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**Title**

# D3.1 Agent-Based Simulation Model for the Analysis of Tactical Slot and Trajectory Allocation Mechanisms

**Keywords**

UDPP, flight prioritisation, agent-based model, cost of delay, CASA algorithm, slot swapping, auction

**Summary**

The purpose of this document is to provide a detailed and exhaustive description of the agent-based model implemented to simulate the flight prioritisation mechanisms proposed in deliverable D2.1, in order to compute the performance indicators defined in D1.1.

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# 1. Introduction

## 1.1 Scope and objectives

The work described in this document is framed within the project “Exploring Future UDPP Concepts through Computational Behavioural Economics”. Particularly, this report is intended to provide a detailed and exhaustive description of the agent-based model implemented to simulate the flight prioritisation mechanisms proposed in deliverable D.2.1, in order to compute the performance indicators defined in D.1.1.

An overall description of the model is provided. This includes:

- the definition of the simulation environment, which consists in a simplified network with a limited number of airports and airspace sectors;
- the modelling of the exogenous variables affecting the simulation, including the generation of a flight schedule and the passenger connectivity; and
- the modelling of the airline agents. Both the agents’ individual characteristics, such as the computation of the cost of delay function, and the agents’ interactions within the different processes are described.

Finally, the implementation of each one of the selected flight prioritisations is illustrated, highlighting the actions carried out by each of the agents integrating the model.

## 1.2 Document structure

This document is structured as follows:

- Section 1 introduces the document explaining its aim and scope, includes a list of acronyms, and describes the structure of the report.
- Section 2 provides an overview of the agent-based model and its applicability to the evaluation of different flight prioritisation mechanisms.
- Section 3 describes the model characteristics, including an overall description, the main modelling assumptions, and all the necessary information about the generation of the model environment and inputs.
- Section 4 discusses our implementation of the CASA algorithm for the Network Manager to issue a regulation.
- Section 5 illustrates the implementation of the model agents and the interactions between agents in each of the processes contained in the different prioritisation mechanisms.
- Annex I illustrates the functional block diagrams defining the architecture of the model.

## 1.3 List of acronyms

| Acronym | Definition |
|---|---|
| ABM | Agent Based Modelling |
| AIBT | Actual In-Block Time |
| AOBT | Actual Off-Block Time |
| ATC | Air Traffic Control |
| ATM | Air Traffic Management |
| ATFM | Air Traffic Flow Management |
| ANSP | Air Navigation Service Providers |
| CASA | Computer Assisted Slot Allocation |
| ETO | Estimated Time Over |
| ESS | Enhanced Slot Swapping |
| E-SFP | Enhanced Selective Flight Protection |
| FPFS | First Planned First Served |
| FPL | Late Flight-Plan |
| GIS | Geographic Information System |
| ICAO | International Civil Aviation Organization |
| NM | Network Manager |
| MTOW | Maximum Take-Off Weight |
| OD | Origin - Destination |
| SESAR | Single European Sky ATM Research |
| SFP | Selective Flight Protection |
| TMA | Terminal Manoeuvring Area |
| UDPP | User Driven Prioritisation Process |

# 2. Agent-based modelling: applicability to UDPP

Most existing studies about flight prioritisation mechanisms make use of normative economic models that predict the behaviour of the system under idealised 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 the decision. In the last twenty years, agent-based computational economics has raised increasing interest as a way to overcome these issues. Agent-based modelling (ABM) allows the observation of the emergent behaviour arising from agents' interactions in a bottom-up process, combining formality and rigour with the minimisation of disadvantages such as strong hypothesis dependency.

## 2.1 Overview of agent-based modelling

ABM can be defined as an essentially decentralised, individual-centric approach to model a system composed of interacting, autonomous agents. Agents have behaviours defined by simple rules (main drivers, reactions, memory, states...) and interact with the environment and with other agents, influencing their behaviours. When running the simulation, the global behaviour emerges as a result of the interactions of many individual behaviours, showing patterns, structures, and behaviours that were not explicitly programmed into the model, but arise from the agent interactions. ABM offers a way to model social systems composed of agents that interact with and influence each other, learn from their experiences, and adapt their behaviours.

### 2.1.1 Structure of an agent-based model

A typical agent-based model has three main elements:

- A set of agents, their attributes and their behaviours.
- A set of agent relationships and methods of interaction.
- The agents' environment.

#### 2.1.1.1 Agents

Agents, which can represent people, companies, projects, assets, vehicles, animals, etc., are discrete entities with their own goals and behaviours. The essential characteristics of agents are:

- An agent is a self-contained, modular, and uniquely identifiable individual.
- An agent is autonomous, i.e., it can function independently in its environment and in its interactions with other agents.
- An agent has a state that varies over time.
- An agent is social, i.e., it has dynamic interactions with other agents that influence its behaviour.

Agents may also have other useful characteristics:

- An agent may be adaptive, by having rules or more abstract mechanisms that modify its behaviour. For example, an agent may have the ability to learn and adapt its behaviour based on its accumulated experiences.

- An agent may be goal-directed, having goals to achieve with respect to its behaviours. This allows an agent to compare the outcome of its behaviour with its goals and adjust its responses and behaviour in future interactions.
- Agents may be heterogeneous.

#### 2.1.1.2 Interactions

One of the main elements of ABM is that only local information is available to an agent. Agent-based systems are decentralised systems, which means that there is no central authority that controls agents' behaviour in an effort to optimise system performance. As in real world systems, agents interact with a subset of other agents, termed the agent's neighbours. Local information is obtained from interactions with an agent's neighbours and from its local environment. An agent's set of neighbours may change as a simulation proceeds.

The way agents are connected to each other is defined by the topology of the agent-based model, which describes who transfers information to whom. Typical topologies include a spatial grid, a spatial network of nodes (agents) and links (relationships), or a non-spatial model. In some applications, agents can interact according to multiple topologies.

#### 2.1.1.3 Environment

Agents interact with their environment. The environment may simply be used to provide information on the spatial location of an agent relative to other agents or it may provide a richer set of geographic information, as in a Geographic Information System (GIS). An agent's location included as a dynamic attribute is sometimes needed to track agents as they move across a landscape, contend for space, acquire resources, and encounter other situations.

### 2.1.2 Added value

Most computational modelling research describes systems in equilibrium or as moving between equilibria. Agent-based modelling, however, using simple rules, can result in different sorts of complex behaviour and allows the examination of how the scenario behaves out of equilibrium, when it is not at a steady state (Arthur, 2006; Cardoso et al and Bonabeau, 2002). A more detailed discussion of the benefits of ABM over other modelling techniques is included below.

