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Research Article

A New Air Traffic Flow Management User-Driven Prioritisation Process for Low Volume Operator in Constraint: Simulations and Results

Sergio Ruiz, Laurent Guichard, Nadine Pilon, and Kris Delcourte

DECMA/RTD/NET, EUROCONTROL Experimental Centre (EEC), Brétigny-sur-Orge, France

Correspondence should be addressed to Sergio Ruiz; sergio.ruiz@eurocontrol.int

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This document presents a new potential feature for the User Driven Prioritisation Process (UDPP) concept to give access and flexibility to Airspace Users (AUs) when they operate a low number of flights involved in a particular hotspot, a.k.a., Low Volume Users in Constraint (LVUC). Capacity constraints and congestion in the Air Traffic Management system impose delay to flights that cause large costs on airlines and passengers alike, with no significant capacity increases expected in the near-nor medium-term. Current UDPP features such as Enhanced Slot Swapping can increase flexibility for AUs to adapt their operations during capacity constrained situations. However, AUs are often impacted in their flight schedules by constraints that only affect a reduced number of flights, thus being in a situation of reduced flexibility—or no flexibility at all—to prioritise those flights. Some AUs are more vulnerable to this problem because they typically operate a low number of flights, e.g., business aviation. The new method proposed, named Flexible Credits for LVUC (FCL), is based on the use of "credits", as a virtual currency, to increase the flexibility of LVUCs irrespective of the number of flights operated or affected by delay. FCL aims at facilitating the smooth coordination between AUs during the optimisation of their operations across multiple constraints and over the time. An initial set of simulations performed under credible conditions are presented to preliminarily analyse the feasibility and limitations of the method and to shed light on future research aspects. A first empirical evidence is given in this paper showing that increasing flexibility for LVUCs is possible without jeopardising equity.

1. Introduction

The Air Traffic Flow and Capacity Management (ATFCM) Function of the air traffic management system aims at protecting airport and airspace sector operational capacities from excessive traffic during periods of saturated levels of traffic. For that purpose, if a significant imbalance between forecasted traffic and available capacity is predicted, a.k.a., *hotspot*, the ATFCM may impose delays or other measures on certain flights before they depart to maintain the operational safety level [1, 2]. The ATFCM measures that consist of applying predeparture ATFCM delays to the flights are denoted in Europe as *traffic regulations* [1] and in the US as *ground delay programs* [3].

In the current ATFCM paradigm, the delay imposed may cause flight cancellations and delay costs that impact the Airspace Users (AUs) through numerous cost elements (fuel, maintenance, crew, plus passenger "hard" and "soft" costs [4–6]). Since profitability in air transport industry is very sensitive to cost variations (profit margins were in 2017 around 7%, but they might be as low as 1-2% when fuel prices are high) [7, 8], the AUs would like more *flexibility*, i.e., the ability to accommodate their changing business priorities into the air traffic management system, to reduce the *"impact of delay"* (cost of delay) during irregular operations. However, under the current paradigm, the AUs are most of the time passive/reactive agents that have little influence on the slot allocation process.

To achieve additional flexibility for AUs to adapt their operations in a more cost-efficient manner, SESAR envisioned the development of the User Driven Prioritisation Process (UDPP) [9, 10]. UDPP is a concept that embraces several mechanisms/features, some of them at different maturity levels of development, to give flexibility to the AU to

- How to give *flexibility* to Low Volume Users in Constraint (*LVUCs*), i.e., AUs with a few flights (e.g., 3 or less), while preserving *equity* for the rest of the AUs?

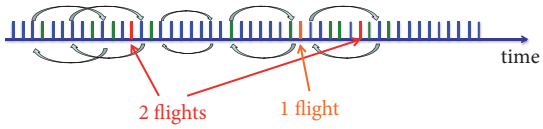

Figure 1: Illustration of the need to give access and flexibility to LVUCs.

redistribute the delay across its fleet, through prioritisation of flights with high economic value over flights with relative low cost of delay. With UDPP, the AUs have more opportunities to get their most important flights, i.e., typically the ones with greater impact on their all-day schedule, to be scheduled back on track. Through a reduction of delay in their most important flights, the AUs can often be able to satisfy their most important time-constraints in the schedule (e.g., connecting flights, curfews, crew constraints, among others). Thanks to such flexibility, cancellations and delay-induced cost for freight—including reactionary delay costs—can be reduced substantially. On the other hand, for UDPP, *equity* is the main constraint; i.e., the actions of one AU shall not generate a direct negative impact on another AU's flights (e.g., not increasing the delay of another's flights).

UDPP concept is currently under development and new features are being progressively incorporated aiming to fulfil different operational requirements and implementation constraints. Some of these features have already been proposed and validated with different levels of maturity, such as Enhanced Slot Swapping, which was validated in 2015 in terms of impact on equity and acceptability by the AUs and ATFCM, and have been deployed to operations in May 2017. Other less mature features are still under development and are being validated, such as the ones explained by N. Pilon *et al.* [10]. However, these UDPP features are especially available for AUs that have several flights/slots in a hotspot, a condition that will only occur at those airports where they have many flights scheduled in short periods, typically at their base airports. Unfortunately, AUs are not always in the ideal situation of having low priority flights (flights with enough margins and/or relatively low economic value) in positions nearby their most impacted flights (the high priority ones), so that they might not be able to swap their positions. A typical situation of lack of flexibility is when an AU has a small number of flights affected in a hotspot (e.g., 3 or less). In that case, the AU is called an LVUC (*Low Volume User in Constraint*) [11].

Figure 1 illustrates the lack of flexibility that AUs may experience if they are LVUCs at a given hotspot. In the figure, it is shown that AUs with a large number of flights can use the current UDPP features based on slot swapping between their own fleet, while two LVUCs in the example cannot: one AU has two flights in the sequence but if those are too far from each other they may be non-swappable; the other LVUC has only one flight, which makes it totally impossible for that AU to have access to the UDPP features based on slot swapping.

