Evaluation of Flight Prioritization Mechanisms Through Agent-Based Modelling

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Abstract— **This work presents an agent-based modelling (ABM) approach aimed at enabling a rigorous and comprehensive study of flight prioritization mechanisms in the context of demand and capacity imbalances. The main model components are described, including a simplified network environment and the two types of agents included in the model: The Network Manager and the Airspace Users. The paper also shows how different flight prioritization mechanisms, including SFP, E-SFP and slot auctioning, are modelled and evaluated. Finally, a comparative performance analysis of the simulated mechanisms is presented, evaluating their impact, aggregated or disaggregated by airline, on punctuality, cost-efficiency and equity. Results show how SFP, counterintuitively, worsens the baseline performance due to unexpected network effects, while the slot auctioning concept provides the best performance.**

Keywords-flight prioritization mechanisms; agent-based modelling; network effects; punctuality; cost efficiency; equity.

I. INTRODUCTION

During Air Traffic Flow Management (ATFM) tactical phase, when the capacity of an en-route sector or at the destination airport is expected to be exceeded by the demand, flights are delayed at the origin airport and assigned new take-off times. This is called issuing a regulation. Each of the flights involved in the regulation receives a slot (ATFM slot) in a new reference-time list for departure. These slots are currently assigned following the First Planned First Served (FPFS) policy, which is widely accepted by all the stakeholders involved because it minimizes the total delay while preserving equity constraints among all Airspace Users (AUs) [1]. However, this solution is far from being optimal from the point of view of AUs' cost: due to the cost of delay being highly non-linear and different for every flight, AUs may want to prioritize some of their flights against others which they consider less valuable.

Within the current concept of operations, AUs are able to swap ATFM slots under certain circumstances. However the level of flexibility provided by this mechanism is rather limited: only flights involved in the same regulation can be swapped, and although theoretically flights between different AUs can be swapped, this barely happens. The User Driven Prioritization Process (UDPP) concept was born within SESAR with the aim of improving existing fligth prioritization mechanisms, searching for extra flexibility for AUs in the frame of the Collaborative Decision Making (CDM) philosophy, which aims to involve all the stakeholders in working more transparently and collaboratively. Some of the earliest solutions proposed by SESAR UDPP are already being deployed, while newer concepts are currently being investigated [2]. Nevertheless, there is still room for improvement in both the development of advanced mechanisms and the modelling techniques used for their examination.

II. BACKGROUND AND MOTIVATION

Most existing studies about flight prioritization mechanisms make use of normative economic models that predict the behavior of the system under idealized circumstances, such as perfect information and agents' rationality. However, these conditions are often not fulfilled in the real world, where decisions are made in the presence of incomplete or uncertain information, and rationality is limited by the tractability of the decision problem, the cognitive limitations of the decision makers, and the time available to make a decision.

Agent-based modelling (ABM) presents a way to overcome these issues. ABM allows the observation of the emergent behaviour arising from agents' interactions in a bottom-up process [3], combining formality and rigour with the minimization of disadvantages such as strong hypothesis dependency. Generally, an agent-based model is a computer model consisting of a number of software objects, the agents, interacting within a virtual environment. The agents, which often have a one-to-one correspondence with the real world actors, have a degree of autonomy, react to and act on their environment and on other agents, and have goals that they aim to satisfy.

Agent-based modelling has prominent synergies with behavioural economics, where deviations from the assumed theoretical behaviour play an outstanding role. In this paper, however, we will focus on the analysis of emergent phenomena and network effects that could not be captured with other modelling approaches. Former SESAR projects, like TREE, already proved the agent-based approach validity to simulate propagation phenomena in compex networks (e.g, delay propagation) [4].

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Future steps for the extension of the model, aiming to explore the impact of agents' behaviors that depart from the assumption of perfect rationality, are discussed at the end of the paper.

III. AGENT-BASED MODEL

A. Overall Description

The model simulates a day of air traffic operations, where the Network Manager takes care of flow management and airlines make decisions on how to deal with the delays imposed in congestion situations. The model comprises three main elements:

- The simulation environment, which provides the network characteristics for the agents to operate in.
- Agents. Two types of agents are considered, representing the main actors of the simulation: the Network Manager and the airlines.
- Exogenous variables, which represent arbitrary external conditions that affect the model but are not affected by it. They include fuel prices and air navigation charges.