#### 2.1.2.1 ABM captures emergent phenomena

Emergent phenomena result from the interactions of individual agents. By definition, they cannot be reduced to the system's parts: the whole exhibits new properties not observed in the individual elements. Classical examples of these phenomena are the behaviour of bird flocks, fish schools, traffic jams, etc.

An emergent phenomenon may have counterintuitive properties that are decoupled from the properties of the parts. As a result, emergent phenomena are difficult to understand and predict. ABM is, by its very nature, the most accurate approach to modelling emergent phenomena: in ABM, the modeller simulates the behaviour of the system's agents and their interactions, capturing emergence from the bottom up.

#### 2.1.2.2 ABM provides a natural description of a system

In many cases, ABM is the most natural modelling approach for describing and simulating a system composed of behavioural entities. ABM makes the model seem closer to reality. As an example, it is more natural to describe how drivers move than to come up with the equations that govern the dynamics of the density of traffic. Because the density equations result from the behaviour of individual vehicles, ABM will also allow aggregate properties to be studied.

#### 2.1.2.3 ABM is flexible

The flexibility of ABM can be observed along multiple dimensions. For example, it is easy to add more agents to an existing model. ABM also provides a natural framework for tuning the complexity of the agents: behaviour, degree of rationality, ability to learn and evolve, and rules of interactions. Another dimension of flexibility is the ability to change the levels of description and aggregation: one can easily play with aggregate agents, subgroups of agents, and single agents, with different levels of description coexisting in a given model.

## 2.2 Applicability to UDPP

ABM constitutes a particularly suitable framework to represent and simulate market instruments and other flight prioritisation mechanisms where agent interactions are heterogeneous and can generate network effects. Furthermore, it offers a more intuitive and tractable description of the system units including individual behaviours that would otherwise be very difficult to represent as equations.

Additionally, ABM has prominent synergies with behavioural economics, where deviations from the assumed theoretical behaviour play an outstanding role. The convergence of agent-based modelling and behavioural economics into computational behavioural economics provides a natural framework to incorporate behavioural economics insights about human and institutional behaviour into operational simulation models (Mueller and Pyka, 2016). Particularly, some of the features that are interesting to analyse are:

- Network effects: the application of certain prioritisation mechanisms to solve the demand-capacity problem in a given time and air sector may cause one or more imbalances in other places later on as a result of the interaction between the agents.
- Different behaviours: flight prioritisation mechanisms are designed so that airlines can decide what action to take when they face ATFM delays. These decisions may respond to different strategies or be influenced by certain cognitive biases which depart from purely rational choices.
- Robustness of mechanisms: assigning different behaviours to airlines allow us to explore the different results that could be obtained with flight prioritisation mechanism and how they would be affected by “irrationalities”.

# 3. Model description

## 3.1 Overall description

The model simulates a day of operations at air traffic level, 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. They include fuel prices, air navigation charges price, and airlines' cost index.
- Agents. Two types 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.
- 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.

## 3.2 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[1].
- 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.

[1] 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 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.

## 3.3 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-centered metrics.

These inputs are synthetically generated from real data as explained below.

### 3.3.1 Flight schedule

The flight schedule is one of the most important and critical inputs of the simulation. 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.

The process of generating this data becomes of great importance to create the right conditions which help us achieve the objectives of the simulation. This process can be divided in three stages:

**Extract and clean real data**

In this stage, to recreate a realistic level of traffic in our model, flight schedules of a subset of airports are reconstructed from the information contained in the s06 file of a random traffic day. The process followed is explain below:

1. Data filtering:
    a. Repeated data is deleted
    b. Flights between the most congested airports in Europe (EGLL, EHAM, LFPG, EDDF, LTFM) are selected.
    c. Real airport ICAO codes are replaced by pseudo codes.
    d. The format of the departure times is changed to the datetime format HH:MM:SS.
    e. Only flights departing from 9:00 to 23:00 are collected.
2. The resulting data are allocated to airlines. To maintain a certain level of realism, the airlines are grouped by alliances.
3. The schedule is ordered by departure time and a new column indicating a flight identifier is added.
4. The original aircraft type associated with each flight is changed to one of the two different aircraft included in the model (narrow-body and wide-body)
5. A new column is added to the schedule indicating the estimated arrival time of each flight.
6. The aircraft ids are generated and assigned to each corresponding flight following a rotation pattern. The approach to generate the rotations works as follows:
    a. Define an aircraft id
    b. Assign an aircraft id to the first flight in the list of flights
    c. Calculate the flight arrival time to destination

d. Check for possible rotations by checking flights departing from the destination airport of that flight and belonging to the same airline. The departure time limit for the rotation will be equal to the arrival time of the previous flight plus the defined turnaround time of the aircraft.
e. Assign the defined aircraft id to the first flight meeting the previous condition. The buffer time is defined as the time between the departure time limit and the schedule departure time of the flight finally chosen as rotation.

This procedure is followed iteratively until there are no flights that meet the conditions and the process is repeated with the next flight of the list.

The resulting flight schedule contains the following information: origin, destination, departure time, arrival time, airline id, aircraft type, aircraft id and flight id.

**Create point-to-point schedules**

The schedule coming from the processed s06 file does not yet meet the desired requirements for the simulation. Almost every airline that was captured in the file corresponds to a carrier airline, which has a well-known hub and spoke behaviour. However, the point-to-point strategy characteristic of low-cost airlines is still missing. To include this strategy new flights are included in the schedule. This process is explained below:

1. New “low cost” airlines are defined and a dummy schedule with point-to-point flights between two predefined airports is generated. The method creates a first flight going from one airport to the other and calculates the flight duration between these two airports. Then, a return flight is generated at the destination airport. The definition of the schedule departure time of the new fight is calculated from the addition of a defined waiting time (turnaround time plus buffer time) to the scheduled arrival time of the first flight.
2. The schedule is ordered by departure time and a new column indicating a flight identifier is added.
3. A new column is added to the schedule indicating the estimated arrival time of each flight.
4. The aircraft ids are generated and assigned to each corresponding flight following a rotation pattern in the same way as in the previous stage.

**Merge the schedules**

Finally, both the flight schedule coming from the filtered real data and the schedule coming from the generated point-to -point flights are merged and ordered by schedule departure time.

### 3.3.2 Network capacity definition

The declared capacity of each of the sectors defining the network of the simulation 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 a 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. In the event that the maximum expected demand is less than 3 flights, the capacity will be directly assigned to 3 flights per time window. The capacity in the simulation is understood as the number of flights that the Network Manager considers that can be safely manage inside a sector during a defined period of time (e.g., 15 minutes).

Once the file is generated following all the previous indications, the user is able to manually change capacity values to simulate capacity shortages and generate hotspots.

