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Improved flexibility and equity for airspace users during demand-capacity imbalance - an introduction to the user-driven prioritisation process

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Improved Flexibility and Equity for Airspace Users During Demand-capacity Imbalance

An introduction to the User Driven Prioritisation Process

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Abstract—**ATFM slot-swapping represents the first step towards the participation of airspace users (AUs) in air traffic management and airport collaborative processes. SESAR is advancing this through development of the user driven prioritisation process (UDPP) to achieve additional flexibility for AUs to adapt their operations in a more cost-efficient manner in the presence of unforeseen demand and capacity imbalances that require the application of delays to flights. The contribution of this paper is twofold: (i) to present the challenges achieved so far with respect to UDPP concepts, in particular regarding fleet delay apportionment and selective flight protection; (ii) to pave the way towards future UDPP concepts through the introduction of enhanced selective flight protection.**

Keywords-air traffic flow and capacity management (ATFCM), flexibility, hotspot, low-volume user in a constraint (LVUC), SESAR, user driven prioritisation process (UDPP).

I. INTRODUCTION

A. The impact of demand-capacity imbalances

Demand-capacity imbalances in Europe affected approximately 15% of flights in 2015, i.e., this proportion of flights either had an air traffic flow management (ATFM) slot or was otherwise regulated at airports [1]. The average impact of en-route ATFM delays, in 2015, was a delay of 0.73 minutes per flight on average [2], as compared with a target performance (ibid. p.23) of 0.5 minute per flight. It has been estimated that irregular operations may cost airlines some 2-3% of annual revenue [3] and have a significant impact on airlines' annual costs and revenues. ATFM delays are one of many such irregularities, but one over which airlines have little influence.

To mitigate such impacts, flights are (sometimes) prioritised to redistribute delay on the basis of the consequences on operations and costs, which could be due to factors such as crew out-of-hours constraints, maintenance slot requirements (such as a ramp check), passenger missed-connection costs, high-yield passenger business-retention ('soft') costs, or a missed airport curfew, etc.

Today, the air traffic management (ATM) system in Europe allows little flexibility to airspace users (AUs). Take for example ATFM slot swapping: in 2013, 1548 swaps [4, p.39] over 9.6 million flights represented less than 0.2% of all flights [5]. More flexibility, i.e. the ability of the ATM system to accommodate AUs' changing business priorities, could result in a better recovery process with substantial reductions of operational and cost impacts. Flexibility and equity (in the sense that one AU's prioritisation does not negatively impact another's) are key considerations.

B. The current prioritisation process

Since the mid-1990s, airspace users in Europe have been able to use ATFM slot-swapping to reduce their costs in the face of delays. If delays occur due to ATFM regulations, they can request the swapping of two flights involved in the same most penalising regulation.

SESAR has increased AU flexibility through early user-driven prioritisation process (UDPP) developments in Step 1. Enhanced ATFM slot swapping (ESS) offers an estimated average benefit (in terms of avoided losses) of EUR 4900 per swap for the AU [4, p.44]. The business case for ESS over 20 years is in the order of magnitude of hundreds of millions of euros [6]. ESS will be deployed by EUROCONTROL in 2017. Also an early development at airports, departure reordering can be requested in the context of airport collaborative decision-making (CDM), and UDPP has included an automated process

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for such reordering requests in the pre-departure sequence at CDG Airport, where important benefits have been measured during the demonstration project 'DFlex' [7], [8].

Those short-term improvements increase the AU's flexibility in the tactical phase. In certain circumstances, greater strategic mitigation can be effected earlier in the planning phase by AUs' flight operation centres - for example, by looking ahead to likely hotspots (due to capacity constrained situations) later in the day and pre-planning the response (these terms are defined in section II.A).

C. Incentive to change

The current ATM environment based on static flight plans (time-based operations) is evolving through SESAR towards a trajectory-based environment in order to improve airport and ATM network performance. Better performance of ATM operations depends on improved knowledge of the true demand at the planning stage and on better adherence to the plan during operations.

Beyond slot swapping, the aim of UDPP is to provide AUs with more flexibility to rearrange flight sequences during hotspots, through AU-driven prioritisation. Airspace users' participation in ATM and airport collaborative processes, including UDPP executed in such a way that the performance of all stakeholders is considered, is essential to minimise the impacts of deteriorated operations on all such stakeholders.