Based on the analysis of all the European airport regulations in 20 consecutive AIRAC cycles (roughly, one year and a half from Jan 2016 to July 2017, i.e. AIRACs from 1601 to 1707, taken from EUROCONTROL's Demand Data Repository), we have found that (a) the proportion of LVUCs in daily hotspots is large, being more than 2/3 of the AUs typically affected by regulations; since a typical regulation affects 9 AUs in average, it means that 6 of these AUs would be LVUCs; see Figure 2; and, (b) all AUs are often LVUCs: in 85% of the regulations in which AUs are involved (typically hundreds every day for most commercial airlines), they typically have only a few flights (see Figure 3), meaning that in most regulations the affected AUs will find their flexibility strongly limited.

Such problem is worse for those AUs that often operate just a few flights, since they have little flexibility and may even never be able to prioritise their relatively important flights (e.g., business aviation is especially vulnerable to that problem). This is considered to be inequitable from the *access* KPA point of view. Therefore, there is a need to explore new features in UDPP to enable more flexibility for all the AUs, in particular for LVUCs.

This paper introduces the problem of lack of flexibility of LVUCs for using UDPP and presents a new potential UDPP feature as a solution: the Flexible Credits for LVUCs (FCL), developed under the SESAR PJ07 project (Optimised Airspace Users Operations). The study in this paper has a special focus on the design phase for reaching operational feasibility of the concept with a potential for future deployment. An early assessment through fast time simulations has been conducted and is also presented in this paper, to preliminary explore the potential operational feasibility and limitations of the proposed mechanism.

The rest of the paper unfolds as follows. Section 2 discusses the state of the art and the research gaps approached by this paper. Section 3 presents the FCL model. Section 4 discusses the preparation of the simulations and scenarios. Section 5 shows the case studies and results. Section 6 contains the conclusions and identifies future work lines. In Appendix, a brief description of the optimisation model used in the simulations is provided.

2. State of the Art

2.1. Classical and Modern Literature about Collaborative Decision-Making in Slot Allocation. ATFCM slots currently follow the First Planned First Served (FPFS) method, i.e., sorting the flights by the estimated time of arrival at or over (ETA/ETO) the constrained airport or sector, according to the information present in the filed flight plans and assigning the slots in such order. This procedure is sometimes called Ration-By-Schedule (RBS) [12]. FPFS is widely accepted by the AUs because it preserves the original sequence of flights (considered fair), and it is well accepted today in ATFCM operations because it minimises the total delay in a regulation [12, 13]. However, although this policy was proven to be effective for the resolution of demand and capacity imbalances

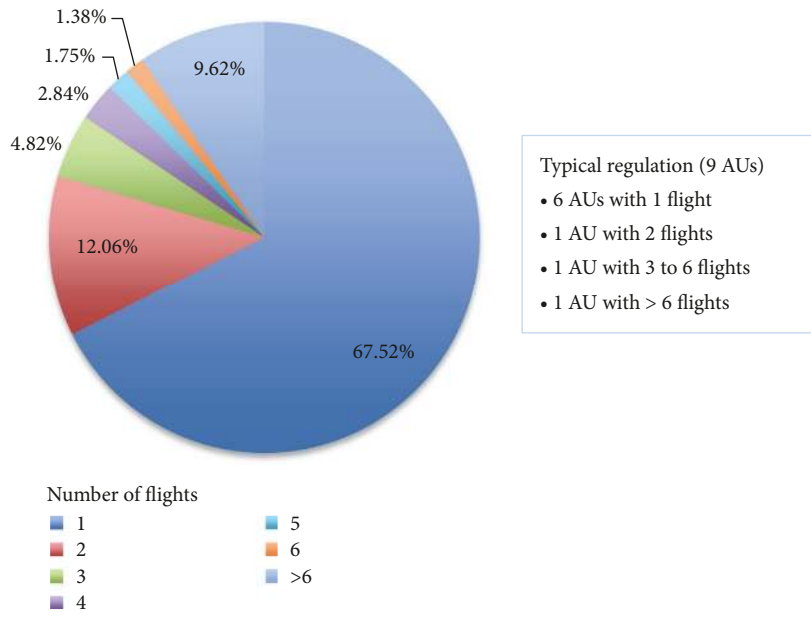

Figure 2: Statistically typical regulation/hotspot in terms of number of AUs and number of flights per AU.

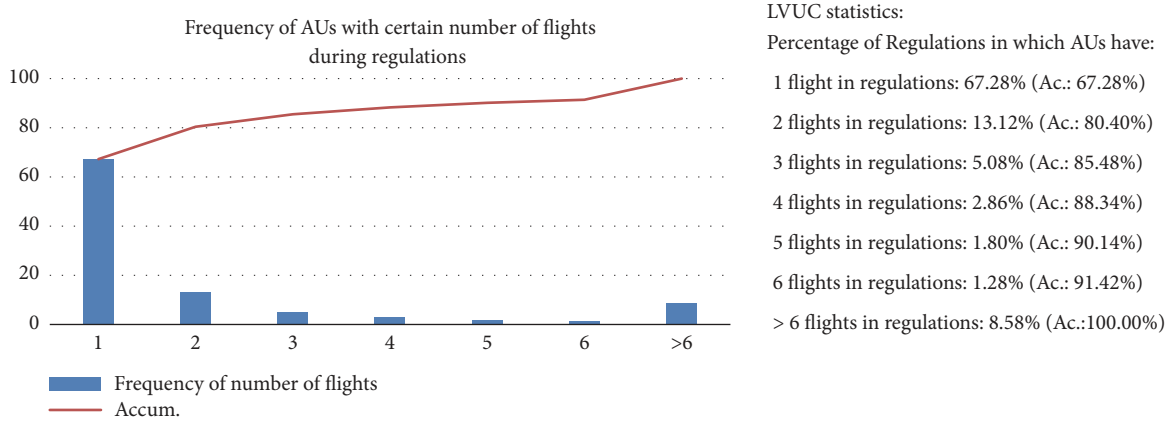

Figure 3: Statistically typical AU in terms of percentage of regulations/hotspots in which the AU has a certain number of flights.

(*hotspots*), it typically does not lead to an optimal allocation of the ATFCM slots in terms of costs for the AUs [14, 15]. Due to the level of saturation in both the European and US airspaces, a massive number of flights receive ATFCM delays every day, which causes important operational disruptions and costs to the Airspace Users (AUs), the airports, and passengers [4, 5]. Similar congestion issues are also faced today—or will be in next years—in other countries due to the worldwide increase of traffic, especially in Asia [4, 16, 17].