### 3.3.3 Passenger connectivity

To measure the impact that different prioritisation mechanisms have on passengers, it is necessary to include passenger connectivity in the model. As for this project there was no data source from which to obtain this type of information, a configuration file was artificially generated with all the information regarding passenger connectivity. For this, the following assumptions were set:

- Only flag carrier airlines have connections.
- The passengers can only have a maximum of one connection in their journey.
- The waiting time for passengers connecting flights lies between 45 and 120 minutes.
- The connections are only between flights operated by the same airline.
- All flights departing from 18:00 onwards are direct flights.
- The number of total passengers inside a particular flight and aircraft is randomised between the following percentages:
    - 80-85% of aircraft capacity for flag carriers
    - 85-90% of aircraft capacity for charter airlines
- 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.
- 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 inside the actual flight.

According to the previous assumptions, the following approach was implemented to generate the connectivity file:

- The total number of passengers is calculated from the total capacity of the particular aircraft and a load factor associated with the airline type.
- The total number of passengers is divided in two different groups: passengers coming from a previous flight and passengers waiting at the origin airport, whose first flight is the current one.
- The possible future flights receiving connecting passengers from the actual flight are computed from the actual flight information, the schedule and the maximum number of connections allowed. These flights are found by filtering the schedule searching for flights operated by the same airline that depart from the actual flight destination airport in a time range going from 45 min to 2 hours.
- The encountered flights and the final number of connecting passengers boarding them, if any, are saved as connection information of the actual flight.

The generated file consists of several rows corresponding to each of the flights included in the simulation. Each row contains the following flight information:

- Flight id: the id of the flight.
- Pax at origin: number of passengers at the origin airport. These are the passengers that come directly from the airport and not from another flight.
- Pax from connections: number of passengers coming from another flight.
- Pax total: total number of passengers inside the flight.
- Connection info: list of flight ids and number of connecting passengers boarding future flights.

The generation of the passenger objects will follow a 1 to 1 ratio, meaning that a passenger in the connectivity file equals a passenger object in the simulation. Once the passenger objects are generated, they are added to their corresponding airport of origin.

During the simulation, each time a flight departs, the passengers belonging to that flight are moved from the airport to the flight. On the opposite side, when a flight reaches its destination, all the passengers are removed from the simulation, with the exception of passengers connecting with another flight, which are moved to the corresponding airport to wait there for their next flight.

## 3.4 Simulation environment

The environment is used to provide information on the spatial location of an agent relative to other agents and to provide a fundamental set of network characteristics.

### 3.4.1 Airport configuration

The defined network consists of 5 different airports, a mix of hubs and secondary airports. Table 1 shows a more detailed description of the type and characteristics of each one of the airports included.

| Airport Id | Airport Type | Connections |
|---|---|---|
| Airport A | Regional Airport | Sector 1, Sector 3, Sector 9 |
| Airport B | Regional Airport | Sector 2, Sector 5, Sector 9 |
| Airport C | Hub Airport | Sector 1, Sector 3, Sector 4, Sector 6, Sector 7 |
| Airport D | Hub Airport | Sector 2, Sector 4, Sector 5, Sector 7, Sector 8 |
| Airport E | Regional Airport | Sector 6, Sector 7, Sector 8 |

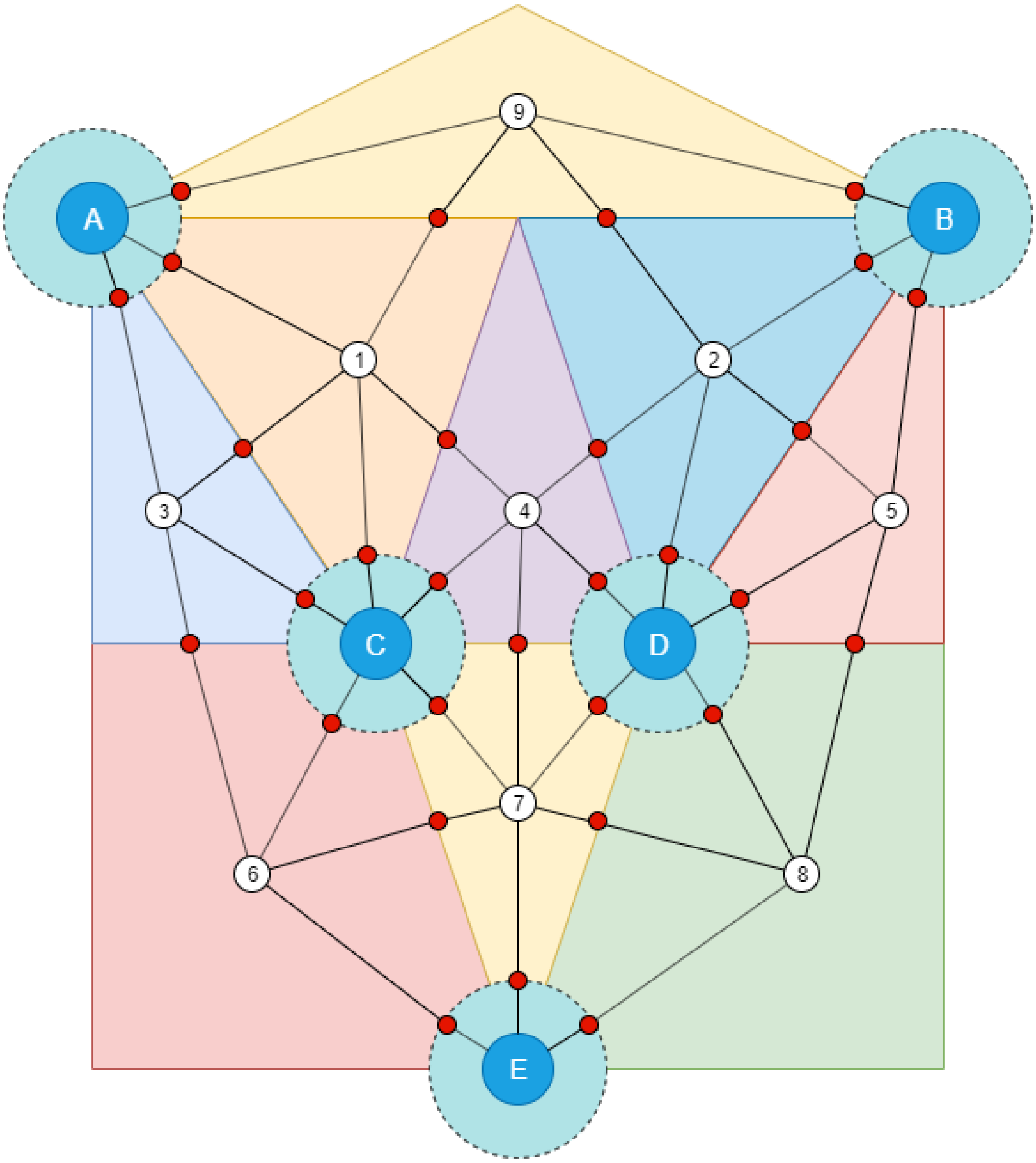
Table 1. Airport configuration

### 3.4.2 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).

An illustration of the resultant network topology is shown in **¡Error! No se encuentra el origen de la referencia.**. The white circles designate the id of the particular sector, while the red dots exemplify the




connection entry and exit points between sectors.

