SESAR Engage KTN – Catalyst Fund Project Final Technical Report

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Consortium partners:	-
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1. Abstract and executive summary

1.1 Abstract

When the demand of an airspace sector is expected to exceed capacity, flights are delayed and assigned new take-off times through ATFM slots. This delay represents a significant cost for airlines and passengers. The possibility of rearranging flight sequences offers remarkable potential to reduce the impact of ATFM delay. Several prioritisation instruments are proposed in the literature, but their implementation is hindered by the limitations of classical modelling approaches to represent Airspace Users (AUs) behaviour and network effects in a realistic manner. The aim of the project is to overcome these limitations through the combined use of agent-based modelling (ABM) and behavioural economics. The model developed by the project has been used to simulate the performance of a variety of flight prioritisation under different network conditions and AU behaviours, allowing the observation of emergent phenomena and opening the way for a rigorous and comprehensive assessment of innovative approaches to User Driven Prioritisation Process (UDPP).

1.2 Executive summary

The goal of the project is to develop new modelling approaches enabling a rigorous and comprehensive study of highly flexible, advanced UDPP mechanisms. To this end, it adopts the paradigm of computational behavioural economics, as a particularly suitable framework for the representation of features that are not properly captured by classical approaches, such as bounded rationality, hyperbolic discounting, and asymmetric, imperfect and uncertain information.

The project started by defining a set of Key Performance Areas (KPAs) and Key Performance Indicators (KPIs) for the comprehensive assessment of the impact of the different flight prioritisation and trajectory allocation mechanisms. While looking for maximum alignment with the SESAR Performance Framework, the project has also proposed some additional KPAs and KPIs to address aspects that have received less attention in previous studies, but are however considered essential for a thorough evaluation of flight prioritisation mechanisms, such as equity and robustness against unexpected AU behaviours. The proposed assessment framework, which was refined and validated through a dedicated stakeholder workshop, encompasses 5 KPAs: Predictability and Punctuality, Flexibility, Access and Equity, Cost Efficiency, and Robustness.

A detailed literature review served to identify the tactical slot and trajectory allocation mechanisms that have been proposed in previous research. From this initial list, a subset of mechanisms was selected for simulation within the project. The selection criteria aimed at exploring a range of mechanisms providing different levels of flexibility, from the instruments proposed so far by SESAR to more complex and flexible mechanisms. The final set of mechanisms that were modelled and evaluated includes: (i) a baseline mechanism representative of current operations, consisting of the First Planned First (FPFS) policy and the solutions provided by SESAR UDPP Step 1 (Enhanced Slot Swapping, ESS); (ii) Selective Flight Protection (SFP); (iii) Enhanced Selective Flight Protection (ESFP), also known as Flexible Credits for Low Volume Users in Constraint; and (iv) Slot Auctioning.

To evaluate the impact of the selected prioritisation mechanisms on the proposed KPIs, the project has developed an agent-based simulation model. The model, which simulates air traffic during a day of operations, comprises three main elements:

- A network formed by a limited number of airports and airspace sectors. The goal was to work with a simplified network, but complex enough to study the emergence of network effects.

- The agents: the Network Manager, in charge of flow management, and AUs, which make decisions on how to deal with ATFM delays. The rules governing these interactions depend on the prioritisation mechanism implemented in each simulation scenario. AU agents can be configured to behave as rational cost minimisers, but also to incorporate non-rational behaviours based on the insights provided by behavioural economics, such as loss aversion, endowment effects, bounded rationality and hyperbolic discounting.
- A set of exogenous variables, which represent external conditions that affect the model but are not affected by it, such as fuel prices, air navigation charges price, and airlines' cost index.

The simulation comprises four main stages: in the first stage, the Network Manager estimates the future demand for all the sectors within a given time window. If the Network Manager detects a demand-capacity imbalance, it initiates a regulation. In the second stage, delays are calculated and assigned to each of the flights affected by the hotspot. In the simulations based on the FPFS principle (baseline, SFP, ESFP), the Network Manager sequences the flights in the order in which they would have arrived at the constrained airport or sector according to the filed flight plans. In the simulations based on the auction paradigm, the sequence of flights is the result of the successive auctions of all the slots inside the hotspot.

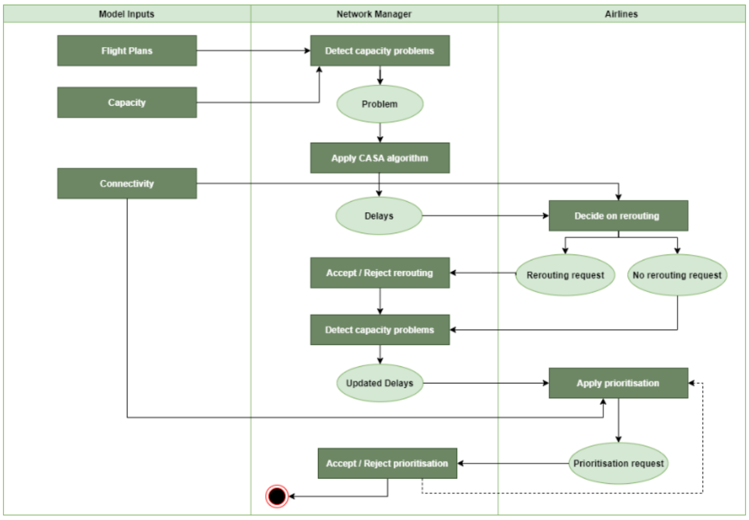

Figure 1. Simulation workflow for mechanisms based on FPFS

The third stage comprises the decision process of the airlines: once the affected flights receive an initial ATFM slot, the AUs evaluate all possible actions with the objective of reducing the cost of delay, according to the rules imposed by the prioritisation mechanism that is being simulated. Finally, the Network Manager accepts or rejects the requests sent by the airlines. Once this process is completed, delays are definitive and the model computes the different KPIs.

In the last stage of the project, the selected prioritisation mechanisms were simulated under a variety of scenarios with different levels of congestion and various combinations of AU behaviours. The simulation results allowed the extraction of a number of interesting conclusions. The experiments show that network effects have a strong impact on the KPAs under study. As expected, they confirm that the ability to reduce the cost of delay is directly related to the flexibility provided by the mechanisms, with the auction mechanism providing the most cost-efficient results, but some unexpected and non-trivial phenomena are also observed: for example, the SFP mechanism only outperforms the baseline scenario when combined with the rerouting of some flights. The model has also allowed us to explore how different behavioural biases affect the resulting performance, and how the benefits of each mechanism are distributed among the airlines depending on the characteristics of their network, their business model, and their decision-making strategy.

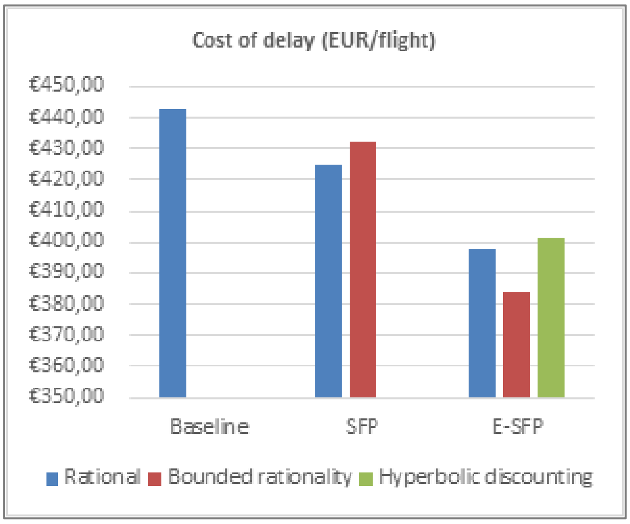

Figure 2. Example of simulation outcomes

Future research should address questions such as the exploration of other network configurations, more complex airlines strategies and more extreme behaviours, and the extension of the simulation time frame in order to incorporate airlines learning capabilities and adaptive behaviour. A proper understanding of these questions will be essential to achieve a rigorous and comprehensive assessment of innovative prioritisation mechanisms.

