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Title

D2.1 Tactical Slot and Trajectory Allocation Mechanisms: Qualitative Assessment

Keywords

UDPP, flight prioritisation, rule-based mechanisms, monetary market-based mechanisms, non-monetary market-based mechanisms

Summary

The purpose of this document is to provide a detailed and exhaustive review of the flight prioritisation and trajectory allocation mechanisms proposed in the literature, including concepts that are currently operationally active as well as more futuristic approaches. The ultimate goal is to identify which of the examined mechanisms are the most promising to improve the performance of the ATM system in situations of demand-capacity imbalance.

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1. Introduction

1.1 Scope and objectives

The goal of the ENGAGE Catalyst project 'Exploring Future UDPP Concepts through Computational Behavioural Economics' is to develop new modelling approaches enabling the study of User Driven Prioritisation Process (UDPP) mechanisms. To this end, the project adopts the paradigm of computational behavioural economics. This report is intended to provide a detailed and exhaustive review of the flight prioritisation and trajectory allocation mechanisms proposed in the literature, including both currently operationally active concepts and more futuristic approaches. The ultimate goal is to identify which of the examined mechanisms are the most promising to improve the performance of the ATM system in situations of demand-capacity imbalance, and select the mechanisms that will be simulated in the context of the project.

1.2 Document structure

This document is structured as follows:

- Section 1 introduces the document, explaining its aim and scope, includes reference documents and acronyms, and describes the structure of the report.
- Section 2 describes the current approach used in Air Traffic Flow and Capacity Management (ATFCM) to deal with demand-capacity imbalances and provides an overview of the work conducted by SESAR for the development of the UDPP concept.
- Section 3 presents the future steps proposed in the scope of the SESAR UDPP programme in the search of the extra flexibility demanded by the AUs.
- Section 4 describes other, more ambitious prioritisation approaches proposed in the literature.
- Section 5 presents the subset of mechanisms that have been selected to be modelled and evaluated within the project.

1.3 List of acronyms

Acronym	Definition
ATM	Air Traffic Management
ATFM	Air Traffic Flow and Capacity Management
ATFCM	Air Traffic Flow and Capacity Management
ANSP	Air Navigation Service Providers
AU	Airspace User
BPBS	Best Performing Best Served
CTOT	Calculated Take-Off Time
CPLP	Central Peak-Load Pricing
CDM	Collaborative Decision Making
CP	Central Planner

Acronym	Definition
DC	Delay Credit
DFlex	UDPP Departure
ETO	Estimated Time Over
ESS	Enhanced Slot Swapping
ESFP	Enhanced Selective Flight Protection
FCL	Flexible Credits for Low Volume Users in Constraint
FPFS	First Planned First Served
FDR	Fleet Delay Reordering
LVUC	Low Volume Users in Constraint
NM	Network Manager
PDS	Predeparture Sequence
PBO	Performance Based Operations
RBE	Ration by Effort
SESAR	Single European Sky ATM Research
SFP	Selective Flight Protection
SOBT	Scheduled Off-Block Time
UDPP	User Driven Prioritisation Process
TSAT	Target Start-up Time
TTOT	Target Take-Off Time

2. Current Concept of Operations

2.1 First Planned First Served (FPFS)

In Europe, every time an imbalance between demand and capacity is detected, the Network Manager imposes a regulation (Castelli et al, 2011). A regulation consists in the assignment of take-off delays (ground delays) to the flights affected by the capacity and demand imbalance. Currently, the assignment of the new departure time slots, the so-called ATFM slots, is performed following the First Planned First Served (FPFS) principle. This means that flights are sequenced according to flights' Estimated Time Over (ETO) the specific sector or airport. The FPFS policy has been accepted and deployed for many years, as it ensures that the total delay is minimised and provides equitable access to airspace (Vossen and Ball, 2006). However, it does not minimise the total cost of the delay, as there might be flights for which the same amount of delay generates different costs for Airspace Users (AUs) or passengers, connecting flights being an obvious case (Cook and Tanner, 2005). In order to overcome this drawback, since the mid-1990s, AUs have been allowed to exchange ATFM slots between flights affected by the same regulation. However, the flexibility provided by this mechanism is rather limited.