### 3.4.3 Route configuration

The route configuration defined for the model follows a fixed trajectory approach with defined entry and exit points for each sector. Additionally, the sector configuration is built in such way to allow 3 possible different route trajectories for every OD pair. Table 2 shows all the different route combinations for the network.



Figure 1. Network topology

| OD Pair | Route 1 | Route 2 | Route 3 |
|---|---|---|---|
| Airport A - Airport D (AD) | Airport A - Sector 1 - Sector 4 -Airport D | Airport A - Sector 9 - Sector 2 - Airport D | Airport A - Sector 3 - Sector 6 - Sector 7 - Airport D |
| Airport A - Airport E (AE) | Airport A - Sector 3 - Sector 6 - Airport E | Airport A - Sector 1 - Sector 4 - Sector 7 - Airport E | Airport A - Sector 9 - Sector 2 - Sector 5 - Sector 8 - Airport E |
| Airport B - Airport C (BC) | Airport B - Sector 2 - Sector 4 - Airport C | Airport B - Sector 9 - Sector 1 - Airport C | Airport B - Sector 5 - Sector 8 - Sector 7 - Airport C |
| Airport B - Airport D (BD) | Airport B - Sector 2 - Airport D | Airport B - Sector 5 - Airport D | Airport B - Sector 9 - Sector 1 - Sector 4 - Airport D |
| Airport B - Airport E (BE) | Airport B - Sector 5 - Sector 8 - Airport E | Airport B - Sector 2 - Sector 4 - Sector 7 - Airport E | Airport B - Sector 9 - Sector 1 - Sector 3 - Sector 6 - Airport E |
| Airport C - Airport D (CD) | Airport C - Sector 4 - Airport D | Airport C - Sector 7 - Airport D | Airport C - Sector 1 - Sector 9 - Sector 2 - Airport D |
| Airport C - Airport E (CE) | Airport C - Sector 7 - Airport E | Airport C - Sector 6 - Airport E | Airport C - Sector 4 - Sector 2 - Sector 5 - Sector 8 - Airport E |
| Airport D - Airport E (DE) | Airport D - Sector 7 - Airport E | Airport D - Sector 8 - Airport E | Airport D - Sector 4 - Sector 1 - Sector 3 - Sector 6 - Airport E |
| Airport A - Airport D (AD) | Airport A - Sector 1 - Sector 4 - Airport D | Airport A - Sector 9 - Sector 2 - Airport D | Airport A - Sector 3 - Sector 6 - Sector 7 - Airport D |
| Airport A - Airport E (AE) | Airport A - Sector 3 - Sector 6 - Airport E | Airport A - Sector 1 - Sector 4 - Sector 7 - Airport E | Airport A - Sector 9 - Sector 2 - Sector 5 - Sector 8 - Airport E |

**Table 2. Route configuration**

### 3.4.4 Network calibration

The topological illustration of the network needs to be translated into a physical representation. First, 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 air navigation services provided by the Air Navigation Service Providers (ANSP) over a portion of airspace, in our case coincident with the defined sectors.

According to EUROCONTROL, the charges for the use of air traffic services are computed according to the three following factors:

- Distance factor: the distance factor by charging zone is obtained by dividing, by one hundred (100), the number of kilometers in the great circle distance between the aerodrome of departure (or entry point of the charging zone) and the aerodrome of arrival (or exit point of the charging zone). For simplicity, the distance values in the model correspond to the great circle distance.
- Aircraft Weight Factor: the weight factor (expressed to two decimals) is determined by dividing, by fifty (50), the Maximum Take-Off Weight (MTOW) of the aircraft (in metric tonnes, to one decimal) and subsequently taking the square root of the result rounded to the second decimal.
- Unit Rate Factor: the unit rate of charge is the charge in euro applied by a charging zone to a flight operated by an aircraft of 50 metric tons (weight factor of 1.00) and for a distance factor of 1.00.

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.

Finally, 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.

## 3.5 Agents

### 3.5.1 Agents characteristics

#### 3.5.1.1 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 prioritisation mechanisms.

#### 3.5.1.2 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 modelled as cost-minimisers but their final 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 trigger the use of the available prioritisation mechanisms.

**Cost of rerouting**

The calculation of the cost of changing from one route to another is based on the direct cost associated with flying a certain route. This cost depends on several factors, both external and internal:

- External factors: the total distance of the route and the cost of the air navigation charges.
- Internal factors: the cost index of the airline and the cost of delay function associated with each flight.

The cost index, which corresponds to the ratio between the unit cost of time and the unit cost of fuel, is used to calculate the cost of time for an airline. Consequently, the direct cost of flying a certain route is calculated using Equation 1, where fuel burn is the kg of fuel burn per minute; fuel cost is the cost of 1 kg of fuel in Euros; flight time is the duration of the flight in minutes; and the charges cost represent the total cost paid in air navigation charges for flying that specific route.

$$Direct_{cost} = fuel_{burn} * fuel_{cost} + flight_{time} * time_{cost} + charges\_cost \qquad \text{(Eq. 1)}$$

When deciding whether to do a certain rerouting, it is necessary to calculate the difference in cost of flying one route or another. However, to make a fair comparison between the different route options, we must take into account the cost of the delay associated with all alternatives.

This way, the cost of flying the original route is equal to the addition of the direct cost plus the cost of any delay assigned to the flight following that specific trajectory. Likewise, the calculation of the alternative route follows the computation of the new direct cost for that new trajectory plus any possible delay, for instance a potential flight arrival delay due to the new route length.