In a real operational environment, the AUs are in the best position to take business decisions on their own flights, because they have the required internal (and typically private) information; for this reason, different collaborative decision-making (CDM) processes have been studied in the last decades to allow the AUs to participate in the ATFCM decision loop [2, 15, 18, 19], as an essential strategy to minimise the impacts of deteriorated operations on all such stakeholders [20, 21]. The network and the airports can also be benefited from AUs optimising their own operations, since the reactionary delay is minimised and the adherence to airport slots increased [21]. In Europe, the CDM philosophy is the backbone of the UDPP concept.

Some early developments under CDM include the allocation of arrival capacity to the airlines according to the procedure RBS [12]. See Figure 4. This procedure has improved the collaboration between airlines and ATCFM Function with respect to the previous paradigm in which the flights were sequenced giving priority to the *most recent estimated time of arrival*. As a result, airlines do not forfeit a slot by reporting a delay or a cancelation, which was the case prior to the CDM improvement; thus the accuracy of information about delays and cancelations has increased significantly [12].

An important concept introduced with the CDM philosophy is the concept of "property", by which each AU has total control over the slots allocated to their flights by FPFS/RBS mechanism. It means that AUs have flexibility to

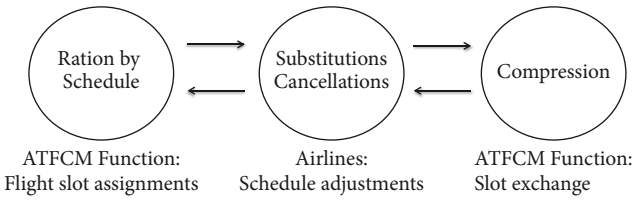

Figure 4: Classical CDM architecture.

exchange/substitute the flights allocated to the slots, without invading the allocations of competing companies (and then equity is preserved) [11]. The trade-off between efficiency and equity is well known and has become an important topic for discussion in the last years [11, 15, 19].

The procedure for inter-airline slot exchange under CDM is called Compression [12]. This procedure seeks to maximize, in a fair and equitable manner, the utilization of the available airport capacity during hotpot situations. If a flight allocated to a slot is cancelled, the concept of "priority" is taken into account by the system, which will try to allocate first those flights of the AU that owns the vacant slot. On this basis, more advanced inter-airline slot exchange mechanisms have been explored to increase the efficiency, but these new approaches are not today in operations, e.g., the ones proposed by Schefers *et al.* [14], by Vossen and Ball [19], or by Ivanov *et al.* [21].

In Europe, the slot swapping concept has also been adopted by UDPP, with some particularities to adapt it to the European context and with some operational enhancements developed under the SESAR programme. To increase the flexibility for AUs, the Enhanced Slot Swapping has refined some of the low-level operational and implementation rules, e.g., allowing multislot swapping instead of multiple binary slot swaps [9]. In addition, some functionalities to enhance the level of usability and automation of the optimisation processes that are controlled by the AUs have been developed and partially validated, such as the Fleet Delay Apportionment concept. In this concept, the AU can send a priority list to the ATFCM system so that the system will allocate the flights of the AU according to the list and not according to the FPFS/RBS rule [9]. Further evolutions built on the top of slot swapping concept were developed in the Selective Flight Protection feature of UDPP [9]. With such a feature, the AU can ask ATFCM to reduce the delay of a selected flight by increasing the delay of another flight placed earlier in the sequence. This has as advantage that the AU does not need to request multiple slot swaps to reach the desired result. Another advantage is that the AU does not sacrifice flights if there is the flight protection requested that cannot be implemented. It can happen, for instance, that a hole in the sequence generated by a flight releasing a slot cannot be filled with another flight. If the system cannot reduce the delay of the protected flight, then the extra delays requested for the earlier flights are not implemented. Similar advantages can be achieved with the Slot Credit Substitution implemented in USA [3].

2.2. Identification of Research Gaps: Lack of Flexibility for Low Volume Operators. In all the above mechanisms, AUs can adjust their schedules by substituting and cancelling flights. The equity is preserved because there is no negative impact to flights of other AUs when slot swapping is used between flights of the same AU. If compression is applied on the other hand (e.g., after a cancellation of a flight), it typically may generate a positive impact to other flights, often to the flights of the owner of the cancelled flight and quite often to flights of other AUs too. However, none of the above mechanisms has been designed to give flexibility to LVUCs; thus all of them fail for that purpose. Indeed, up to the best of our knowledge, no previous approach has been addressing the needs of LVUCs, while it is key—compulsory in Europe indeed—from the point of view of "access and equity" to find a new feature that allows the LVUCs to participate to the UDPP mechanism.

S. Ruiz *et al.* [11] showed that due to the nature of the problem (lack of available "owned" slots by LVUCs) it may be necessary to relax the equity constraints (no impact to others) at least momentarily in some situations. However, the impact generated by these new features for LVUCs to other flights might be negligible and thus acceptable by others, or might not be negligible but still accepted by others if they can obtain some direct benefits as a kind of compensation (see Figure 5), e.g., using the same mechanism when they are LVUCs in a hotspot, or if they are compensated with some better slots for some of their high-priority flights in exchange, yet in the same hotspot or in the long-term after multiple hotspots. The compensation should not be necessarily given by exactly the same AU that causes the impact, but rather others can compensate the negative impact. What is important is that in the long-term all the AUs should have no significant deviation from their baseline delay, i.e., no significant deviation from the total FPFS delay they would have gotten at the end of the reference period if UDPP was not enabled (equity should be preserved in the long term, e.g., after 1 year), and that the net economic impact is positive for all AUs.

A survey reported by Crown Consulting Inc. (M. Ball *et al.*) [22] concluded that market mechanisms present promising characteristics to achieve the many objectives of NextGen (or SESAR) while giving flexibility to the AUs and improving the economic efficiency of the air transportation industry. Due to the lack of acceptability of the AUs to pay money directly, a system of "credits"—referred to as Priority Points in the report cited—understood as a virtual currency without monetary value could be developed to increase the level of coordination between AUs and facilitate complex slot exchanges between AUs so that efficient and equitable slot sequences can be found.