2.2 SESAR UDPP Step 1

The lack of flexibility provided by the FPFS system has a significant impact on airlines' annual costs and revenues. SESAR is tackling this problem through the development of the UDPP programme. The objective is to provide AUS with additional flexibility to readjust their operations in a more cost-efficient manner in the presence of unforeseen demand and capacity imbalances that require the application of ATFM delays. UDPP research is framed in the scope of the Collaborative Decision Making (CDM) philosophy, which aims to involve stakeholders in working more transparently and collaboratively, by exchanging relevant, accurate and timely information. Early UDPP developments in Step 1 introduced Enhanced Slot Swapping (ESS) and UDPP Departure (DFlex).

2.2.1 Enhanced Slot Swapping (ESS)

The **Enhanced Slot Swapping (ESS**) mechanism is intended to upgrade the current slot swapping procedure by improving the flexibility to react to imposed delay. The ESS principle can be subdivided in several concepts or "features", which are smaller, independent operational improvements (SESAR JU, 2015).

- **ATFM Pre-Allocated Slot Swap**: this concept provides AUs with the option to pre-allocate an ATFM slot to a flight 'A', in order to swap it with a flight 'B', which is already in slot-issued status. The flexibility provided by this mechanism overcomes the strict requirement imposed by the previous system to only swap issued slots. This upgrade is relevant when there is a need to exchange slots in advance due to the earlier Calculated Take-Off Time (CTOT) of one of the flights.
- **Multi-Swap of ATFM Slots**: this principle provides AUs with the flexibility to swap slots multiple times between flights sharing the most penalising regulation. The flight can be improved in several independent swap requests (Type 1), or in several consecutive steps in the same request (Type 2).
- **Substitution on Cancellation**: this mechanism allows AUs to cancel a flight and instantly assign the free slot generated to another of its flights. The flight that takes the empty slot must be affected by the same most penalising regulation. The empty slot created by the promoted flight is given back to the

Network Manager to fill it with another flight. This concept follows the so-called “Ration-by-Effort” (RBE) principle.

- **Most Penalising Delay**: with this system AUs are allowed to swap flights that depart from the same airport, with different most penalising regulation, if the delays generated by the airport exceed the most penalising regulation delays of the two flights in question.

According to SESAR Step 1 V3 UDPP Validation Report (SESAR JU, 2015), Enhanced Slot Swapping (ESS) offers an estimated average benefit of 4,900 EUR per swap. The expected savings due to ESS over 20 years are in the order of magnitude of hundreds of millions of euros (Pilon et al, 2016). ESS is being successfully deployed by EUROCONTROL since 2017.

2.2.2 UDPP Departure (DFlex)

SESAR UDPP Step 1 introduced another solution named UDPP Departure or DFlex, for which maturity has been assessed as sufficient to support a decision for industrialisation. Here, the ATM operational improvement comes from the extra flexibility provided in the departure swapping stage, which allows AUs in an airport to change the priority order of unregulated flights among themselves and via the airport authorities.

Prior to the day of operations, the airport receives all the flight plans and sorts them by reference time. From this, a reference-time list is built, which is processed by an algorithm to define the Pre-departure Sequence (PDS), and then allocating the Target Start-up Time (TSAT) with a retro calculation of the taxi-time. The UDPP Departure solution consists in re-prioritising the flights in the reference-time list, with a recalculation of the Pre-departure Sequence and a new TSAT allocation. DFlex provides three different features for implementation (Release 4 Local SESAR Solution #57, 2015):

- **Departure Reference Time Reordering**: this mechanism provides AUs with the ability to reorder their flights in the reference-time list. The reordering procedure is only possible between flights belonging to the same group or alliance and needs to adhere to constraints such as Calculated Take-Off Time (CTOT), Scheduled Off-Block Time (SOBT) and Target Take-Off Time (TTOT).
- **First Priority for Departure**: the mechanism is similar to the Departure Reference Time Reordering, but here AUs just request the prioritisation of one of the flights. The prioritised flight is promoted up while the rest of the AU’s flights are cascaded down through the list. Again, constraints such as CTOT, SOBT and TTOT are respected by the PDS.
- **Upwards Cascade on Departure Cancellation**: this concept states that whenever an AUs cancels a flight in an airport, its remaining flights in the reference-time list are cascaded upwards.

The DFlex operational concept has already been successfully implemented in the CDG Airport, where important benefits have been measured (Pilon et al, 2016).

3. SESAR UDPP Step 2

SESAR UDPP Step 2 took a step ahead in the search for extra flexibility. Two new mechanisms were proposed and consolidated in a meticulous process involving several AU delegates (Air France, Austrian, British Airways, the European Low Fares Airline Association, HOP!, the International Air Transport Association, SWISS, Turkish). The solutions that emerged from the detailed study were Fleet Delay Reordering (FDR) and Selective Flight Protection (SFP), which aim to increase the control AUs have to adapt flight schedules in the case of disruptions (Pilon et al, 2016).