UDPP applies to departure, to en-route travel and to arrival, principally in a hotspot. Only UDPP for departure hotspots has been validated to date, although with very promising initial results also observed for arrival processes.

D. UDPP as a viable solution

As introduced in section A, capacity constraints and congestion impose large costs on airlines and passengers alike, with no significant capacity increases expected in the near- or medium-term. A thorough review, examining research trends and opportunities with regard to the management of air transportation demand and capacity is presented [9]. Directions for improvement through marginal capacity increases and better management of demand and available capacity are discussed, in addition to potential airline and state strategic initiatives.

Research into flight prioritisation methods covers a range of approaches. A points system based on flights (tending to favour smaller-aircraft operators), distances flown and seat-miles is explored in [10]. Credit-based human-in-the-loop simulations are investigated in [11] and a novel approach of assigning alternative routes with prioritisations is presented in [12]. Combinatorial auctions have been assessed in [13] in an optimisation approach for flight prioritisation, in a paper examining monetary and non-monetary mechanisms. A comprehensive NextGen review [14] established four prioritisation mechanisms as the most promising, out of ten mechanisms reviewed: priority-by-schedule; best-performing, best-served; priority points (similar to the operating credits of

UDPP Step 2, discussed below) and non-monetary market mechanisms (such as auctions, advance contracts and congestion pricing).

Resulting from an iterative UDPP concept elaboration and validation process involving AU representatives (Air France, Austrian, British Airways, the European Low Fares Airline Association, HOP!, the International Air Transport Association, SWISS, Turkish) since 2012, two new concept components, fleet delay apportionment (FDA), and selective flight protection (SFP), as shown in Table I below, can be employed to facilitate anticipative management of flight schedules.

Underpinning SFP is the 'ration-by-effort' (RBE) principle - first give, then receive. Each AU may voluntarily participate, by suspending a flight (i.e., moving it later in a departure sequence), for which it receives operating credits that may be used to benefit other flights of its own by protecting them: those protected flights revert to being almost on-time and flights from other AUs may also benefit from this move. RBE thus gives incentives to participants that generate positive externalities for other users (i.e., contribute to reduce the delay to other flights). Other rationing mechanisms have been compared in the literature, such as rationing by passengers, aircraft size or flight duration [15], with ration-by-schedule (slots assigned in order of scheduled arrival time) often preferred, for example when airline and passenger equity are primary concerns (*ibid.*) and for delivering minimum total delay under market principles [16]. RBS has also been explored in the collaborative-decision making context, relaxing slot ownership, also under market principles [17].

For UDPP, equity is the main constraint: the actions of one AU must not impact another's flights. The expected benefits of UDPP to AUs arise from a reduction of delay and cost for important flights during a hotspot. The UDPP concept allows the AUs to redistribute the delay across its fleet, through prioritisation of flights with high economic value over flights with lower economic value. The overall delay of all the flights in the hotspot remains the same (c.f. for FDA, the total delay remains the same for each AU).

TABLE I.   ANTICIPATIVE MANAGEMENT PRINCIPLES

Concept	Acronym	Principle
Fleet delay apportion-ment	FDA	AUs give relative priorities to their flights. For flights that become involved in a hotspot, the system apportions the delay among them according to the priority.
Selective flight protection	SFP	AUs 'protect' important flights relative to the schedule, to the detriment of less important flights that are moved to the end of the hotspot and are 'UDPP-suspended'

The final decision regarding the revised flight sequence is the result of a collaborative process involving all stakeholders (AUs, network management function, airports, flow managers, and air traffic control) and is currently created and managed by demand-capacity balancing (DCB) only in safety-critical

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(overloaded) situations. After safety priorities, the focus for ATM is to ensure optimised capacity and to expedite the recovery of the hotspot (by using 100% of available resources, such as runway throughput) until no delay remains. The AUs will focus on tactical costs (e.g., efficiently managing passenger delay) and operating close to schedule, especially for important flights, to avoid airport curfew infringements, aircraft out of position, and crew assignment issues, etc.

E. Structure of the paper

In the next section, the UDPP concept and definitions are presented in more detail, before an extended mechanism (enhanced selective flight protection) is introduced in section III. In section IV, wider conclusions are drawn and we take a look ahead to future research.