The simulation comprises four main stages:

- In the first stage, with some time in advance (e.g., 2 hours), the Network Manager estimates the future demand for all the sectors within a given period of time (e.g., 15 minutes). This expected demand is checked against the corresponding declared capacity, i.e., the number of flights allowed inside that area during the mentioned period of time (occupancy counts). If the Network Manager detects an imbalance between demand and capacity in a certain sector or group of sectors (hotspot), it will initiate a regulation and the excess demand will be displaced over time.
- In the second stage delays are calculated. Flights involved in the hotspot are delayed at the origin airport and assigned new take-off times through ATFM slots. At this stage we distinguish two different resolution paradigms that differentiate some prioritization mechanisms from others: First Planned First Served (FPFS) and Auctions. In the simulations based on the FPFS principle, the Network Manager sequences the flights in the order in which they would have arrived at the constrained airport or sector according to the information present in the filed flight plans. The simulations based on the auction paradigm do not restrict the initial slot position of the flights to any given order; the final sequence of the flights is a result of the successive auctions of all the slots identified inside the hotspot.
- The third stage comprises the airlines' decision process. Once the affected flights receive an initial ATFM slot, the airlines evaluate all possible actions available with the objective of reducing the cost of delay associated with all their affected flights within the hotspot. The number and complexity of airlines' actions depend on the level of flexibility provided by the flight prioritization mechanisms being simulated.
- Finally, the fourth and last stage covers the study and subsequent acceptance or rejection of each of the requests sent by the airlines by the Network Manager. Once this process is completed, the delays are definitive and the airlines can update the flight plans of their affected flights accordingly.

The first stage is repeated iteratively for each of the time windows into which the simulation time is divided. Whenever an imbalance is detected, the second, third and fourth stages are performed. The simulation finishes when the temporal horizon is reached.

B. Simulation Environment

1) Airport Configuration

The defined network consists of 5 different airports, which comprise a mix of hubs and secondary airports.

2) Sector Configuration

The process of sector definition comprises the virtual division of airspace. Thus, the provision of air traffic services is decomposed, in the different sectors, into tasks with manageable workload. Our network decomposition in air traffic volumes consists of two different types of sectors. First, 9 en-route sectors are modelled, defining the different airspace structures crossed by the flights after the departure and before landing. Additionally, one extra sector is defined around each airport simulating a Terminal Manoeuvring Area (TMA).

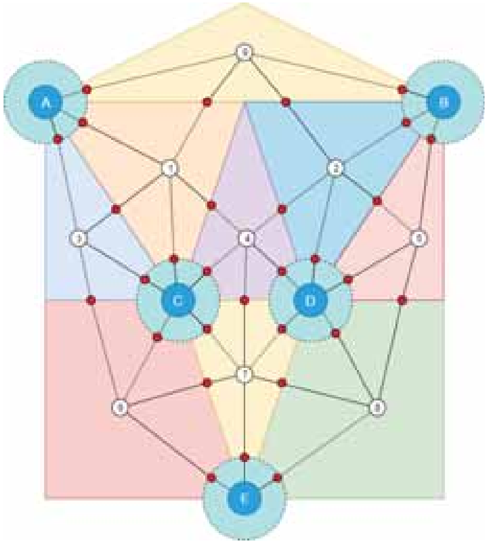

Figure 1. Network topology

An illustration of the resultant network topology is shown in *Figure 1*. The blue circles define the airports, labelled with letters, the white circles designate the id of each particular sector, and the red dots exemplify the connection entry and exit points between sectors.

3) Route Configuration

The route configuration defined for the model follows a fixed trajectory approach with defined entry and exit points for each sector. The sector configuration is built in such way to allow 3 possible disjuntive trajectories for each OD pair, which only share the departure and arrival legs within the airport area.

4) Network Calibration

The topological description of the network needs to be translated into a physical representation. Each of the lines connecting the nodes in the topology diagram (route trajectory) needs to be assigned a distance. Additionally, air navigation charges need to be modelled in order to cover the services provided by Air Navigation Service Providers (ANSP) over a portion of airspace, in our case coincident with the defined sectors. With the ultimate objective of getting realistic values of cost and distances for each of the routes, we have considered each airport to be a representation of a real airport in the ECAC area. Consequently, the unit rate factor of each charging zone (sectors) and the route distances can be approximated to reality. At the end, the model is calibrated with values such that the 3 different routes between each OD pair are not equal in terms of cost and distance, neither do they present large differences.

C. Agents

1) Agents Characteristics

a) Network Manager

The role of the Network Manager is to apply the corresponding ATFM processes throughout the simulation. It is in charge of the detection of possible demand-capacity imbalances in the air traffic network, as well as of the correct application of the prioritization mechanisms.

b) Airlines

The airline agents are the main agents of the simulation. They make decisions to achieve their objectives according to their internal parameters and the environment. In this paper they are modelled as cost-minimizers, but the model allows the modification of their behaviour by including different biases that depart from purely rational choices.

Airline costs are impacted by air navigation charges (which depend on the distance flown within each sector), the cost of fuel (modelled in a simplified manner, as proportional to the flight distance), and the cost of delay. The calculation of the cost of delay is of special interest for the model because its inherent non-linearity could trigger the use of the available prioritization mechanisms. The costs included in the cost of delay calculation are maintenance costs, crew costs and passenger costs, which can in turn be broken down into soft and hard costs. The maintenance, crew costs and passenger soft costs are extracted from the corresponing tables from the University of Westminster document [5]. Passenger hard costs are due to such factors as passenger rebooking, compensation and care. The modelling of these costs are based on the Regulation (EC) No 261/2004 [6] and the Articlesº 91(1) and 100(2) of the Treaty on the Functioning of the European Union (TFEU). Flight cancellations are only considered when an airport curfew is missed. In that case, the final departure time of that particular flights is scheduled to the next day and the costs are calculated accordingly applying the same rules as before.