3.1 Fleet Delay Reordering

Fleet Delay Reordering (FDR) (formerly 'Fleet Delay Apportionment', FDA) is an operational concept which gives AUs the ability to reorder their delayed flights in a hotspot. The airlines which acknowledge in advance the relative value or importance of their operating flights can submit a prioritisation list to the Network Manager, which will use it to reorder the departure sequence according to these preferences if a hotspot is declared. Reordering preferences are indicated by assigning numbers from 1 to xxx, being 1 the flight with the highest priority. Letters B and S are used to respect the imposed baseline delay and to suspend a flight, respectively (Pilon et al, 2019).

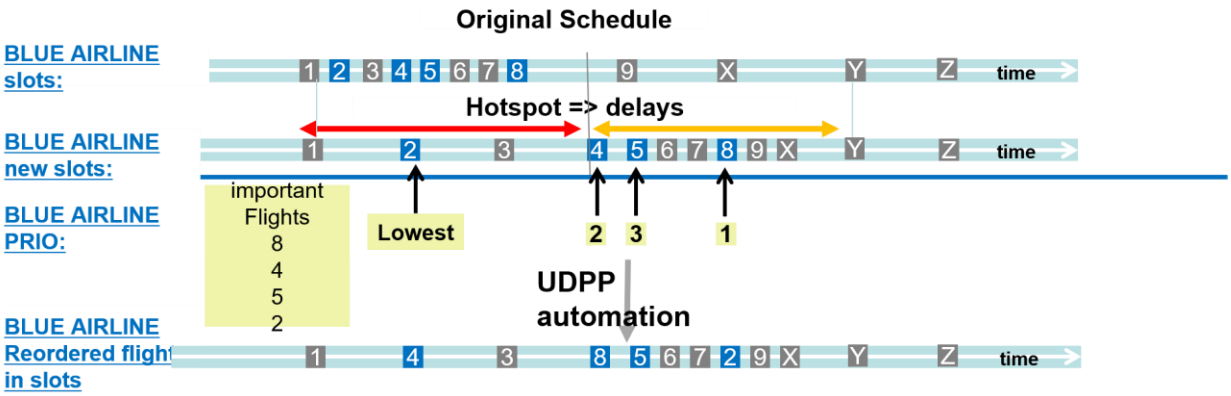

Figure 1. Fleet Delay Reordering mechanism. Source: EUROCONTROL

Figure 1 illustrates a use case of the mechanism. The blue airline is impacted with four regulated flights, corresponding to numbers 2, 4, 5 and 8, which are originally sequenced following the FPFS principle. Using the Fleet Delay Reordering mechanism, the airline delivers a prioritisation list, indicating its preferences, to the Network Manager. The submitted list reorders the flight slots according to their value for the airline; in this example, the most important flight is number 8 followed by 4, 5, and 2. Finally, the resulting departure sequence submitted by the Network Manager follows the airline preference list respecting the constraint imposed by the original scheduled departure time of each flight, meaning that no flight can get a slot prior to their original departure time.

3.2 Selective Flight Protection

The Selective Flight Protection (SFP) mechanism is a UDPP feature which provides AUs with the ability to protect their most valuable flight in a hotspot. It is very useful for situations where a simple swap is not allowed due to restrictions imposed by the rule of not departing before the original flight scheduled time. A use case is illustrated in Figure 2 for clarity. In the hotspot example, the blue airline owns two flights, 2 and 8. The value of both flights, in terms of delay, is significantly different, being the most delayed flight the most important too. Accordingly, the affected airline decides to protect its most valuable flight by using the SFP feature. The mechanism is divided in two consecutive phases. The first step consists in directly swapping the ATFM slots of the two flights. The second step readjusts the time slot of the prioritised flight, number 8, to match it with their original departure time, meaning that the protected flight will receive zero delay and will depart on time. Additionally, due to the readjustment process, flights belonging to other airlines, number 3 and 4 here, are positively impacted by climbing a position in the final sequence departure, thus reducing the imposed delay.

