing notes** were published as inputs for the *second Call for catalyst funding*, which opened in January 2020.

Table 1 provides an overview of the two sets of briefing notes.

Table 1: Overview of the thematic challenge briefing notes

Thematic challenge	Engage partners *(no implied order)*	First set published	Second set published
TC1 Vulnerabilities and global security of the CNS/ATM system	Innaxis, EUROCONTROL, Frequentis, EASA	Ed 2.0, November 2018	Ed 4.1, December 2019
TC2 Data-driven trajectory prediction	University of Belgrade, EUROCONTROL	Ed 2.0, December 2018	Ed 3.0, December 2019
TC3 Efficient provision and use of meteorological information in ATM	University of Trieste, Technical University of Delft	Ed 2.0, November 2018	Ed 3.0, December 2019
TC4 Novel and more effective allocation markets in ATM	University of Westminster, University of Trieste, Frequentis	Ed 2.0, November 2018	Ed 3.0, December 2019

For completeness, Sections 2 and 3 collate the first and second sets of TC briefing notes, however the second set updates and supersedes the earlier content. Section 3 contains links to the published PDFs.

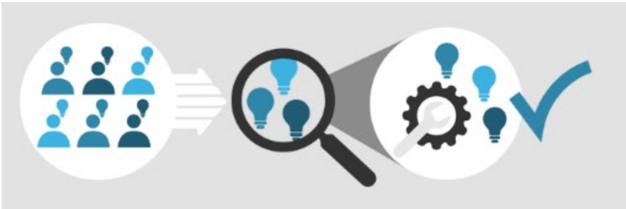
2 First set of briefing notes

The following four sub-sections contain copies of the published first set of thematic challenge briefing notes, with corresponding references. Please note that the second set of briefing notes (Section 3) update and supersede these earlier editions.

2.1 TC1 Vulnerabilities and global security of the CNS/ATM system (2018)

Thematic challenge 1

Vulnerabilities and global security of the CNS/ATM system



Edition 2.0, November 2018

This is an evolving document that summarises the key concepts (and, later, findings) for thematic challenge 1.

Abstract

CNS/ATM components (e.g., ADS-B, SWIM, datalink, Asterix) of the current and future air transport system present vulnerabilities that could be used to perform an 'attack'. Further investigations are necessary to mitigate these vulnerabilities, moving towards a cyber-resilient system, fully characterising ATM data, its confidentiality, integrity and availability requirements. A better understanding of the safety-security trade-off is required. Additional security assessments for legacy systems are also needed to identify possible mitigating controls in order to improve cyber-resilience without having to replace and refit. Future systems security by design is essential: a new generation of systems architectures and applications should be explored to ensure confidentiality, cyber-resilience, fault tolerance, scalability, efficiency, flexibility and trust among data owners. Collaborative, security-related information exchange is essential to all actors in aviation. This is specially challenging in a multi-stakeholder, multi-system environment such as ATM, where confidentiality and trust are key.

Description of challenge

Data science applications are revolutionising many industries, including aviation. The increasing availability of data, coming from an increasingly sensorised and communicating sector, is multiplying the opportunities of delivering data and information-based solutions to diverse challenges, including fuel efficiency, safety, predictability and crew training. However, this is also opening new vulnerabilities or hazards that need to be faced, as declared by the Industry Consultation Body (2017) in its information paper, noting that the increasing reliance on inter-connected ATM systems, services and technologies increases the risk of cyberattacks.

Aviation stakeholders, airlines, airports, and air navigation service providers all operate different information management systems for their operational purposes. This generates a complex, multi-stakeholder, multi-system environment where the global security of the system architecture needs to be ensured and its cyber-resilience needs to be further reinforced through a combination of organisational, procedural and technological elements (Everdij *et al.*, 2016). The reliability of the information displayed and used by ATM/CNS components is crucial to ensure the safe operation of a flight. Different ATM systems (e.g. ADS-B, datalink, SWIM, Asterix) are vulnerable to certain attacks (some of which might still be unknown), such as: corrupting, through false instructions or information, aeronautical communications broadcast in known frequencies (Strohmeier *et al.*, 2015); ADS-B false-aircraft transmissions – so-called false data injection attacks (FDIA; e.g. see Cretin *et al.*, 2018); and, attacking key infrastructure elements such as SWIM (system wide information management; e.g. see Everdij *et al.*, 2016).

Considering the growing importance of communications, information and data sharing among ATM stakeholders, systems and components, it is necessary to ensure adequate protection against these and future potential attacks. Considering current global threats, it is pertinent to perform an initial security assessment of the elements supporting air navigation as well as their relationships, in order to identify its vulnerabilities. The collaboration of the different stakeholders plays a crucial role in achieving this objective, as highlighted by the ICB in its information paper (Industry Consultation Body, 2017), where sharing information about previous attacks and effective mitigations are considered a necessary step to protect the industry from future attacks. A European holistic, coherent, affordable and adaptable response that first understands the risks and then establishes mitigation measures is needed. The risk assessment should consider the potential impact of additional security measures to avoid unwanted effects regarding safety (e.g. TCAS encryption). On the other hand, it is necessary to apply controls to existing aviation and air traffic systems to detect exposure to attacks and make them cybersecure without having to replace and refit. Certification, legal and liability issues should also be taken into account. Identifying the vulnerabilities and anticipating potential risks should then be used to design adequate mitigation actions and procedures that may imply certain changes in the system.

In a growing environment of data-driven applications (machine learning, artificial intelligence, data science, etc.) likely capable of further improving aviation performance, we need innovative data-sharing architectures capable of connecting and providing access to distributed data while preserving data privacy. The optimal data-sharing framework for a multi-stakeholder, multi-systems system like ATM, should be built on data owners' trust, placing data privacy at the heart of its architecture. The application of innovative, secure, distributed architectures, needs to be explored in the aviation domain as a potential path to ensure trust from both the technical and data usage/protocol perspectives. Further studies should also analyse the use of advanced, secure computing functions for privacy-preserving applications built over distributed applications.

The information and communication technologies sector has made significant progress in this respect and, in particular, in the cybersecurity domain, which could be transferred to the aviation industry where several initiatives have also been launched. This previous work should serve as a basis for future research in the field. The SESAR cybersecurity strategy and framework study (SESAR, 2015), in particular, provides a European framework enabling the application of an aviation security maturity model to define the roadmap towards fully secured aviation. Challenges covered therein are: bridging the gap between security risk management and the system-of-systems architecture (EATMA); strengthening cyber-resilience by linking with operational contingency; and, assessing different architectural options from a security perspective.

The CANSO *Cyber Security and Risk Assessment Guide* provides an overview of the threats and risks, including considerations for managing them and suggestions for a cybersecurity programme (CANSO, 2014). In addition, a number of workshops and research projects have been organised around this topic, helping to progress beyond the state of the art, foster the debate and promote the creation of an associated community. The following (non-exhaustive) list collects some of the most relevant activities.

- The EUROCONTROL ART workshop on cybersecurity (EUROCONTROL, 2016) focused on providing recommendations to foster progress in the field, covering regulatory, liability, validation, human and organisational aspects, including cooperation and harmonisation with other non-EU programmes.
- EASA and EUROCAE (2017) organised a workshop on technical standards to initiate the discussion about future rule-making and standardisation for cybersecurity in aviation.
- The GAMMA project (2017) developed a new vision, representing a concrete proposal for the day-to-day operation of air traffic management security. The ATM security solution proposed by GAMMA builds on the principles and concepts related to security management in a collaborative, multi-stakeholder environment, while maintaining a strong link with the current international and European legal frameworks, and the constraints imposed by national sovereignty issues.
- The European Strategic Coordination Platform (2017) on cybersecurity in aviation, organised by EASA, accepted a declaration which "called upon the European Commission and the European Aviation Safety Agency to develop and adopt Implementing Regulations addressing Cybersecurity in Aviation with harmonised common objectives but tailored requirements for subjects and sub-sectors, assuring commensurate responses to risks, called on airports, ground handling operators, maintenance organisations, air navigation service providers to develop information security management systems in accordance with specific procedures and appropriate standards, recommended to harmonise the security risk assessment methodologies, recognised that cybersecurity is an interdisciplinary problem in transport that has its challenges in aviation, but also in shipping, rail and road transport, called upon a stronger partnership between regulators, operators, service providers, and manufacturing industry, in particular within the ESCP, where EASA welcomes and supports the Industry to come with standards."

Making the most of the latest progress achieved in previous and on-going activities, this thematic challenge aims to pave the way towards a privacy-preserving, cyber-resilient, fault-tolerant and trustworthy system of systems, with all layers ensuring the integrity and availability of aeronautical data.

Update from consultation

In order to further develop specific lines of potential research activities for this challenge, an internal consultation was performed involving Engage partners and thematic challenge 1 proposers. The result of this exercise is presented below and will be complemented by a workshop (expected to take place in Spring 2019).

From the human and organisational perspective, the growing potential impact of the described cyber threats require the cooperation and adaptation of mental models within the sector. Stakeholders involved in aviation and air transportation, and especially those directly interacting with the systems and basing their operations on them, need to be trained and prepared to understand and face the threats.

From the technological perspective, the complex, multi-stakeholder, multi-system environment that is developed for CNS/ATM, requires updates of software and firmware of IT components in order to resolve security vulnerabilities of any critical infrastructure. The problem of ensuring that vendors will indeed guarantee development and delivery of security upgrades and security patches for ten years or more will soon become of crucial importance. This is currently unsolved and involves several difficult issues: technical, economic and legal. These difficulties include either how to upgrade each component, while ensuring capability with all other elements, or how to guarantee that this activity is economically sustainable over a long period. Taking into consideration the risks involved in the IT supply chain is an extremely challenging problem.

Moreover, the legal frameworks necessary for providing concrete operational guidelines suitable for these novel forms of dependence are often still excessively vague. Assessing and managing these hazards is rapidly becoming an inescapable necessity in safety critical systems.

Focusing on the crucial security analysis and strategic protocols that are needed to mitigate the system's vulnerabilities, there is a necessity to analyse whether or not protocols contain weaknesses themselves or protocols scale to the new trust mechanisms required (i.e. do they contain the required security mechanisms, or have the ability to flexibly adopt new security mechanisms?).

A deeper study of the security analysis of aviation-specific protocol implementations has to be carried out, especially for the case of a common software library used across vendors to implement a protocol specification, to know the security vulnerabilities content that these products could expose.

To move to the managed service provision of surveillance data, such as space-based ADS-B, introduces the need for service suppliers to provide adequate assurance that the data are secure. Models applied have to ensure data integrity while considering security quality for data sources from multiple parties. A greater degree of technical integration and sharing data is also introduced with the intention of rationalising traditional radar information and the utilisation of layers of newer surveillance technologies to advance capabilities. This leads to the requirement of tight security of the information, further leading to the difficulty of how to constrain data accessibility with the potential reduction of precision that this action involves.

The following have been identified as *example* ideas for potential further exploration:

1. Assessing the security of ATM elements and relationships to identify vulnerabilities and ensure protection against global threats;
2. Enhancing cybersecurity of systems without having to replace and refit, including certification, legal and liability issues;
3. Building data-sharing architectures capable of connecting and providing access to distributed data while preserving privacy;
4. Adapting mental models to prepare operators to understand and manage cyber threats
5. Updating software and firmware of IT components to resolve security vulnerabilities of critical infrastructures;
6. Further researching security analyses of aviation-specific protocol implementations (vulnerabilities, trust, software libraries).

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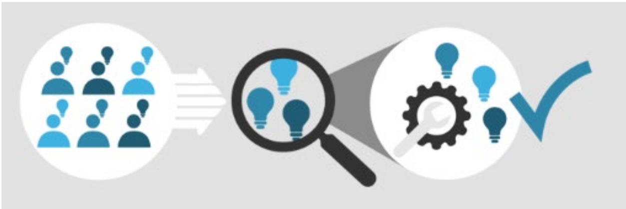
2.2 TC2 Data-driven trajectory prediction (2018)

Thematic challenge 2

Data-driven trajectory prediction



Edition 2.0, December 2018

This is an evolving document that summarises the key concepts (and, later, findings) for thematic challenge 2.

Abstract

Accurate and reliable trajectory prediction (TP) is a fundamental requirement to support trajectory-based operations. Lack of advance information and the mismatch between planned and flown trajectories caused by operational uncertainties from airports, ATC interventions, and 'hidden' flight plan data (e.g., cost indexes, take-off weights) are important shortcomings of the present state of the art. New TP approaches, merging and analysing different sources of flight-relevant information, are expected to increase TP robustness and support a seamless transition between tools supporting ATFCM across the planning phases. The exploitation of historical data by means of machine learning, statistical signal processing and causal models could boost TP performance and enhance the TBO paradigm. Specific research domains include machine-learning techniques, the aggregation of probabilistic predictions, and the development of tools for the identification of flow-management 'hotspots'. These could be integrated into network and trajectory planning tools, leading to enhanced TP.

Description of challenge

Accurate and reliable trajectory prediction (TP) is a fundamental requirement to support the Trajectory-Based Operations (TBO) paradigm. The lack of flight planning information sufficiently in advance and the mismatch between planned and flown trajectories caused by operational uncertainties from airports, ATC interventions, and 'hidden' flight plan data (e.g., cost indexes, take-off weights) are important shortcomings of the state of the art, regarding pre-tactical and tactical trajectory prediction technologies. Indeed, various stakeholders need different aspects of TP *across all phases* of operations, and user needs vary as a function of these purposes and their temporal focus.

New TP approaches, merging and analysing different sources of relevant flight information, are expected to increase TP robustness and support a seamless transition between tools supporting air traffic control (ATC) and air traffic flow and capacity management (ATFCM) in the different planning phases. The exploitation of historical data by means of machine learning, statistical signal processing and causal models can boost TP performance and enhance the TBO paradigm.