2. Overview of catalyst project

2.1 Operational/technical context

Air Traffic Flow and Capacity Management (ATFCM) is a vital part of ATM. The goal of ATFCM is to enable the full capacity of the ATM system to be exploited while avoiding the risk of safety being compromised. ATFCM makes use of strategic measures, which take place 7 days or more prior to the day of operations, pre-tactical measures, applied 6 days to 1 day before operations, and tactical measures, which adjust the daily plan considering real-time demand on the day of operations. In the 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 by applying Calculated Take-Off Times (CTOTs), which is also known as issuing a regulation or issuing ATFM slots. The duration between the last take-off time requested by the Airspace User (AU) and the take-off slot allocated by the Network Manager is the so-called ATFM delay.

The policy used today to allocate ATFM delay is the FPFS principle, which sequences the flights in the order in which they would have arrived at the constrained airport or sector according to the filed flight plans. FPFS is widely accepted because it preserves the original sequence of flights, which is considered fair, and minimises the total delay in a regulation, but it provides no flexibility for AUs to prioritise their flights. Due to the cost of delay being highly non-linear and varying from one flight to another because of factors such as crew out-of-hours constraints, passenger connections, etc., the possibility of rearranging flight sequences when facing regulations offers remarkable potential to reduce the cost of ATFM delay. For this reason, since the mid-1990s AUs in Europe have been allowed to use ATFM slot-swapping, i.e., to request the swapping of two flights involved in the same regulation. To provide AUs with more flexibility, SESAR has developed the UDPP concept. Early UDPP developments in Step 1 introduced Enhanced Slot Swapping and UDPP Departure, which extended the options for AUs to rearrange flights. More recently, other UDPP mechanisms allowing higher levels of flexibility have been proposed, such as Fleet Delay Apportionment, where each AU can decide how to distribute the delay it must absorb in a hotspot among its flights, and Selective Flight Protection, where AUs can voluntarily suspend certain flights (i.e., move them later in a departure sequence) to generate operating credits that they can use to protect other more important flights.

Despite these improvements, the level of flexibility provided by these basic UDPP mechanisms still has significant margin for improvement. A variety of other, more flexible instruments have been proposed, including (monetary and non-monetary) market mechanisms, but their implementation is hindered by the difficulties to design, test and validate such instruments and demonstrate their benefits to all relevant stakeholders, including their ability to preserve equity, which is one of the key constraints of UDPP. To make progress towards more flexible and efficient UDPP mechanisms, there is a need for a thorough assessment of the impact of these mechanisms. Classical modelling approaches from economics and operations research, such as game theory and linear programming, have been extensively used for this purpose. However, the strong assumptions behind these approaches, such as agents' rationality and perfect information, make such models unrealistic in certain circumstances, and may lead to overlooking the risks and the potential unintended consequences of certain mechanisms when stakeholders' behaviour departs from these rigid assumptions.

2.2 Project scope and objectives

The main objective of the project is to implement new modelling strategies that allow a detailed and complete study of advanced flight prioritisation mechanisms. For that reason, we have embraced the paradigm of agent-based computational economics, as a particularly suitable framework for the representation of features that are not properly captured by classical approaches. The specific objectives of the project are the following:

1. developing an assessment framework for the comprehensive evaluation of the impact of flight prioritisation mechanisms on network performance and on ATM stakeholders, including aspects such as their ability to ensure equity and their resilience and robustness in the presence of irrational or strategic behaviour of AUs;
2. performing a detailed review of the tactical slot and trajectory allocation mechanisms proposed in the literature and identify the most promising to improve UDPP;
3. developing an agent-based model allowing the evaluation of different flight prioritisation mechanisms according to the proposed assessment framework;
4. running a set of simulation experiments, considering different AUs' behavioural assumptions, in order to conduct a systematic assessment and comparison of the identified prioritisation mechanisms and derive conclusions on their advantages and disadvantages.

2.3 Research carried out

The research carried out within the project comprises four main activities:

- Development of an UDPP assessment framework.
- Review and qualitative assessment of tactical slot and trajectory allocation mechanisms.
- Development of model for the simulation of flight prioritisation mechanisms based on computational behavioural economics.
- Execution of a set of simulation experiments and analysis of results.

2.3.1 Proposed UDPP Assessment Framework

The UDPP assessment framework proposed by the project takes as a starting point the SESAR Performance Framework, complemented with other specific KPAs and KPIs that are considered relevant for the problem under study. A thematic workshop held in Madrid on 12th November 2019 served to gather inputs from a variety of ATM experts from both industry and academia, which reflected on the perspective of the different ATM stakeholders concerned with UDPP. During the workshop, several KPAs were discussed and various new metrics were proposed. The proposed framework is described in detail in deliverable **D1.1 UDPP Assessment Framework: Indicators and Metrics**. The SESAR KPAs finally selected for the evaluation of flight prioritisation mechanisms are Predictability and Punctuality, Flexibility, Access and Equity, and Cost Efficiency. Additionally, a new KPA, Robustness, was suggested with the intention to capture the ability of different mechanisms to cope with unexpected or 'irrational' airline behaviours. Each of these five KPAs is discussed below, together with their corresponding KPIs.

2.3.1.1 Predictability and Punctuality

The metrics proposed in the SESAR Performance Framework are complemented with new indicators that try to capture aspects such as the punctuality from the passenger point of view. On the other hand, some of the metrics considered in the SESAR Performance Framework are not included in our UDPP Assessment Framework due to the practical limitations to capture such information in the simulation model. The proposed indicators and the associated metrics are presented below.

Table 1. Punctuality and Predictability metrics

Indicator	Unit	Metric	Baseline
% Flights departing within +/- 3 minutes of the scheduled departure time	%	% Departures so that |AOBT – SOBT| < +/- 3 min difference in actual departure time vs. scheduled time due to ATFM causes	SESAR KPI PUN1
Flight departure delay	Minutes/Flight	Total flight departure delay in minutes divided by the number of flights. This information can be later aggregated, for instance, by airport, by group of airports or by airlines	-
Pax arrival delay	Minutes/Pax	Total passenger arrival delay in minutes divided by the number of passengers. This information can be later aggregated, for instance, by airport, by group of airports or by airlines	-

2.3.1.3 Cost Efficiency

The Cost Efficiency KPA is closely related with the delay airlines face in their operations and how they manage it. The SESAR Performance Framework distinguishes three main focus areas inside this KPA:

direct gate-to-gate ANS cost, direct AU costs and indirect AU Cost. Following the objectives of the project, we will restrict our vision to AU costs. For practical reasons, we only consider direct operating costs, which are related to handling the aircraft and passengers (fuel, staff, passenger service costs, navigation charges, etc). The proposed indicators and the associated metrics are shown below.

Table 2. Cost Efficiency metrics

Indicator	Unit	Metric	Baseline
Per-flight direct cost	EUR/Flight	Impact on direct costs related to aircraft and passengers: fuel, staff expenses, passenger service costs, navigation charges, strategic delay[1]	Derived from SESAR PI AUC3
Per-flight cost of delay (tactical)	EUR/Flight	Cost of delay[2] of each flight. This can be aggregated by airline	-

2.3.1.2 Flexibility

The SESAR Performance Framework defines the Flexibility KPA as the ability of the ATM System to respond to changes in planned flights and late FPL request (non-scheduled traffic). Accordingly, the indicators and metrics used to measure flexibility focus on evaluating how the system is capable of absorbing late FPL requests in the presence of different prioritisation mechanisms.