**Cost of delay**

The seed of the airlines' decisions within the simulation is the calculation of the cost of delay associated with the different flights affected by demand-capacity imbalances. To compute this cost we have mainly used two reference documents. Regulation (EC) No 261/2004 was comprehensively reviewed to assess the current common rules on compensation and assistance to passengers in the event of denied boarding and of cancellation. The report "European airline delay cost reference values", developed by the University of Westminster, was also considered to extract updated reference values for the cost of delay for European airlines. The modelling of these costs in the simulation is based on the following assumptions:

- All the delays are issued when the aircraft is still on the ground, meaning that we are only interested in the at-gate delay cost reference values. For simplicity, we are not modelling any turnaround process.
- Both the maintenance and the crew costs are extracted from the corresponding tables in the University of Westminster's report. The exact crew and maintenance costs per minute are selected based on the base scenario.
- The passenger soft costs are often a dominant component in the economics of airline unpunctuality. These are the costs associated with a revenue loss or market value decrease. Unlike crew and maintenance costs, these delay costs are not linear over time. Large delay values are associated with a high cost value per minute, per person. In order to include them in the delay cost function, the slope values (Euros per minute, per passenger) found in the University of Westminster's document have been integrated to calculate the accumulated soft costs at each of the delay values indicated in the table. To get the entire range of possible delay values, an interpolation is made.
- The passenger hard costs are due to such factors as passenger rebooking, compensation and care. The modelling of these costs is based on Regulation (EC) No 261/2004 and the Articles 91(1) and 100(2) of the Treaty on the Functioning of the European Union (TFEU).
    - Flight cancellations are not included in the simulation. In the case that a particular aircraft cannot finally depart during the simulation time, for whatever reason, it is considered that the final departure is scheduled the next day.
    - Delays < 3 hours: the airline is obliged to offer assistance in the form of meals, refreshments and free of charge two telephone calls, telex or fax messages, or e-mails. However, even in the worst-case scenario, this cost is not significant enough for the project so it is not included in the calculation.
    - Delays > 3 hours: In the event of a delay longer than three hours, passengers should be offered a compensation as in the event of cancellation:
        - EUR 250 for all flights of 1,500 kilometres or less;
        - EUR 400 for all intra-Community flights of more than 1,500 kilometres, and for all other flights between 1,500 and 3,500 kilometres;
        - EUR 600 for all flights not falling under (1) or (2).

- To trigger passenger compensations, we study the passenger arrival delay of both the direct and the connecting passengers. The calculation of the arrival delay of direct passengers is straightforward. However, the arrival time of the connecting passengers extremely depends on the connection or other possible re-booking connections. No extra compensation for loss of connection has been modelled. In the event that the connecting passengers miss their next flight, the airline will try to re-book them in other flights and only in the case that they reach their final destination with more than three hours of delay they will receive the appropriate compensation.
- There are certain cases in which the airline will also have to pay passengers the cost of accommodation and transportation. This cost is approximated to 150 EUR per person.
  - No re-booking: in the event that connecting passengers cannot be re-booked to another subsequent flight, they must spend the night at the airport and therefore require accommodation and transportation.
  - Curfew missed: if an aircraft cannot depart due to curfew reasons, either at the destination airport or at the origin airport, the airline must pay accommodation and transportation expenses for some of the passengers, according to the following criteria:
    - All the passengers coming from a connection receive the overnight compensation.
    - Only 50% of the passengers not coming from connections will receive the overnight compensation. This 50% ratio is an approximation for the passengers who are at the home airport and the ones which are not.

Two additional considerations have been taken into account in the calculation of the delay cost function:

- In order to take into account the cost of delay propagation to the next flight of the same rotation, at the moment in which the delay of a flight produces a delay in the next rotation, the slope of the delay curve will be increased by multiplying the passenger soft costs by a certain factor.
- With the sole intention of adding variability to the different cost of delay curves, different flights have been assigned different weights to the passenger soft costs. This allows us to simulate the importance of certain specific flights, which could be for instance the representation of business flights, whose value is usually superior for airlines.

### 3.5.2 Agents interaction rules

Depending on the flight prioritisation mechanism evaluated in the simulation, the sequence of agents' decisions and actions follows a different pattern. However, 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.

#### 3.5.2.1 First Plan First Served (FPFS) 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.

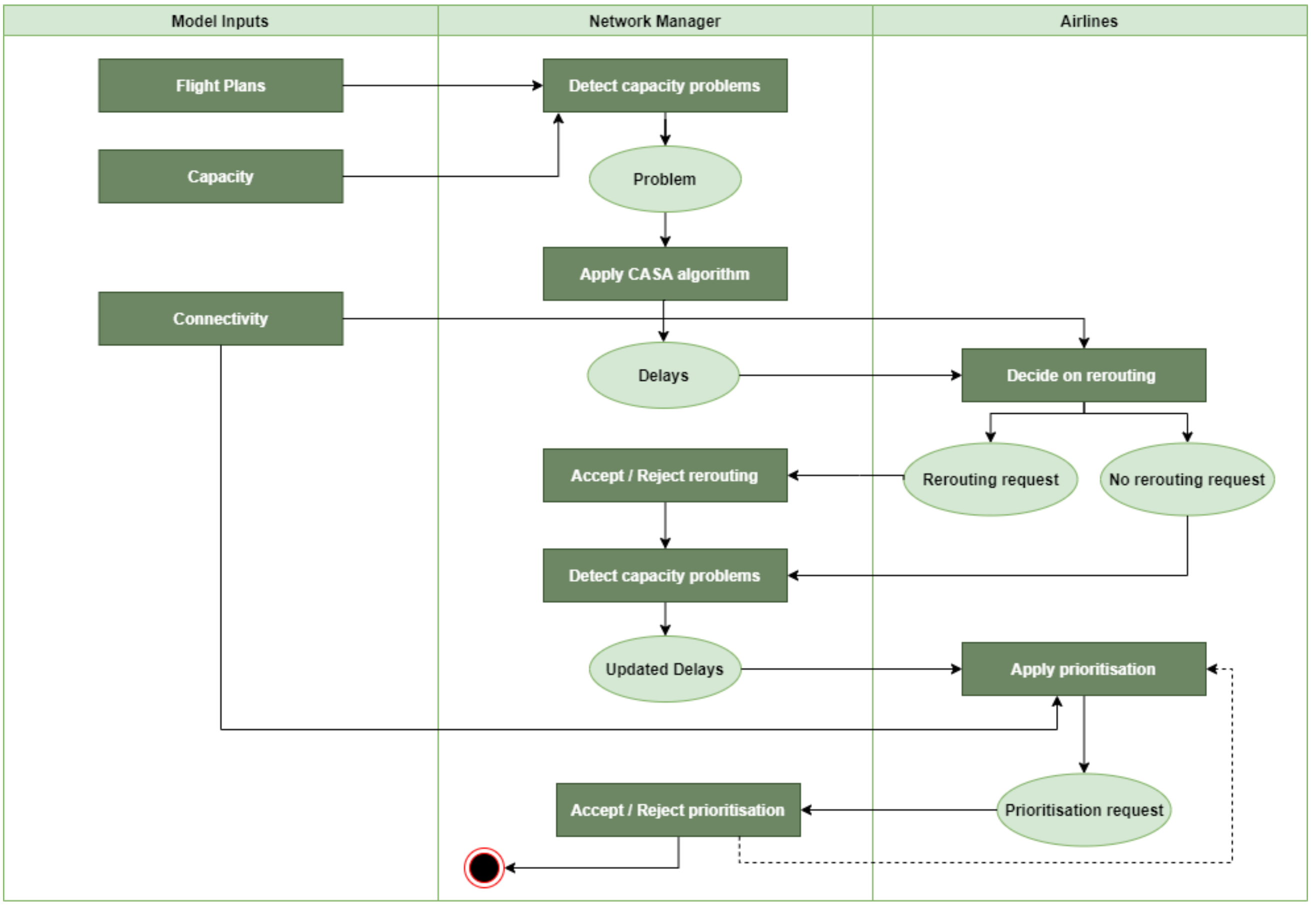



**Figure 2. FPFS workflow**

The main actions performed by each agent are the following.