A non-exhaustive list of relevant research topics includes the:

- use of machine-learning techniques to infer airspace users' (AUs') behavioural drivers from historical data and enhance tactical and pre-tactical trajectory prediction;
- aggregation of probabilistic predictions into probabilistic traffic counts reducing the uncertainty when predicting traffic volumes;
- development of tools for the identification of 'hotspots' and the evaluation of different ATFCM measures;
- bridging the gaps between the temporal phases of ATFCM.

All of these developments could be integrated into the Network Manager's and/or flight operations centres' 4D trajectory planning tools, leading to enhanced collaboration in trajectory management, such that AUs can benefit from ATM interventions better fitted to their business models. One of the recent examples of the successful implementation of such tools in the operational environment is the Traffic Prediction Improvements (TPI) tool introduced by Maastricht Upper Area Control Centre, which is based on innovative machine-learning techniques to predict real-time flight routes and better manage traffic flows[1].

Robust demand forecast is a fundamental requirement to support the Trajectory-Based Operations paradigm and a key enabler of ATFCM service delivery. Network planning is continuously refined at different temporal planning horizons, from months to few minutes before operations. This implies using different forecasting methods adapted to the different sets of input data, each one with its associated uncertainty and granularity levels. This presents a series of challenges, and notably a lack of flight planning information sufficiently in advance – with a mismatch between planned and flown trajectories, caused by the operational context uncertainties identified above.

[1] https://www.eurocontrol.int/publications/traffic-prediction-improvements-tpi-factsheet-and-technical-documentation

Current demand prediction tools are based on heuristic decision rules and/or simplified dynamic models, which fail to consider other important contextual flight attributes (e.g., airspace user specificity, meteorology). Additionally, the resulting forecast is often deterministic, without any quantification of the uncertainty of the prediction. These shortcomings limit the accuracy of the forecasts and create a gap between the different temporal phases of ATFCM, leading to inefficient or sub-optimal ATFCM measures.

Considering previous research in this field, sophisticated trajectory prediction models are often hindered by the need to estimate operational flight intentions, which might differ from one airspace user to another, and by aircraft type, etc. Certain sensitive information, such as the cost index, take-off weight or other unknown aircraft performance parameters also contribute to the problem. Additionally, much of past research has focused on the tactical planning phase, relying on flight plans, which may be available only a few hours before operations and can be subsequently modified, leading to mismatches between predicted and actual flown trajectories.

The increasing availability of data at different scales, together with recent advances in the fields of data analysis and visualisation, present opportunities to develop new modelling techniques to improve trajectory prediction performance and robustness by:

- integrating and analysing different sources of flight-relevant information;
- the application of new modelling methods, such as machine-learning techniques, causal modelling and statistical signal processing solely, or in combination with traditional methods;
- inferring airspace users' drivers from historical data;
- engaging airspace users to collaborate and benefit from potential air traffic management interventions (better) fitting their business needs.

Workshop conclusions

Different stakeholders in the aviation system use trajectory predictions with different objectives and timelines. These embrace demand assessment and capacity planning in ATFCM at the strategic, pre-tactical and tactical level, operations planning and execution by AUs across the same phases, conflict detection and resolution (i.e. separation management) for ATC, collision avoidance in certain safety nets, and performance monitoring.

For example, operations planning by AUs at the pre-tactical (e.g. flight dispatch) and tactical levels (e.g. self-separation, in-flight trajectory updates) and assessments made by (ATM) performance monitoring and/or target setting agencies, require *different* trajectory predictors. Owing to these diverse applications, requirements vary and hence the best TP implementation also varies depending on the purpose and prediction horizon.

Closer to flight execution, data become available that were not available in earlier planning phases: an example is the absence of flight plan data in the pre-tactical planning phases, when the Network Manager together with national service providers match airspace capacity with the anticipated demand. Accurate demand predictions are a central requirement in the demand-capacity balancing process. A smooth transition is desirable between all phases of the planning process as, for example, flight plan data and local restrictions become available.

The availability and quality of relevant data is a prerequisite for accurate TPs. This concerns: physical access to clean data across a number of types and protocols; overcoming stakeholders' concerns regarding data sharing (e.g. confidentiality and competition issues); and, the implications for hardware/software (avionics, electronic flight bags (EFB), data link). Appropriately sharing trajectory data as widely as possible benefits both operations and research objectives, as opposed to only sharing data that allows the calculation of trajectories using specific TP implementations.

Trajectory predictors do not currently have access to the range of data that could benefit improved predictions: this includes trend data, as well as stakeholder preferences and intentions. Some of these missing data might be extracted from historical datasets. TPs are also often 'blind' to operationally relevant information, for example leading to (very) high false alert rates for conflict detection systems such as medium-term conflict detection (MTCD) and short-term conflict alerts (STCAs). Tactical ATC interventions, for example flight-path shortening through radar vectoring, are not usually considered, whereas a TP anticipating (or suggesting) controller interventions and conflict resolutions would be more powerful.

The following have been identified as *example* ideas for potential further exploration:

1. Trajectory predictors supporting airborne self-separation: definition of requirements & concept development of enabling technologies;
2. Improved DCB: enhanced TPs integrating uncertainty assessment, robust planning and cost-efficiency assessment at network level;
3. Data-driven approaches for understanding and prediction of AU preferences and behaviours enabling improved NM operations;
4. Mapping requirements definition and concept development of data-driven TP in support of collaborative multi-sector CD&R;
5. Optimising and integrating local planning activities with a view to assess, contain and communicate their network effects;
6. Improving data-sharing and data access to satisfy AU, NM and ANSP technical and organisational requirements and expectations.

References (further reading)

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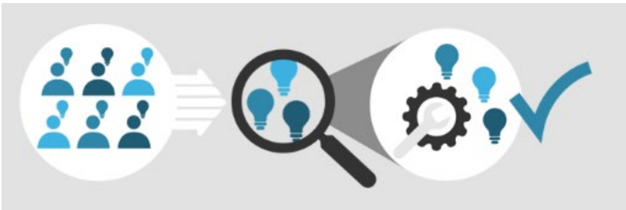
2.3 TC3 Efficient provision and use of meteorological information in ATM (2018)

Thematic challenge 3

Efficient provision and use of meteorological information in ATM



Edition 2.0, November 2018

This is an evolving document that summarises the key concepts (and, later, findings) for thematic challenge 3.

Abstract

The main objective of this challenge is to improve overall ATM system performance by providing better user-support tools based on improved meteorological ('MET') products. The focus is on the synergy of several methods and techniques in order to better meet the needs of operational users and to support aviation safety (e.g., through creating early warning systems) and regulation-makers (e.g., moving from text-based to graphical information provision). All stakeholders may benefit from this synergy: ANSPs (e.g., sector reconfiguration and separation provision), airlines (e.g., storm avoidance), airport operators (e.g., airport management under disruptive events), and the Network Manager (e.g., demand-capacity balancing). The challenge is, therefore, to bring the following perspectives closer: (a) for meteorological/atmospheric science, the development of products tailored to ATM stakeholders' needs, which are unambiguous and easy to interpret; (b) for stakeholders, the identification of the most suitable information available and its integration into planning and decision-making processes.

Description of challenge

Weather is an integral part of ATM, especially in the light of increasing traffic levels, where weather conditions present a significant source of uncertainty in the planning process, and one of the major causes of disruption and consequent delay during operations. About 20-30% of total ATFM delay has been caused by weather in recent years, while this grew to 20-45% in the first six months of 2018, thus challenging the achievement of the Performance Scheme goals for this year. In addition, extreme weather phenomena such as hail, severe icing and lightning present significant hazards as they can inflict substantial damage to aircraft. As extreme weather events are becoming more frequent in Europe, and forecast certainty is apparently decreasing, ATM performance is negatively impacted.

This thematic challenge aims at understanding how ATM may benefit more from the advances in meteorology/atmospheric sciences, especially in the light of climate change and the weather uncertainty that it brings. This is a key issue in the current European ATM research arena because on the one hand, extreme weather patterns are changing with climate change and, on the other hand, the impact of weather on different parts of the ATM network and its stakeholders (e.g. airports, ANSPs, airlines, passengers, Network Manager) varies in the type and magnitude of disruption, and consequent costs. For example:

- Airports – different conditions (e.g. rain, fog, snow) can cause capacity reductions and even closures (see also the ACI policy brief[2] on climate adaptation by airports);
- En-route – winds impact aircraft speed, weather cells can cause ANSPs to change flights' trajectories, etc;
- Airlines – trajectory changes[3], delays and schedule disruption occur, resulting in various types of cost (e.g. passenger reaccommodation);
- Network level – the Network Manager coordinates and circulates the information to all stakeholders regarding local weather impacts on flow management, without taking decisions on local weather-related actions, apart from facilitating network-level harmonisation; an overarching, reliable and shared view on weather is still not in place in the European network.

Hence, meteorological information needs differ across stakeholders, either in the type of information, or in the useful time horizon and in the certainty/uncertainty that can be tolerated in the decision-making processes. The time horizon may span from a few days to real-time, depending on the stakeholder and the function the stakeholder performs (e.g. ATC, or baggage handling at the airport). Furthermore, different forecast (and observation) resolutions are needed - a grid of 100 km^2 could be quite adequate for an ANSP, but lacks necessary detail for terminal manoeuvring/airport management. Another important component is the level of uncertainty that weather conditions impose. In the planning processes, higher uncertainty is tolerated, while in real time operations more certain information on the extent and trend of meteorological conditions is needed.

[2] https://store.aci.aero/wp-content/uploads/2018/10/Policy_brief_airports_adaption_climate_change_V6_WEB.pdf

[3] Improved trajectory prediction *per se* falls within the remit of Engage thematic challenge 2.

At present, the delivery and format of meteorological information provision is regulated by ICAO Annex 3, EASA and national regulations (in Europe). Regulated MET services and products[4] from certified MET ANSPs are quality controlled and are, in principle, free. In the USA, the National Weather Service provides a comprehensive set of forecasts, observations and tools *via* the Aviation Weather Center, and the Federal Aviation Authority deploys various weather-related decision-support tools aimed at more efficient air traffic management. In Europe, there are about 40 MET information service providers, some being certified National Meteorological and Hydrological Services (NMHS), some Air Traffic Service (ATS) organisations, or a mixture of the two. Each has different responsibilities and cost structures. Commercial value-added services exist, and allow tailoring to user needs. These can be provided by a commercial MET provider or MET ANSP (for a fee). The Pilot Common Project (EU 716/2014) and Regulation EU 2017/373 are calling for additional MET services, and there is a widespread belief that if action is not taken promptly, new climate conditions will pose ever greater challenges to all ATM stakeholders.

In fact, the number and the intensity of extreme weather events increased in recent decades in some areas of the globe including Europe (Hov *et al*., 2013). Damage is mostly caused by strong winds, hail and precipitation intensity. Studies suggest that higher precipitation intensity for northern Europe, dry-spell periods for southern Europe, high intensity and extreme precipitation are expected to become more frequent within the next 70 years. The increased frequency is estimated to be larger for more extreme events, but will vary considerably from region to region (*ibid*). For instance, Black *et al*. (2010) reported decreasing winter rainfall over southern Europe and the Middle East and increased rainfall further north caused by a poleward shift of the North Atlantic storm track.

Long-term changes in European storminess are not very clear and sometimes show conflicting results. Some studies show a strong multidecadal variability (Alexandersson *et al*., 2000; Bärring and von Storch, 2004; Wang *et al*., 2009), and analyses of extreme wind speeds highlight significant upward trends in central, northern and western Europe (Donat *et al*., 2011b; Brönnimann *et al*., 2012). Models under scenarios with increasing greenhouse gas concentrations indicate an increase in the number of severe storms in north-western and central Europe, which is also in accordance with other simulation results (Beniston *et al*., 2007). These simulations also suggest a significant increase in cyclone intensity and the number of intense cyclones over northwest, central and western Europe, under future climate conditions (Leckebusch *et al*., 2006, 2008; Pinto *et al*., 2009; Ulbrich *et al*., 2009). A belt stretching from the United Kingdom to Poland will experience an increase in extreme storminess and wind speed, while southern Europe and the Mediterranean will rather see a decrease in strong winds (Leckebusch *et al*., 2006; Donat *et al*., 2011a).

It must be recognised that recent years have witnessed important improvements in observational (e.g., satellites, LIDARs) and numerical weather prediction (NWP) models in the atmospheric sciences (e.g., models for air quality in megacities that consider topography and resolution of under 100m). However, little has yet filtered down to the ATM world. Several workshops and MET-related projects came to similar conclusions: it is important to bring ANSPs, airlines, academics, MET service providers and atmospheric scientists together to better understand the effects and requirements of mitigation actions to convective, winter and hazardous weather at trajectory, network and airport levels. In some

[4] MET products refer to different types of meteorological information, such as forecasts, observations, now-casts.

cases, tools and know-how exist, in others better models and outputs became available but are not exactly what ATM needs. Thus, the initial step towards delivering the improved MET information needed for more efficient air traffic management consists of both learning about improvements in the atmospheric sciences, and about ATM needs in the light of the uncertainty that weather imposes on the network (and related uncertainty management) and, possibly, associated regulatory issues.

The ultimate goal of this thematic challenge is therefore to define further research and operational needs regarding the use of weather information for more efficient ATM.

Update from the workshop

MET-related research should enhance situational awareness of MET conditions for all ATM stakeholders, using state-of-the-art MET products. MET provision in Europe is fragmented, as each state is responsible for the provision for its territory. This is one of the reasons behind the lack of a consistent and agreed weather 'picture' for ATM in Europe. The Network Manager and several MET offices are working on the creation and usage of European forecasts for network management.

Currently, the trend in MET research is focused on ensemble prediction systems. Thus, in the next 5-10 years we should expect MET products to be realised as ensembles, providing measures of uncertainty in different atmospheric variables. A long-term educational and communication effort should be undertaken so that ATM stakeholders are prepared to understand these new MET products and take advantage for better planning of resources.