II. UDPP CONCEPT AND DEFINITIONS

A. Environment

The future SESAR Step 2 environment in which UDPP was devised is a continuous process of detection of demand-capacity imbalance, where the confidence in data becomes one of the major drivers in decision-making.

When a constraint arises at a local level, e.g., at an airport, impacting the airport actors on elements such as landing or departure runway capacity, the capacity constrained situation is declared for such elements, with a start and end time, per cent of remaining capacity, and a confidence index (CI).

This declaration triggers the definition of hotspots defined by the DCB processes per traffic volume within a time window (e.g., airport landing or airport departure), and managed by the local (airport) DCB processes.

A hotspot is defined by its stress period (during which demand is over the available capacity) and the recovery period (time needed to return to no-delay for all flights): i.e., hotspot = stress period + recovery period.

More than one hotspot can be defined within a capacity constraint, as shown in Fig. 1. In that case, UDPP addresses each one independently.

If there are dependency links between flights (due to aircraft, crew, connecting passengers, etc), they shall be managed by the AU through shared business trajectory (SBT) management and flight rotation management.

B. UDPP characteristics

1) Baseline delay

When a hotspot is detected, DCB applies a 'smoothing' policy (e.g., according to first-planned, first-served in the European ATFM system today) to allocate a delay to each flight involved in the hotspot. This baseline delay is used by the UDPP mechanism as reference value to calculate the delay after flight prioritisation, in particular at airports. UDPP allows airspace users to prioritise their flights in terms of IBT (in-block time) or OBT (off-block time). It defines a new UIBT/UOBT (UDPP in-block time/UDPP off-block time) that becomes the new demand from the AU in the hotspot. (It is important to note that these new times are still subject to change based on ATC constraints and optimisations).
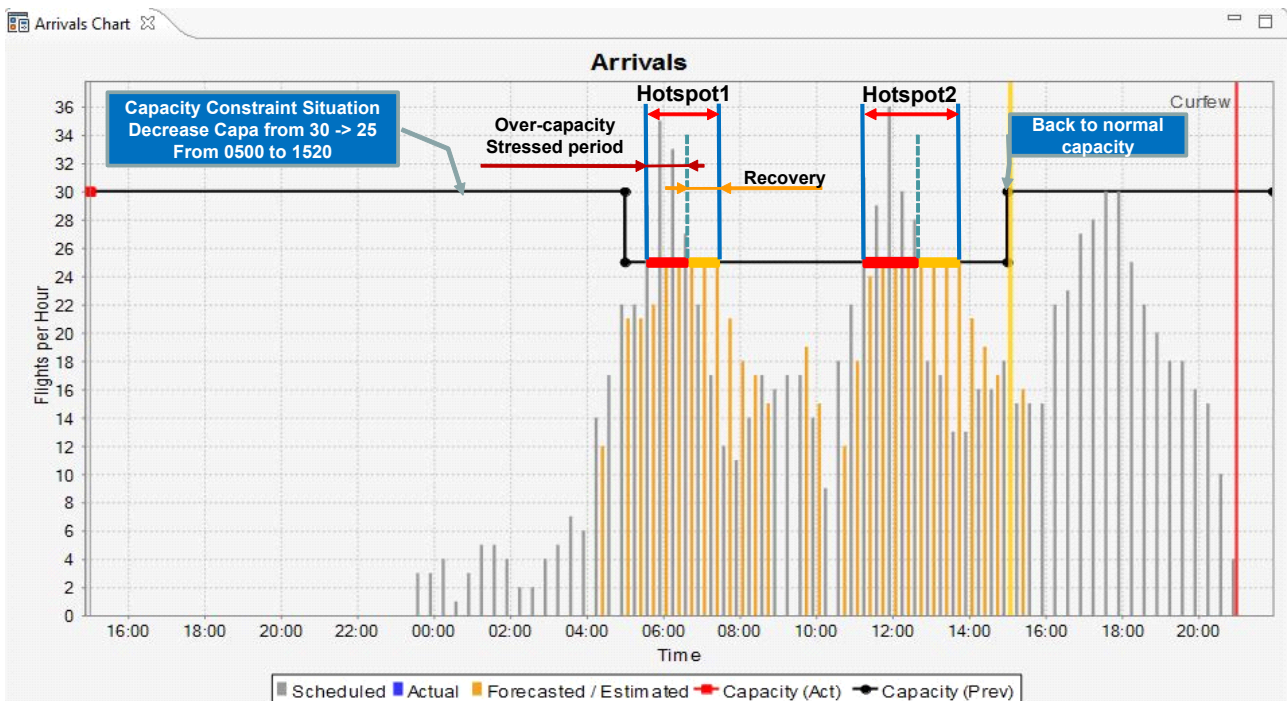

Figure 1.   Capacity constraint and hotspot definition

2) UDPP equity

All UDPP features are based on a very important characteristic: the equity between AUs, which prevents one AU's prioritisation actions from impacting negatively on the flights of others.