The Network Manager:

- computes the number of flights crossing each of the sectors at a given time slot and compares it with the declared capacity of the sector;
- In the event that the capacity is exceeded for any sector or group of sectors, starts a regulation;
- orders the flights within the regulation according to their ETO using the CASA algorithm.

Once delays are properly computed, the information is sent to the airlines involved. The airlines:

- compute cost of delay of the affected flights;
- calculate the cost of:
    - re-routing: this procedure gives airlines the flexibility to change the route when any of their flights faces a delay;
    - all the possible prioritisation actions: these give the airlines the flexibility to redistribute the total delay received in a hotspot between the affected flights with the aim of reducing the associated cost of delay. The flexibility provided by the prioritisation process depends on the type of mechanism available;

- based on the cost difference between all options, decide whether to request a re-routing or a prioritisation action;
- If the request is denied, then issues a new one. For the sake of simplicity, re-routing can also be asked for the once and always before asking any prioritisation process, and the number of allowed prioritisation requests is limited to 3, if none of these are accepted the airline is forced to accept the original delay.

Each time a request is received, the Network Manager:

- performs a recalculation of the hotspot to update the delays of the other flights and at the same time check if the hotspot has been solved by the re-routing, if requested;
- accepts or rejects the requests according to the following requirements:
  - do not generate any additional demand-capacity imbalance in a previous time window already solved;
  - no request can modify the status of another airline that has already made its decision and therefore already has its definitive ATFM slots;
  - no flight can occupy a 'before schedule' ATFM slot;
- when a request is rejected, sends it back to the airline which decides another action to take.

The rejection process slightly deviates from the way in which the Network Manager proceeds inside the UDPP Programme during real operations, but it has been considered as a reasonable assumption due to the existence of enough time to answer several requests (2 hours in advance). In reality, with such time in advance (the flow is less predictable), some airlines may prefer to wait a bit in case the problem is resolved by the application of other measures to the flow.

Once all the airlines have managed to make their prioritisation requests, the simulation proceeds to the next time step and the whole process is repeated. The order in which the airlines make the requests is random.

#### 3.5.2.2 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. The workflow illustrating the whole process is depicted in Figure 3.

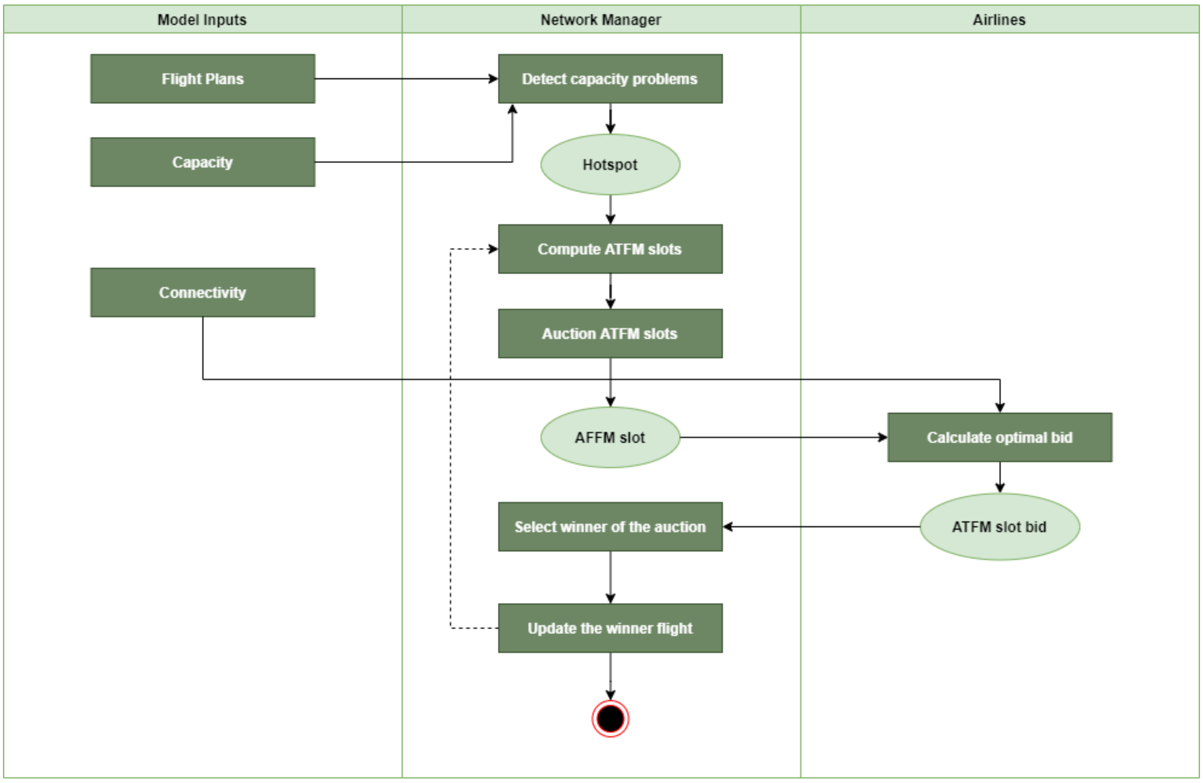



Figure 3. Auction workflow

The main actions performed by each agent are listed below.

The Network Manager:

- computes the quantity of flights crossing each sector and compares it with their declared capacity;
- if demand exceeds capacity for any sector or group of sectors, starts a regulation;
- within the regulation, computes all the ATFM slots in which the hotspot is divided. This is similar to the sequence of ATFM slots based on a FPFS ordering but without the initial allocation of the slots to each corresponding flight;
- performs the auction process by time window auctioning each of the ATFM slots individually;
- for each ATFM slot to be auctioned, computes the possible flights that can bid for it according to the schedule restrictions and offers the slot for auction to the airlines that operate those flights;
- allocates the slot to the winning flight;
- once the auction of all the ATFM slots located inside the particular time window has finished, recalculates the traffic and updates the sequence of the remaining ATFM slots in case there has been a variation due to the definitive placement of the winning flights in the slots already auctioned.