The simulation scenarios consider 5 airlines classified in two groups which are diferentiated according to their network configuration model.

- Airline 1, Airline 2 and Airline 3: Flag carrier airlines with a hub-and-spoke network configuration.
- Airline 4 and Airline 5: Low-cost airlines with a point-to-point network configuration.

2) Agent Interaction Rules

Depending on the flight prioritization mechanism evaluated in the simulation, the sequence of agents' decisions and actions follows a different pattern. This variety of interactions can be divided into two main paradigms depending on how the Network Manager originally imposes delays in the context of a demand-capacity imbalance.

a) First Plan First Served (FPFS) Paradigm

The FPFS principle ensures that the affected flights within a hotspot are ordered according to the estimated time over (ETO) the specific sector. The delays imposed to the ordered flights are then sent to the airlines as an initial endowment from which to study a possible prioritization. The main actions performed by each agent are schematized in the *Figure 2*. The opportunity to ask for a rerouting has not been considered in the initial implementation of the model described in this paper, but will be considered in future extensions of the model.

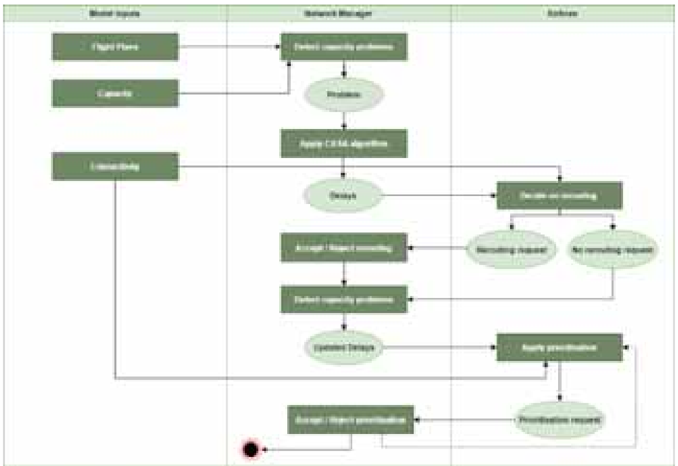

Figure 2. FPFS workflow

b) Auction Paradigm

Unlike the mechanisms based on the FPFS principle, in an auction the ATFM slots are not filled following the ETO of the specific sector, but the sequence is the result of the amount of money airlines are willing to pay to occupy each of the auctioned slots. The workflow illustrating the whole process is depicted in *Figure 3*. The implemented auction is a Vickrey auction, which is a type of sealed-bid auction. Airlines submit written bids without knowing the bid of the other participants in the auction. The highest bidder wins, but the price paid is the second-highest bid. This type of auction is strategically similar to an English auction and gives bidders an incentive to bid their true value [7].

As in the FPFS mechanisms, the opportunity to ask for a rerouting has not been included in the initial implementation of the auction mechanism described in this paper, but will be incorporated in future extensions of the model.

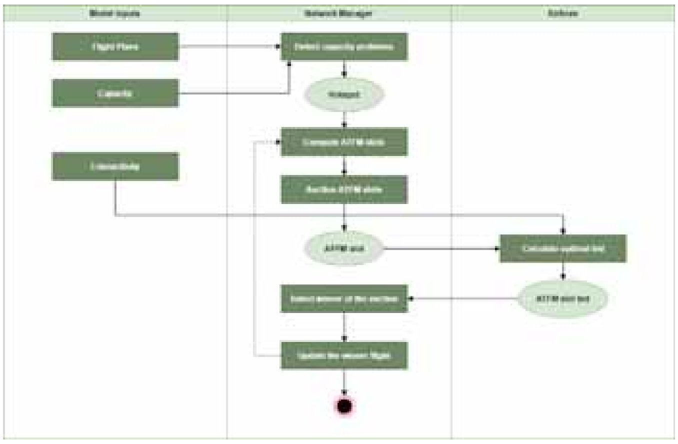

Figure 3. Auction workflow

D. *Simulation Inputs*

1) *Flight Schedule*

A flight schedule is required to provide all the necessary information for the Network Manager to perform ATFM functions. It includes all the flights involved in the simulation and provides the necessary information about the origin and destination of the flight, a flight code, the operating airline, the type of aircraft used, and an aircraft identifier. In this study, this data has been synthetically generated from real data. To recreate a realistic level of traffic in our model, flight schedules of a subset of 5 European airports are reconstructed from the information contained in the the last filed flight plan contained in EUROCONTROL's Demand Data Repository 2 (DDR2) for a random traffic day.