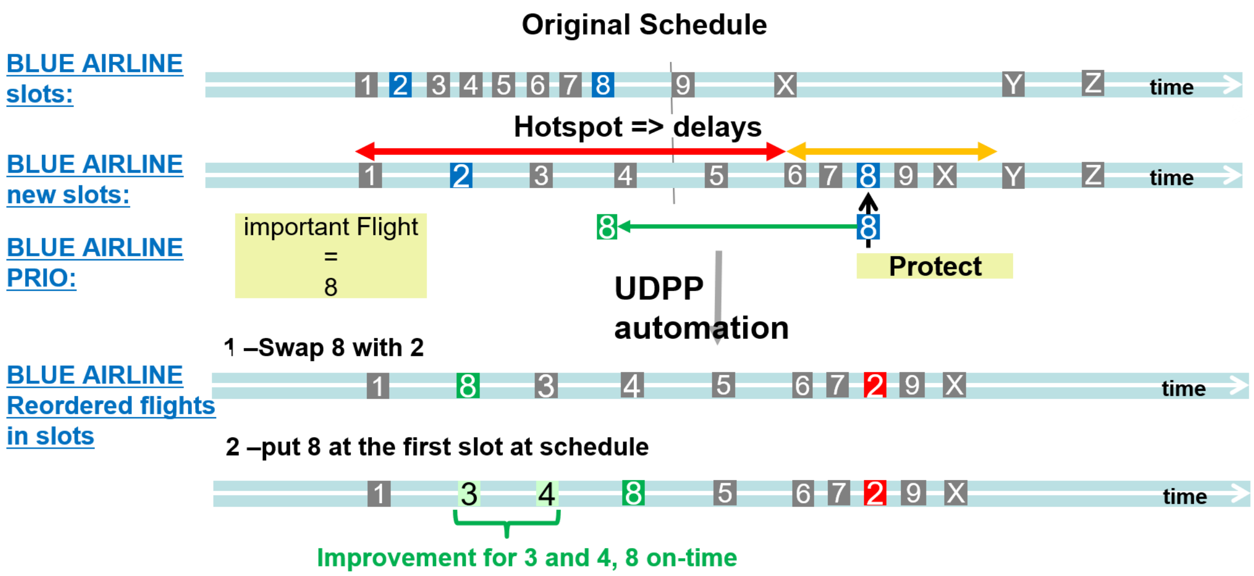

Figure 2. Selective Flight Protection. Source: EUROCONTROL

3.3 Flight Margins

TBD[1].

[1] Pending on receiving detailed information from EUROCONTROL. The description of the Flight Margins mechanism will be included in a future update of this document.

4. Other approaches for user-driven prioritisation

In addition to the concepts developed within the context of SESAR, a variety of allocation mechanisms have been investigated and proposed in the literature. The proposed mechanisms put the emphasis on the assignment of ATFM slots, on the priorities assigned to flights in case of disruption, on the potential re-routing paths, or everything at the same time. Depending on the nature of the principles underpinning the prioritisation concept, the different mechanisms can be divided into three groups:

1. The mechanisms concerning the implementation of operational standards and regulations can be grouped under the **rule-based** category.
2. **Monetary, market-based mechanisms** rely on the use of money and the forces of supply and demand to determine the optimal solution in situations where different entities are competing for scarce resources.
3. Finally, and in part due to the reluctance of many AUs to use actual monetary exchanges, some mechanisms make use of virtual currencies, such as credits, to carry out certain prioritisation strategies. We will name these mechanisms as **non-monetary, market-based mechanisms**.

It is important to note that not all mechanisms are applicable for every stage of ATFCM. Within this project, we will focus on those mechanisms for which all related decisions take place within ATFCM tactical phase, i.e., within the day of operations.

4.1 Rule-based Mechanisms

4.1.1 Best Performing Best Served (BPBS)

In the context of the detailed study on flight prioritisation carried out by NextGen (NextGen JPDO, 2011), a mechanism named **Best Performing Best Served (BPBS)** is proposed. The concept follows the rationale of prioritising best performing aircraft. The BPBS mechanism plays a double role: it encourages AUs to invest in new equipment and technologies, and at the same time helps enhance the performance of the airspace system by generating additional system capacity and improved airspace services.

The BPBS mechanism follows the philosophy of Performance Based Operations (PBO), by which AUs are encouraged to embrace capabilities that improve the performance and capacity of the airspace system. As the opportunity to participate is made available to all operators that meet the criteria, BPBS offers high transparency and perceived fairness. For future applications, the criteria for participation in BPBS and the effects of the application of BPBS on performance still need to be refined, as well as the required precision and performance for each element (NextGen JPDO, 2011).

