Engage

At the core of the Engage KTN is the definition of various thematic challenges: new ideas suggested by the research community, not already included within the scope of an existing SESAR project. They are developed along with the ATM concepts roadmap and complementarily with some of the network's PhDs and theses.

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[1], under different types of uncertainty and information sharing? Which mechanisms are more robust against behavioural biases ('irrationalities'[2]) 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 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

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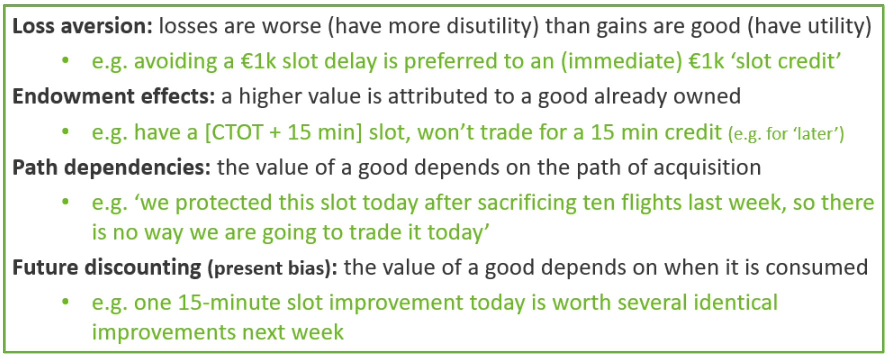
[1] Improved trajectory prediction *per se* falls within the remit of Engage thematic challenge 2. Readers should be mindful of the different objectives of the two thematic challenges.

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

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[3] 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.

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[3] 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.

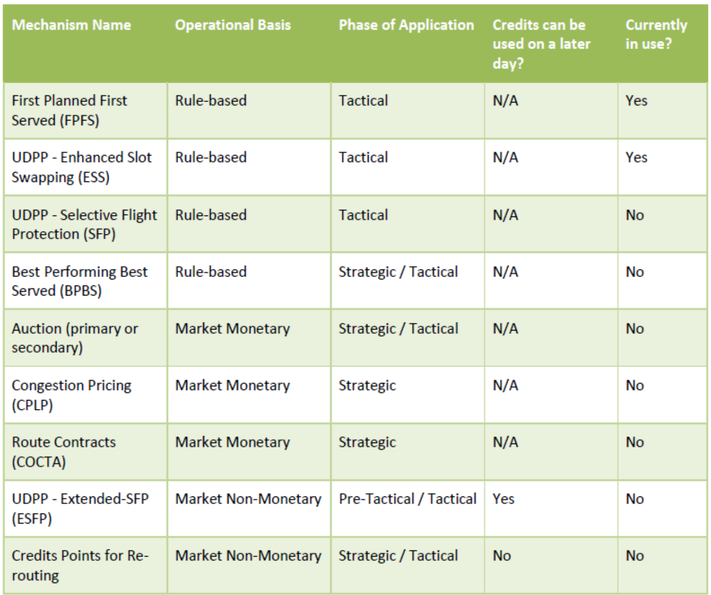
Workshop conclusions

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 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[1], 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[4], 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 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

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

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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