Table 3. Flexibility metrics

Indicator	Unit	Metric	Baseline
Average delay for flights with late FPL request	Minutes	Total delay of flights with late FPL request divided by number of flights with late FPL request	Derived from SESAR PI FLX1
% of late FPL requests that are successful[3]	%	Total number of successful late FPL requests divided by the total number of late FPL requests during the day of operations.	-

2.3.1.4 Access and Equity

Within SESAR's UDPP programme, Equity is considered as a mandatory constraint. SESAR Solutions must not result in inequitable impacts across individuals or groups of AUs. A lack of Equity can arise, for example, when one AU receives an advantage or net gain relative to others. The proposed indicators and the associated metrics are shown in the table below.

[1] Due to the tactical nature of the simulation model being developed, the strategic delay will be considered as given, as the model will take as input a predefined flight schedule. Consequently, the minutes of strategic delay potentially saved by a certain mechanism will not be measured.

[2] Cost of delay calculated based on University of Westminster (UoW) reference values (European airline delay cost reference values report, version 4.1)

[3] In the simulation developed by the project, documented in deliverable D3.1, flights with late FPL requests are endowed with a maximum tolerance to delay. In the event that the system (with its specific associated prioritisation mechanism) enables the flight to depart within its allowed margin, the late FPL request will be considered as 'successful'.

Table 4. Access and Equity metrics

Indicator	Unit	Metric	Baseline
Change in AU's delay or cost compared with the total change in delay or cost of all AUs together	%	Difference in delay (or cost) of the AU concerned divided by the total delay (or cost) of all the AUs between the Solution Scenario and the Reference Scenario[4]	Derived from SESAR PI EQUI1
Change in AU's delay or cost per flight compared with the total change in delay or cost per flight of all AUs together	%	Difference in delay (or cost) per flight of the AU concerned divided by the total delay (or cost) of all the AUs between the Solution Scenario and the Reference Scenario	Derived from SESAR PI EQUI1
AU total delay relative to baseline AU total delay	%	Total delay (per AU) in the Solution Scenario divided by the total delay (per AU) in the Reference Scenario	SESAR PI EQUI3
AU delay or cost per flight compared to baseline	%	Delay (Cost) per flight of AU concerned in the Solution Scenario divided by the delay (cost) per flight of AU concerned in the Reference Scenario	SESAR PI EQUI5
Number of flights advantaged and/or disadvantaged	No.	Number of flights impacted (+ or -) by a certain change in terms of cost or delay	SESAR PI EQUI4
Number of AUs that use the prioritisation mechanism in a hotspot	No.	Number of AUs that use the prioritisation mechanism in a hotspot	-

2.3.1.5 Robustness

One of the core elements of this project is the development of a new methodology for assessing prioritisation mechanisms following the paradigm of computational behavioural economics. While classical approaches require the use of rigid assumptions such as perfect rationality and complete information, computational behavioural economics allows these assumptions to be relaxed, which in turn allows us to test the performance of different mechanisms in situations where AUs behave in an "irrational" or strategic manner. It is therefore essential to study each potential prioritisation mechanism in the presence of these behaviours in order to detect possible undesired consequences that can go unnoticed in classical approaches. The robustness of each mechanism is measured by comparing a baseline "perfectly rational" situation with other simulations where the behaviour of the AUs is modified to simulate "irrational" practices. The metrics belonging to each of the previously selected KPAs are calculated and the difference between the values for the different behavioural scenarios are analysed.

2.3.2 Selected flight prioritisation mechanisms

The following table summarises the prioritisation mechanisms reviewed within the project, indicating the operational nature of the prioritisation concept, the ATFM phase(s) impacted by each mechanism, and whether they are currently in use in the ATM system. Each of the prioritisation mechanisms listed is described in detail in deliverable **D2.1 Tactical Slot and Trajectory Allocation Mechanisms: Qualitative Assessment**.

[4] The Reference Scenario corresponds to the simulation of the current concept of operations, the FPFS mechanism plus a limited swapping capability, which is understood as "equitable".

Table 5. List of flight prioritisation mechanisms

Mechanism Name	Operational Basis	ATFM Phase	Currently in use?
First-Planned First-Served (FPFS)	Rule-based	Tactical	Yes
UDPP - Enhanced Slot Swapping (ESS)	Rule-based	Tactical	Yes
UDPP - Departure (DFlex)	Rule-based	Pre-Tactical / Tactical	Yes
UDPP - Fleet Delay Reordering (FDR)	Rule-based	Tactical	No
UDPP - Selective Flight Protection (SFP)	Rule-based	Tactical	No
Best-Performing Best-Served (BPBS)	Rule-based	Strategic	No
Auction (primary or secondary)	Market Monetary	Tactical	No
Congestion pricing (CPLP)	Market Monetary	Strategic	No
Route contracts (COCTA)	Market Monetary	Strategic	No
UDPP - Extended-SFP	Market Non-monetary	Tactical	No
Credit Points for Rerouting	Market Non-monetary	Strategic / Tactical	No

From all the mechanisms examined, only a subset of them have been chosen for simulation within the project. The selection has been based on two main criteria: (i) the conclusions drawn from the Engage TC4 workshop regarding the interest and potential benefits of each mechanism; (ii) the feasibility of simulating each mechanism within the project scope, which is limited to the simulation of the ATFM tactical phase. The mechanisms selected for the different simulation experiments are shown in the table below.

Table 6. List of simulations

Simulation Experiment	Mechanisms	Operational Basis	Phase
Simulation 1	Baseline (ESS + FPFS)	Rule-based	Tactical
Simulation 2	Baseline + SFP	Rule-based	Tactical
Simulation 3	E-SFP	Market non-monetary	Tactical
Simulation 4	Primary Auction	Market monetary	Tactical

2.3.3 Agent-based model

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

- Geographical context, which provides the environment and the network characteristics for the agents to operate in.
- Exogenous variables, which represent arbitrary external conditions that affect the model but are not affected by it, such as fuel prices, air navigation charges price, and airlines' cost index.
- Agents. Two type of agents, representing the main actors of the simulation, are considered: the Network Manager and the airlines.

The simulation comprises four main stages:

- In the first stage, with some time in advance (e.g., 2 hours in advance), 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, it will initiate a regulation and the excess demand will be displaced over time. Flights involved in the hotspot are delayed at the origin airport and assigned new take-off times through ATFM slots.

- In the second stage delays are calculated and assigned to each of the flights affected by the hotspot. At this stage we distinguish two different resolution paradigms that differentiate some prioritisation 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 direct result of the successive auctions of all the slots identified inside the hotspot. In this case the Network Manager only calculates here the size of the hotspot, based on an approximation of the FPFS order, to find out the ATFM slots to auction.
- The third stage comprises the decision process of the airlines. 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 of actions and the complexity of these are defined by the rationale and the flexibility of the various flight prioritisation mechanisms simulated (e.g., slot swapping, use of credits, auction bids).
- Finally, the fourth and last stage covers the Network Manager process of study and subsequent acceptance or rejection of each of the requests sent by the airlines according to compliance with the traffic restrictions imposed by the model. 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 stage are performed. The simulation finishes when the temporal horizon is reached.

The main features of the model are summarised below. A more detailed description can be found in deliverable **D3.1 Agent-Based Simulation Model for the Analysis of Tactical Slot and Trajectory Allocation Mechanisms**.