The airlines:

- compute the cost of delay of the affected flights;
- make a bid for the slot according to different strategies which are described in more detail later.

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.

Unlike in the case of FPFS, airlines here do not have the opportunity to ask for a rerouting. This is simply a design decision according to the scope of the project and the time limitation, but it does not mean that the re-routing capability cannot be added to the auction modality.

Once all the ATFM slots have been auctioned the simulation proceeds to the next time step and the whole process is repeated.

# 4. Implementation of CASA algorithm

When the Network Manager detects a sector where demand exceeds capacity during a certain time window, it applies a regulation using the CASA algorithm, based on the FPFS principle. The implementation of the CASA algorithm consists of the following steps:

1. **Identify allowed entrances into the sector**. This is the subtraction between the capacity (flights which can be managed per time window) and the flights already crossing the sector. For instance, consider a sector with a declared capacity of 4 flights per 15 min. The Network Manager studies the traffic from 9:00 to 9:15 (15 minutes time window) and identifies a flight which will already be flying inside the sector at 9:00. This means that there are 3 allowed entrances, to avoid exceeding the capacity level during that time window.

2. **Divide the time step in the corresponding entrance slots.** Once the allowed entrances have been identified, the next step consists in computing the associated slots in which the time step will be divided. Taking the previous example, we had a sector with only 3 allowed entrances between 9:00 and 9:15. Consequently the algorithm computes 3 slots of 5 min each corresponding to the following time ranges: 9:00-9:05, 9:05-9:10, 9:10-9:15.

3. **Slot assignment following the FPFS principle.** At this stage the entering flights are ordered in the corresponding entrance slots according to the ETO of the specific sector. Let us imagine that we have 5 flights arriving to the previous sector, with a capacity of 4 flights per 15 min and 3 allowed entrances. The different flights are planned to arrive at the following times: 9:02 (FLIGHT 1), 9:04 (FLIGHT 2), 9:07 (FLIGHT 3), 9:10 (FLIGHT 4), 9:12 (FLIGHT 5). The first entrance slot (9:00-9:05) will be assigned to FLIGHT 1, meaning a delay of 0 min. FLIGHT 2 arrives at 9:04, but the first slot is already occupied by FLIGHT 1; consequently it is assigned to the next entrance slot (9:05-9:10), which means a delay of 1 min. Finally, FLIGHT 3 should be originally assigned to the second slot because it arrives at 9:07; however the slot is again already filled with FLIGHT 2, so it is sent to the third and final slot (9:10-9:15), which means a 3 min delay.

4. **Shift the extra flights to the next time window.** The flights that arrive at certain sector during a time window but cannot be assigned to any slot due to their late ETO are shifted to the next time window. Following with the proposed example, FLIGHT 4 and FLIGHT 5 cannot be allocated inside the time window 9:00-9:15 because the maximum available capacity would be exceeded. Consequently, they are shifted to the next time step (9:15-9:30) and are assigned a preliminary delay of 5 min and 3 min respectively. The final delay for these flights will be assigned at the next time window iteration according to the steps 1 to 4.

# 5. Implementation of the prioritisation mechanisms

## 5.1 Slot Swapping

The slot swapping mechanism is included in the baseline scenario because it is currently available for use by airlines in real operations. It offers the possibility of changing 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 implicated 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 or options and send the request to the Network Manager.

## 5.2 Selective Flight Protection (SFP)

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 the slot swap, 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 or options 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.
- Reorganise the impacted flights by the relocation.

## 5.3 Enhanced – Selective Flight Protection (E-SFP)

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. This 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, 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 on the position of flight B in the hotspot. This should be taken into account when calculating of the cost of the action for flight A. The airline can use the prioritisation 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.

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 proper operation of the prioritisation process described, 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:

- Conservative: it imitates a more conservative behaviour where the airline tends to earn credits, absorb delay, when not very important flights are affected. Thus, the monetary value assigned to the credits is significant and the number of initial credits is high. For this case, the airline considers a credit value between 25 and 30 EUR.
- Optimistic: it represents an optimistic behaviour where the airline will tend to spend credits, prioritising not so important flights, rather than to earn credits by absorbing delay. It reflects a behaviour where the airline does not expect to need the credits in the future and decides to spend them quickly when it has the opportunity. Thus, the monetary value assigned to the credits is low and the number of initial credits is small. For this case, the airline considers a credit value between 10 and 15 EUR.
- 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. For this case, the airline considers a credit value between 15 and 25 EUR.

## 5.4 Slot Auction

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

- Conservative: it imitates a more conservative behaviour where the airline will bid aggressively according to a value very close to the worst possible situation for the flight within the hotspot.
- Optimistic: it represents an optimistic behaviour where the airline will tend to bid lower, in many cases overestimating its ability to win the auction.
- Neutral: corresponds to a neutral behaviour between the two previous patterns.

An airline participating in the auction of a particular ATFM slot take 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 current 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 75$^{th}$ percentile of the cost distribution calculated in the previous step
    - Optimistic: the airline bids according to the 25$^{th}$ percentile of the cost distribution calculated in the previous step
    - Neutral: the airline bids according to the 50$^{th}$ 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 for the auction mechanism is equal to the total amount 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 monetary 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.