From all the selected flights, the various operating airlines are grouped by alliances. According to the flight network configuration and the identified alliances, three artificial flag carrier airlines (Airlines 1, 2 and 3) are considered for the model. Finally, with the intention of including an additional point-to-point network configuration, characteristic of low-cost airlines, a series of extra flights were manually added to the schedule. Two artificial low-cost airlines (Airlines 4 and 5) are considered for the operation of these set of flights.

2) *Capacity Configuration*

The declared capacity of each of the sectors defining the network needs to be modelled. This capacity depends on a complex combination of factors such as traffic flow direction, coordination procedures, in-sector flight times, etc. For the sake of simplicity, the capacity estimation in our model is only based on the expected demand. Given the flight schedule previously generated, the expected demand values per sector and time window are computed. With that information, the capacity values are generated following a sliding windows approach: the capacity of a sector during a certain time window is equal to the maximum expected demand for the next 5 time windows. Then, the user is able to manually change capacity values to simulate capacity shortages and generate hotspots.

3) *Passenger Connectivity*

The SESAR project POEM (Passenger-Oriented Enhanced Metrics) evidencied that passenger-centric metrics are needed to see the full impacts of operational change [8]. Passenger connectivity is then required to evaluate the impact of different prioritization mechanisms on the passengers.

For the experiments described in this paper, a configuration file was artificially generated with all the information regarding passenger connectivity, according to the following assumptions: (i) only flag carrier airlines have connections; passengers can only have a maximum of one connection in their journey; (ii) the waiting time for passengers connecting flights lies between 45 and 120 minutes; (iii) the total number of connecting passengers, inside a particular flight, which will take a second flight later, is computed by applying a 20% to the total number of passengers on the actual flight who have not made a connection yet; (iv) in the event that the connecting passengers inside a flight take different second flights, the number of passengers going to each one of these next flights is randomised from the total number of connecting passengers.

IV. IMPLEMENTATION OF FLIGHT PRIORITIZATION MECHANISMS

Four flight prioritizarion mechanisms have been modelled: Slot Swapping, Selective Flight Protection, Enhanced Selective Flight Protection, and Slot Auctions.

A. *Slot Swapping*

The slot swapping mechanism is included in our baseline scenario because it is currently available for use by airlines in real operations. It offers the possibility of exchanging the position of two flights belonging to the same airline and affected by the same hotspot as long as no flight occupies a 'before schedule' position after the swap. An airline using the slot swapping mechanism will take the following actions:

- Identify all the airline flights involved in the hotspot and their associated data.
- Get all the possible slot swap possibilities between the airline affected flights.
- Take only the slot swaps that comply with the schedule restrictions and:
    - Compute the cost of delay associated with the baseline delay imposed to the flights involved in the swap.
    - Perform the swap and calculate the new delays for the swapped flights.
    - Compute the cost of delay with the new configuration.
    - Compute the cost difference between the baseline cost of delay and the new computed cost of delay after applying the slot swap.
- Based on the study of all the possible swaps, choose the best option and send the request to the Network Manager.

B. *Selective Flight Protection*

The SFP mechanism offers extra flexibility for airlines to redistribute the initial FPFS delay imposed on their flights. This mechanism offers the possibility of protecting important flights that due to schedule limitations could not be protected with a normal slot swap. Consequently, it is understood as a complementary mechanism to slot swapping, meaning that for the specific simulations evaluating the SFP, both mechanisms will be active. An airline using the SFP mechanism will take the following actions:

- Identify all the airline flights involved in the hotspot and their associated data.
- Get all the possible slot swap possibilities between the airline affected flights.
- Take only the slot swaps that cannot be performed with the baseline slot swapping mechanism due to schedule limitations and:
    - Compute the cost of delay associated with the baseline delay imposed to the flights implicated in the swap.
    - Perform the swap and calculate the new delays for the swapped flights.
    - Compute the cost of delay of the new configuration. The protected flight is at that moment before schedule and the Network Manager will have to place it back at schedule (zero delay). Consequently, the cost of delay for the protected flight is 0.
    - Compute the cost difference between the baseline cost of delay and the new computed cost of delay after applying the slot swap.
- Based on the study of all the possible protections, choose the best option and send the request to the Network Manager.

The Network Manager will take the following action prior to rejecting or accepting the request:

- Identify the protected flight which is placed before schedule.
- Place the protected flight at the first possible ATFM slot at schedule.
- Reorganize the impacted flights by the relocation.

C. *Enhanced Selective Flight Protection*

The E-SFP mechanism involves the possibility of selecting the slots for specific flights in a hotspot, either by spending credits if the desired slot reduces the delay proposed by the Network Manager, or by earning credits if the slot change brings a delay increase. The described process has an impact on other flights, as their preliminary assigned ATFM slots can be taken by the flight that uses this mechanism. As an example, let’s assument that an airline has two flights in a hotspot, flight A and flight B. If the airline protects a slot for flight A through the credit mechanism, this may cause a change of the position of flight B in the hotspot. This should be taken into account when calculating the cost of the action for flight A. The airline can use the prioritization mechanism again to reduce the impact of protecting flight A on flight B. Therefore, the development of the credit-based mechanism cannot be solved individually for each flight, but it must take into account all the flights of the airline at the same time, and thus generate a response that includes all of them.