MET products can be classified along two dimensions: spatial and temporal resolution. In terms of spatial resolution, forecasts can be cast as global (resolution of about 1 degree), limited-area models (covering regions such as Europe, resolution in terms of tens of kilometres), and of very high-resolution (smaller areas, such as terminal manoeuvring areas, resolution of hundreds of metres). In terms of temporal resolution, there are long- (about 1 week), medium- (about 1 day), short- (about 3-6 hours), and very short-range (about 1 hour) forecasts. Both the temporal and spatial resolution are important depending on the stakeholder application. For example, the Network Manager is interested in medium-range / limited-area forecasts; dispatchers, in short-range / limited areas; pilots/controllers, in very short-range / very high-resolution when facing storms; airports, in very short-range / very high-resolution, etc.

The higher the resolution, the forecast becomes more challenging. NWPs alone are not sufficient for this type of product, and call for data assimilation of the observed values of varied atmospheric characteristics (e.g. lightning, deep convection). *In situ* sensors and sensor networks that collect and deliver information for forecasting are needed. The aggregation of different sources of data for blended ensemble forecasts in the very high-resolution, very short-range scales seems to be the trend for the next 10 years.

The most cited barriers to the progress of MET and MET/ATM research were the inadequacy of research funding available to the MET offices (only partial funding), and fragmented provision of MET products for aviation (coupled with regulatory and sovereignty matters). Further important barriers revolve around the trust the ATM users have in available MET products, and not particularly high usage in operational decision-making. This points to the two underlying issues:

1. fitness of purpose of MET products (e.g. medium-range, limited-area forecasts are of little practical use to airport tower supervisors, while the very high-resolution, very short-range forecasts would be more easily included in this decision-making process);
2. ATM stakeholder knowledge of the available MET products, especially on the characteristics and meaning of MET products being developed.

The following have been identified as *example* ideas for potential further exploration:

1. Very high-resolution, very short-range forecasts using numerical weather prediction models and observational data assimilation;
2. Quantifying the sensitivity of operational processes to MET uncertainty, comparing these with other sources of uncertainty;
3. Incorporation of ensemble weather information into decision-support tools, adapted for different ATM stakeholders;
4. Accurate prediction of weather conditions (e.g. visibility, glide-path wind) influencing airport arrival and departure operations;
5. Consolidation of climate risk assessment methodologies for airports;
6. Creating a climate forecast 'baseline' for aviation from the IPCC UN panel report.

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2.4 TC4 Novel and more effective allocation markets in ATM (2018)

Thematic challenge 4

Novel and more effective allocation markets in ATM

Edition 2.0, November 2018

This is an evolving document that summarises the key concepts (and, later, findings) for thematic challenge 4.

Abstract

This research explores the design of new allocation markets in ATM, taking into account real stakeholder behaviours. It focuses on designs such as auctions and 'smart' contracts for slot and trajectory allocations. It seeks to better predict the actual behaviour of stakeholders, compared with behaviours predicted by normative models, taking into account that decisions are often made in the context of uncertainty. Which mechanisms are more robust against behavioural biases and likely to reach stable and efficient solutions, equitably building on existing SESAR practices? The research will address better modelling and measurement of these effects in ATM, taking account of 'irrational' agents such as airline 'cultures'. A key objective is to contribute to the development of improved tools to better manage the allocation of resources such as slots and trajectories, and incentivising behaviour that benefits the network - for example by investigating the potential of centralised markets and 'smart' contract enablers.

Description of challenge

Air traffic management (ATM) is an example of a system where demand often exceeds capacity. In Europe, for a flight flying from a given origin to a destination, a shortfall in either en-route capacity (e.g. insufficient controllers to handle the flight) or at the destination (e.g. insufficient runway capacity to receive the flight), results in the flight being delayed at the origin until an appropriate trajectory and tactical departure slot are available. Each year, such delays generate large costs for the airspace users (airlines) and passengers. During such capacity constraints challenges remain regarding, *inter alia*, the trade-off between minimising the delay in the network as a whole and the delay for given airspace users.

This thematic challenge explores the design of new market mechanisms for the (re-)allocation of trajectories/routes and slots (often linked resources) to airlines in the tactical phase. "Market" mechanism does not necessarily imply the use of money as a medium for transactions. Moving beyond first-planned, first-served principles, matching market, centralised batch auctions, primary and secondary markets (double auction or bilateral exchanges) may each bring advantages. The challenge also seeks to explore better ways to predict the *actual* behaviour of stakeholders (airspace users in particular), compared with behaviours predicted by classical models, also taking into account that decisions are often made in the context of uncertainty. Such uncertainty may be aleatory (due to chance, such as weather) or epistemic (due to lack of information). The challenge poses questions such as: which types of mechanism are likely to work best in tactical slot and trajectory management[5], under different types of uncertainty and information sharing? Which mechanisms are more robust against behavioural biases ('irrationalities') and likely to reach stable and efficient solutions more quickly, e.g. without leaving unused slots? How can we equitably build on existing SESAR practices, such as Enhanced Slot Swapping, and planned SESAR functionalities such as the User-Driven Prioritisation Process (UDPP)?

A number of economic models applied in ATM (and air transport) are *normative*, such as Nash equilibria and linear programming. They make several assumptions about agent rationality that do not always work as expected predictors of behaviour. This is because real decisions are often made by human beings, or at least with human intervention, and are not fully 'rational', in the sense of adopting the solution suggested by some type of optimisation process. Behavioural science in general, and behavioural economics in particular, may bring complementary solutions to ATM in order to better predict actual behaviour in the network. Behavioural economics is based on a number of related principles, examples of which are summarised below:

[5] Improved trajectory prediction *per se* falls within the remit of Engage thematic challenge 2.

- **Loss aversion**
  - losses are worse (have more disutility) than gains are good (have utility), e.g. avoiding a €1k slot delay is preferred to an (immediate) €1k 'slot credit'
- **Endowment (inertia) effects**
  - a higher value is attributed to a good already owned, e.g. "we will 'pay' as much to avoid an initial 15 minutes of slot delay, as to avoid a further (more expensive) 15 minutes of delay"
- **Path dependencies**
  - the value of a good depends on the path of acquisition, e.g. "we protected this slot today after sacrificing ten flights last week, so there is no way we are going to trade it today"
- **Future discounting**
  - the value of a good depends on when it is consumed, e.g. one 30-minute slot improvement today is worth two identical improvements next week

Whilst more broadly, behavioural science may consider aspects such as airline general 'beliefs' (or 'cultures', e.g. that a certain type of action results in a certain type of delay), behavioural economics tends to focus more specifically on understanding financial trade-offs, taking into account that agent rationality is 'bounded' (such agents are not willing or capable of solving complex optimisation problems, as they are assumed to in normative models predicting behaviour). Classically, market forces are often assumed to establish rationality and, ultimately, to produce a predictable equilibrium – although this is often not the case.

Behavioural science, with behavioural economics, thus focuses on what agents *actually* do, rather than what they 'should' do, and is driven by *descriptive* models. This thematic challenge may thus investigate the extent to which ATM can move from objective functions to 'subjective' functions, i.e. that take account of 'irrational' agents. In a 2014 review, Whitehead *et al*. (2014) state that "the behavioural sciences are clearly having a global impact on public policy initiatives [...] 136 states have seen the new behavioural sciences have some effect on aspects of public policy delivery in some part of their territory [...] 51 states have developed centrally directed policy initiatives that have been influenced by the new behavioural sciences." Several ATM stakeholders have expressed a need to take advantage of behavioural science to improve operational predictability. However, notwithstanding limited examples considering actual human behaviour in the context of wider transport planning and environmental policy (e.g., Avineri, 2012; Garcia-Sierra *et al.,* 2015), there are no known formal considerations of the applications of behavioural science in ATM.

Several SESAR exploratory research (ER) projects (e.g., SATURN, ACCESS, COCTA) have advanced the market mechanism state of the art already, exploring ways in which the efficiency of existing solutions might be improved, including market-based demand-management mechanisms for air traffic flow management (Bolic *et al.*, 2017; Castelli *et al.*, 2011), auctioning for strategic airport slots (De Neufville and Odoni, 2013; Herranz *et al.*, 2015), and controlling tactical delay distributions to minimise propagated delay and increase adherence to (strategic) airport slots at coordinated airports (Ivanov *et al.*, 2017). Further development opportunities lie ahead, in that modelling in these domains variously investigates the optimal use of limited capacities but (necessarily) assumes unbounded rationality, for example regarding flight scheduling and demand management that might "create opportunities for strategic behaviours from the airlines, i.e., potential incentives to provide scheduling inputs that do not reflect their true preferences in order to gain a strategic advantage over their competitors"

(Jacquillat and Odoni, 2018). Regarding airport capacity and demand management, these authors further comment that "abstractions and simplifications of reality that necessarily underlie these mathematical and simulation models cannot fully capture all the operating complexities found in practice". In a comprehensive review comparing and contrasting the operations research and economics perspectives in ATM, it is concluded that "significant opportunities exist to [...] extend the scope of economic studies to integrate more realistic models of flight scheduling and airport operations [...] addressing them incrementally would enable the development of cross-disciplinary approaches to airport demand management and more effective congestion mitigation policies" (Gillen *et al*., 2016).

Whilst **(strategic) airport slots are not in scope for this challenge**, let us consider briefly a current tactical example. SESAR continues to develop UDPP to achieve additional flexibility for airspace users to adapt their operations in a more cost-efficient manner. This makes use of mature mechanisms such as Enhanced Slot Swapping (deployed in 2017) and continues to validate mechanisms such as fleet delay apportionment and selective flight protection (Pilon *et al*., 2016). It is also exploring future options for even greater flexibility regarding cost minimisation and equity for 'low volume' airspace users with less market power, although integration of accurate airline decision-making and cost models in this context remains a challenge, and the best models to date assume unbounded rationality and utility maximisation (Ruiz *et al*., 2017).

Behavioural science is not a panacea with regard to resolving certain shortcomings of the classical approaches to operations research, and assumptions of utility maximisation, for example, that still serve the ATM community well. Nor can it model the full scope of agent subjectivity. Rather, this thematic challenge seeks, *inter alia*, to identify and explore key areas in which behavioural science may advance the state of the art regarding ATM modelling, complementarily bridging existing gaps. This will involve identifying methods and solutions where an absence of behavioural modelling is particularly likely to compromise model usefulness and, where possible, to collect evidence of such (anticipated) shortfalls. More broadly, can we identify the first steps towards improved tools to better manage the costs of delay, and of uncertainty, and to better incentivise behaviour that benefits the network, in the wider context of tactical slot and trajectory allocation? What new technologies might be appropriate to support the negotiation of tactical contracts? For example, might cryptoeconomic tools[6] have a role to play in delivering 'smart' contracts? From a user-acceptability perspective, could such tools deploy a centralised market with real money, or would only 'credits' be acceptable?

Workshop conclusions

Behavioural science could be used to better capture 'irrational' (non-normative) behaviour from airlines in future, and build improved models, for example in terms of (tactical) routing and slot choices. This could deliver improved forecasting and traffic demand tools for ANSPs, and better predict behaviour under UDPP (for example) by validating key prospect theory principles, such as loss framing, risk-seeking behaviour under loss, and endowment effects. New market designs for the allocation, and trading, of tactical slots may support potential future mechanisms for slot swapping and trading between different airlines. Key to such progress will be understanding ways to more effectively

[6] Note that vulnerabilities and global security of the CNS/ATM system falls within the remit of Engage thematic challenge 1.

manage airspace user cooperation and motivation, how these vary by airline type, and whether incentives or penalties work better. Is the better underlying driver of behaviour cooperation or competition, and can social norms be used to make airline behaviour more collaborative? The objective is to offer airspace users improved choice, whilst avoiding undesirable behaviours, such as gaming of the system. Improved definitions of 'equity' and 'fairness' are needed, potentially differentiating or consolidating the two terms, examining the definitions and trade-offs across different stakeholders (e.g. airports treating all flights equally, unlike airlines), plus trade-offs with flexibility. Are there ways in which tactical uncertainty could be exploited to offer more flexibility to airspace users? There is no unique way to define equity and fairness, since these may or may not invoke monetary value, and may depend on the stakeholder perspective and impacts, both at the local and network levels. Further work is also needed on the precise definition of the 'best' trajectory[7], by stakeholder type, not only across airspace user types. Greater elucidation is required of the need to adopt a compromise between individual rationality, budget balance, allocative efficiency and incentive compatibility (see Castelli *et al.*, 2011) in the design of new mechanisms. This should build on existing exploratory research in SESAR examining the trade-offs between centralised and decentralised markets. As raised above, part of the move towards improved models of stakeholder behaviour could assess gaming, and mature the state of the art advanced by projects such as AeroGame[8], which investigated how serious games can support change in ATM. It is necessary to model more realistic human interactions in a multi-stakeholder, complex socio-technical environment, rather than in highly constrained and limited simulation environments, and to determine which (incentive) solutions are best in terms of non-manipulability (Schummer and Abizada, 2017; Schummer and Vohra, 2013).

The robustness of (tactical) slot allocation mechanisms and airspace users' choice of flight plan as a function of time is made more difficult to predict in the context of uncertainty from exogenous factors and the airspace user's response to the evolving traffic situation as they adapt from the originally-filed flight plan. Integrating new behavioural models with a more systematic exploration of the impact of computer-based flight planning and how this responds to different scenarios, with models of feedback loops and inclusion of machine learning could also be beneficial[7]. Airspace user cost functions need to be taken into account, and may be usefully framed in terms of flexibility characterisations, such as elasticity functions and 'not before' and 'not later than' departure rules. Such functions and rules could be deployed to empower airspace users to make better choices. Additional investigation of the potential role of ANSPs coordinating with the Network Manager to manage tactical demand (and route choices) is required, building on the work of COCTA, for example, assessing the impacts of uncertainty and disturbance, and the implications for policy recommendations regarding the Single European Sky performance scheme. Barriers to progressing the state of the art include the calibration and validation of new models such as those identified above, and obtaining quality stakeholder cooperation and buy-in. This might be overcome by running models and tools in shadow-mode, with usable and practical user interfaces, also demonstrating their value in terms of metrics such as predictions of (sector) overloads, delays and delay costs, and valuations of equity, fairness and efficiency. Data collection quality could be improved through the use of stated preference techniques, commonly deployed in socio-economic and psychological research, and sensitivity analyses would need to be run to test model and tool efficacies. Capturing gaming behaviours often requires projective techniques.