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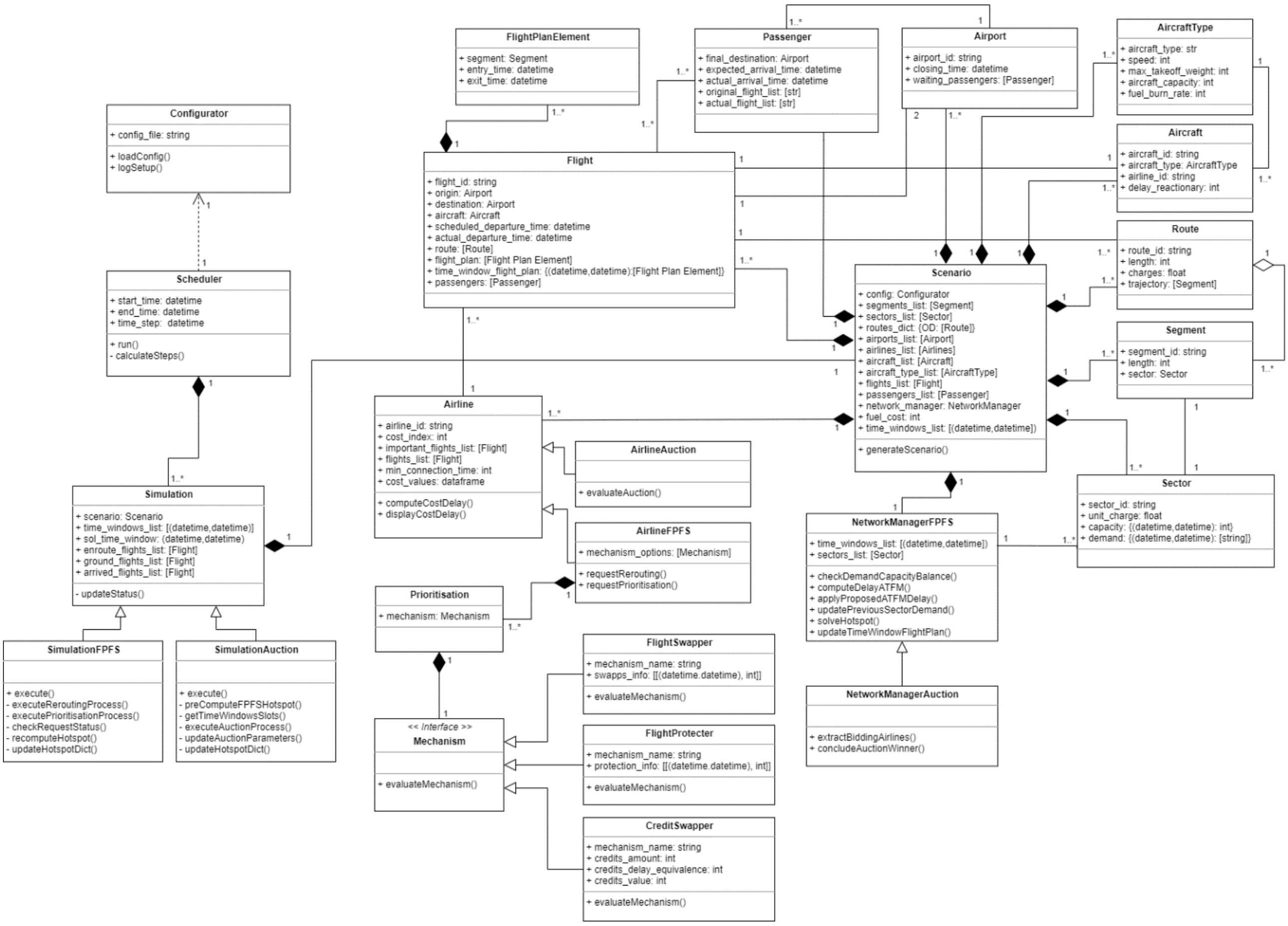
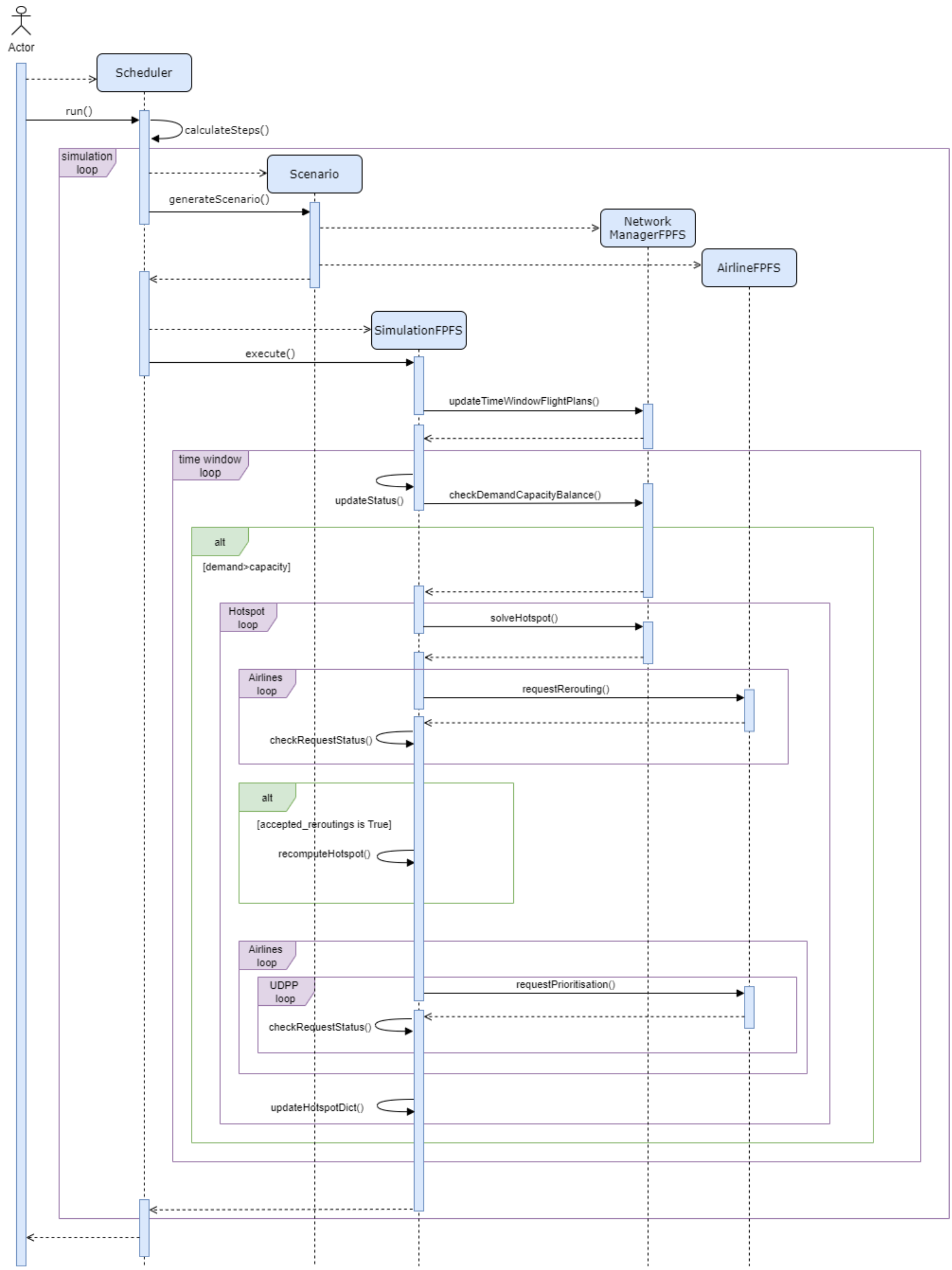
# Annex I. Model architecture

## Class diagram




The main objective of this class diagram is to show the interdependencies between all the implemented classes building the model. For this reason, and in order to make the diagram more readable, less important methods belonging to some classes have been omitted.

# Sequential diagram for the FPFS paradigm



## Sequential diagram for the Auction paradigm