The prioritisation carried out by the AUs can have a negative impact on other AUs’ flights. However, according to AU experts consulted by EUROCONTROL during the development of the mechanism, this negative impact on other airlines can be considered negligible [9].

An airline using the E-SFP mechanism will take the following actions:

- Identify all the airline flights involved in the hotspot and their associated data.
- Calculate the airline total cost of delay for that ATFM slot arrangement.
- Get all the possible ATFM slots where each flight could be located according to schedule restrictions.
- Get all the feasible ATFM slot combinations between the possible slot positions of each affected flight.
- Compute the difference in cost between the baseline total cost of delay and the total cost of delay for each combination.
- Compute the needed or earned credits for requesting each combination.
- If the airline has enough credits to request that ATFM slot combination (or if the combination does not consume any credit):
    - Calculate the value of used or earned credits in the combination.
    - Compare that value with the calculated cost difference with respect to baseline to get the final cost reduction (or increment) of applying that ATFM slot combination.
- Based on the study, choose the best combination and send the request to the Network Manager.

This mechanism is implemented so that each airline has an initial number of credits at the start of the simulation. This initial allocation represents the number of credits that the airline earned the previous days but did not use yet. For the sake of simplicity, the equivalence between delay and credits is set to a constant value of 1, meaning that 1 minute of delay equals to 1 credit, independently of the characteristics of the congested airspace (size, location or temporal scope).

For the proper operation of the prioritization process, it is essential to calibrate both the initial credits and the monetary value that each airline assigns to the credits. Due to the inherent limitations caused by the fact that the duration of the simulation represents only one day of operations, the calibration process was done defining a series of decision-making behaviours for each airline. The credit values for each behaviour were defined by trial and error so as to incentivize the airlines to use the prioritization mechanism:

- Conservative: it imitates a behaviour approximation where the airline tends to earn credits by absorbing delay when not very important flights are affected in order to use them in the future to prioritise more valuable flights. The monetary value assigned to the credits is significant and the number of initial credits is high. For this case, we have assumed that the airline considers a credit value between 25 and 30 EUR. Airline 1 and Airline 2 are modelled following this behavioral approach.
- Optimistic: it represents a behaviour where the airline tends to spend credits, prioritizing not so important flights, rather than to earn credits by absorbing delay. The airline does not expect to need the credits in the future and decides to spend them quickly when it has the opportunity. The monetary value assigned to the

credits is low and the number of initial credits is small. For this case, we have assumed that the airline considers a credit value between 10 and 15 EUR. Airline 3 and Airline 4 follow this strategy.

- Neutral: it corresponds to a neutral behaviour between the two previous patterns. The monetary equivalence and the number of initial credits values are between the values of the previous levels. Airline 5 is modelled following this strategy.

D. *Slot Auctioning*

The formulation of optimal bidding by airlines is the most interesting aspect of this kind of prioritization mechanism. Once again, since the simulation time window of just one day does not allow the implementation of any learning capability or adaptive behaviour, airlines are divided according to three levels of action equivalent to those defined for the E-SFP mechanism.

- Conservative: it imitates a behaviour where the airline bids aggressively according to a value very close to the worst possible situation for the flight within the hotspot. Airline 1 and Airline 2 include this bidding strategy.
- Optimistic: it represents a behaviour where the airline tends to bid lower, in many cases overestimating its ability to win the auction. Airline 3 and Airline 4 include this bidding strategy.
- Neutral: corresponds to a neutral behaviour between the two previous patterns. Airline 5 includes this bidding strategy.

An airline participating in the auction of a particular ATFM slot takes the following actions:

- Identify all the airline flights involved in the hotspot and their associated data.
- Collect the actual sequence of ATFM slots in which the hotspot is divided.
- Calculate the cost of delay associated with placing the flight in each of the remaining ATFM slots, from the one being auctioned to the last slot of the hotspot.
- Formulate the bid according to its corresponding behaviour:
    - Conservative: the airline bids according to the 75th percentile of the cost distribution calculated in the previous step.
    - Optimistic: the airline bids according to the 25th percentile of the cost distribution calculated in the previous step.
    - Neutral: the airline bids according to the 50th percentile of the cost distribution calculated in the previous step.
- Choose the highest bid between the bidding flights, if more than one, and send the bid to the Network Manager.

The money spent by the airlines is redistributed so that the total amount paid by all the airlines as direct expenses (air navigation charges plus auction prices) is equal to the total amount of air navigation charges paid by the airlines for the mechanisms based on the FPFS paradigm. This means that all the money that the airlines have spent on the successive slot auctions must be returned to them through some specific mechanism. The approach implemented in the simulation is based on a redistribution proportional to the amount of money spent in charges. Thus, the reduction percentage applied to each airline is equal to the percentage that the same airline has paid in charges over the total amount of air navigation charges paid by all the airlines.