Many advanced slot allocation mechanisms have been proposed by researchers with the aim of optimising the slot allocation process, such as mechanisms based on game theory, auctions, combinatorial auctions, market mechanisms, and a system based on credits, e.g. [13, 14, 19, 21, 23–25]. However, a large set of these methods have the handicap of being too difficult to implement in real operational environments and/or too complex to be operated by human operators. Therefore, the mechanism developed for LVUCs should be based on simplicity of design and usage; e.g., long iterative negotiation processes should be avoided to avoid generating too much workload to the flight dispatchers. S. Ruiz *et al.* [11]

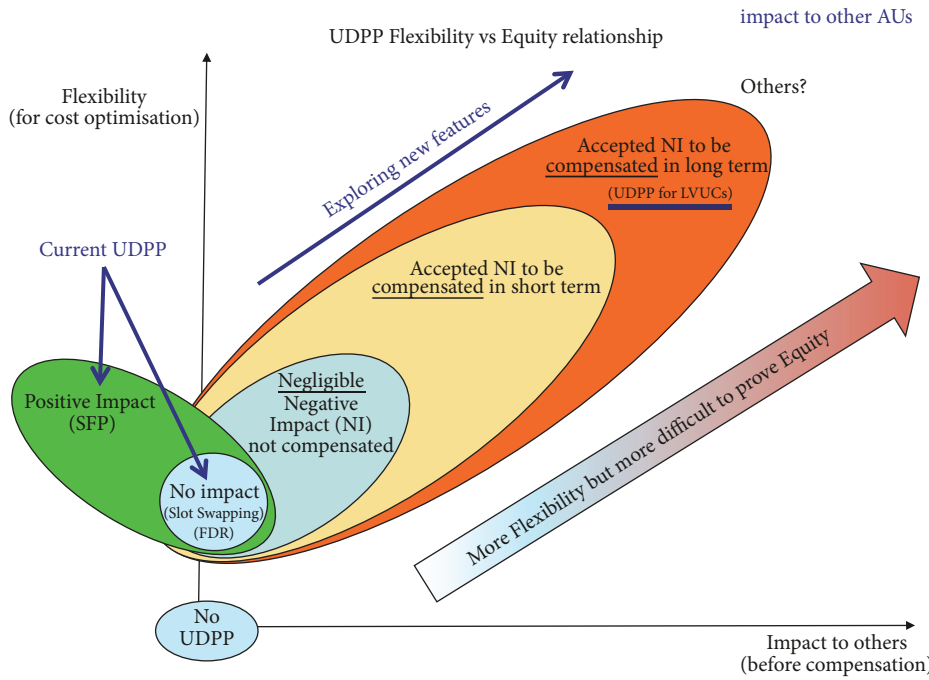

Figure 5: Conceptual relationship between flexibility and equity.

showed some early findings based on mathematical analysis suggesting that it might be possible to find a system with such characteristics. This paper builds on the top of such findings, as explained in the following sections, and presents the first empirical evidence that increased access to flexibility might be possible for LVUCs without jeopardising equity.

3. Flexible Credits for LVUCs (FCL): A New UDPP Feature

3.1. Overview of the Mechanism. The Flexible Credits for LVUCs (FCL) is a new UDPP feature built upon the existing collaborative decision-making mechanisms that will allow the AUs to participate in the reallocation of slots. FCL is considered as an extension and complementary to other UDPP features such as the Enhanced Slot Swapping (ESS) or the Selective Flight Protection (SFP).

The new proposed mechanism is based on the use of delay credits (DCs), a virtual currency without monetary value that can be used by LVUCs to enhance their flexibility for redistributing delays among their flights. To make it operationally acceptable for AUs, the FCL feature aims at facilitating the smooth coordination between AUs for the optimisation of their operations during hotspots.

The mechanism follows a *ration-by-effort* principle, i.e., aiming at keeping a fair balance between the delay saved and given to others. Thus, DCs can be earned and accumulated by AUs when they are LVUCs only if they accept extra delay in their low-priority flights. This will reduce the delay to flights of other AUs. DCs will be used in the right proportion to reduce the delay of their high-priority flights. One important characteristic of the proposed mechanism is that credits can be transferred from one hotspot to another, so LVUCs can increase their chances to prioritise their flights even when they only operate 1 flight in a hotspot. LVUCs can decide at any moment if credits are fully or partially transferred from one hotspot to another or alternatively can be used in the same hotspot (in case that the LVUC has more than one flight in a hotspot).

Business aviation operators usually have few flights involved in a given hotspot, so they will benefit greatly from the introduction of this new mechanism. For instance, an AU operating just one flight may accept more delay in a hotspot when its flight is far from its operational margins (in such situation its cost of delay is relatively low). Giving up part of its operational margins will help other AUs to reduce their delays, and in exchange the AU will earn some credits that he will be able to use in future hotspots to reduce the overall cost when his flight is impacted severely by delay (beyond the operational margins).

Consider the illustrative case in Figure 6 in which an LVUC has only one flight (FL001) in Hotspot 1 and one flight (FL002) in Hotspot 2. In both cases, the AU cannot improve his situation (lower the cost impact of delay) with the current Enhanced Slot Swapping, FDR nor SFP features. However, with FCL the AU could have access to UDPP and could substantially improve his situation. Note that in this example the flight FL001 has a certain amount of delay (D1) that could be increased, due to the operational margins available, with relatively low impact in terms of cost. Accepting the extra delay (D1' > D1), the AU is giving up his position and reducing the delay (positive impact) of the AUs between the original and the new sequence position. The AU can then be rewarded for this, with an amount of delay credits proportional to the extra delay accepted (in this document 1 DC = 1 minute of delay). In Hotspot 2, the LVUC could use the credits available

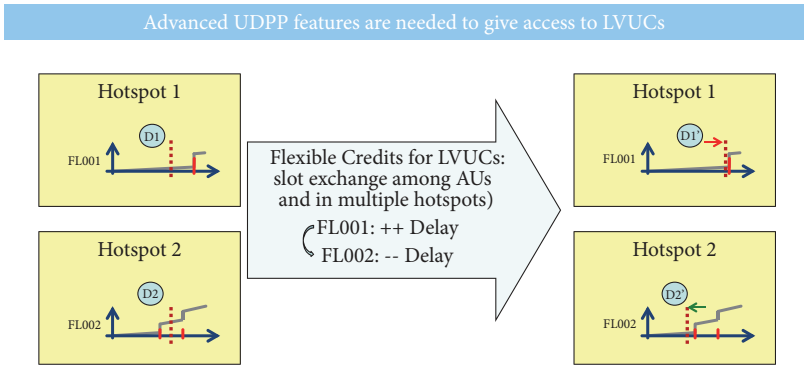

Figure 6: Illustration of an LVUC exchanging delay and credits between two hotspots.