The implementation of equity in the UDPP algorithm uses the baseline delay, defined as the amount of delay a flight would be assigned if no UDPP prioritisation were applied. The total baseline delay of each AU in a constraint should remain the same as, or less than, the level before UDPP. Only those AUs that suspend flights to be able to prioritise may incur more delays (but with fewer cost impacts).

3) UDPP prioritisation

During UDPP prioritisation, the ability to re-organise the flights list in a hotspot is given to AUs. The outcome of the AU prioritisation does not impact the hotspot itself (same duration and same list of flights).

The UDPP prioritisation process is based on two features that AUs can use independently, or at the same time, depending on their needs: FDA and SFP. In the following sections we present briefly FDA first, and then SFP in more detail, as it is the basis for the following section on enhanced SFP (ESFP).

C. Fleet delay apportionment

The fleet delay apportionment component of UDPP Step 2 provides prioritisation options to AUs that recognise that some of their flights will have to operate behind schedule due to a hotspot and want control over how much each flight will be delayed. With FDA, each AU can distribute the amount of delay it must absorb among its flights, via a priority given to each flight.

The FDA priority value can be given prior to the hotspot declaration according to the business priority of a flight. These values could typically be set by the AU at the time of planning, before any hotspot is signalled by DCB. However, nothing in the concept prevents an AU from adding, removing or modifying FDA priority values after a hotspot appears.

The allowable FDA values are integers 1 through 9, with a value of 1 indicating the highest priority flights and of 9 indicating the lowest priority.

D. Selective flight protection

Selective flight protection allows an AU to protect some of its flights in the sequence, in exchange for the suspension of its other flights in the same hotspot. SFP entitles prioritised flights to operate at, or close to, their schedule.

In section II.D, we introduced the principle of ration-by-effort (RBE) and how this applies to SFP; we also introduced the main UDPP constraint of equity.

The third principle is that with SFP, AUs can (see Fig. 2):

- Suspend (UDPP-suspend) a flight: it will be pushed to the end of the hotspot. For convenience, we will use the term "suspension" in place of "UDPP-suspension" in the rest of the paper.

- Protect a flight: it will be on time.

Depending on operational considerations (e.g., the delay duration), the AU may ultimately decide to cancel a suspended flight – but flight cancellation is not part of UDPP.
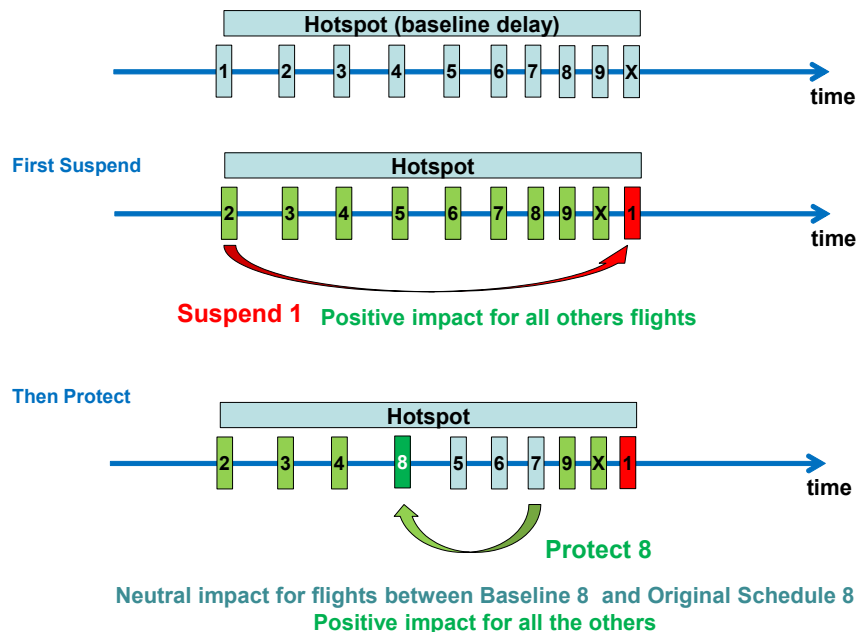

Figure 2. Selective flight protection high level description

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1) SFP operating index definition

It is assumed that the DCB function can predict the demand-capacity imbalance accurately to develop an operating index - associated with a confidence index - on which AU prioritisation can be based.