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[7] Improved trajectory prediction *per se* falls within the remit of Engage thematic challenge 2.

[8] https://www.sesarju.eu/newsroom/brochures-publications/aerogame

Ultimately, can the two main themes of this challenge be integrated, i.e. embedding agent 'irrationality' inside the development of new market mechanisms?

The following have been identified as *example* ideas for potential further exploration:

1. Incorporating behavioural science methods into improved traffic demand and distribution predictor tools for ANSPs and UDPP;
2. Assessing if incentives or penalties work as better drivers of behaviour: whether social norms can be used to improve collaboration;
3. Predicting and avoiding undesirable behaviour, such as gaming, in ATM allocation mechanisms;
4. Building a better understanding of 'equity' and 'fairness', plus trade-offs across different stakeholders, and with 'flexibility';
5. Improving the assessment of uncertainty and disturbance, and of new mechanism implications for policy recommendations;
6. Running models and tools in shadow-mode, with practical user interfaces and value in output metrics (e.g. costs, overloads).

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3 Second set of briefing notes

The following four sub-sections contain copies of the published second set of thematic challenge briefing notes, with corresponding references. Please note that these update and supersede the first set of briefing notes (Section 2).

The second set of briefing notes are available on the Engage website [2], see "Fuller text here".

The individual links to the PDFs are:

TC1: https://engagektn.com/wp-content/uploads/2019/12/Thematic-challenge-1-Ed-4.1.pdf

TC2: https://engagektn.com/wp-content/uploads/2019/12/Thematic-challenge-2-Ed-3.0.pdf

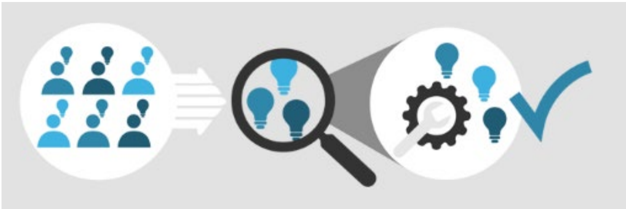
TC3: https://engagektn.com/wp-content/uploads/2019/12/Thematic-challenge-3-Ed-3.0.pdf

TC4: https://engagektn.com/wp-content/uploads/2019/12/Thematic-challenge-4-Ed-3.0.pdf

3.1 TC1 Vulnerabilities and global security of the CNS/ATM system (2019)

Thematic challenge 1

Vulnerabilities and global security of the CNS/ATM system



Edition 4.1, December 2019

This is an evolving document that summarises the key concepts (and, later, findings) for thematic challenge 1.

Abstract

CNS/ATM components (e.g., ADS-B, SWIM, datalink, Asterix) of the current and future air transport system present vulnerabilities that could be used to perform an 'attack'. Further investigations are necessary to mitigate these vulnerabilities, moving towards a cyber-resilient system, fully characterising ATM data, its confidentiality, integrity and availability requirements. A better understanding of the safety-security trade-off is required. Additional security assessments for legacy systems are also needed to identify possible mitigating controls in order to improve cyber-resilience without having to replace and refit. Future systems security by design is essential: a new generation of systems architectures and applications should be explored to ensure confidentiality, cyber-resilience, fault tolerance, scalability, efficiency, flexibility and trust among data owners. Collaborative, security-related information exchange is essential to all actors in aviation. This is specially challenging in a multi-stakeholder, multi-system environment such as ATM, where confidentiality and trust are key.

Description of challenge

Data science applications are revolutionising many industries, including aviation. The increasing availability of data, coming from an increasingly sensorised and communicating sector, is multiplying the opportunities of delivering data and information-based solutions to diverse challenges, including fuel efficiency, safety, predictability and crew training. However, this is also opening new vulnerabilities or hazards that need to be faced, as declared by the Industry Consultation Body (2017) in its information paper, noting that the increasing reliance on inter-connected ATM systems, services and technologies increases the risk of cyberattacks.

From the human and organisational perspective, the growing potential impact of the described cyber threats require the cooperation and adaptation of mental models within the sector. Stakeholders involved in aviation and air transportation, and especially those directly interacting with the systems and basing their operations on them, need to be trained and prepared to understand and face the threats. Aviation stakeholders, airlines, airports, and air navigation service providers all operate different information management systems for their operational purposes. This generates a complex, multi-stakeholder, multi-system environment where the global security of the system architecture needs to be ensured and its cyber-resilience needs to be further reinforced through a combination of organisational, procedural and technological elements (Everdij *et al.*, 2016). The reliability of the information displayed and used by ATM/CNS components is crucial to ensure the safe operation of a flight. Different ATM systems (e.g. ADS-B, datalink, SWIM, Asterix) are vulnerable to certain attacks (some of which might still be unknown), such as: corrupting, through false instructions or information, aeronautical communications broadcast in known frequencies (Strohmeier *et al.*, 2015); ADS-B false-aircraft transmissions – so-called false data injection attacks (FDIA; e.g. see Cretin *et al.*, 2018); and, attacking key infrastructure elements such as SWIM (system wide information management; e.g. see Everdij *et al.*, 2016).

From the technological perspective, the complex, multi-stakeholder, multi-system environment that is developed for CNS/ATM, requires updates of software and firmware of IT components in order to resolve security vulnerabilities of any critical infrastructure. The problem of ensuring that vendors will indeed guarantee development and delivery of security upgrades and security patches for ten years or more will soon become of crucial importance. This is currently unsolved and involves several difficult issues: technical, economic and legal. These difficulties include either how to upgrade each component, while ensuring capability with all other elements, or how to guarantee that this activity is economically sustainable over a long period. Taking into consideration the risks involved in the IT supply chain is an extremely challenging problem.

Considering the growing importance of communications, information and data sharing among ATM stakeholders, systems and components, it is necessary to ensure adequate protection against these and future potential attacks. Considering current global threats, it is pertinent to perform an initial security assessment of the elements supporting air navigation as well as their relationships, in order to identify its vulnerabilities. The collaboration of the different stakeholders plays a crucial role in achieving this objective, as highlighted by the ICB in its information paper (Industry Consultation Body, 2017), where sharing information about previous attacks and effective mitigations are considered a necessary step to protect the industry from future attacks. A European holistic, coherent, affordable and adaptable response that first understands the risks and then establishes mitigation measures is needed. The risk assessment should consider the potential impact of additional security measures to avoid unwanted effects regarding safety (e.g. TCAS encryption). On the other hand, it is necessary to apply controls to existing aviation and air traffic systems to detect exposure to attacks and make them cyber secure without having to replace and refit.

Certification, legal and liability issues should also be taken into account. Identifying the vulnerabilities and anticipating potential risks should then be used to design adequate mitigation actions and procedures that may imply certain changes in the system. Moreover, the legal frameworks necessary for providing concrete operational guidelines suitable for these novel forms of dependence are often still excessively vague. Assessing and managing these hazards is rapidly becoming an inescapable necessity in safety critical systems.

In a growing environment of data-driven applications (machine learning, artificial intelligence, data science, etc.) likely capable of further improving aviation performance, we need innovative data-sharing architectures capable of connecting and providing access to distributed data while preserving data privacy. The optimal data-sharing framework for a multi-stakeholder, multi-systems system like ATM, should be built on data owners' trust, placing data privacy at the heart of its architecture. The application of innovative, secure, distributed architectures, needs to be explored in the aviation domain as a potential path to ensure trust from both the technical and data usage/protocol perspectives. Further studies should also analyse the use of advanced, secure computing functions for privacy-preserving applications built over distributed applications.

As a particular example, to move to the managed service provision of surveillance data, such as space-based ADS-B, introduces the need for service suppliers to provide adequate assurance that the data are secure. Models applied have to ensure data integrity while considering security quality for data sources from multiple parties. A greater degree of technical integration and sharing data is also introduced with the intention of rationalising traditional radar information and the utilisation of layers of newer surveillance technologies to advance capabilities. This leads to the requirement of tight security of the information, further leading to the difficulty of how to constrain data accessibility with the potential reduction of precision that this action involves.

The information and communication technologies sector has made significant progress in this respect and, in particular, in the cybersecurity domain, which could be transferred to the aviation industry where several initiatives have also been launched. This previous work should serve as a basis for future research in the field. The SESAR cybersecurity strategy and framework study (SESAR, 2015), in particular, provides a European framework enabling the application of an aviation security maturity model to define the roadmap towards fully secured aviation. Challenges covered therein are: bridging the gap between security risk management and the system-of-systems architecture (EATMA); strengthening cyber-resilience by linking with operational contingency; and, assessing different architectural options from a security perspective.

Focusing on the crucial security analysis and strategic protocols that are needed to mitigate the system's vulnerabilities, there is a necessity to analyse whether or not protocols contain weaknesses themselves or protocols scale to the new trust mechanisms required (i.e. do they contain the required security mechanisms, or have the ability to flexibly adopt new security mechanisms?). A deeper study of the security analysis of aviation-specific protocol implementations has to be carried out, especially for the case of a common software library used across vendors to implement a protocol specification, to know the security vulnerabilities content that these products could expose.

The CANSO *Cyber Security and Risk Assessment Guide* provides an overview of the threats and risks, including considerations for managing them and suggestions for a cybersecurity programme (CANSO, 2014). In addition, a number of workshops and research projects have been organised around this topic, helping to progress beyond the state of the art, foster the debate and promote the creation of an associated community. The following (non-exhaustive) list collects some of the most relevant activities.

- The EUROCONTROL ART workshop on cybersecurity (EUROCONTROL, 2016) focused on providing recommendations to foster progress in the field, covering regulatory, liability, validation, human and organisational aspects, including cooperation and harmonisation with other non-EU programmes.
- EASA and EUROCAE (2017) organised a workshop on technical standards to initiate the discussion about future rule-making and standardisation for cybersecurity in aviation.
- The GAMMA project (2017) developed a new vision, representing a concrete proposal for the day-to-day operation of air traffic management security. The ATM security solution proposed by GAMMA builds on the principles and concepts related to security management in a collaborative, multi-stakeholder environment, while maintaining a strong link with the current international and European legal frameworks, and the constraints imposed by national sovereignty issues.
- The European Strategic Coordination Platform (2017) on cybersecurity in aviation, organised by EASA, accepted a declaration which "called upon the European Commission and the European Aviation Safety Agency to develop and adopt Implementing Regulations addressing Cybersecurity in Aviation with harmonised common objectives but tailored requirements for subjects and sub-sectors, assuring commensurate responses to risks, called on airports, ground handling operators, maintenance organisations, air navigation service providers to develop information security management systems in accordance with specific procedures and appropriate standards, recommended to harmonise the security risk assessment methodologies, recognised that cybersecurity is an interdisciplinary problem in transport that has its challenges in aviation, but also in shipping, rail and road transport, called upon a stronger partnership between regulators, operators, service providers, and manufacturing industry, in particular within the ESCP, where EASA welcomes and supports the Industry to come with standards."
- In 2018, DGAC France and EASA hosted the European Strategic Coordination Platform (ESCP) High Level Meeting. The purpose was to bring together States, industry, partners and other key players to raise awareness of cyber threats and attacks that could damage or disrupt critical infrastructures endangering airlines, airports and air traffic management. Potential actions, sustainable policies, approaches and measures to protect against them and mitigate their impact were also discussed and developed. See: DGAC and EASA (2018).
- In April 2019, IATA held, for the first time, an Aviation Cyber Security Roundtable (ACSR) in Singapore. This aimed to better understand and manage cybersecurity risks in civil aviation by sharing knowledge and experience, as well as developing tangible actions for the aviation industry. See: IATA (2019).

- In November 2019, the Israel Airports Authority (IAA) and EUROCONTROL conducted a joint cybersecurity exercise on aviation systems. The exercise consisted of various challenges in different fields related to cybersecurity. The objective was to help train cybersecurity experts of both organisations in order to maintain their skills in a fast-evolving domain. The IAA hopes to host similar annual events involving stakeholders from other EUROCONTROL Member States. See: Israel Airport Authority and EUROCONTROL (2019).
- 2019 also saw the launch of two Engage catalyst fund projects aligned with thematic challenge 1: “Authentication and integrity for ADS-B” (project coordinator: TU Kaiserslautern, Germany), and “The drone identity – investigating forensic-readiness of U-Space services” (project coordinator: The Open University, UK). Please refer to the link in the next section for further details.

Making the most of the latest progress achieved in previous and on-going activities, this thematic challenge aims to pave the way towards a privacy-preserving, cyber-resilient, fault-tolerant and trustworthy system of systems, with all layers ensuring the integrity and availability of aeronautical data.

Workshop conclusions

This section consolidates conclusions from the first workshop. See the Engage website for the presentations. Readers are also invited to refer to abstracts of on-going research by projects funded through the first catalyst funding wave.

Progress in security risk assessment is required (including the development of indicators for key risks) as a first step in understanding, controlling and preventing the vulnerabilities of the systems. In correctly addressing this need, the role of the operator needs to be considered as the end user of the system to be assessed and secured. Adequate training for operators should be provided in order to increase the awareness and develop operational procedures for risks identification and reaction.

To maintain safety levels, current ATM/CNS systems are subject to rigorous change-management procedures to ensure that required system updates do not have an adverse impact on the reliability of the system. However, if new security vulnerabilities are identified in an ATM/CNS system, there is pressure to update the system as quickly as possible to prevent it from being subject to attack. New approaches are required to develop systems that are capable of addressing these conflicting demands while maintaining resilience. As an example, the application of AI algorithms could be explored to proactively detect patterns and mitigate attacks.