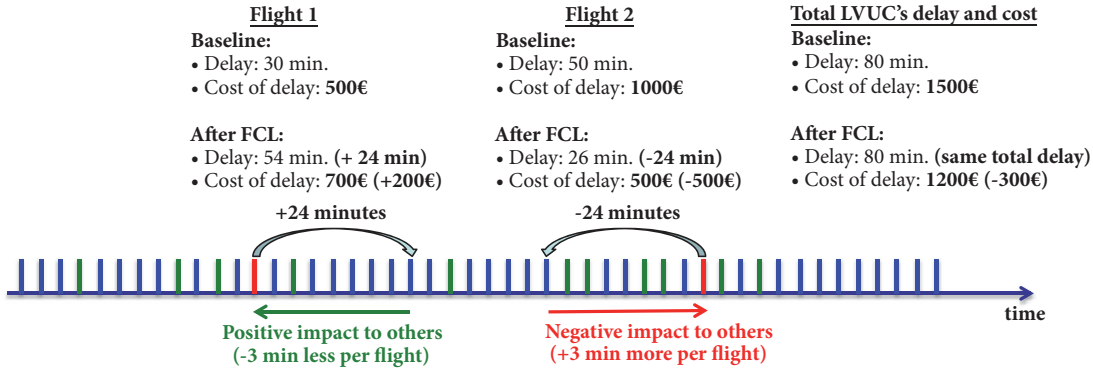

Figure 7: Illustration of an LVUC exchanging delay and credits in the same hotspot.

from Hotspot 1, because flight FL002 has an amount of delay D2 that has an important impact in terms of costs for the LVUC. After using part or all of the credits available, the AU can reduce the delay for that flight from D2 to D2', which is an amount of delay within the operational margins available for that flight, and therefore with marginal cost of delay. The AUs between the baseline and the new position are impacted negatively, but with just one position in the sequence (typically it means 2 or 3 minutes or less of extra delay).

The consideration of an AU as a LVUC may change in different hotspots according to the circumstances; therefore, even large airlines can often be considered as LVUCs in many hotspots (typically in hotspots at airports in which they operate a few flights). The access to FCL and LVUC rules to any AU—in those hotspots in which the AU can be considered as LVUC—can help to accept some degree of inequity in favour of LVUCs at some moment in time (but with equity compensated over time).

Another example is illustrated in Figure 7. The sequence in the example is dominated in presence by two AUs that are not LVUCs, represented by sticks coloured in green and blue, whereas there is a LVUC with only two flights, identified in the sequence in orange. The example illustrates how the LVUC can reduce the total impact of delay (costs) in the same hotspot by increasing +24 minutes the delay of flight 1, to obtain 24 delay credits, and then reducing the delay of flight 2 by giving the 24 credits gotten previously. In this example, a 20% of cost reduction could be achieved, due to the nonlinear relationship between the fleet cost structure and its delay. The impact on other flights can be considered negligible (3 minutes of extra delay per flight, if impacted), according to the AU experts that have reviewed such figures (further research will be conducted to fully validate such assumption).

3.2. FCL Rules to Preserve Equity under High Flexibility Conditions. In FCL, high flexibility is given to LVUCs to minimise their own global delay costs; i.e., the LVUC has full freedom to transfer its total *baseline delay* (i.e., initial ATFCM delay) among its flights and to exchange freely flight sequence positions with other AUs while only being subject to two particular equity constraints: (1) AU's total baseline delay cannot be reduced, and (2) the Maximum Negative Impact of Time (MNIT) for individual flights in a hotspot must be respected.

The main rules of FCL are defined as follows:

(1) Any AU with a given number of flights (3 or less is considered as an initial proposal) in a hotspot is considered as LVUC in the context of such a hotspot (note: perhaps other criteria might be used in the future to determine whether an AU is an LVUC in a given hotspot, e.g., the AUs' share of flights in the hotspot, but such a concept requires further research).

(2) Any LVUC in a hotspot can save credits obtained by increasing the delay in some flights (thus giving better

sequence positions to other AUs) and use them in that particular hotspot or keep them to use in future hotspots.

(3) Any LVUC in a hotspot can use Leftover Operational Credits (LOCs) obtained in the past to protect flights in the current hotspot; LOCs could be weighted up to take into account the differences of the hotspots in terms of duration and severity, so that the equity among AUs can be preserved (out of the scope of this research, though).

(4) LVUCs can request any target place in the sequence (e.g., corresponding to the optimal delay allocation for that flight), irrespective of where and when the efforts were done to obtain the credits (note that this rule applies only for LVUCs, which, by definition, are expected to have less flexibility than other AUs; it may occur that in a particular hotspot the only flight available for a suspension could be in positions after the one that is tactically important for the LVUC).

(5) The AUs' total delay at the end of the reference period (e.g., 1 year) must be the same (or near the same) as the baseline delay (delay without UDPP, e.g., FPFS).

(6) The Maximum Negative Impact of Time (MNIT) represents the maximum minutes of additional delay that LVUCs can cause to a flight of another AU. LVUCs might be unable to protect and reduce the delay for a particular flight if the MNIT has been reached for any of the flights it affects.

(7) All the requests will be sorted by the requested time and will be integrated in the sequence in FIFO order and by minimising the impact to others. No empty positions should be found in the sequence (compression) and requests that could generate impact greater than MNIT will be allocated to the nearest feasible solution.

3.3. Assumptions and Principles of the Mechanism. The proposed method is based on the following assumptions:

(i) All transactions of credits and slots exchanges will be initiated through the Airport or ATFCM actor triggering the UDPP mechanism, which will act as a broker and supervisor.

(ii) AUs must be consistent and accept any consequence derived from their own decisions.

(iii) Regarding the NM and the CFL system, one minute of delay will be considered as having the same "value" for all the flights (i.e., 1 minute delay = 1 DC). (note: to have more control on equity aspects, future research may consider different value of delay depending on the position in the sequence and the level of delay already allocated to such position).