V. RESULTS AND DISCUSSION

In this section the results obtained from the execution of the simulations are presented. The performance indicators used to evaluate each mechanism take as a starting point the SESAR Performance Framework, complemented with other specific metrics that are considered relevant for the problem under study. The final set of selected Key Performance Areas (KPAs) are: Punctuality and Predictability, Cost Efficiency, and Equity.

A. *Punctuality and Predictability*

From an airline point of view, it is crucial to measure whether a certain prioritization mechanism increases the punctuality of its flights. For airports, the importance of measuring predictability and punctuality lies in the fact that higher predictability levels allow the airport to fully utilize its current capacity. Finally, from the Network Manager perspective, improving predictability and punctuality is one of the goals of the ATFM process.

Predictability and punctuality are merged into one KPA in the SESAR Performance Framework 2018 due to the strong interdependencies between them. However, the chosen metrics for the project only reflect the punctuality performance due to the limitations in the scope of the simulation model: for instance, neither the ability of the airlines to change the cost index (change the flight speed) nor the assignments of en-route delays (e.g. holding patterns) are modelled. Then, the only two selected metrics are flight departure delay (PUN1) and passenger arrival delay (PUN2), displayed in Figure 4 and Figure 5 respectively.

$$PUN1 = \frac{\sum_{i=1}^{n} d_{flight_i}}{N_{flights}} \tag{1}$$

$$PUN2 = \frac{\sum_{i=1}^{n} d_{pax_i}}{N_{pax}} \tag{2}$$

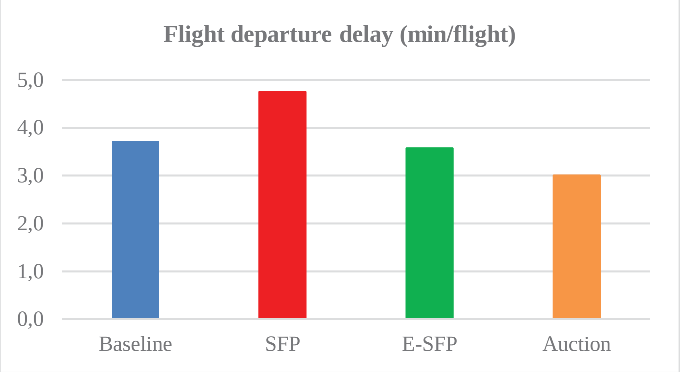

Figure 4. Average flight departure delay

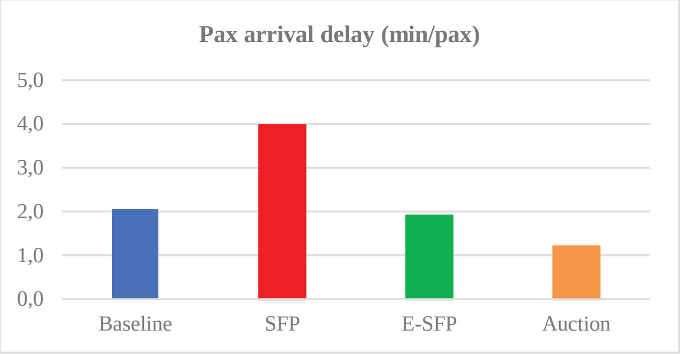

Figure 5. Average passenger arrival delay

These results offer some insights that at first glance may seem counterintuitive. The SFP mechanism punctuality performance is the worst of all the mechanisms. Despite offering more flexibility to airlines, the SFP mechanism ends up with worst results than the baseline configuration. The reason is that the extra level of flexibility allows airlines to make more optimal requests, compared with the baseline scenario, which in most cases involve larger alterations in the flight plans of the affected flights. This fact has a direct impact on other flights, which on certain occasions generates downstream network effects motivating the cancellation of several flights due to curfew. These cancellations explain the drastic deterioration in the punctuality levels for the SFP scenario.

On the other hand, the E-SFP mechanism presents a slight improvement compared to the baseline scenario. The flexibility offered by this mechanism exceeds that of the SFP and, in the same way as before, this is associated with the appearance of network effects due to the high variability of flight demand. However, in this case airlines have more tools to solve the problems brought by these network effects, avoiding long delays or possible cancellations, which is accompanied by an improvement in the punctuality performance.

Finally, it is very interesting to observe how the auction scenario provides the best punctuality results among all the flight prioritization mechanisms tested. The auction does not order the flights by the ETO of the specific congested sector but according to how much the airline is willing to pay to win the slot. This paradigm ends up with fewer empty slots because the FPFS order does not have to be enforced and consequently the usability of the network is increased.

B. *Cost Efficiency*

The Cost Efficiency KPA is strongly related to the delay airlines face in their operations and how they manage it. From this perspective, it is essential to measure if a certain prioritization mechanism is able to provide effective tools to decrease the costs associated with the imposed ATFM delays. A mechanism that allows airlines to adjust their operations in a cost-efficient way is also expected to have a positive impact on airports, which can see their income increase due to the greater attractiveness of the system.