Assuring the security of CNS/ATM systems requires shorter implementation times and updates/upgrades. Safety regulations are therefore challenged to face cybersecurity needs (e.g. patch management). The ability to rapidly patch vulnerabilities will be necessary when aircraft become more connected, which implies further development in certification processes of certified software (ED12-C). The requirements for certification of safety-critical systems should also include best practices from the security community.

While security information is usually protected as part of the security policies themselves, cooperation among security stakeholders is required in order to learn from previous security issues and attacks. The secure sharing of this information between ATM/CNS stakeholders is required at many levels.

Examples include: post-incident forensics; real-time alerting of security incidents to connected partners; threats and vulnerabilities; lessons learned, for example detection, response and recovery methods.

New open models to enhance security should be developed in addition to the more traditional approach of security by obscurity. Aviation could learn from other sectors (e.g. banking) in order to overcome national sensitivities and confidentialities, to the benefit of a collaborative security culture.

When considering new security procedures and technologies, it is important to consider the social dimension. New developments in screening, monitoring, and tracking may potentially breach accepted norms for ethics, privacy, societal acceptance, and could be in breach of the regulatory framework. Consideration of such non-technical potential issues in advance of embarking on such programmes would be prudent. Engaging the whole society would help building cyber-resilient culture. Security governance framework needed to establish the common policies, legal aspects and procedures for all stakeholders to collaborate as a resilient ecosystem.

One of the main barriers that needs to be overcome for enabling data sharing is the confidentiality of the data sources. Nevertheless, the relative importance of confidentiality, integrity, and availability depends on the information in question and on the application area. There are particular data (e.g. ANSP staff personal data or state flights) where confidentiality and data anonymisation are essential. To address this challenge, there are research opportunities for applying encryption methodologies without compromising safety. However, for ephemeral operational data (e.g. radar tracks) integrity and availability are probably more important and their assessment needs to be further investigated.

Collaboration will be required beyond the aviation stakeholders. Future research projects will require cooperation between multiple transport modes and other sectors to obtain funding. Reducing environmental impact will be a key requirement, as well as the provision of evidence that core components are close to industrialisation. Contributing to the streamlining of safe and secure transport is also key.

The following have been identified as *example* ideas for potential further exploration:

1. Perform an initial security assessment of the elements supporting air navigation as well as their relationships, in order to identify its vulnerabilities and to ensure adequate protection against future
   potential attacks and current global threats;
2. Apply controls to existing aviation and air traffic systems to detect exposure to attacks and make
   them cyber secure without having to replace and refit. Certification, legal and liability issues should be
   taken into account;
3. Innovate data-sharing architectures capable of connecting and providing access to distributed data
   while preserving privacy, including the use of advanced, secure computing functions;
4. Confidentiality, availability and integrity requirements for aeronautical data need to be assessed per dataset and particular application;
5. Adapt mental models within the sector to prepare operators to understand and manage cyber threats;
6. Requirement of updating software and firmware of IT components in order to fix security

vulnerabilities of any critical infrastructure;

7. Further research into the security analysis of aviation-specific protocol implementations (vulnerabilities, trust, software library) is required;
8. Explore open models to enhance security, complementing traditional approaches towards protection, potentially drawing on lessons learned and best practice from other sectors.

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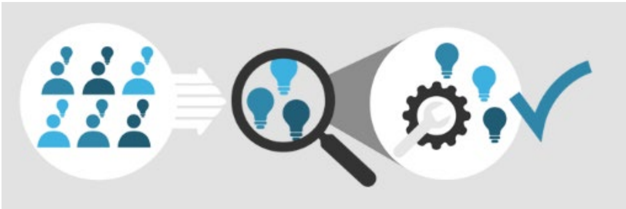
3.2 TC2 Data-driven trajectory prediction (2019)

Thematic challenge 2

Data-driven trajectory prediction



Edition 3.0, December 2019

This is an evolving document that summarises the key concepts (and, later, findings) for thematic challenge 2.

Abstract

Accurate and reliable trajectory prediction (TP) is a fundamental requirement to support trajectory-based operations (TBO). Lack of advance information and the mismatch between planned and flown trajectories caused by operational uncertainties from airports, ATC interventions, meteorological conditions, airspace user intentions and 'hidden' flight plan data (e.g., cost indices, take-off weights) are important shortcomings of the present state of the art. New TP approaches, merging and analysing different sources of flight-relevant information, are expected to increase TP robustness and support a seamless transition between tools supporting ATFCM across the planning phases. The exploitation of historical data by means of machine learning, statistical signal processing and causal models could boost TP performance and thus contribute to TBO. Specific research domains include machine-learning techniques, the aggregation of probabilistic predictions, and the development of tools for the identification of flow-management 'hotspots'. These could be integrated into network and trajectory planning tools, leading to enhanced TP.

Description of challenge

Accurate and reliable trajectory prediction (TP) is a fundamental requirement to support the trajectory-based operations (TBO) paradigm. The lack of flight planning information sufficiently in advance and the mismatch between planned and flown trajectories caused by operational uncertainties from airports, ATC interventions, and 'hidden' flight plan data (e.g., cost indices, actual take-off weights) are important shortcomings of the state of the art, regarding pre-tactical and tactical trajectory prediction technologies. In addition, integrating predictions about meteorological conditions[9], including their uncertainties, could contribute to better trajectory predictions (see, for example, the Engage PhD, "Integrating weather prediction models into ATM planning" – please refer to the link in the next section for further details).

Indeed, various stakeholders need different aspects of TP *across all phases* of operations, from the strategic, across the pre-tactical and to the tactical phases. User needs vary as a function of these purposes and their temporal focus.

New TP approaches, merging and analysing different sources of relevant flight information, are expected to increase TP robustness and support a seamless transition between tools supporting air traffic control (ATC) and air traffic flow and capacity management (ATFCM) in the different planning phases. The exploitation of historical data by means of machine learning, statistical signal processing, stochastic models and causal models can boost TP performance and enhance the TBO paradigm. A non-exhaustive list of relevant research topics includes the:

- use of machine-learning techniques to infer airspace users' (AUs') behaviour, intentions and preferences from historical data and enhance tactical and pre-tactical trajectory prediction; calibrating these against actual/revealed AU operational drivers (such as costs (route charges, fuel, delay); passenger connections and punctuality targets; crew rosters; maintenance and curfew restrictions);
- aggregation of probabilistic predictions into probabilistic traffic counts at a strategic and pre-tactical level thus reducing the uncertainty when predicting traffic volumes;
- integrating predictions about factors affecting flight planning and execution, including meteorological conditions, airspace configuration and route availability, also including the respective uncertainties associated with these predictions;
- development of tools for the identification of 'hotspots' and the evaluation of different ATFCM measures;
- bridging the gaps between the temporal phases of ATFCM.

All of these developments could be integrated into the Network Manager's, ANSPs' and/or flight operations centres' 4D trajectory planning tools, leading to enhanced collaboration in trajectory

[9] Note that Engage thematic challenge 3 is concerned with improving overall ATM system performance by providing better user-support tools based on improved meteorological products. Readers should be mindful of the different objectives of the two thematic challenges.

management, such that capacity can be better matched to demand by a better anticipation of AU behaviour, including operations planning and flight plan filing, and such that AUs can benefit from ATM interventions better fitted to their business models.

One of the recent examples of the successful implementation of such tools in the operational environment is the Traffic Prediction Improvements (TPI) tool introduced by Maastricht Upper Area Control Centre, which is based on innovative machine-learning techniques to predict real-time flight routes and better manage traffic flows[10].

Robust demand forecast is a fundamental requirement to support the Trajectory-Based Operations paradigm and a key enabler of ATFCM service delivery. Network and capacity planning is continuously refined at different temporal planning horizons, from months to few minutes before operations. This implies using different forecasting methods adapted to the different sets of input data available at different times, each one with its associated uncertainty and granularity levels. This presents a series of challenges, and notably a lack of flight planning information sufficiently in advance – with a mismatch between planned and flown trajectories, caused by the operational context uncertainties identified above.

Current demand prediction tools are based on statistical observations, heuristic decision rules and/or simplified dynamic models, which fail to consider other important contextual flight attributes (e.g., airspace user specificity, meteorology[9]). Additionally, the resulting forecast is often deterministic, without any quantification of the uncertainty of the prediction. These shortcomings limit the accuracy of the forecasts and create a gap between the different temporal phases of ATFCM, leading to inefficient or sub-optimal ATFCM measures.

Considering previous research in this field, sophisticated trajectory prediction models are often hindered by the need to estimate operational flight intentions, which might differ from one airspace user to another, and by aircraft type, etc. Certain sensitive information, such as the cost index, take-off weight or other unknown aircraft performance parameters also contribute to the problem. Additionally, much of past research has focused on the tactical planning phase, relying on flight plans, which may be available only a few hours before operations and can be subsequently modified, leading to mismatches between predicted and actual flown trajectories.

The increasing availability of data at different scales, together with recent advances in the fields of machine-learning, data analysis and visualisation, present opportunities to develop new modelling techniques to improve trajectory prediction performance and robustness by:

- the application of new modelling methods, such as machine-learning techniques, advanced statistical and/or causal modelling and statistical signal processing solely, or in combination with traditional methods (the reader is invited to refer to a range of such activities across the Engage PhDs and catalyst fund projects – please see the link in the next section for further details);

[10] https://www.eurocontrol.int/publications/traffic-prediction-improvements-tpi-factsheet-and-technical-documentation

- integrating and analysing different sources of endogenous and exogenous factors affecting flight planning and execution, including meteorological predictions[9], airspace configuration and capacity, and the uncertainty inherently associated with these predictions;
- inferring airspace users' behavioural drivers from historical data;
- engaging airspace users to collaborate and benefit from potential air traffic management interventions (better) fitting their business needs.

Workshop conclusions

This section consolidates conclusions from the first two workshops. See the Engage website for the presentations. Readers are also invited to refer to abstracts of on-going research by the Engage PhDs and projects funded through the first catalyst funding wave.

Different stakeholders in the aviation system use trajectory predictions with different objectives and timelines. These embrace demand assessment and capacity planning in ATFCM at the strategic, pre-tactical and tactical level, operations planning and execution by AUs across the same phases, conflict detection and resolution (i.e. separation management) for ATC, collision avoidance in certain safety nets, and performance monitoring.

For example, planning and decision-making by AUs at the pre-tactical and tactical levels (e.g. (most) flight plan filing; dispatch; self-separation and in-flight trajectory updates thereafter) and assessments made by (ATM) performance monitoring and/or target setting agencies, require *different* trajectory predictors. Owing to these diverse applications, requirements vary and hence the best TP implementation also varies depending on the purpose and prediction horizon.

Closer to flight execution, data become available that were not available in earlier planning phases: an example is the absence (at least from the ANSP/NM viewpoint) of (sufficient) flight plan data in the pre-tactical planning phases, when the Network Manager together with national service providers attempt to match airspace capacity with the anticipated demand. Accurate demand predictions are a central requirement in the demand-capacity balancing process. A smooth transition is desirable between all phases of the planning process as, for example, flight plan data and local restrictions become available. Understanding and, to a certain degree, predicting the behaviour of airspace users before flight plans are filed, goes a long way towards anticipating demand for airspace capacity. Studies have also revealed that the flight planning behaviour of different airlines is often very different in terms of when the first and last flight plans are filed, and to what degree the last-filed flight plan differs from the first-filed. This illustrates that differences between different AUs need to be considered.

The availability and quality of relevant data is a prerequisite for accurate TP. This concerns: physical access to clean data across a number of types and protocols; overcoming stakeholders' concerns regarding data sharing (e.g. confidentiality and competition issues); and, the implications for hardware/software (avionics, electronic flight bags (EFB), data link). Appropriately sharing trajectory data as widely as possible benefits both operations and research objectives, as opposed to only sharing data that allows the calculation of trajectories using specific TP implementations.

Trajectory predictors do not currently have access to the range of data that could benefit improved predictions: this includes trend data, as well as stakeholder preferences and intentions. Some of these missing data might be extracted from historical datasets. TP is also often 'blind' to operationally relevant information, for example leading to (very) high false alert rates for conflict detection systems such as medium-term conflict detection (MTCD) and short-term conflict alerts (STCAs). Tactical ATC interventions, for example flight-path shortening through radar vectoring, are not usually considered, whereas a TP anticipating (or suggesting) controller interventions and conflict resolutions would be more powerful.

A significant challenge not only for TP but also for researchers attempting to improve this, is access to data, including historical surveillance and flight plan data, aircraft performance data, delay data, meteorological data and airspace-related data. A number of alternative sources have emerged, specifically those using ADS-B data (Flightradar24, OpenSky). In addition to using these datasets directly, some models have recently been proposed that use them to derive 'hidden' information, e.g. related to aircraft performance. Whilst these developments are encouraging, providing access to high quality, primary data and providing guidance as to their use, remains a vital concern for TP research.

The following have been identified as *example* ideas for potential further exploration:

1. Trajectory predictors supporting airborne self-separation: definition of requirements and concept development of enabling technologies;
2. Improved DCB: enhanced TP integrating uncertainty assessment, robust planning and cost-efficiency assessment at network level;
3. Data-driven approaches for understanding and predicting AU preferences and behaviours, (including 'hidden factors' such as the cost index or actual take-off weight) enabling improved NM operations; the calibration of such approaches;
4. Improving the transition between ATM phases (strategic, pre-tactical, tactical) through TP approaches that model and anticipate flight-relevant factors that typically only become available later than desired, e.g. the use of advanced meteorological models[9];
5. Integrating data sources and models not presently widely used in TP, including the modelling of prediction uncertainty;
6. Mapping requirements definition and concept development of data-driven TP in support of collaborative multi-sector CD&R;
7. Optimising and integrating local planning activities with a view to assess and communicate their network effects;
8. Improving data sharing and data access to satisfy AU, NM and ANSP technical and organisational requirements and expectations.