(iv) No negative delays are allowed during the slot reallocation (this could be relaxed later, but for the moment this assumption is taken for the sake of simplification).

(v) No uncertainty associated with the new slot allocations planned during UDPP is considered (i.e., Confidence Index = 1).

(vi) Having credits is useful and positive for the AUs since credits provide flexibility to adapt the operations to changing and unforeseen conditions. AUs must contribute to the network with something in exchange, e.g., assuming extra delays for some flights under a regulation, to give their sequence positions to other AUs.

(vii) No loss of value or expiry of credits is currently considered (although this may be reviewed later).

(viii) AUs are able to and have the necessary information (e.g., historical records) to make decisions involving different hotspots over the time, thus making a stochastic/probabilistic management of delay and management of impact of delay.

(ix) The FCL decisions should be made and supervised carefully by expert human operators that will ensure the stability of the system and the application of good practice (i.e., automation shall only be provided to support human decision-making and control).

(x) If an AU sends no sequence position request for a given participating flight, it is assumed that it is willing to take advantage of any delay reduction opportunity for such flight (this assumption is consistent with the assumptions behind the compression algorithm detailed by T. bossen and M. Ball [12]).

(xi) FCL can coexist with the FDR and SFP features that will be used by non-LVUC operators.

(xii) Special care should be taken when extending the validity of the credits through different hotspots, as the severity, duration, or the flights involved are different in each situation. Hence, the credits should not have the same value in all hotspots. This is out of the scope of this research, but in future research an equivalence factor could be developed to update the number of credits to transfer credits from one hotspot to another, being equitable for the AUs involved, e.g., associating the number of credits given or requested according to the amount of delay associated with the positions released or taken.

4. Preparation of the Simulations

4.1. User Delay Optimisation Model (UDOM) Used in the Simulations. In order to generate trustworthy evidence through simulations, it is necessary to approximate the expected decisions potentially made by LVUCs using FCL with regard to the management of delay. For that purpose, the User Delay Optimisation Model (UDOM) presented by S. Ruiz *et al.* [11] has been used. A summary of the model together with an extension to include some implementation aspects can be found in Appendix.

4.2. Description of the Traffic Scenario. The scenario used for the case study has been previously used in some UDPP

Flights	ETA	CTA FPFS	Baseline delay	UCTA FCL	Delay UDPP	Diff. Delays
OA3 5896D	12:16	12:15	0	12:15	0	0
HUB 8384	12:16	12:18	2	12:18	2	0
Empty	12:21	12:21	0	12:21	0	0
LC2 2213	12:26	12:24	0	12:24	0	0
Empty	12:27	12:27	0	12:27	0	0
HUB 9757	12:31	12:30	0	12:30	0	0
LC1 311	12:31	12:33	2	12:33	2	0
HUB 6068	12:36	12:36	0	12:36	0	0
HUB 5701	12:36	12:39	0	12:39	0	0
HUB 6612	12:36	12:42	6	12:42	6	0
HUB 5229	12:38	12:45	7	12:45	7	0
LC2 6426	12:41	12:48	7	12:48	7	0
HUB 1988	12:46	12:51	5	12:51	5	0
OA2 320D	12:49	12:54	5	12:54	5	0
HUB 4325	12:51	12:57	6	12:57	6	0
LC1 2612	12:51	13:00	9	13:00	9	0
HUB 3422	12:56	13:03	7	13:03	7	0
HUB 8106	12:56	13:06	10	13:06	10	0
HUB 9359	13:02	13:09	7	13:09	7	0
HUB 9293	13:03	13:12	9	13:12	9	0
OA8 6731	13:05	13:15	10	13:15	10	0
OA5 727D	13:06	13:18	12	13:18	12	0
HUB 5126	13:06	13:21	15	13:21	15	0
LC1 4740	13:06	13:24	18	13:24	18	0
HUB 9649	13:07	13:27	20	13:27	20	0
OA1 5626	13:16	13:30	14	13:30	14	0
HUB 9173	13:17	13:33	16	13:33	16	0
HUB 9423	13:18	13:36	18	13:36	18	0
HUB 5366	13:19	13:39	20	13:39	20	0
HUB 4009	13:19	13:42	23	13:42	23	0
HUB 8488	13:21	13:45	24	13:45	24	0
HUB 4025	13:22	13:48	26	13:48	26	0
HUB 1723	13:26	13:51	25	13:51	25	0
HUB 5084	13:27	13:54	27	13:54	27	0
HUB 4624	13:28	13:57	29	13:57	29	0
HUB 1654	13:28	14:00	32	14:00	32	0
OA8 4205	13:33	14:03	30	14:03	30	0
HUB 9873	13:34	14:06	32	14:06	32	0
HUB 3784	13:38	14:09	31	14:09	31	0
LC2 2413	13:39	14:12	33	14:12	33	0
HUB 5912	13:46	14:15	29	14:15	29	0
LC1 1592	13:46	14:18	32	14:18	32	0
HUB 1746	13:46	14:21	35	14:21	35	0
LC2 2315	13:46	14:24	38	14:24	38	0
LC1 6825	13:47	14:27	40	14:27	40	0
HUB 6434	13:47	14:30	43	14:30	43	0
OA1 318	13:47	14:33	46	14:33	46	0
HUB 4321	13:48	14:36	48	14:36	48	0
HUB 761	13:48	14:39	51	14:39	51	0
HUB 6242	13:51	14:42	51	14:42	51	0
HUB 8150	13:51	14:45	54	14:45	54	0
LC2 2119	13:54	14:48	54	14:48	54	0
HUB 591	13:55	14:51	56	14:51	56	0
HUB 5618	14:00	14:54	54	14:54	54	0
LC2 8387	14:02	14:57	55	14:57	55	0
OA8 8611	14:04	15:00	56	15:00	56	0
LC2 5206	14:04	15:03	59	15:03	59	0
LC1 7103	14:06	15:06	60	15:06	60	0
OA3 2151	14:10	15:09	59	15:09	59	0
OA8 8667	14:11	15:12	61	15:12	61	0
LC1 1105	14:16	15:15	59	15:15	59	0
HUB 3749	14:24	15:18	54	15:18	54	0
LC2 2373	14:24	15:21	57	15:21	57	0
LC2 532	14:26	15:24	58	15:24	58	0
OA5 108	14:26	15:27	61	15:27	61	0
OA1 192	14:36	15:30	54	15:30	54	0
OA1 1714	14:41	15:33	52	15:33	52	0
OA6 7277	14:56	15:36	40	15:36	40	0
HUB 3535	14:56	15:39	43	15:39	43	0
HUB 8114	15:06	15:42	36	15:42	36	0
LC2 6219	15:06	15:45	39	15:45	39	0
OA8 356	15:08	15:48	40	15:48	40	0
HUB 6065	15:09	15:51	42	15:51	42	0
OA6 1107	15:16	15:54	38	15:54	38	0
HUB 4033	15:16	15:57	41	15:57	41	0
HUB 8308	15:19	16:00	41	16:00	41	0
OA1 414	15:31	16:03	32	16:03	32	0
HUB 6072	15:34	16:06	32	16:06	32	0
HUB 5723	15:41	16:09	28	16:09	28	0
HUB 8639	15:42	16:12	30	16:12	30	0
HUB 5622	15:46	16:15	29	16:15	29	0
LC1 1844	15:48	16:18	30	16:18	30	0
OA1 824	15:52	16:21	29	16:21	29	0
LC2 1052	15:56	16:24	28	16:24	28	0
HUB 8374	15:56	16:27	31	16:27	31	0
LC2 9998	15:57	16:30	33	16:30	33	0
HUB 8498	16:03	16:33	30	16:33	30	0
HUB 8214	16:06	16:36	30	16:36	30	0
OA4 8655	16:06	16:39	33	16:39	33	0
HUB 8635	16:15	16:42	27	16:42	27	0
HUB 1729	16:15	16:45	30	16:45	30	0
OA2 101D	16:21	16:48	27	16:48	27	0
HUB 5815	16:21	16:51	30	16:51	30	0
OA6 955	16:33	16:54	21	16:54	21	0
OA5 680D	16:36	16:57	21	16:57	21	0
OA6 2033	16:46	17:00	14	17:00	14	0
HUB 771	16:48	17:01	13	17:01	13	0
OA8 8223	16:51	17:02	11	17:02	11	0