The operating index (OI) is nominally 100 and will be greater than 100 when demand exceeds the available capacity.

During the stress period, only a part of the demand can be accommodated (e.g., 75%). This ratio between the demand and the available capacity during the stress period drives the calculation of the OI as in (1), where D is the number of flights during the stress period and C the capacity during the stress period (i.e., number of available positions in the sequence).

$$OI = 100 \text{ x } D/C \qquad (1)$$

If only 75% of the flights are satisfied during the stress period, the OI is 133, calculated as the ratio 100/0.75.

During the recovery period, the OI/OC principles and use do not change with an OI value set to the last published OI in the stress period.

2) SFP operating credits definition

The operating credits are used to protect flights while respecting the constraint in the hotspot and the equity between AUs:

- Originally, each flight has 100 operating credits.

- An AU can suspend any flight, which simultaneously liberates its 100 OCs and moves the suspended flight to operate at the end of the hotspot (but still within it).

- Once it has liberated OCs by suspending flights, the AU can protect a number of its flights, this number depending on the OI (i.e., on the severity of the congestion): in this case, liberated OCs are allocated to those protected flights so that each protected flight has a number of OC equal to the OI.

- A flight whose OCs are equal to the OI will operate at (or as close as possible to) the original schedule.

Therefore, the number of flights that an AU can protect as a reward for a single suspension is OC/(OI-100). If this ratio is not an integer, then, given that one cannot protect half a flight, some of the liberated operating credits are not usable. Unused OCs can be used in future possible variations of the OI and are referred to as 'leftover' operating credits.

Fig. 3 below presents the evolution of the OCs (blue line) depending on the suspensions and protections made by an AU during a hotspot characterised by an operating index of 140.

It should be noted that when one or more AU uses SFP, in most cases this reduces the total delay for the other AUs as well.

3) Validity of the operating credits

An AU's flight can be protected only if the AU has sufficient operating credits to assign to it, i.e., after an effort has been made through suspension of another flight. When a flight is suspended, it liberates OCs only at its original schedule time – because the suspension liberates a space in the sequence and allows the protection of (an)other flight(s).
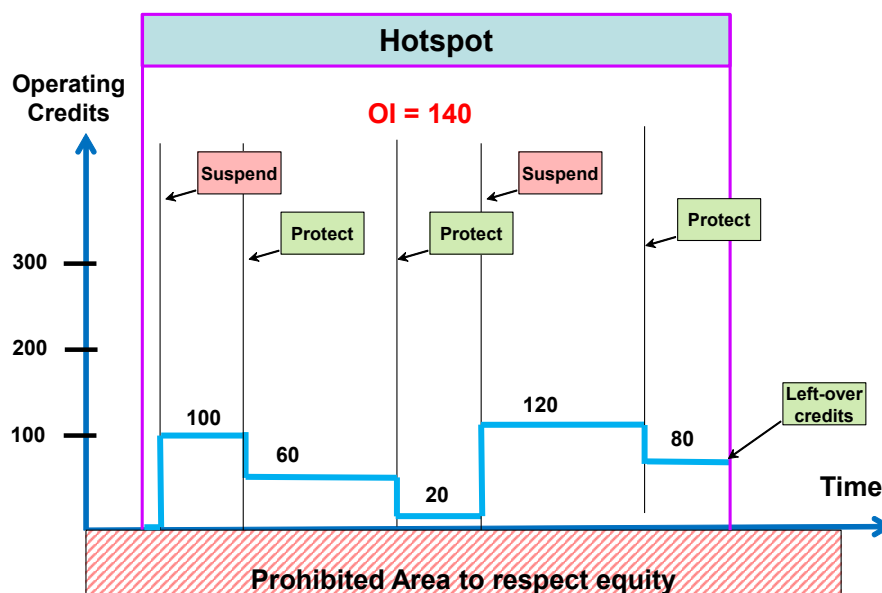

Figure 3. Operating credits dynamics

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The AU can then use these liberated OCs to protect any flight(s) with a scheduled time later than the position of the suspended flight, and in the same hotspot.