The chosen metric to evaluate the cost efficiency of the tested flight prioritization mechanisms is the per-flight cost of delay (CEF1).

$$CEF1 = \frac{\sum_{i=1}^{n} C(d_{flight_i})}{N_{flights}} \tag{3}$$

Figure 6 shows a similar trend to that observed for the punctuality indicators. Due to the dramatic increase in the flight delay as a result to the cancellations, the cost of delay per flight of the scenario with the SFP mechanism increases considerably and exceeds the values for the baseline scenario. On the other hand, the extra flexibility provided by the E-SFP allows airlines to make more optimal decisions and, at the same time, to efficiently solve the possible downstrem network problems that arise from the prioritizations. Consequently, the cost of delay values are lower for the scenarios with the E-SFP mechanism.

Consistently with punctuality results, the auction-based mechanism presents the best cost efficient levels, thanks to the better usability of the network.

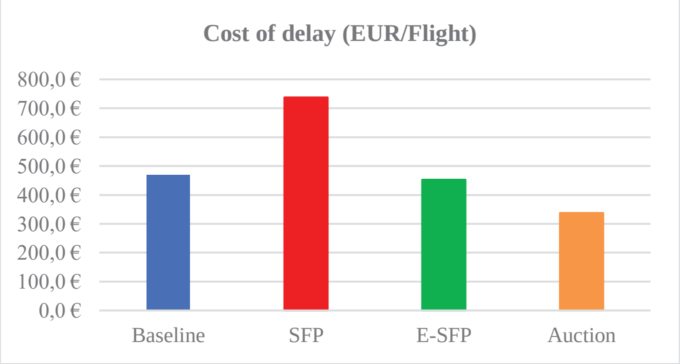

Figure 6. Cost of delay (EUR/Flight)

C. *Equity*

Within SESAR's UDPP programme, Equity is considered as a mandatory constraint. A lack of Equity can arise, for example, when one AU receives an advantage or net gain relative to others. This is an essential requirement from AUs' perspective and is closely related with Access, which refers to the need to offer the same prioritization possibilities to all involved AUs.

The metrics selected to measure equity are calculated in relation to a baseline scenario which is understood as equitable. This baseline scenario corresponds to the simulation of the current concept of operations, the FPFS mechanism plus the swapping capability. The subset of chosen metrics are: the change in AU's delay compared with the total change in delay of all the AUs (EQUI1) and the AU delay increment or decrease relative to the baseline total delay (EQUI2).

$$EQUI1_j = \frac{d_{AU_j}^{baseline} - d_{AU_j}^{new}}{\sum_{j=1}^{n} d_{AU_j}^{baseline} - \sum_{j=1}^{n} d_{AU_j}^{new}} * 100 \tag{4}$$

$$EQUI2_J = \frac{d_{AU_j}^{new} - d_{AU_j}^{baseline}}{d_{AU_j}^{baseline}} * 100 \tag{5}$$

Due to the disaggregated nature of these indicators (data per AU), equity metrics are analyzed by mechanism. Results indicate how the situation of the different airlines change with respect to the baseline situation. However, some precautions must be taken when analyzing the results and drawing strong conclusions. A simulation time of one day is not enough to accurately characterize the behaviour of the airlines and especially their learning capabilities. Results could thus be sensitive to the reduced simulation time window and the rigidity of the behaviours imposed on the airlines together with the specific traffic and the network used in the simulation.

Figure 7 shows the delay change of each airline with respect to the total delay change for all the airlines for the scenario with the SFP mechanism. As already mentioned, the total delay for the scenario with the SFP mechanism exceeds that of the baseline case. Figure *7* represents the distribution among the airlines of this increase in delay due to the worsened situation. All airlines show an increase in their associated delay, but there are two airlines in particular that take most of this increase, Airline 1 and Airline 3. These are the airlines that for some cases suffer flight cancellations due to the network effects caused by previous prioritizations.

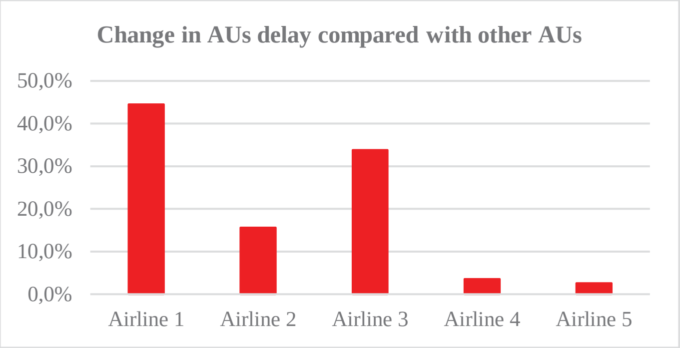

Figure 7. Change in AUs delay compared with the other for SFP

As previously seen, the E-SFP mechanism reduces the global delay in the network. However, Figure 8 shows how this global improvement in the delay situation is distributed in an unequal way among the airlines. Airline 1 is negatively affected by the inclusion of the mechanism, while there is another, Airline 4, that obtains significant benefit.