Figure 8: Schedule list with ETAs, CTAs, and calculated delays.

validation exercises and has been slightly adapted for the purpose of this new research. It is based on historical traffic demand of 96 flights at a coordinated airport from 12:15 to 17:00 approximately.

Figure 8 shows the schedule list in detail, showing the Expected Time of Arrival (ETA) planned for each flight, the new Controlled Time of Arrival (CTA) assigned by FPFS policy (CTA FPFS), and the calculated delay, also the new user-preferred CTA after the application of FCL prioritizations (UCTA FCL) and the calculated delay. The last column shows, for each flight, the difference in the delay allocated by FPFS and ESFP mechanisms. Note that ESFP takes as a baseline the same policy applied at a given airport, in this case FPFS; thus at the beginning there is no difference in the baseline delay.

Figure 9 shows the evolution of the delay in the hotspot, which is directly correlated with the number of positions, k_i, that a flight i is far from its original position in the sequence (delay is proportional to the number of positions and the size in time of each position in the sequence).

Table 1 shows the distribution of flights and delay per Airspace User. Note that delay is distributed among AUs, after aggregating the delay of all their flights, as a direct proportion of the share of flights. A certain degree of concentration of some flights has been identified after analysing the flight positions, especially for the user HUB and LC2. In this particular case, HUB has many of its flights in positions with low delay and LC2 has the flights concentrated in positions subject to relatively long delay.

Note that some AUs have three or less flights in the sequence and therefore they can be considered as LVUCs.

4.3. Description of the Cost Model Used and Its Parameterisation. A simplified cost model has been taken into account in the simulations to quantify the impact of delay on flights. The costs of delay for flights have been modelled with a quadratic function as follows:

$$c(d) = \frac{\varepsilon}{2} d^2 \tag{1}$$

Using a quadratic model instead of more realistic nonsmooth and nonconvex utility curves is a strong simplification (see Figure 16) that cannot be made in all the contexts to generate reliable evidence. However, for the purpose of

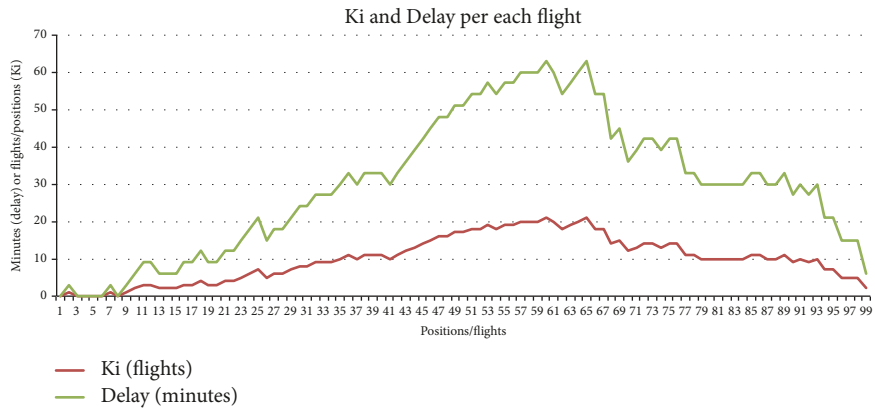

Figure 9: Ki and delay per flight.

Table 1: Distribution of flights and delay per AU.

AU name	Total flights	% of flights	Baseline delay (min.)	% of B. Delay	Baseline Cost (€)	% of B. Costs
HUB	52	54.17%	1316	48.74%	-29283	45.04%
LC1	8	8.33%	248	9.19%	-4735	7.28%
LC2	12	12.50%	421	15.59%	-12471	19.18%
OA1	6	6.25%	227	8.41%	-7178	11.04%
OA2	2	2.08%	27	1.00%	-425	0.65%
OA3	2	2.08%	59	2.19%	-1131	1.74%
OA4	1	1.04%	33	1.22%	-811	1.25%
OA5	3	3.13%	73	2.70%	-2632	4.05%
OA6	4	4.17%	99	3.67%	-1658	2.55%
OA7	0	0.00%	0	0.00%	0	0.00%
OA8	6	6.25%	197	7.30%	-4691	7.22%
	96		**2700**		**-65017**	