4.2 Monetary Market-based Mechanisms

Due to the intrinsic nature of the flight prioritisation concept, it appears reasonable to consider some kind of market mechanism to define it. Previous studies (NextGen JPDO, 2011) have concluded that market mechanisms are potentially suitable to contribute to the achievement of many of the targets set by NextGen and SESAR, while at the same time providing extra flexibility for AUs and improving the economic efficiency of the airspace system. Different market concepts have been proposed by researchers with the aim of optimising the ATFM slot allocation process.

4.2.1 Prioritisation by Auction

In an environment as structured and constrained as the airspace system, **auction** processes appear to be suitable for the allocation of the scarce resources available. Accordingly, slot auctions can be classified into primary and secondary auctions:

- **Primary Auction**: a primary slot auction consists in the process by which AUs compete for ATFM slots by offering them up for bid to an honest broker, the Network Manager, which then sells each item to the highest bidder. The auction could be conducted strategically during negotiation of 4D trajectories or in real time, as the dispute over operating resources arises. In the case of a tactical primary auction, each ATFM slot is auctioned following the restrictions imposed by the scheduled departure time of the flights affected by the regulation, meaning that airlines cannot bid for time slots whose new expected departure (EOBT) is earlier than the original departure time of the flight willing to take that position.
- **Secondary Auction**: a secondary auction provides the participants with the ability to exchange valuable resources with possible side payments and also to buy and sell them. In the case of a slot auction, AUs are allowed to buy or sell ATFM slots within them. The inherent nature of a secondary market implies that a first allocation of the resources has already been performed, which in the case of ATFM could be done by following the current FPFS policy. Then, some AUs may want to purchase an earlier time slot in a regulation while other AUs may be interested in selling their slot and receiving a compensation for the delay increase.

Castelli et al. (2011) proposed a slot allocation mechanism based on market principles which enables AUs to pay for delay reduction or receive compensation for delay increase. The mechanism takes the FPFS allocated slots as the initial endowment of each flight and enforces the rule that no compensation is given for cancelled flights releasing the slots, in order to avoid the creation of ghost flights just to make money. The proposed mechanism is distributed, meaning that it directly involves each AU in the decision process of the slot reallocation and does not require the disclosure of delay costs, which AUs are very reluctant to reveal. Additionally, it does not require an external subsidisation to work, nor produces an economical benefit to be distributed outside the set of participants.

4.2.2 Centralised Peak Loading Pricing (CPLP)

This concept is based on the same ideas as the high-occupancy toll lanes used on toll roads. The idea is using a price mechanism to make AUs pay for the extra congestion they generate, encouraging the redistribution of demand to less congested options (in space or time). For the use of terminal and en-route air navigation services, AUs are required to pay some charges to Air Navigation Service Providers (ANSPs). En-route charges depend on the states crossed by the route path and the distance flown within each state. The national charge is equal to the product of the distance factor, the weight factor of the aircraft, and the national unit rate. With that in mind, Bólic et al. (2017) proposed a **Centralised Peak-Load Pricing (CPLP)** mechanism which allows the modulation of en-route charges to prevent demand and capacity imbalances. The mechanism approaches the pricing concept in a centralised manner, defining a central authority which is responsible for setting en-route charges in the network. CPLP consists of two phases. Firstly, congested airspace sectors and their related peak and off-peak hours are detected. In the second phase, the central planner adjusts en-route charges and AUs react to the pricing strategy by changing from expensive routes to cheaper ones. As unit rates are currently set once per year, the effect of the pricing mechanism is only evaluated at the strategic level, meaning that last-minute disruptions are not taken into consideration.

4.2.3 Route Contracts

Route contracts are another solution proposed in the literature to mitigate the impact in terms of cost which AUs experience during capacity-demand imbalances. By signing an advanced route contract with the ANSP, AUs agree on a minimum level of airspace operational services according to the limits, terms and conditions of the contract. Route contracts signed with the ANSPs can also be seen as a first endowment to be exchanged in a secondary market (NextGen JPDO, 2011).

A promising use of route contracts for delay mitigation was illustrated in the SESAR Exploratory Research project **COCTA** aimed at improving the efficiency as well as the quality of air navigation service provision in Europe through better coordination of capacity and demand. The concept proposed by COCTA reinforces the role of the Network Manager with the ability of having contractual relations with ANSPs and AUs. The Network Manager displays a dual role, being in charge of both the capacity definition, with the ANSPs (strategic and pre-tactical phase), and the demand management, with AUs.