If a modification of the OI is published, a complete recalculation of the SFP values is performed to re-assess each flight status: suspended or protected. A new flight situation results in which if the OCs needed to protect a flight are not sufficient anymore, the flight is no longer protected: only compatible protected flights (with sufficient OCs available at the time of protection) will remain protected. Non-compatible flights return to their baseline delay.

4) Use of leftover operating credits

Leftover OCs can originate from several situations such as:

- The OI/OC ratio does not give a clear-cut number of flights that can be protected.

- Flights were protected but the OI changes and some OCs cannot be used anymore.

- The AU does not need/cannot use all its liberated OCs in the hotspot.

The question of what constitutes an allowable use for leftover OCs remaining after SFP decisions has been an open issue in UDPP. These leftover OCs could be:

- Exchanged with other AUs as a result of negotiation.

- Given to other alliance members to protect the network of the AU's alliance.

- Put in a 'common pot' for use by AUs that have only a few flights in the hotspot; these so-called low volume airspace users in a constraint (LVUC), could be either scheduled AUs with only a few/one flight(s) involved in the hotspot, or business or general aviation operating at an airport often but on an ad hoc basis.

- Several LVUCs (e.g., business aviation operators), may group their UDPP operations together in order to behave as a single 'virtual' AU.

These different possibilities, not explored as part of the UDPP mechanisms elaboration so far, are not developed further in the present document. However, one potential use of leftover OCs in future hotspots has been investigated and is presented in the next section.

III. ENHANCED SELECTIVE FLIGHT PROTECTION MECHANISM

According to SFP principles and rules, OCs obtained in a hotspot cannot be used to protect flights outside it, i.e., in other hotspots that may occur in a different place and/or at a different time. This restriction may unnecessarily penalise AUs with a low number of flights, i.e., LVUCs (see section 0). In fact, LVUCs usually have fewer chances to take advantage of the flexibility provided by the SFP mechanism than the other AUs.

For instance, if the OI of a hotspot is 115, an AU suspending one flight can protect six other flights (100/(115-100)). However, an AU with fewer than six flights cannot fully exploit its effort (i.e., the suspension). Likewise, an AU that operates just one single flight in a period and region affected by congestion will never be able to prioritise it, as it cannot make any prior suspension. This situation applies, for instance, to business aviation operators, that usually have only a few flights involved in a given hotspot. Similarly, a large AU may sometimes be classified as an LVUC at a spoke airport. Hence, any AU can be considered as an LVUC, depending on the circumstances.

The extended selective flight protection (ESFP) mechanism widens the scope of SFP to allow leftover OCs accumulated by an LVUC in a hotspot to be used in other hotspots (occurring in a different space and/or time). ESFP improves the equity level of SFP as it makes it possible to compensate LVUCs for their current and previous efforts, which - under SFP - provides benefits to other AUs only.

A. Equivalence factor for credits in different hotspots

ESFP allows LVUCs to save unused credits in hotspot i and carry them over to hotspot j. However, the carried-over credits should be weighted with an equivalence factor ($EF_{i,j}$) to preserve two key SFP's conditions, i.e., 1) no reward is given without a previous effort; and 2) no negative (significant) impact is allowed in the aggregated delay of other AUs. The equivalence factor between hotspots i and j is defined as in (2), where ω is the duration (in minutes) of the hotspot taking into account the stress and recovery periods in order to consider the differences between the hotspots in terms of demand-capacity imbalance, as shown in Fig. 4.

The second hotspot has a longer duration due to the lower capacity available during the recovery period, which can be used to absorb the excess demand after the stress period. Hence, the average delay will be larger than in the first hotspot, even if both have the same imbalance during the stress period. Such differences in the duration of hotspots must be taken into account to preserve the equity among AUs if OCs are brought from one hotspot to another.

$$EF_{ij} = \omega_i/\omega_j \qquad (2)$$

In a simplified scenario where credits can only be transferred from hotspot i to hotspot j, ESFP calculates the number of credits Cr_i and Cr_j for any AU as in (3) and (4), where S_i, S_j and P_i, P_j represent the number of suspended and protected flights in hotspots i and j, respectively. Cr_i and Cr_j are non-negative.