2.3.2.1 Main assumptions and model restrictions

The following assumptions and restrictions have been considered:

- Flight traffic is checked by the Network Manager in time windows of 15 min and with 2 hours in advance.
- Only ground delays are modelled.
- A flight cannot occupy an ATFM slot if this creates an additional demand-capacity problem in an already resolved time window. When due to this restriction a flight cannot occupy a certain hotspot position, that position will be left empty and the next slot will be checked, assuming an inevitable increase in the total flight delay[5].

[5] This is a centralised abstraction of a problem, which in real operations may be solved by the decentralised work of different Flow Management Positions (FMPs). In fact, when the CASA algorithm is applied to sequence the flights, this is done regardless of whether it is creating problems in another place. In the event that a new problem appears, the issue is often solved by the new affected FMP, by applying the necessary Demand Capacity

- Airports are approximated as Terminal Manoeuvring Areas (TMA). For the sake of simplicity, the taxi and the runway time are not taken into account, therefore the Actual Off-Block Time (AOBT) is equal to the Actual Take Off Time and in the same way the Actual In-Block Time (AIBT) is equal to the Actual Landing Time.
- The resolution order of the identified hotspots in the same time window, as well as the order in which the airlines request prioritisation, are randomised.
- Airlines only have three opportunities to prioritise their flights in a hotspot. If the third request is rejected, the airline is forced to accept the delay originally imposed.
- The network topology is built in such way to provide three different routes, without repeating any en-route sector, between each origin-destination pair.
- The aircraft speed is constant throughout the entire route.
- Flight cancellations are only considered due to airport curfew.
- No accumulated delays from the previous day are considered.
- Initial delays are randomly imposed on some flights. These delays mimic the possibility of technical failure delays on aircraft.

2.3.2.2 Simulation inputs

The model takes as inputs:

- The flight schedule, required to provide all the necessary information for the Network Manager to perform ATFM functions.
- The capacity of each of the sectors in the network.
- Passenger connectivity, required to evaluate the impact of each of the different prioritisation mechanisms on the passenger-centric metrics.

2.3.2.3 Simulation environment

The environment is used to provide a fundamental set of network characteristics, including:

- Airport configuration: the defined network consists of 5 different airports, which area a mix of hubs and secondary airports.
- Sector configuration: first, 9 en-route sectors are modelled, defining the different airspace structures crossed by the flights after the departure and before the landing; additionally, one extra sector is defined around each airport simulating a Terminal Manoeuvring Area (TMA).
- 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 different route trajectories for every origin-destination pair.

2.3.2.4 Agents

The model includes two different agents:

- Network Manager: the role of the Network Manager is to apply the corresponding ATFM processes. 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 prioritisation mechanisms.
- 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. They are

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Balancing (DCB) measures. Considering our abstraction of all the DCB measures in the figure of the Network Manager, the extra delay applied to the flight creating that previous demand issue can be interpreted as a DCB time-based delay measure.

modelled as cost-minimisers but their behaviour can be modified by the inclusion of different behavioural biases which depart from purely rational choices. Airline costs are impacted by ATC charges, the cost of fuel and specially the cost of delay.

The calculation of the cost of delay is of special interest for the model because its inherent non-linearity could inevitably trigger the airlines use of the available prioritisation mechanisms.

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

- First Plan First Served paradigm: the FPFS principle ensures that the affected flights within a hotspot are ordered according to the ETO of 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 prioritisation.

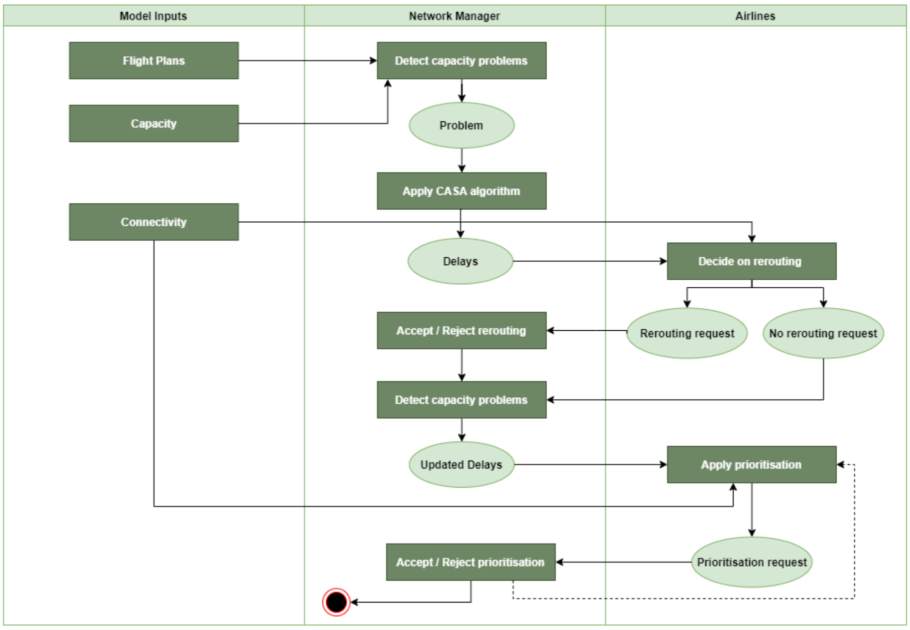


Figure 3. FPFS workflow

- Auction paradigm: unlike the mechanisms based on the FPFS, in the 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.

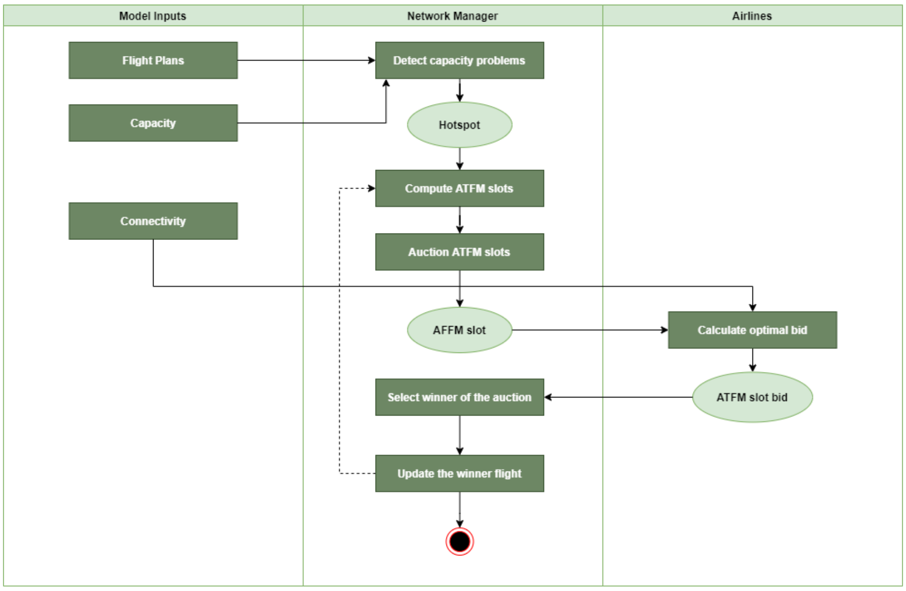


Figure 4. Auction workflow

2.3.4 Simulation experiments

Simulation scenarios are configured through the definition of three main aspects:

- **Capacity configuration**: it provides the traffic congestion level and the characteristics of this congestion. The approach followed for the manual generation of capacity shortages sought to limit as much as possible the rerouting options of the airlines. In the end, the chosen capacity configuration generates a scenario where the congestion level oscillates between 10 and 15 hotspots, mostly due to network effects, depending largely on the prioritisation mechanism activated and the possibility or not of rerouting.
- **Behavioural configuration**: The behavioural configuration determines the behavioural rules of the AU agents. Three types of behavioural biases are considered. The mechanisms to which they are applied and the way they are implemented are summarised in the following table:

Table 7. Behavioural configurations

	Applicability to the model	Mechanism where it applies	Implementation
Prospect Theory	Due to a certain loss aversion, an airline can outbid for a slot paying more money in order to avoid losing the slot	Auction	The airline will increase the value of the slot bids, which are generated from a calculated distribution of the cost of delay across all the slot options in the hotspot.
Bounded Rationality	An airline can possibly underestimate or overestimate the value of a flight due to limited available information when making the decision	SFP, E-SFP, Auction	Modify the cost of delay of the delayed flights by applying an increase or decrease of 15% to the final cost value to some flights randomly selected
Hyperbolic Discounting	An airline can possibly underestimate the value of the credits due to the lack of immediacy in its use	E-SFP	A 20% decrease in the monetary value that each airline assigns to their own credits

- **Rerouting configuration**: it adds the possibility of choosing whether to include the rerouting process or not. As described in D3.1, due to the resources available for the project, the implementation that was carried out to simulate the prioritisation mechanism based on the auction of slots does not include the possibility of rerouting, although this should be possible and will be explored in future research. Due to this fact, and with the intention of making a fair comparison between the performance of the different flight prioritisation mechanisms, the mechanisms based on the FPFS paradigm have also been tested without including the rerouting option.

The series of scenarios finally chosen to carry out the simulation of each mechanism is the result of the combination of the aforementioned variables. The chosen scenarios, shown in the table below, represent a limited selection of all these possible combinations; in future research, it will be interesting to extend this set of scenarios to more combinations.

Table 8. Simulation scenarios

	Rerouting ON				Rerouting OFF			
	Rational	Bounded rationality	Hyperbolic discounting	Prospect theory	Rational	Bounded rationality	Hyperbolic discounting	Prospect theory
Baseline	✓				✓			
SFP	✓	✓			✓			
E-SFP	✓	✓	✓		✓			
Auction					✓	✓		✓

2.4 Results

This section presents a summary of the most interesting results of the simulation experiments. A detailed and exhaustive analysis of the experiment results is included in deliverable **D4.1 Results of Simulation Experiments: Comparative Analysis of Different Tactical Slot and Trajectory Allocation Mechanisms**.

2.4.1 Punctuality and Predictability

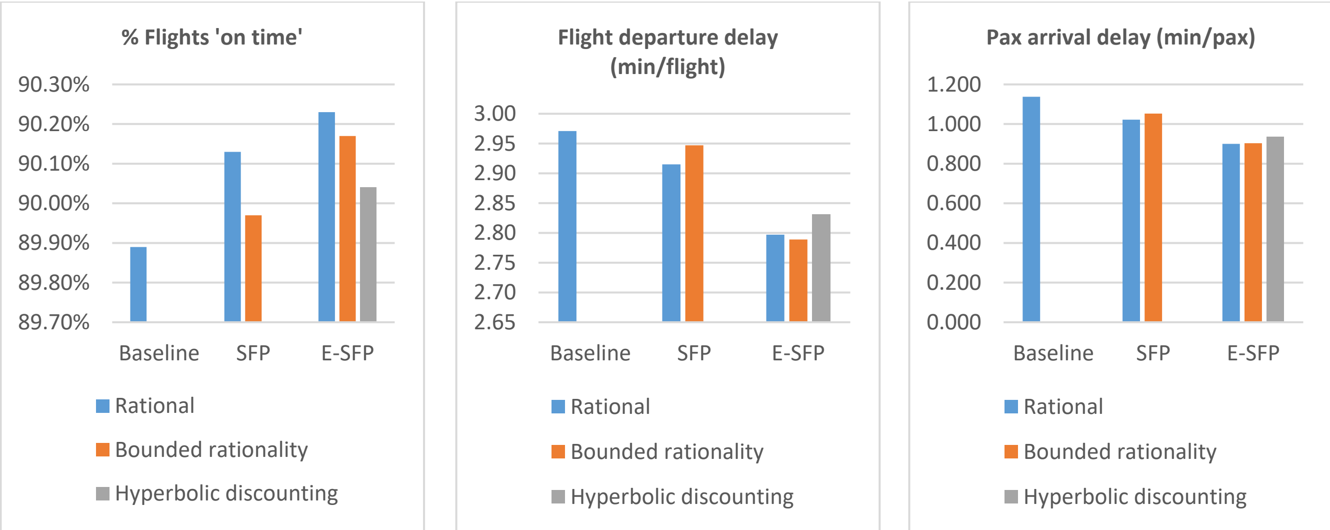


Figure 5. Punctuality metrics for scenarios with rerouting on

Figure 5 displays the metrics results for the simulated scenarios with the ability to change the route activated. It can be observed that the punctuality values offered by the SFP mechanism improve those offered by the baseline scenario, where only slot swapping is available. Additionally, it is also noticeable that the credit-based E-SFP mechanism provides the best punctuality results of all the mechanisms simulated with the rerouting capacity available. As expected, these results suggest that a higher level of airline flexibility relates with an improvement in delay indicators.

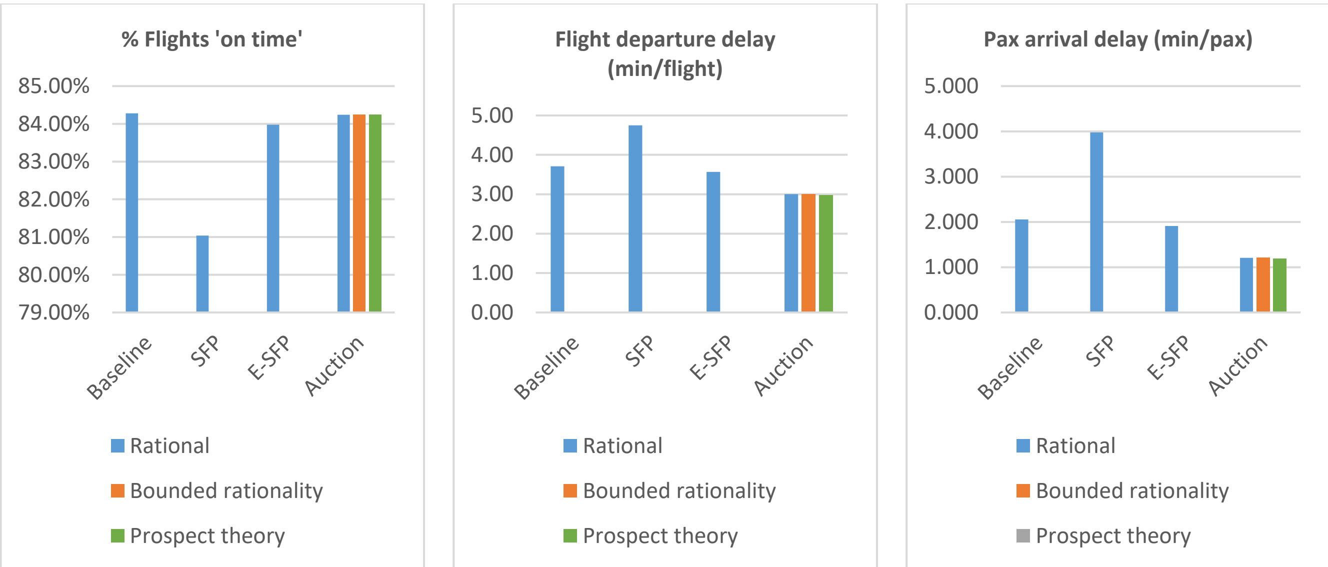
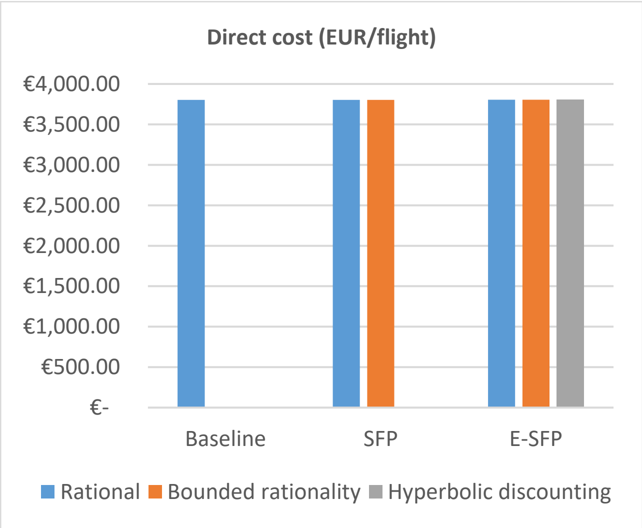