On the capacity side, the Network Manager matches airspace capacity with expected demand by means of a network-centred and demand-driven approach. Consequently, excessive provision of airspace capacity is reduced, with associated cost savings. On the demand side, the Network Manager makes use of trajectory pricing to offer different routing options to AUs. AUs are not charged for the air navigation services by the sectors crossed but rather for the city-pairs they are flying. Therefore, there is no motivation for AUs to choose longer routes just to avoid expensive sectors, which also brings in environmental benefits. AUs choose between different route packages, which are contractual permissions to fly within a given margin of spatial deviation from the shortest route between a city-pair. When AUs purchase this permission (in the strategic phase) they obtain the right to fly a route within these margins, however it is the Network Manager who decides shortly prior to departure (tactical phase) on which route exactly the aircraft needs to fly. The charges that the aircraft needs to pay depend on the flexibility margin granted by the Network Manager, being more expensive for the products with smaller margins (which means that the route will be closer to the optimal one). The project results show that the COCTA approach allows the same traffic volume to be handled with 6% less use of capacity, with a reduction of (up to) 83% in the total minutes of delay (Jovanovic et al, 2018).

4.3 Non-monetary Market-based Mechanisms

Some stakeholders are reluctant to accept prioritisation mechanisms which involve monetary transactions. Non-monetary market mechanisms, based on the use of a virtual currency, or credits, provide an alternative to avoid this problem. Credit mechanisms are often designed to allow AUs to participate, reflecting the value of their flights involved in an operation without explicitly divulging sensitive information regarding business strategies and costs of delay.

4.3.1 Flexible Credits for Low Volume Users in Constraint (FCL)

All the proposed prioritisation mechanisms are aimed at improving the flexibility by which AUs can change their operational strategies to minimise the impact of the delay (cost of delay) in case of disruptions. However, many of these allocation mechanisms are ineffective when an airline has a low number of impacted flights in a hotspot, creating a situation of reduced flexibility or even no flexibility at all. Based on the analysis of all the European airport regulations over 20 consecutive AIRAC cycles, it has been estimated that the proportion of Low Volume Users in Constraint (LVUCs) in daily hotspots is large: on average, two thirds of the AUs affected by a regulation can be considered LVUCs (Ruiz et al, 2019).

Flexible Credits for Low Volume Users in Constraint (FCL) (also known as **Extended-SFP, ESFP**) is a concept proposed in the scope of SESAR research on new UDPP features. The potential advantage is the ability to also provide flexibility to AUs with a low number of flights involved in a regulation, thus improving equity and access. It is based on the use of a virtual currency without monetary value, named delay credits. It is considered as an extension, or a complementary mechanism, to other UDPP features such as Selective Flight Protection (SFP).

ESFP follows a ration-by-effort principle, meaning that AUs can gain delay credits by accepting extra delay on their lower-priority flights, and then spend these credits to protect higher-priority flights. For instance, an airline with just one flight affected by a regulation could accept more delay when it is far from its operational margins and the disruption does not come with an excessive increment in cost, positively impacting other delayed flights in the hotspot. In exchange for this delay absorption, the AU earns some credit points which can be used in other or future hotspots to cut down the cost when one of its flights is impacted by severe delay. In order to tackle LVUCs' lack of flexibility, the concept of operation enables AUs to gain credit points in one hotspot and use them in another, so that even AUs with just one regulated flight in a hotspot can make use of the mechanism.