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3.3 TC3 Efficient provision and use of meteorological information in ATM (2019)

Thematic challenge 3

Efficient provision and use of meteorological information in ATM

Edition 3.0, December 2019

This is an evolving document that summarises the key concepts (and, later, findings) for thematic challenge 3.

Abstract

The main objective of this challenge is to improve overall ATM system performance by providing better user-support tools based on improved meteorological ('MET') products. The focus is on the synergy of several methods and techniques in order to better meet the needs of operational users and to support aviation safety (e.g., through creating: early warning systems; an EU-wide weather picture) and regulation-makers (e.g., moving from text-based to graphical information provision). All stakeholders may benefit from this synergy: ANSPs (e.g., sector reconfiguration, separation provision, runway use), airlines (e.g., storm avoidance), airport operators (e.g., airport management under disruptive events), and the Network Manager (e.g., demand-capacity balancing). The challenge is, therefore, to bring the following perspectives closer: (a) for meteorological/atmospheric science, the development of products tailored to ATM stakeholders' needs, which are unambiguous and easy to interpret; (b) for stakeholders, the identification of the most suitable information available and its integration into planning and decision-making processes.

Description of challenge

Weather is an integral part of ATM, especially in the light of increasing traffic levels, where weather conditions present a significant source of uncertainty in the planning process, and one of the major causes of disruption and consequent delay during operations. About 20-30% of total ATFM delay has been caused by weather in recent years, while this grew to 20-45% in the first six months of 2018, thus challenging the achievement of the Performance Scheme goals for the year. In addition, extreme weather phenomena such as hail, severe icing and lightning present significant hazards as they can inflict substantial damage to aircraft. As extreme weather events are becoming more frequent in Europe, and forecast certainty is apparently decreasing, ATM performance is negatively impacted.

This thematic challenge aims at understanding how ATM may benefit more from the advances in meteorology/atmospheric sciences, especially in the light of climate change and the weather uncertainty that it brings. This is a key issue in the current European ATM research arena because on the one hand, extreme weather patterns are changing with climate change and, on the other hand, the impact of weather on different parts of the ATM network and its stakeholders (e.g. airports, ANSPs, airlines, passengers, Network Manager) varies in the type and magnitude of disruption, and consequent costs. For example:

- Airports – different conditions (e.g. rain, fog, snow) can cause capacity reductions and even closures (see also the ACI policy brief[11] on climate adaptation by airports);
- En-route – winds impact aircraft speed, weather cells can cause ANSPs to change flights' trajectories, or impose regulations for more severe weather, etc;
- Airlines – trajectory changes[12], delays and schedule disruption occur, resulting in various types of cost (e.g. passenger reaccommodation);
- Network level – the Network Manager (NM) coordinates and circulates the information to all stakeholders regarding local weather impacts on flow management, without taking decisions on local weather-related actions, apart from facilitating network-level harmonisation; an overarching, reliable and shared view on weather is not yet fully in place in the European network. Initial testing of cross-border forecasts and ATFM procedures with five States (with related ANSPs and MET providers) took place in summer 2019.

Hence, meteorological information needs differ across stakeholders, either in the type of information, or in the useful time horizon and in the certainty/uncertainty that can be tolerated in the decision-making processes. The time horizon may span from a few days to real-time, depending on the stakeholder and the function the stakeholder performs (e.g. ATC, or baggage handling at the airport). Furthermore, different forecast (and observation) resolutions are needed - a grid of 100 km^2 could be quite adequate for an ANSP, but lacks necessary detail for terminal manoeuvring/airport management. Another important component is the level of uncertainty that weather conditions impose. In the

[11] https://store.aci.aero/wp-content/uploads/2018/10/Policy_brief_airports_adaption_climate_change_V6_WEB.pdf

[12] Improved trajectory prediction *per se* falls within the remit of Engage thematic challenge 2. Readers should be mindful of the different objectives of the two thematic challenges.

planning processes, higher uncertainty is tolerated, while in real time operations more certain information on the extent and trend of meteorological conditions is needed.

At present, the delivery and format of meteorological information provision is regulated by ICAO Annex 3, EASA and national regulations (in Europe). Regulated MET services and products[13] from certified MET ANSPs are quality controlled and are, in principle, free. In the USA, the National Weather Service provides a comprehensive set of forecasts, observations and tools *via* the Aviation Weather Center, and the Federal Aviation Authority deploys various weather-related decision-support tools aimed at more efficient air traffic management. In Europe, there are about 40 MET information service providers, some being certified by National Meteorological and Hydrological Services , some by air traffic service organisations, or a mixture of the two. Each has different responsibilities and cost structures. Commercial value-added services exist, and allow tailoring to user needs. These can be provided by a commercial MET provider or MET ANSP (for a fee).

The Pilot Common Project (EU 716/2014) and Regulation EU 2017/373 are calling for additional MET services, and there is a widespread belief that if action is not taken promptly, new climate conditions will pose ever greater challenges to all ATM stakeholders.

In fact, the number and the intensity of extreme weather events increased in recent decades in some areas of the globe including Europe (Hov *et al*., 2013). Damage is mostly caused by strong winds, hail and precipitation intensity. Studies suggest that higher precipitation intensity for northern Europe, dry-spell periods for southern Europe, high intensity and extreme precipitation are expected to become more frequent within the next 70 years. The increased frequency is estimated to be larger for more extreme events, but will vary considerably from region to region (*ibid*). For instance, Black *et al*. (2010) reported decreasing winter rainfall over southern Europe and the Middle East and increased rainfall further north caused by a poleward shift of the North Atlantic storm track.

Long-term changes in European storminess are not very clear and sometimes show conflicting results. Some studies show a strong multi-decadal variability (Alexandersson *et al*., 2000; Bärring and von Storch, 2004; Wang *et al*., 2009), and analyses of extreme wind speeds highlight significant upward trends in central, northern and western Europe (Donat *et al*., 2011b; Brönnimann *et al*., 2012). Models under scenarios with increasing greenhouse gas concentrations indicate an increase in the number of severe storms in north-western and central Europe, which is also in accordance with other simulation results (Beniston *et al*., 2007). These simulations also suggest a significant increase in cyclone intensity and the number of intense cyclones over northwest, central and western Europe, under future climate conditions (Leckebusch *et al*., 2006, 2008; Pinto *et al*., 2009; Ulbrich *et al*., 2009). A belt stretching from the United Kingdom to Poland will experience an increase in extreme storminess and wind speed, while southern Europe and the Mediterranean will rather see a decrease in strong winds (Leckebusch *et al*., 2006; Donat *et al*., 2011a).

It must be recognised that recent years have witnessed important improvements in observational (e.g., satellites, light detection and ranging (LIDAR), Global Navigation Satellite System (GNSS) receivers) and numerical weather prediction (NWP) models in the atmospheric sciences (e.g., models for air quality

[13] MET products refer to different types of meteorological information, such as forecasts, observations, now-casts.

in megacities that consider topography and resolution of under 100m). However, little has yet filtered down to the ATM world. Several workshops and MET-related projects came to similar conclusions: it is important to bring ANSPs, airlines, academics, MET service providers and atmospheric scientists together to better understand the effects and requirements of mitigation actions to convective, winter and hazardous weather at trajectory, network and airport levels. In some cases, tools and know-how exist, in others better models and outputs became available but are not exactly what ATM needs.

Thus, the initial step towards delivering the improved MET information needed for more efficient air traffic management consists of learning about improvements in the atmospheric sciences, about ATM needs in the light of the uncertainty that weather imposes on the network (and related uncertainty management), possible educational needs to foster better understanding between the two scientific and operational groups and, possibly, associated regulatory issues. The ultimate goal of this thematic challenge is therefore to define further research and operational needs regarding the use of weather information for more efficient ATM.

Workshop conclusions

This section consolidates conclusions from the first two workshops. See the Engage website for the presentations. Readers are also invited to refer to abstracts of on-going research by the Engage PhDs and projects funded through the first catalyst funding wave.

MET-related research should enhance situational awareness of MET conditions for all ATM stakeholders, using state-of-the-art MET products. MET provision in Europe is fragmented, as each state is responsible for the provision for its territory. This is one of the reasons for the lack of a consistent and agreed weather 'picture' for ATM in Europe. To overcome this issue, and to reduce the impact of weather on delays, the NM and EUMETNET trialled a procedure with the goal of introducing a common weather picture and to better cope with adverse weather and the consequent delays. The trial involved the NM, DSNA, NATS, DFS and MUAC, and EUMETNET comprising: the Met Office (UK), KNMI (Netherlands), Skeyes (Belgium), Météo France and Deutsche Wetterdienst (Germany). As the impact of weather is usually worse in the period from May to July, as the high traffic demand coincides with summer convection, the trial took place during the summer season.

The procedure was based on existing technology, with the goal to improve collaboration, planning and dissemination of information with the ultimate intention of reducing the number of weather regulations, increasing lead times of regulation application and increasing stability. The MET providers established a common weather picture over the agreed geographical area, for the pre-tactical period (Day-1), where it was concluded that a 'consistent' view of the weather collaboratively agreed between stakeholders is more important than a 'perfect' view of the weather. An important part of the trial was the need for simple communication between meteorologists and controllers. With that in mind, EUMETNET developed a coloured risk matrix across two dimensions - probability/confidence and distribution/frequency, categorising the events into N (none), L (low), M (medium), H (high) and VH (very high), where only H and VH are of interest for the impact on the network. That forecast was then shared with the participating ANSPs and any H or VH events would trigger the teleconference to agree on the plan of action for the next day (i.e. 'red' coding leads to action).

The procedure was assessed as a good first step, with the following benefits: increased situational awareness - as forecast and insight from other ANSPs gave context on what to expect the next day; the risk matrix allowed for clear decision making as everyone knew when collaboration was expected;

the triggers (H or VH) were about right; some issues (prompting further discussion) emerged regarding some medium-risk occasions; teleconferences gave a wider network overview; additional participants were invited when needed, which generated positive feedback. The plan is to continue this collaboration, extending the geographical scope, and then to work on including jet streams, more tactical forecasts and collaborations. This common weather picture should be available in the Network Operations Portal, i.e. in an easily accessible place. The Engage catalyst fund project, "MET enhanced ATFCM", aims to develop a MET product for convection (multi-model/multi-parameter) to support ATFCM decision making, ultimately leading to optimised en-route weather regulations.

Regarding common awareness, the OPAS project aims to develop an alert product for sulphur dioxide, which is often used as a proxy for the presence of volcanic ash in the atmosphere. Currently, the Volcanic Ash Advisory Centers do not need SO_2 information. However, there are discussions to include it in ICAO considerations around volcanic ash alerting for aviation.

Another aspect of MET-related situational awareness relates to the information available to pilots, which EASA has been addressing in recent years. A strategy paper on weather information for pilots was published in March 2018 (EASA, 2018a), and lists nine, non-binding recommendations to be taken forward by the "Best intervention strategy" proposal. EASA also published the results of a survey on the use of electronic flight bags and installed weather applications to facilitate in-flight weather updates to the cockpit by the airlines (EASA, 2018b). All survey respondents had EFBs, with about half having weather applications for pre-flight briefings, while for in-flight briefing, including in-flight updates, only 15% of respondents had them included in EFBs (whilst many planned to include some functionalities in the next five years).

Currently, the trend in MET research is focused on ensemble prediction systems. Thus, in the next 5-10 years we should expect MET products to be realised as ensembles, providing measures of uncertainty in different atmospheric variables. A long-term educational and communication effort should be undertaken so that ATM stakeholders are prepared to understand and interpret these new MET products, in order to incorporate them into their decision-making processes, taking advantage of better information. The Engage catalyst fund project, "PSA-Met", and the Engage PhD, "Stormy", both address ensemble forecasts and the development of decision-support tools for stochastic storm avoidance, using different methods for storm evolution prediction.

The climate impacts of aviation, comprise more than CO_2 impacts – such as NO_x, ozone and contrails. Aviation emissions impact the climate and more research is needed to establish these quantitative effects and whether there is (further) potential for mitigation actions. The Aviation and Global Atmosphere report by the Intergovernmental Panel on Climate Change lists the different components of aviation emissions. There is consensus on the direction of impact of these components, but there is still no consensus on their magnitude. An interesting point, is that some regions of the atmosphere are more sensitive to certain types of emissions than others, and negative effects can be propagated to larger regions and last longer. The climate impact of non-CO_2 emissions depends on the time and position of aircraft, actual weather conditions (processes, transport pathways, temperature and humidity) and background (emissions) concentrations. This points to the importance of having 4D (weather-like) forecasts of environmental impact, which could enable trajectory planning to account for these environmental impacts.

MET products can be classified along two dimensions: spatial and temporal resolution. In terms of spatial resolution, forecasts can be cast as global (resolution of about 1 degree), limited-area models (covering regions such as Europe, resolution in terms of tens of kilometres), and of very high-resolution (smaller areas, such as terminal manoeuvring areas, resolution of hundreds of metres). In terms of temporal resolution, there are long- (about 1 week), medium- (about 1 day), short- (about 3-6 hours), and very short-range (about 1 hour) forecasts. Both the temporal and spatial resolution are important depending on the stakeholder application. For example, the NM is interested in medium-range / limited-area forecasts; dispatchers, in short-range / limited areas; pilots/controllers, in very short-range / very high resolution when facing storms; airports, in very short-range / very high-resolution, etc.

The higher the resolution, the forecast becomes more challenging. NWPs alone are not sufficient for this type of product, and call for data assimilation of the observed values of varied atmospheric characteristics (e.g. lightning, deep convection). *In situ* sensors and sensor networks that collect and deliver information for forecasting are needed. The aggregation of different sources of data for blended ensemble forecasts in the very high-resolution, very short-range scales seems to be the trend for the next 10 years.