Figure 6. Punctuality metrics for scenarios with rerouting off

Figure 6 displays the results for the simulated scenarios without the ability to change the route. In general, as expected, all the mechanisms experiment a deterioration in the punctuality levels. However, this series of simulations offers some others insights that at first glance seem counterintuitive. Now, unlike the previous case where the SFP mechanism provided better results than the baseline scenario, the punctuality values of the SFP mechanism are the worst of all the mechanisms. Despite offering more flexibility to airlines, the SFP mechanisms 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. Additionally, it is interesting to observe how the auction scenario provides the best punctuality results among all the flight prioritisation mechanisms tested. Since the auction does not order the flights by 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. It will be very interesting to see, as a future step, if the good results offered by the auction refer exclusively to the most efficient way of ordering the traffic or if it is the market mechanism itself that offers the advantages.

2.4.2 Cost efficiency



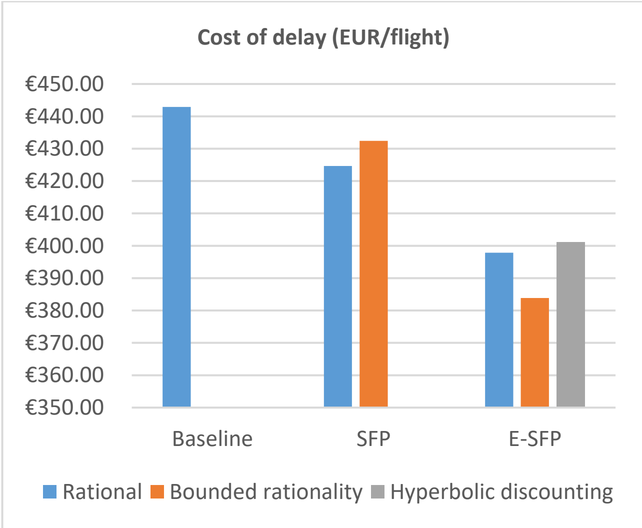


Figure 7. Cost Efficiency metrics for scenarios with rerouting on

Figure 7 displays the results for the simulated scenarios with the ability to change the route activated. The results of the cost of delay do present a significant difference in the performance of each prioritisation mechanism. The E-SFP mechanism provides the lowest cost of delay per flight improving the values for the SFP mechanism and for the baseline respectively. From these data it is possible to derive that the cost of delay is directly related to the flexibility provided by the mechanisms.

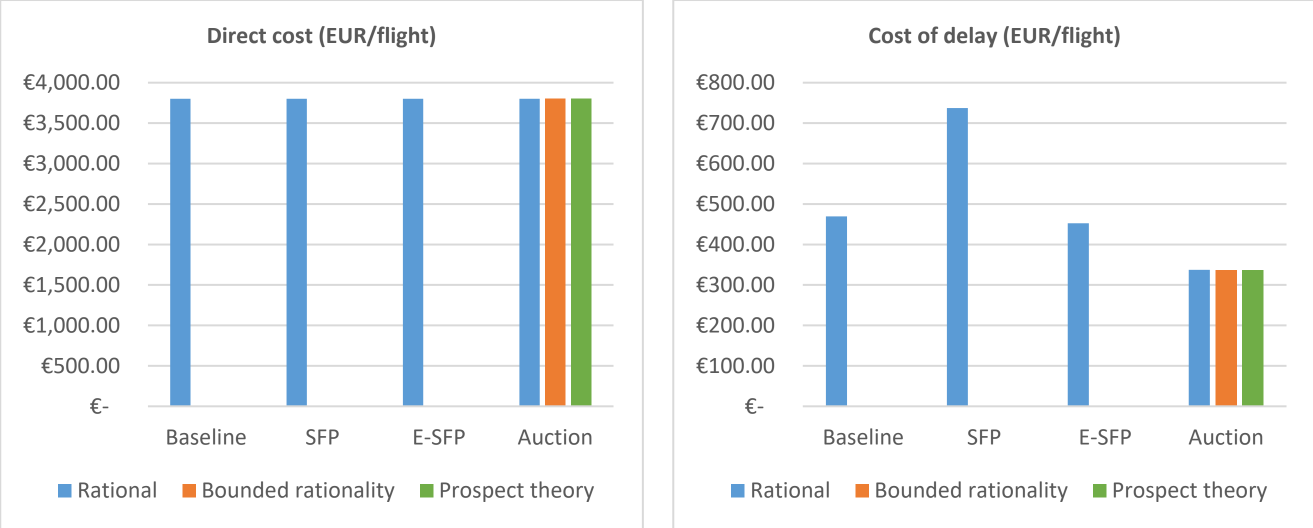


Figure 8. Cost Efficiency metrics for scenarios with rerouting off

Figure 8 displays the results for the simulated scenarios without the ability to change the route. As expected, all the mechanisms experiment a deterioration in the cost levels. The detected trend is similar to that observed for the punctuality indicators. Due to the dramatic increase in the flight delay as a result to the cancellations that appear in some simulations of the scenario with the SFP mechanism, the cost of delay per flight increases considerably and exceeds the values for the baseline scenario. In the same way, consistently with punctuality results, the auction-based mechanism presents the best performance levels and it's not affected by the 'irrationalities' introduced inside airlines' behaviour. Again, in future research it will be very interesting to check if the good results are only due to the better usability of the network.

2.4.3 Flexibility

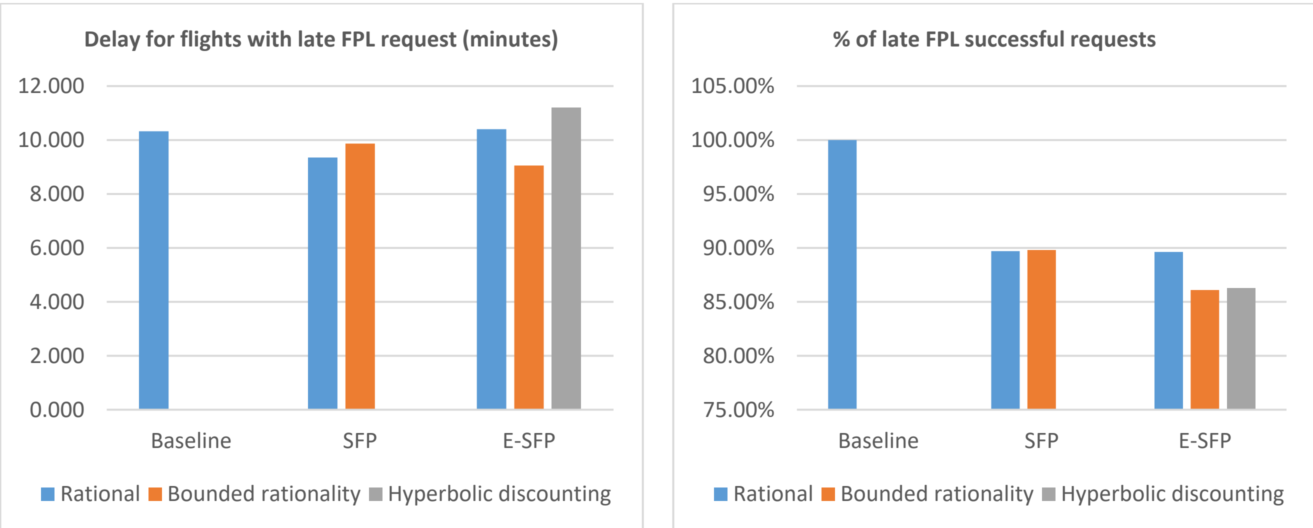


Figure 9. Flexibility metrics for scenarios with rerouting on

Figure 9 displays the results for the simulated scenarios with the rerouting option activated[6]. The values of average delay for flights with late FPL requests are extremely similar for the different