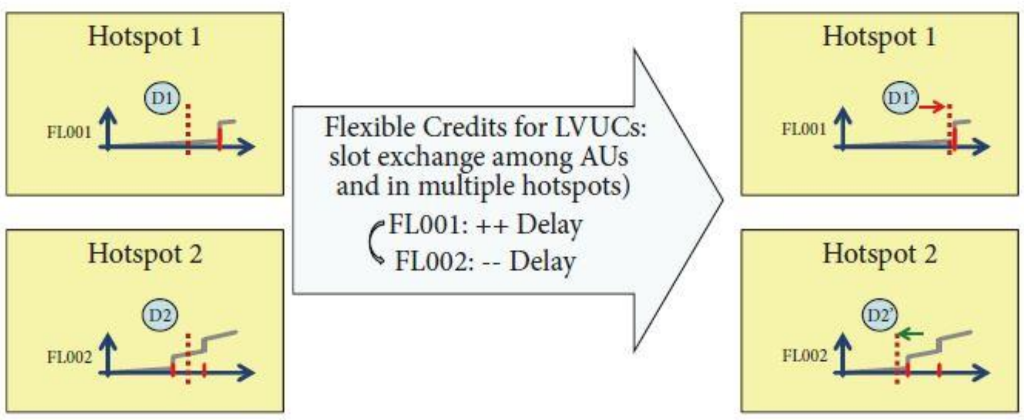

Figure 3. FCL mechanism with two hotspots. Source: EUROCONTROL

The operational concept underpinning ESFP is shown in ***Figure 3***. The case of an LVUC airline having only one flight in two different hotspots is illustrated. With the mechanisms proposed by UDPP so far (ESS, SFP and FDR) the airline cannot make use of any prioritisation system in order to reduce the imposed delay and the associated cost of delay. The ESFP mechanism enables the airline to sacrifice more delay in flight FL001 (Hotspot 1), whose operational margin is wider, without a relatively low increase of the cost of delay. In exchange for this delay absorption, the airline receives an amount of credit points in accordance with the extent of delay accepted and can make use of these credit points to reduce the amount of delay imposed to flight FL002 in Hotspot 2, which has a higher impact in terms of cost.

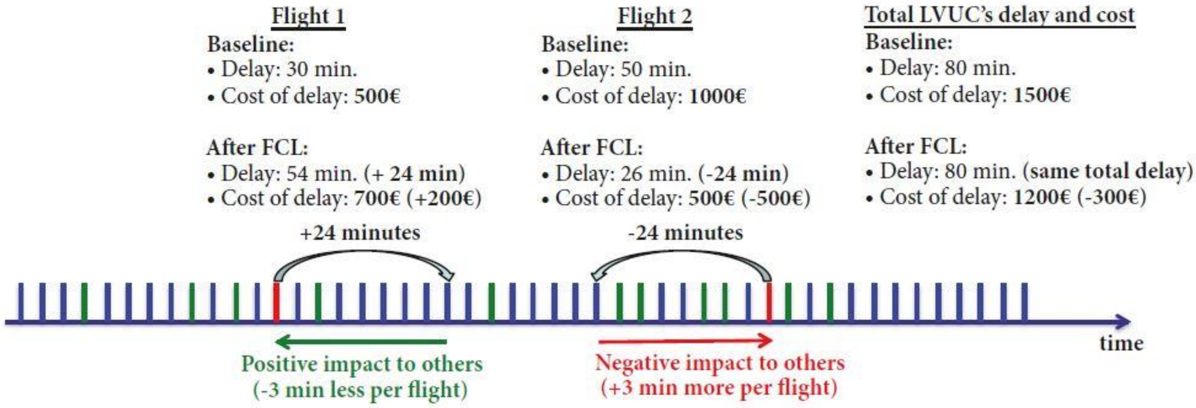

Figure 4. FCL mechanism with one hotspot. Source: EUROCONTROL

The ESFP mechanism is also suitable for use in a single hotspot. The mechanism is illustrated in ***Figure 4***. The timeline represents a sequence of ATFM slots belonging to different affected airlines. The airline represented by the red colour is a LVUC for the hotspot and can make use of the prioritisation mechanism. Accordingly, the airline decides to absorb some delay for Flight 1 (24 minutes), earning credit points (24 delay credits) which uses downstream to reduce the delay imposed to its second regulated flight in the hotspot (Flight 2). As a consequence, due to the non-linear nature of the cost of delay, the airline ends up reducing the total impact of delay (cost) in 300 euros, while the total delay in the hotspot remains constant. The prioritisation carried out by LVUCs can have a negative impact on the flights originally scheduled between the baseline position and the new prioritised flight position upstream the timeline, meaning approximately 2 or 3 minutes of extra delay. However, according to AU experts consulted by EUROCONTROL during the development of the mechanism, this negative impact on other airlines can be considered negligible (Ruiz et al, 2019).

The requirements for an AU to be classified as LVUC may be different from one hotspot to another. Even large airlines can often be considered as LVUCs in many hotspots (typically at airports in which they operate a few flights). The fact that any AU can be considered an LVUC at some point is expected to generate a higher level of acceptance, leading AUs to tolerate some degree of inequity in favour of LVUCs at some moment in time, but with equity being compensated over time (Ruiz et al, 2019).

4.3.2 Credit Points for Re-routing

Another concept making use of credits is proposed by Sheth and Gutierrez-Nolasco (2010), which extends the credit-based paradigm to route prioritisation. Currently, AUs are only permitted to specify one route when delivering the Flight Plan. This route is set, as far as possible, according to their business model and utility function; however, during times of reduced airspace or airport capacity AU preferences may change. The **Credit Points for Re-routing** mechanism relies on the possibility for AUs to deliver several optional routes for their flights, prioritising each route with credit points.