The case of Airline 1 is particularly interesting. As explained before, this airline is characterised by a conservative behaviour, meaning that it starts with a high number of credits to deal with possible delays. We have observed that in some simulations Airline 1 uses these credits at the beginning of the day, in order to prioritize one or more important flights heavily affected by a hotspot, resulting in a reduction of the cost of delay. Even though the decision taken is optimal from the point of view of the hotspot, the airline has no visibility of the impact that this change has at network level. This leads to the appearance of future hotspots in other parts of the network that end up affecting other flights of the same airline, significantly increasing the total delay of the airline with respect to the baseline scenario.

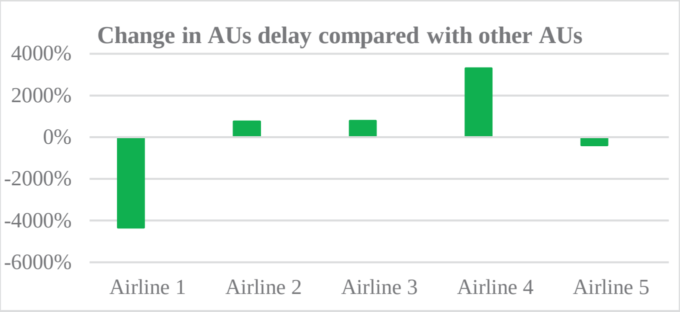

Figure 8. Change in AUs delay compared with other AUs for E-SFP

Figure 9 offers a slightly different situation. The Auction mechanism displays a more balanced outome: three of the airlines included decrease their associated delay in the same proportion. However, there is still an airline (Airline 3) that is harmed by the inclusion of the new prioritization mechanism with respect to the baseline scenario and other airline that it is practically unaffected (Airline 5).

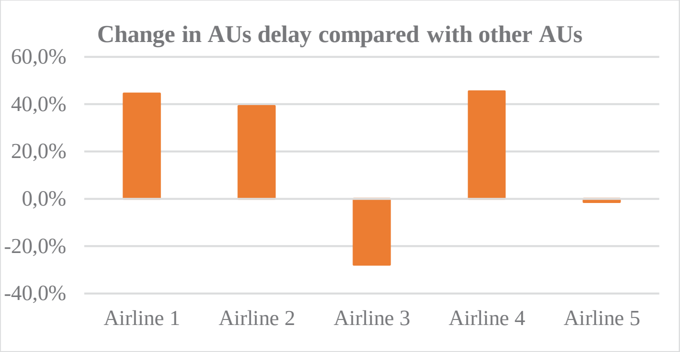

Figure 9. Change in AUs delay compared with the otherAUs for Slot Auctioning

Figure 10 sums up the results. It shows how every ariline increases or decreases its total delay relative to the baseline situation for each one of the mechanisms tested. It can be observed that the situation of each airline considerably varies depending on the mechanism implemented, and that no mechanism achieves a high level of equity measured in the chosen terms.

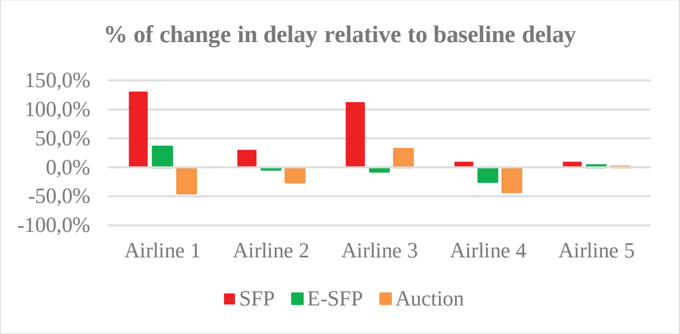

Figure 10. AU % of change in delay relative to baseline delay

VI. CONCLUSIONS AND FUTURE STEPS

From the detailed analysis of the experiment results, the following main conclusions can be drawn:

- It is interesting and unexpected to see how the performance of the SFP mechanism, despite offering more flexibility to airlines, provides a worse performance than the baseline situation.
- The auction mechanism has the most cost-efficient results and offers the best punctuality performance.
- No mechanism offers a high degree of equity: some airlines are much benefited while others are, on some occasions, even harmed with respect to their baseline situation.

These results are however highly conditioned by the modelling assumptions and require further investigation. The following conclusions and future research avenues can be drawn:

- ABM can be a valuable tool to measure the performance of flight prioritization mechanism. Emergent and counterintuitive phenomena which would have been ignored otherwise have been identified for some scenarios.
- Network effects have a strong influence on the results and therefore are very relevant for the proper evaluation of the prioritization mechanisms: the use of a network model is required
- The results seem to be very sensitive to some modelling assumptions (e.g., lack of re-routings, airline strategies and behaviours, traffic and network definition). Future research should conduct a more thorough sensitivity analysis to evaluate the response of the model when these factors are modified.

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