$$Cr_i = 100 \times S_i - (OI_i - 100) \times P_i \qquad (3)$$

$$Cr_j = 100 \times S_j - (OI_j - 100) \times P_j + Cr_i \times EF_{ij} \qquad (4)$$

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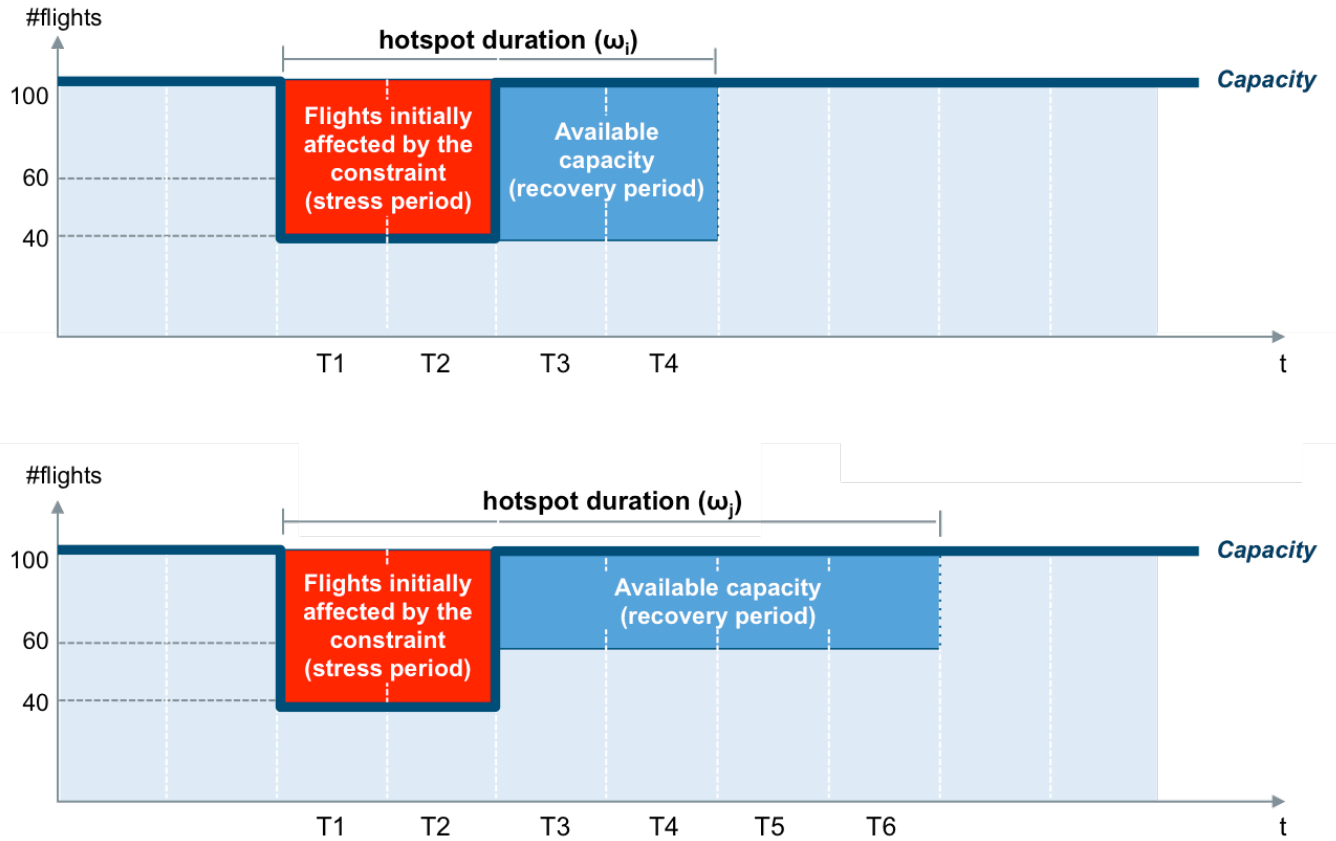Hosted by Technical University of Delft, the Netherlands

Figure 4. Different hotspots depending on their duration

Equations (3) and (4) can be recursively applied to use credits in multiple hotspots: if credits obtained in hotspot i (3) are used first in hotspot j (4) and later in hotspot k (i.e., k uses the remaining credits of j that in turn were the remaining credits from i), (3) is to be applied for j and then (4) for k. Therefore, the credits granted in i are weighted both in j and k.