The Engage catalyst fund project, "CARGO", is studying the use of low cost GNSS receivers, and lightning detectors, to develop nowcasting forecasts for convection at very short range / very high resolution. Input from different sensors will be fed into a neural network model. The Engage PhD, "IWA", is evaluating the impact of weather conditions on route planning in the TMA. Probabilistic models are to be applied on the weather data, and mathematical tools to be used to develop a prototype for decision-making.

Often-cited barriers to the progress of MET and MET/ATM research are the inadequacy of research funding available to the MET offices (only partial funding), and fragmented provision of MET products for aviation (coupled with regulatory and sovereignty matters). Further important barriers revolve around the trust the ATM users have in available MET products, and not particularly high usage in operational decision-making. This points to the two underlying issues:

1. fitness of purpose of MET products (e.g. medium-range, limited-area forecasts are of little practical use to airport tower supervisors, while the very high-resolution, very short-range forecasts would be more easily included in this decision-making process);
2. ATM stakeholder knowledge of the available MET products, especially on the characteristics and meaning of MET products being developed.

The following have been identified as *example* ideas for potential further exploration:

1. Very high-resolution, very short-range forecasts using numerical weather prediction models and observational data assimilation;
2. Quantifying the sensitivity of operational processes to MET uncertainty, comparing these with other sources of uncertainty;
3. Incorporation of ensemble weather information into decision-support tools, adapted for different ATM stakeholders;
4. Accurate prediction of weather conditions (e.g. visibility, glide-path wind) influencing airport arrival and departure operations;
5. Consolidation of climate risk assessment methodologies for airports;
6. Creating a climate forecast 'baseline' for aviation from the IPCC UN panel report;
7. Developing quality EU-wide weather information in the tactical air traffic control context (an integrated, pre-tactical EU-wide picture is beginning to be developed);

8. Forecasters and end-users (e.g. controllers and pilots) co-developing products that are easy to interpret in terms of the impact weather will have on such users (e.g. airspace, flights);
9. Transferring knowledge to end-users (e.g. controllers and pilots), reflecting that the state of the art in modelling is moving towards probabilistic approaches;
10. Producing an EU-wide, one-stop repository of MET data, addressing data harmonisation and scoping the archiving of such data.

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3.4 TC4 Novel and more effective allocation markets in ATM (2019)

Thematic challenge 4

Novel and more effective allocation markets in ATM

Edition 3.0, December 2019

This is an evolving document that summarises the key concepts (and, later, findings) for thematic challenge 4.

Abstract

This research explores the design of new allocation markets in ATM, taking into account real stakeholder behaviours. It focuses on designs such as auctions and 'smart' contracts for slot and trajectory allocations. It seeks to better predict the actual behaviour of stakeholders, compared with behaviours predicted by normative models, taking into account that decisions are often made in the context of uncertainty. Which mechanisms are more robust against behavioural biases and likely to reach stable and efficient solutions, equitably building on existing SESAR practices? The research will address better modelling and measurement of these effects in ATM, taking account of 'irrational' agents such as airline 'cultures'. A key objective is to contribute to the development of improved tools to better manage the allocation of resources such as slots and trajectories, and incentivising behaviour that benefits the network - for example by investigating the potential of centralised markets and 'smart' contract enablers.

Description of challenge

Air traffic management (ATM) is an example of a system where demand often exceeds capacity. In Europe, for a flight flying from a given origin to a destination, a shortfall in either en-route capacity (e.g. insufficient controllers to handle the flight) or at the destination (e.g. insufficient runway capacity to receive the flight), results in the flight being delayed at the origin until an appropriate trajectory and tactical departure slot are available. Each year, such delays generate large costs for the airspace users (AUs, airlines) and passengers. During such capacity constraints, challenges remain regarding, *inter alia*, the trade-off between minimising the delay in the network as a whole and the delay for given airspace users. This thematic challenge explores the design of new market mechanisms for the (re-)allocation of trajectories/routes and slots (often linked resources) to airlines in the tactical phase. "Market" mechanism does not necessarily imply the use of money as a medium for transactions. Moving beyond first-planned, first-served (FPFS) principles, matching markets, centralised batch auctions, primary and secondary markets (double auction or bilateral exchanges) may each bring advantages. The challenge also seeks to explore better ways to predict the *actual* behaviour of stakeholders (airspace users in particular), compared with behaviours predicted by classical models, also taking into account that decisions are often made in the context of uncertainty. Such uncertainty may be aleatory (due to chance, such as weather) or epistemic (due to lack of information). The challenge poses questions such as: which types of mechanism are likely to work best in tactical slot and trajectory management[14], under different types of uncertainty and information sharing? Which mechanisms are more robust against behavioural biases ('irrationalities'[15]) and likely to reach stable and efficient solutions more quickly, e.g. without leaving unused slots? How can we equitably build on existing SESAR practices, such as Enhanced Slot Swapping, and planned SESAR functionalities such as the User-Driven Prioritisation Process (UDPP)?

Several SESAR exploratory research (ER) projects (e.g., SATURN, ACCESS, COCTA) have advanced the market mechanism state of the art already, exploring ways in which the efficiency of existing solutions might be improved, including market-based demand-management mechanisms for air traffic flow management (Bolic *et al.*, 2017; Castelli *et al.*, 2011), auctioning for strategic airport slots (De Neufville and Odoni, 2013; Herranz *et al.*, 2015), and controlling tactical delay distributions to minimise propagated delay and increase adherence to (strategic) airport slots at coordinated airports (Ivanov *et al.*, 2017). This research has been complemented by findings in ER projects such as APACHE, INTUIT and Vista. Further development opportunities lie ahead, in that modelling in these domains variously investigates the optimal use of limited capacities but (necessarily) assumes full rationality, for example regarding flight scheduling and demand management that might "create opportunities for strategic behaviours from the airlines, i.e., potential incentives to provide scheduling inputs that do not reflect their true preferences in order to gain a strategic advantage over their competitors" (Jacquillat and Odoni, 2018). Regarding airport capacity and demand management, these authors further comment that "abstractions and simplifications of reality that necessarily underlie these mathematical and simulation models cannot fully capture all the operating complexities found in practice". In a

[14] Improved trajectory prediction *per se* falls within the remit of Engage thematic challenge 2. Readers should be mindful of the different objectives of the two thematic challenges.

[15] The terms 'arational' and 'non-rational' are also often used.

comprehensive review comparing and contrasting the operations research and economics perspectives in ATM, it is concluded that "significant opportunities exist to [...] extend the scope of economic studies to integrate more realistic models of flight scheduling and airport operations [...] addressing them incrementally would enable the development of cross-disciplinary approaches to airport demand management and more effective congestion mitigation policies" (Gillen *et al*., 2016). Indeed, further work in this area has modelled slot allocation efficiency and schedule displacement, stressing the importance of the complementary use of (slot) optimisation tools, challenging current views on constraints and boundary conditions (Ribeiro *et al*., 2018, 2019a, 2019b).

Approaches and methodologies applied to (strategic) airport slots are often of value, with transferable insights into the tactical context, although airport slots *per se* are not in scope for this thematic challenge. Let us thus turn to a major tactical example. SESAR continues to develop UDPP to achieve additional flexibility for airspace users to adapt their operations in a more cost-efficient manner. This makes use of mature mechanisms such as Enhanced Slot Swapping (deployed in 2017) and continues to validate mechanisms such as Fleet Delay Reordering and Selective Flight Protection (Pilon *et al*., 2016). It is also exploring future options for even greater flexibility regarding cost minimisation and equity for 'low volume' AUs with less market power, although integration of accurate airline decision-making and cost models in this context remains a challenge, and the best models to date assume full rationality and utility maximisation (Ruiz *et al*., 2017, 2019a). Other mechanisms that enhance first-planned, first-served principles (as implemented, for example, in Europe though the computer-assisted slot allocation (CASA) mechanism) have been explored, such as the mitigation of interacting regulations (Ruiz *et al*., 2019b) and adapting allocations of empty slots in sequences (Ruiz *et al*., 2019c), both discussing the impacts on delay reduction, fairness and equitability.

A number of economic models applied in ATM (and air transport) are *normative*, such as Nash equilibria and linear programming. They make several assumptions about agent rationality that do not always work as expected predictors of behaviour. This is because real decisions are often made by human beings, or at least with human intervention, and are not fully 'rational', in the sense of adopting the solution suggested by some type of optimisation process. Behavioural science in general, and behavioural economics in particular, may bring complementary solutions to ATM in order to better predict actual behaviour in the network. Behavioural economics is based on a number of related principles, examples of which are summarised in Figure 1.

Loss aversion: losses are worse (have more disutility) than gains are good (have utility)
- e.g. avoiding a €1k slot delay is preferred to an (immediate) €1k 'slot credit'

Endowment effects: a higher value is attributed to a good already owned
- e.g. have a [CTOT + 15 min] slot, won't trade for a 15 min credit (e.g. for 'later')

Path dependencies: the value of a good depends on the path of acquisition
- e.g. 'we protected this slot today after sacrificing ten flights last week, so there is no way we are going to trade it today'

Future discounting (present bias): the value of a good depends on when it is consumed
- e.g. one 15-minute slot improvement today is worth several identical improvements next week

Figure 1. Examples of behavioural economic principles in the context of ATM (*Courtesy University of Westminster*)

In loss aversion, losses have more disutility than gains have utility, typically by a factor of about two. With endowment effects, the value attributed to, say, a slot already owned would be higher compared to the value attributed to that exact slot when not yet owned (the 'later' time component is not usually a feature of the pure endowment effect, but is indicated here for purposes of trading realism.) The specific example given for the path dependency is also known as the 'sunk-cost' fallacy. In future discounting, it is observed that the value of a good depends on when it is consumed: people tend to discount the future heavily, putting a very high value on the present. Furthermore, prospect theory (Kahneman and Tversky, 1979) describes risk-aversion in the gain domain (when things are going well) and risk-seeking behaviour in the loss domain, and establishes that such effects depend on our baseline, i.e. are reference-point dependent. These considerations may be important drivers of different airspace user responses under different conditions of relative loss during the imposition of tactical slot delays. Behavioural economics often seeks to 'nudge' the agent into making the 'right' choice, by making it easier, whilst still leaving all choices available. In ATM, we have various key performance areas (KPAs), through which to establish different kinds of 'right'. Whilst more broadly, behavioural science may consider aspects such as airline general 'beliefs' (or 'cultures', e.g. that a certain type of action results in a certain type of delay), behavioural economics tends to focus more specifically on understanding financial trade-offs, taking into account that agent rationality is 'bounded' (such agents are not willing or capable of solving complex optimisation problems, as they are assumed to in normative models predicting behaviour). Whilst classically, market forces are often assumed to establish rationality and, ultimately, to produce a predictable equilibrium, this is often not the case. Human beings often have to take mental shortcuts, and use heuristics, as cognitive resources are scarce. The resulting biases and heuristics, including over-confidence, can lead to suboptimal decision-making. Behavioural science, with behavioural economics, thus focuses on what agents *actually* do, rather than what they 'should' do, and is driven by *descriptive* models. This thematic challenge may thus investigate the extent to which ATM can move from objective functions to 'subjective' functions, i.e. that take account of 'irrational' agents. In a 2014 review, Whitehead *et al*. (2014) state that "the behavioural sciences are clearly having a global impact on public policy initiatives [...] 136 states have seen the new behavioural sciences have some effect on aspects of public policy delivery in some part of their territory [...] 51 states have developed centrally directed policy initiatives that have been influenced by the new behavioural sciences." Several ATM stakeholders have expressed a need to take advantage of behavioural science to improve operational predictability. There are limited examples considering actual human behaviour in the context of wider transport planning and environmental policy (e.g., Avineri, 2012; Garcia-Sierra *et al.,* 2015), and few formal considerations of the applications of behavioural science in ATM. *Classical* modelling approaches from economics and operations research, such as game theory and linear programming, have been used extensively to assess the impact of flight prioritisation mechanisms. The strong assumptions behind these approaches, such as that of agent rationality, make such models unrealistic in certain circumstances. This may result in researchers overlooking the risks and unintended consequences of certain mechanisms, when stakeholder behaviour departs from such assumptions. Agent-based modelling (ABM) offers one way forward to address such issues. It allows the observation of emergent behaviour arising from agents' interactions in a bottom-up process, substantially reducing several disadvantages of traditional models, such as strong hypothesis dependency. The integration of data science (including, but not limited to, methods such ABM and machine learning) with behavioural economics, is often referred to as computational behavioural economics – it provides a natural framework for gaining new insights into human and institutional behaviour from operational simulation models. An important area of research currently being addressed by Nommon Solutions and Technologies (Engage catalyst fund project "Exploring future UDPP concepts through computational behavioural economics") is the generation of a specific assessment framework to evaluate the performance of different flight prioritisation and trajectory allocation mechanisms. The assessment framework generated is focused on certain KPAs, corresponding to the impacts that may be influenced by the application of such allocation mechanisms. Particularly interesting, are certain areas that have not been widely considered in previous studies and are essential to accurately represent and evaluate these mechanisms, such as equity and robustness to unexpected behaviours.