[6] The results for the simulated scenarios without the ability to change the route do not add significant information. A detailed discussion of these results can be found in deliverable D4.1.

mechanisms' scenarios and no trend or conclusion can be clearly drawn. Furthermore, the inclusion of irrational behaviours does not offer any further insight: in some cases the delay worsens, while in others it is reduced. On the other hand, the % of late FPL successful request shows an interesting trend. The higher percentage of successful requests belongs to the baseline scenario, where all FPL requests are successful. The SFP and the E-SFP present almost the same percentage, which is surprisingly lower than in the baseline scenario. This can be explained by the fact that greater mechanism flexibility level when proposing a prioritisation influences in many cases the position of other flights belonging to other airlines and due to the restrictions imposed on the model it is more common that this type of request can be rejected. For that reason, and taking into account that the airlines only have three possible prioritisation requests, the % of late FPL successful requests is lower for the SFP and the E-SFP mechanisms scenarios.

2.4.4 Equity and Access

Due to the disaggregated nature of most equity indicators, these indicators are analysed by mechanism. The results indicate how the performance of the different airlines within the model change with respect to the baseline situation and therefore give an idea of the equity levels regarding each of the mechanism tested. However, some precautions must be taken when analysing the results and drawing strong conclusions about the level of equity of each mechanism. In particular, a simulation time of one day is not enough to accurately characterise the behaviour of the airlines and especially their learning abilities. Results are thus very 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 10 displays the results obtained for the scenarios with the SFP mechanism and with the rerouting capability available. Results for both behavioural levels affecting the SFP mechanism, rational and bounded rationality, are presented [7].

[7] The results obtained for the other mechanisms are included in deliverable D4.1.

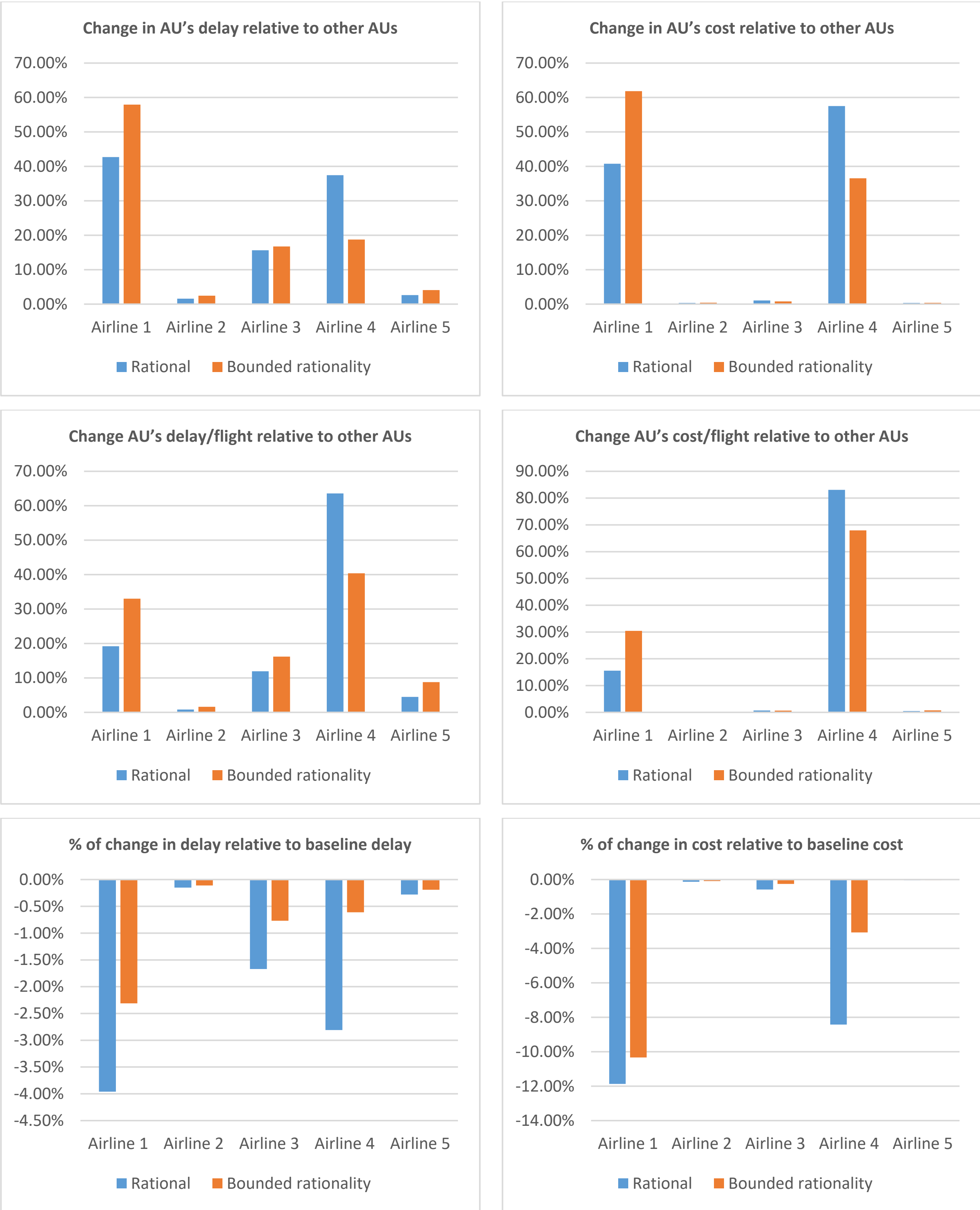


Figure 10. Equity metrics for the Selective Flight Protection mechanism

It is clearly visible that not all the airlines are affected in the same way by the addition of the SFP mechanism. The first indicator, which estimates the percentage of change of one airline relative to the total change of all airlines together, evidences that Airline 1 and Airline 4 take most of the reduction in both delay and cost between the baseline and the SFP scenario. It also demonstrates again the non-linear relation between the delay and cost of delay. The rational scenario is paradigmatic: while the higher delay improvement corresponds to Airline 1, the higher cost improvement is found for Airline 4.

The reason why Airline 1 and Airline 4 are the only airlines that experience a considerable change with respect to the baseline scenario lies in the fact that due to the traffic conditions and capacity of the model, they are the only airlines that make use of the SFP mechanism. The variations experimented by the other airlines are only the result of the network effects generated by the use of the mechanism by former airlines.

As expected, the same trend noticed for the first metric is also observable for the second one. However, in this case, Airline 4 ends up being much more benefited than Airline 1. The rationale behind this difference has to do with the different model representation of the airlines. Unlike Airline 1, which is a flag carrier in the model, Airline 4 is represented as a low-cost carrier implying among other things that it has fewer flights. Consequently, the change per flight is higher for Airline 4.