B. Example of ESFP application

To illustrate the ESFP concept and how the equivalence factor works, a scenario composed of two hotspots H1 and H2 and based on realistic traffic data is presented in Table II.

TABLE II.　　HOTSPOTS CHARACTERISTICS FOR ESFP APPLICATION

Hotspot	Parameters			
	C	D	OI	ω
H1	20	27	135	300
H2	20	23	115	250

If an LVUC in hotspot H1 suspends only one flight ($S_{H1}=1$) it is rewarded with 100 OCs. If it protects only another one ($P_{H1} = 1$), the amount of leftover operational credits at the end of hotspot H1 is calculated according to (5).

$$Cr_{H1} = 100 \times 1 - (135 - 100) \times 1 = 65 \qquad (5)$$

This AU could protect 1 flight more in H1 with these remaining credits as a compensation for the delay reduction caused to other AUs. In the case that it decides to keep the credits and use them in a new hotspot H2, according to (4) and the definition of equivalence factor EF (2), the number of credits available in H2 (previous to any cancellation or suspension in H2, i.e., $S_{H2}=0$ and $P_{H2}=0$) is calculated as indicated in (6).

$$Cr_{H2} = 65 \times 300/250 = 78 \qquad (6)$$

Hence, this AU can protect a maximum of $78/(115-100)=5$ flights in H2 (instead of $65/(115-100)=4$) as a reward for the delay reduction caused to the other AUs in H1 (note that H1's duration is longer than H2's; thus the average delay in H1 is larger than in H2, and this is why a suspension in H1 allows the AU to protect as a reward more flights in H2 than in H1).

IV. CONCLUSIONS AND LOOK AHEAD

Future tactical priorities in ATM identified in [9] include: (i) incorporating robustness into ATFM allocation decisions; (ii) integrated modelling of airline operations recovery with real-time information regarding passengers, crew, and flights; (iii) enabling a dynamic exchange of recovery capacity across airlines, airports, ANSP and Network ATM actors, and time periods. Of course, these considerations are themselves related.

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Regarding (i), a series of human-in-the-loop validation exercises with airspace users on the SFP and FDA mechanisms has allowed us to mature the concept with regard to its feasibility and benefits, and further validation involving the ATM and airport actors is planned in SESAR2020 to complete such integration. In addition, performance modelling will be carried out, where challenges remain regarding the integration of uncertainty into both the modelling and application of ATFM in general, and prioritisation mechanisms in particular. Further research, planned by the authors of this paper, includes the incorporation of uncertainty (e.g., due to unpredictable events and changes in decision-making) into future models and an examination of how this impacts the robustness of solutions. This will also include the use of larger traffic data samples (particularly those with sufficient inclusion of common LVUC traffic mixes) and simulations to allow both the performance assessment of UDPP and the further exploration of assumptions made regarding on-going ESFP development and the extent to which it may be effectively generalised to all airspace users and across different hotspots. This generates further intriguing challenges that we have not had space to explore in this initial paper, particularly with regard to the usage, applicability, transferability and expiry of 'leftover' operating credits. Such future research will also need to establish metrics and indicators that can measure the impact of ESFP on established key performance areas (KPAs) – these impacts are currently relatively poorly understood, with hardly any insights available into the trade-offs between them.

Integrating prioritisation solutions with irregular operations recovery software (such as passenger reaccommodation and crew rostering tools), as flagged in (ii), remains a highly promising target for future development. Only with truly joined-up solutions will the effort invested in flight prioritisations return the highest benefits. This should include solutions minimising the cost of delay for airlines, which is well-established as a non-linear function of delay duration, and thus introduces interesting new relationships into the parameterisation and optimisation of prioritisation sequencing.

The ultimate goal of fully integrated planning and collaborative decision making across stakeholders and time, as per (iii), remains some way off, although this will inevitably be underpinned by system-wide information management (SWIM), at the core of SESAR, and will probably require further enhanced tools for the exchange of information relating to the margins of airspace user adaptability, which may be based on airline cost and passenger data. Nevertheless, clear progress is being made, some of which we have sought to share in this paper, such that improving airspace user flexibility, across all airspace user types, shows much promise for UDPP developments in SESAR 2020.

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