Behavioural science is not a panacea with regard to resolving certain shortcomings of the classical approaches to operations research, and assumptions of utility maximisation, for example, that still serve the ATM community well. Nor can it model the full scope of agent subjectivity. Rather, this thematic challenge seeks, *inter alia*, to identify and explore key areas in which behavioural science may advance the state of the art regarding ATM modelling, complementarily bridging existing gaps. This will involve identifying methods and solutions where an absence of behavioural modelling is particularly likely to compromise model usefulness and, where possible, to collect evidence of such (anticipated) shortfalls. More broadly, can we identify the first steps towards improved tools to better manage the costs of delay, and of uncertainty, and to better incentivise behaviour that benefits the network, in the wider context of tactical slot and trajectory allocation? For example, ATFM slot swapping has previously only been achievable through intra-airline swaps, used by airlines to prioritise flights, with the typical objective of minimising overall (delay) costs, which may be driven by passenger connectivities, crew hour restrictions, maintenance requirements, or night-time curfews on final rotations. Airspace users wish to keep these operational costs confidential. This is currently seen as a barrier to inter-airline slot swapping. What new technologies might be appropriate to support the negotiation of tactical contracts? For example, might cryptoeconomic tools[16] have a role to play in delivering 'smart'/'private' contracts? Specifically, could blockchain technology and secure multi-party computation extend existing UDPP solutions, offering the possibility to protect the participating AUs' sensitive information? Such technologies may allow for secure, auditable transactions without the need for a central broker, where stakeholders would be able to enter slot-swapping transactions without disclosing information to other participants. By demonstrating the feasibility of a privacy-preserving platform for swapping ATFM slots, the foundations could be laid for the development of tools that may contribute to better use of existing resources at airports, improved efficiency for airlines and reduced delays for passengers. From a user-acceptability perspective, could such tools deploy a centralised market with real money, or would only 'credits' be acceptable? Furthermore, it remains a particular challenge to investigate the extent to which such tools may anticipate and control for 'irrational' effects, and become automated features of future slot allocation and management procedures, based on stated user preferences for priorities and route choices.

Workshop conclusions

This section consolidates conclusions from the first two workshops. See the Engage website for the presentations. Readers are also invited to refer to abstracts of on-going research by the Engage PhDs and projects funded through the first catalyst funding wave.

Early UDPP developments introduced Enhanced Slot Swapping (ESS) and UDPP Departure, which extended the options for AUs to rearrange flights, including the multi-swap feature. More recently, other UDPP mechanisms allowing higher levels of flexibility have been proposed, such as Fleet Delay

[16] Note that vulnerabilities and global security of the CNS/ATM system falls within the remit of Engage thematic challenge 1. Readers should be mindful of the different objectives of the two thematic challenges.

Reordering (formerly 'Fleet Delay Apportionment'), where each AU can decide how to distribute the delay it must absorb among its flights in a hotspot, and Selective Flight Protection (SFP), whereby AUs can voluntarily suspend certain flights (i.e., move them later in a departure sequence) and protect others (Pilon *et al.*, 2016).

In addition to the concepts developed within the context of SESAR, a variety of allocation mechanisms have been investigated and proposed in the literature. The proposed mechanisms place emphasis on the assignment of ATFM slots, on the priorities assigned to flights in case of disruption, on potential rerouting paths, or multiple such criteria. Depending on the operational nature underpinning the prioritisation concept, the different mechanisms can be divided into three groups. Firstly, the mechanisms concerning the implementation of several operational standards and regulations fall inside the rule-based category. Secondly, there are several mechanisms that rely on the use of money and the forces of supply and demand to determine the optimal solution in situations where different entities are competing for scarce resources: monetary, market-based mechanisms.

Finally, and in part due to the reluctance of many AUs to use real money, some mechanisms make use of virtual currencies, such as credits, to achieve certain prioritisation strategies: non-monetary, market-based mechanisms. Extended-SFP (ESFP) is such a concept proposed in the scope of SESAR with new prioritisation features. The potential advantage is the ability to also provide flexibility to AUs with a low number of flights involved in a regulation, thus increasing the equity of the system (Ruiz *et al.*, 2019a). It is based on the use of a virtual currency without monetary value: '(delay) credits'. Several mechanisms are summarised in Figure 2.

Mechanism Name	Operational Basis	Phase of Application	Credits can be used on a later day?	Currently in use?
First Planned First Served (FPFS)	Rule-based	Tactical	N/A	Yes
UDPP - Enhanced Slot Swapping (ESS)	Rule-based	Tactical	N/A	Yes
UDPP - Selective Flight Protection (SFP)	Rule-based	Tactical	N/A	No
Best Performing Best Served (BPBS)	Rule-based	Strategic / Tactical	N/A	No
Auction (primary or secondary)	Market Monetary	Strategic / Tactical	N/A	No
Congestion Pricing (CPLP)	Market Monetary	Strategic	N/A	No
Route Contracts (COCTA)	Market Monetary	Strategic	N/A	No
UDPP - Extended-SFP (ESFP)	Market Non-Monetary	Pre-Tactical / Tactical	Yes	No
Credits Points for Re-routing	Market Non-Monetary	Strategic / Tactical	No	No

Figure 2. Summary of flight prioritisation mechanisms
(*Courtesy Nommon Solutions and Technologies*)

NextGen (the US analogue of the SESAR programme) originally proposed BPBS (see Figure 2), providing priority to best performing aircraft in enhanced operations. Centralised Peak Loading Pricing (CPLP) was proposed by Bolić *et al.* (2017); it broadly represents an ATM analogue of toll roads, whereby a variable price is used to control demand. Credit Points for Re-routing extends the credit-based paradigm to route prioritisation (Sheth and Gutierrez-Nolasco, 2010). It deploys the ability of AUs to fly optional routes, prioritising each one with credit points, received daily as a fixed amount, based on the volume of their operations.

Assessing the benefit of these mechanisms across different stakeholders (airlines; passengers; airports; ANSPs, the Network Manager), and the relative importance of KPAs across these stakeholders, it is clear that the corresponding benefits and priorities are distinctly heterogeneous. Monetary mechanisms (and auctions) may be expected to benefit larger AUs more than smaller ones, as may BPBS (although this depends on underlying funding mechanisms and precise definitions of 'best served'), thus delivering low equity. Credit accumulation needs to be carefully controlled so as not to prejudice against smaller AUs (see also Ruiz *et al.*, 2019a), but may then indeed be equitable for AUs, although most susceptible to 'irrationality' effects. Such effects and biases may potentially be measured – in future research – relative to monetary equilibria. The equity of credit-based systems *between airport contexts* is more of a challenging prospect, it seems.

Whilst AUs value simple mechanisms and flexibility in particular, and mechanisms offering the possibility for change as late as possible, airports and ANSPs more typically place higher value on predictability (e.g. regarding gate changes and sectorisations, respectively), disfavour late volatility in the system, and value increased predictability furnished through pre-emptive, congestion-alleviating mechanisms. Regarding AUs' differential prioritisation on KPAs, they are clearly profit-motivated and wish to drive metrics that reflect passenger loyalty and hence market share: cost and punctuality. Airports and ANSPs are likely subject to drivers of customer service delivery to the AUs (and passengers), in addition to often complex regulatory constraints regarding cost efficiencies. Airports are (currently) most susceptible to public pressure regarding environmental impacts.

There is, however, no unique way to define equity and fairness, since these may or may not invoke monetary value, and may depend on the stakeholder perspective and impacts, both at the local and network levels. Within the context of UDPP, equity is defined such that the action of one AU does not generate a direct negative impact (i.e., increase the delay) of other AU's flight(s). Within the context of first-planned, first-served, fairness is defined such that the original sequence of planned flights is preserved. Improved definitions of equity and fairness are needed, potentially differentiating or consolidating the two terms, examining the definitions and trade-offs across different stakeholders (e.g. airports treating all flights equally, unlike airlines), plus the trade-offs with flexibility and, indeed, more mature definitions of the latter.

Further work is also needed on the precise definition of the 'best' trajectory[14], by stakeholder type, not only across airspace user types. Greater elucidation is required of the need to adopt a compromise between individual rationality, budget balance, allocative efficiency and incentive compatibility (see Castelli *et al.*, 2011) in the design of new mechanisms. This should build on existing exploratory research in SESAR examining the trade-offs between centralised and decentralised markets. As raised above, part of the move towards improved models of stakeholder behaviour could assess gaming, and mature the state of the art advanced by projects such as AeroGame[17], which investigated how the research domain of serious games can support change in ATM. It is necessary to model more realistic human interactions in a multi-stakeholder, complex socio-technical environment, rather than in highly

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[17] https://www.sesarju.eu/newsroom/brochures-publications/aerogame

constrained and limited simulation environments, and to determine which (incentive) solutions are best in terms of non-manipulability (Schummer and Abizada, 2017; Schummer and Vohra, 2013).

The robustness of (tactical) slot allocation mechanisms and airspace users' choice of flight plan as a function of time is made more difficult to predict in the context of uncertainty from exogenous factors and the AU's response to the evolving traffic situation as they adapt from the originally-filed flight plan. Airspace user cost functions need to be taken into account, and may be usefully framed in terms of flexibility characterisations, such as elasticity functions and 'not before' and 'not later than' departure rules. Such functions and rules could be deployed to empower airspace users to make better choices. Additional investigation of the potential role of ANSPs coordinating with the Network Manager to manage tactical demand (and route choices) is required, building on the work of COCTA, for example, assessing the impacts of uncertainty and disturbance, and the implications for policy recommendations regarding the Single European Sky Performance Scheme. Barriers to progressing the state of the art include the calibration and validation of new models such as those identified above, and obtaining quality stakeholder cooperation and buy-in. This might be overcome by running models and tools in shadow-mode, with usable and practical user interfaces, also demonstrating their value in terms of metrics such as predictions of (sector) overloads, delays and delay costs, and valuations of equity, fairness and efficiency. Data collection quality could be improved through the use of stated preference techniques, commonly deployed in socio-economic and psychological research, and sensitivity analyses would need to be run to test model and tool efficacies. Capturing gaming behaviours often requires projective techniques.

The introduction of standardised, integrated schedule recovery actions in tactical airline operations, based on microscopic stochastic process chains, with the primary objective of minimising overall network costs, may present a valuable way forward for developing a human-in-the-loop (HITL) decision-support system for airline operations controllers, at the network level. The tactical control of network effects had so far not been explored in a holistic manner. However, these issues are being addressed by the Engage PhD "Stochastic control of tactical airline operations in hub airport networks". Most of the literature has taken only individual aspects into focus, such as the accurate prediction of total turnaround times with stochastic process parameters (e.g. Oreschko *et al.*, 2012) and the adjustment of block times (Kang and Hansen, 2017). Of particular interest, is the fact that over multiple, partially parallel aircraft rotations, prioritisation processes may appear externally 'irrational'. This again links in particular with issues of scale and of cost efficiency.

Behavioural science could be used to better capture 'irrational' (arational, non-normative) behaviour from airlines in future, and build improved (agent) models, for example in terms of (tactical) routing and slot choices. This could deliver improved forecasting and traffic demand tools for ANSPs, and better predict behaviour under UDPP (for example) by validating key prospect theory principles, such as loss framing, risk-seeking behaviour under loss, and endowment effects. Capturing aleatory effects in agents, for choices with similar utilities/prospects, is also a challenge. New market designs for the allocation, and trading, of tactical slots may support potential future mechanisms for slot swapping and trading between different airlines. Key to such progress will be understanding ways to more effectively manage airspace user cooperation and motivation, how these vary by airline type, and whether incentives or penalties work better. Is the better underlying driver of behaviour cooperation or competition, and can social norms be used to make airline behaviour more collaborative? A key objective is to offer airspace users improved choice, whilst avoiding undesirable behaviours, such as gaming of the system. Improved application of interventions in the ATM context may draw on the 'mindspace' approach elaborated by Dolan *et al*. (2012), and earlier investigations already applied to ATC based on the theory of planned behaviour (Cook and Tanner, 2008).

Machine learning in general, and reinforcement learning in particular (exploring the corresponding behavioural incentives), may provide a useful approach to investigating collaboration policies that enhance exchanges between agents in order to maximise performance in given operational contexts (such as airport operations), and across diverse, agentified stakeholders. If new styles and motifs of action emerge (which may appear locally 'bad', but are in fact globally 'good'), it is important to maintain the interpretability of the outputs from such virtual environments, such that 'irrational' behaviour is not replaced with opaque behaviour, and potential policy recommendations (e.g. for enhancing stakeholder cooperation), and tools, are both validated and understood.

Fundamentally, it is also clear that unexploited capacity remains, and it is still possible to make better use of existing capacity without having to invent solutions that are radically different from those currently in use. Opportunities remain for the application of mathematical/analytical models to further evaluate CASA enhancements, for example by relaxing selected, current boundary conditions and constraints, which may still yield significant benefits.

The following have been identified as *example* ideas for potential further exploration:

1. Incorporating behavioural science methods into improved traffic demand and distribution predictor tools for ANSPs and UDPP;
2. Assessing if incentives or penalties work as better drivers of behaviour: whether social norms can be used to improve collaboration;
3. Considering specific incentives for diverse stakeholders to collaborate (e.g. re. implementing flight prioritisation mechanisms) and what KPIs could be used to measure cross-stakeholder integration;
4. Predicting and avoiding undesirable behaviour, such as gaming, in ATM allocation mechanisms;
5. Building a better understanding of 'equity' and 'fairness', plus the trade-offs across different stakeholders, and with 'flexibility' and 'access' metrics;
6. Extending KPA trade-offs to consider: (i) particular stakeholder sub-groups, such as low-volume airspace users c.f. hub carriers, and connecting c.f. non-connecting passengers; and, (ii) effects over time and space (such as decaying or improving equity);
7. Improving assessments of uncertainty and disturbance, both exogenous (e.g. in model environments) and endogenous (e.g. to agents) – better quantifying models' and mechanisms' robustness;
8. Improving the contextualisation of new mechanisms for policy recommendations, ensuring that model outputs are appropriately transparent and validated;
9. Identifying emergent (positive and negative) effects of mechanism design, potentially developing improved measures of system complexity and resilience;
10. Running models and tools in shadow-mode, with practical user interfaces and values in output metrics (e.g. costs, overloads).

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4 Conclusions

This deliverable collates the first and second releases of the Engage thematic challenge briefing notes. The four thematic challenges were selected to address research topics not contemporaneously (sufficiently) addressed by SESAR. For a detailed analysis of the ER programme and the three-pillar approach to proposed future research, with commentary on the relationship with evolving ATM research, please refer to D3.6 [5].

5 References

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6 Acronyms

ATM	Air traffic management
CNS	Communication, navigation, surveillance
ER	Exploratory Research
SESAR	Single European Sky ATM research
SJU	SESAR Joint Undertaking
TC	Thematic challenge

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