Prior to the start of each day, AUs receive a fixed amount of credits based on the size of their operations. Then the AU is expected to privately assign a different amount of credits to each route option, as long as the maximum credit assignment for each flight is within the credit balance. When a sector is flagged as congested due to excessive demand, the flight routes disclosed by the AUs are ranked by credits and the sector is filled up to capacity by the higher credit assignments. The flights whose routes are ranked with the lowest amount of credits are assigned to their next route preference in the list and the whole simulation is repeated. The iterative method is run until there are no regions with excess demand. The mechanism needs the development of a centralised server in charge of processing the routes and computing potential regions of capacity imbalance. Simulation results demonstrate that adding priorities to optional routes improves system performance compared to filing one route per flight and using the FPFS scheme (Sheth et al, 2010).

5. Selection of flight prioritisation mechanisms

The following table summarises all the reviewed prioritisation and slot allocation mechanisms, indicating the operational nature of the prioritisation concept, the ATFM phase(s) impacted by each mechanism[2] and whether they are currently in use in the ATM system. Additionally, a column showing the possibility of each mechanism to use credits on a later day different than the one in which they have been earned, is shown; obviously this only applies to market non-monetary mechanisms. The later will be very significant when simulating each of the selected mechanisms under the behavioural economics paradigm.

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
SESAR UDPP - Flight Margins	Rule-based	Pre-Tactical / Tactical (TBC)	No
Best-Performing Best-Served (BPBS)	Rule-based	Strategic / Tactical	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, ESFP	Market Non-monetary	Tactical	No
Credit Points for Re-routing	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 with the simulation model being developed by the project, which will be limited to the simulation of the ATFM tactical phase. The mechanisms selected for the different simulation experiments envisaged by the project are shown in the table below.

Simulation Experiment	Mechanisms	Operational Basis	Phase
Simulation 1	Baseline (ESS + FPFS)	Rule-based	Tactical
Simulation 2.1	Baseline + SFP	Rule-based	Tactical
Simulation 2.2	Baseline + SFP + FCL	Rule-based + Market non-monetary	Tactical
Simulation 3	Primary Auction	Market monetary	Tactical
Simulation 4	Secondary Auction	Market monetary	Tactical

[2] By "ATFM phase(s) impacted by each mechanism" we refer to those phases where certain decisions are impacted by the selected mechanism: for example, the BPBS mechanism depends on a strategic decision (e.g., retrofitting an aircraft with more advanced technology) and is then applied during the tactical phase to prioritise flights, so it is classified as Strategic / Tactical.

5.1 Simulation 1

As a first step, the current ATM concept of operations needs to be modelled and simulated. The FPFS policy and the solutions provided by SESAR UDPP Step 1 (ESS), as described in Section 2, will be implemented and simulated. The results obtained after the simulation will be used as a baseline for the performance assessment.

5.2 Simulation 2

Flexible Credits for LVUCs and UDPP Extended-SFP have shown potential to provide effective access to LVUCs to prioritisation mechanisms, which was a recurrent handicap for UDPP solutions developed so far. Furthermore, the use of a virtual currency instead of actual monetary transactions is expected to gain a higher level of acceptance by AUs.

FCL is developed as a new potential feature of the SESAR UDPP program, meaning that it is completely compatible with other proposed SESAR UDPP solutions like SFP. For that reason, the simulation will consist of two subsequent steps. First, only the baseline and the SFP mechanism will be simulated; then, the FCL feature will be added. In this way, the performance of each mechanism can be assessed both individually and jointly. Some questions that raised during the previous work will be investigated, as for instance the exact number of flights that could use FCL in any hotspot without jeopardising equity. Especially interesting is the analysis of the mechanism under possible “irrational” behaviours of AUs.

5.3 Simulation 3 and 4

As described in Section 4.2, market-based mechanisms seem to be potentially advantageous for flight prioritisation mechanisms due to the intrinsic nature of the problem, which is related to the efficient allocation of scarce resources. The third simulation will consist in an auction where the time slots in a hotspot are distributed between AUs depending on the bids they submit. The ATFM slot is assigned then to the AU with the highest bid, and consequently to the AU who values it more. The process is repeated for all the slots in the regulation, respecting the constraints defined by the SOBT of the flights.

The simulation of the market mechanism also presents a great opportunity to get a first glance of how AUs deal with the cost of delay. AUs will be modelled following different types of behaviours with the aim to test the robustness of the mechanism against unexpected or irrational practices.

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