Figure 10 also shows the delay and cost change of the airlines relative to their baseline delay or cost. The results reaffirm what we have seen with the first two metrics: the improvement is uneven among all the airlines; Airline 1 and Airline 4 are again the most advantaged airlines. It is interesting to observe how Airline 1 is now the most benefited, experiencing a reduction of delay of almost 4% and a reduction in cost of almost 12%. Although Airline 4 takes most of the improvement from the introduction of the SFP mechanisms, as we observed in the first two equity metrics, it also has a higher cost of the delay in the baseline scenario which explains why its relative improvement is lower than that of Airline 1.

Figure 10 also offers a comparison of the results for each of the different behaviours tested. It is remarkable to see how the introduction of the bounded rationality bias results in an increment in the percentage of change of Airline 1 compared with the rational scenario. At the same time, a general reduction in the cost and delay improvement relative to the baseline is observed for all the airlines. Due to the bounded rationality bias, the airlines do not make optimal decisions and end up with a lower improvement in terms of both delay and cost.

One last important thing to point out from these results is that, although Airline 1 and Airline 4 are the only airlines benefited from the SFP mechanism for the reasons commented before, the rest of the airlines are not negatively affected by this fact.

2.4.5 Robustness

The robustness of each mechanism is determined by the comparison between the results of all the selected KPIs in a rational scenario and the results of the same KPIs for other scenarios with certain behavioural biases included.

The robustness of the SFP mechanism is only evaluated against the results coming from the introduction of the bounded rationality bias inside the airlines behaviour for scenarios with the rerouting on. Bounded rationality worsens the general performance of the mechanism: the punctuality level drops, the cost of delay increases and the equity metrics show a more unbalanced scenario between the airlines. However, despite this worsening, the SFP performance levels are still above those shown by the baseline scenario.

The E-SFP mechanism has been analysed under two different behavioural biases: bounded rationality and hyperbolic discounting. Results show that the mechanism is considerably sensitive to the 'irrationalities'. Surprisingly, the scenario with the bounded rationality bias included does not degrade the performance of the mechanism. In contrast, the hyperbolic discounting bias worsens all the selected performance metrics. It seems that the underestimation of the real value of the credit exchanges prevents airlines from realising the full potential of the mechanism.

Finally, the Auction-based mechanism is also evaluated against two different behavioural biases; bounded rationality and prospect theory. The simulation results show that performance of the mechanism is hardly affected by the inclusion of the 'irrationalities' defined. As no extreme situations have been introduced, the operation of the market mechanism remains almost optimal. Therefore, it appears that the Auction-based mechanism is the most robust of all the mechanisms tested for the defined scenarios. However, it would be very interesting to test how this conclusion may vary by including more extreme airline behaviours inside the auction.

3. Conclusions, next steps and lessons learned

3.1 Conclusions

3.1.1 Conclusions of the simulation experiments

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

- The re-routing option has a strong impact on the selected KPIs.
- It is interesting and unexpected to see how the performance of the SFP mechanism, despite offering more flexibility to airlines, worsens the performance of the baseline situation when the re-routing option is disabled.
- The auction mechanism results are not significantly affected by the behavioural biases applied to the airlines.
- The auction mechanism has the most cost-efficient results.
- As expected, the total cost of delay is directly related to the flexibility provided by the mechanisms.
- The flexibility KPIs, which intend to reflect the network flexibility at absorbing non-schedule traffic or late modifications, have provided some first insightful conclusions but further research is needed.
- 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. However, this is highly conditioned by modelling assumptions and requires further investigation.
- A consolidated equity metric is missing to easily compare some mechanisms with others along this KPA.

3.1.2 Conclusions about the modelling approach

A number of relevant conclusions can also be extracted regarding the proposed modelling approach:

- The added value of agent-based modelling has been demonstrated: emergent and contra intuitive phenomena which would have been ignored otherwise have been identified for some scenarios.
- Network effects have a strong influence on the results and are thus very relevant for the evaluation of the prioritisation mechanisms: the use of a network model is required.
- The results seem to be very sensitive to certain modelling assumptions (e.g., re-routings, airline behaviours, implementation of the CASA algorithm, network definition). The level of sensitivity of the model towards these factors needs a more comprehensive study.

3.1.3 Progress towards applied or industrial research

The main contributions of the project to advancing the state of the art are the following:

- Definition of a comprehensive assessment framework for the evaluation of UDPP mechanisms and more advanced flight prioritisation concepts, which includes selected relevant indicators from SESAR Performance Framework and proposes a number of improvements.
- Implementation of new modelling approaches and simulation tools for the assessment of prioritisation mechanisms based on the paradigm of computational behavioural economics, identifying risks and potential unintended behaviours that are impossible to model using classical approaches.
- Detailed analysis and assessment of different flight prioritisation mechanisms incorporating new angles not addressed by previous research, such as the impact on different AUs as a function of their network, their business strategy and their behavioural biases.

The different workshops and working sessions held during the duration of the project have helped disseminate these findings and establish links with different stakeholders in a position to benefit from the project results, thus setting the basis for reaching higher TRLs in future activities.

3.2 Next steps

A number of dissemination actions are planned to take place before the end of 2020:

- Presentation of the project results in the 2nd Engage Summer School which will be held as a virtual event on 21-25 September 2020.
- Submission of a paper to SESAR Innovation Days 2020.
- Submission of a paper to a peer-reviewed journal.

Regarding future research, the following research lines are suggested:

- Explore a wider range of auction designs, coupled with the rerouting option.
- Explore more complex airlines strategies and ‘irrational’ behaviour.
- Use a more realistic and complex representation of the European network.
- Explore the impact of less rigid modelling assumptions (e.g., modelling of ATFM measures taken at the level of Flow Management Positions).
- Increase the time frame to be simulated to more than one day in order to allow the implementation of airlines’ learning capabilities and adaptive behaviour.

These research questions are expected to be explored in the context of SESAR Exploratory Research project BEACON (https://www.sesarju.eu/projects/beacon).

3.3 Lessons learned

Finally, the execution of the project has allowed to derive a number of lessons learned:

- The duration of the Catalyst Fund project and the proposed project management procedures have proven to be particularly suitable for a project of this size, allowing a robust but agile project coordination and monitoring.
- Close collaboration with IT experts from the early stages of the project has been crucial for the correct implementation of the simulation platform. This has also allowed us to incorporate software requirements related to the scalability and extensibility.

- Although the COVID-19 crisis has not significantly impacted the project schedule, the need to replace some of the stakeholder workshops planned for the second half of the project by virtual meetings has reduced the level of interaction with some stakeholders, particularly regarding the discussion of the simulation results. Future research building on top of this project should carefully address this point by designing mechanisms that allow close online collaboration with stakeholders.

4. References

4.1 Project outputs

Project deliverables:

- D1.1 UDPP Assessment Framework: Indicators and Metrics.
- D2.1 Tactical Slot and Trajectory Allocation Mechanisms: Qualitative Assessment.
- D3.1 Agent-Based Simulation Model for the Analysis of Tactical Slot and Trajectory Allocation Mechanisms.
- D4.1 Results of simulation experiments: comparative analysis of different tactical slot and trajectory allocation mechanisms.

The main dissemination actions conducted so far are the following:

- Poster presented at SESAR Innovation Days 2019. The poster describes the project objectives and the proposed research approach, and provides a high-level view of the simulation platform.
- Presentation of the project at the second Engage workshop on “Novel and more effective allocation markets in ATM”. The presentation provides a detailed description of the project, including the initial selection of prioritisation mechanisms, the proposed evaluation framework, and the design of the simulation platform.
- Presentation used for the working session with EUROCONTROL’s UDPP team in February 2020.
- Presentation of the main project results at the final online workshop held in July 2020.

All the previous outputs are available upon request for all interested stakeholders.