this research, such simplification brings more advantages than disadvantages. For instance, it eases the analytical study—with UDOM—of the dominant strategies of the AUs followed during the optimal redistribution of their delay, and thus to anticipate the expected dynamics in the system, which is the main purpose of this research. The emergent dynamics of the system will be analysed under the hypothetical what-if scenario in which some AUs are allowed to optimise the allocation of their delay by redistributing, under high-flexibility conditions, their baseline delay among their constrained flights. It should be noted that the underlying system dynamics should be similar either with the simplified model or with more realistic utility curves, since these dynamics depend mostly on the trends driven by the AUs' dominant strategies. Such simplified approach also allows calculating a first-order approximation to the cost reduction potential in relative terms (absolute realistic cost figures are hardly difficult to find, due to their privacy nature and their strategic value for airlines). For a more refined study of the potential benefits for the AUs, it may be necessary to adopt realistic nonsmooth curves and the approached with nonsmooth optimisation techniques (see, e.g., G. Stojkovic *et al.* [26], or R. Hoffman [27]).

Each flight of the scenario has been randomly parameterised with different sensitivities to delay, i.e., with different ε (a.k.a., elasticity). The assignation of epsilons/elasticities for each flight has been done randomly following a uniform probabilistic distribution bounded within the range $\varepsilon \in [-2, -0.5]$. All the flights had the same probability to get any value of elasticity within such range. In practice, it means that all the flights were assigned costs as a function of their delay within the maximum and minimum range illustrated in Table 2.

Such approximation of AUs costs is not fully representative of the high level of complexity of the actual cost structures (e.g., different types and sizes of knock-on delay impacts). However, the approach is considered valid at this maturity level to observe the potential benefits and/or impacts of FCL when flights and AUs with heterogeneous cost curves coexist in the same hotspot. The purpose is to early assess the potential feasibility of the FCL concept, to enable the observation of potential emergent dynamics, and to start

Flights	Baseline delay	Epsilon	Baseline cost	Optimal tau	Delay request	Optimal cost	Diff
OA3 5896D	0	-1.34	0	0	0	0	0.00
HUB 8384	2	-1.5	-3	0	2	-3	0.00
Empty	0	-1.85	0	0	0	0	0.00
LC2 2213	0	-1.35	0	0	0	0	0.00
Empty	0	-1.86	0	0	0	0	0.00
HUB 9757	0	-0.51	0	0	0	0	0.00
LC1 311	2	-1.55	-3	0	2	-3	0.00
HUB 6068	0	-1.63	0	0	0	0	0.00
HUB 5701	0	-0.97	0	0	0	0	0.00
HUB 6612	6	-1.69	-30	0	6	-30	0.00
HUB 5229	7	-1.95	-48	0	7	-48	0.00
LC2 6426	7	-0.7	-17	0	7	-17	0.00
HUB 1988	5	-1.39	-17	0	5	-17	0.00
OA2 320D	5	-1.38	-17	0	5	-17	0.00
HUB 4325	6	-1.54	-28	0	6	-28	0.00
LC1 2612	9	-1.44	-58	12	21	-325	-267.06
HUB 3422	7	-1.93	-47	11	18	-298	-250.60
HUB 8106	10	-1.23	-61	18	28	-467	-405.91
HUB 9359	7	-1.31	-32	19	26	-439	-406.77
HUB 9293	9	-1.7	-69	11	20	-338	-269.33
OA8 6731	10	-1.59	-79	16	26	-546	-466.13
OA5 727D	12	-1.19	-86	23	35	-739	-653.18
HUB 5126	15	-1.62	-182	6	21	-355	-172.63
LC1 4740	18	-0.81	-131	20	38	-578	-447.24
HUB 9649	20	-0.88	-176	19	39	-653	-477.31
OA1 5626	14	-1.01	-99	38	52	-1361	-1261.91
HUB 9173	16	-1.02	-131	17	33	-564	-433.08
HUB 9423	18	-1.13	-183	12	30	-509	-325.71
HUB 5366	20	-1.82	-364	-1	19	-316	48.11
HUB 4009	23	-1.42	-376	1	24	-405	-29.28
HUB 8488	24	-0.71	-204	24	48	-810	-605.25
HUB 4025	26	-1.04	-352	7	33	-553	-201.28
HUB 1723	25	-2	-625	-8	17	-287	337.54
HUB 5084	27	-1.39	-507	-3	24	-414	93.05
HUB 4624	29	-0.58	-244	29	58	-991	-747.34
HUB 1654	32	-1.33	-681	-7	25	-432	248.70
OA8 4205	30	-1.65	-742	-5	25	-526	216.71
HUB 9873	32	-1.57	-804	-10	22	-366	437.65
HUB 3784	31	-1.71	-822	-11	20	-336	485.45
LC2 2413	33	-1.43	-779	2	35	-874	-95.65
HUB 5912	29	-0.87	-366	10	39	-661	-294.98
LC1 1592	32	-0.55	-282	24	56	-852	-570.31
HUB 1746	35	-1.5	-919	-12	23	-383	535.48
LC2 2315	38	-0.79	-570	25	63	-1583	-1012.18
LC1 6825	40	-1.15	-920	-13	27	-407	512.56
HUB 6434	43	-1.6	-1479	-22	21	-359	1119.88
OA1 318	46	-1.92	-2031	-19	27	-716	1315.47
HUB 4321	48	-1.12	-1290	-18	30	-513	776.93
HUB 761	51	-0.51	-663	15	66	-1127	-464.02
HUB 6242	51	-1.05	-1366	-19	32	-548	817.99
HUB 8150	54	-2	-2916	-37	17	-287	2628.54
LC2 2119	54	-0.84	-1225	6	60	-1488	-263.64
HUB 591	56	-0.61	-956	0	56	-942	14.00
HUB 5618	54	-0.66	-962	-3	51	-871	91.20
LC2 8387	55	-1.12	-1694	-10	45	-1116	577.73
OA8 8611	56	-0.94	-1474	-12	44	-923	550.99
LC2 5206	59	-1.03	-1793	-10	49	-1214	578.91
LC1 7103	60	-0.56	-1008	-5	55	-837	171.30
OA3 2151	59	-0.65	-1131	0	59	-1131	0.00
OA8 8667	61	-0.96	-1786	-18	43	-904	882.38
LC1 1105	59	-0.87	-1514	-24	35	-539	975.67
HUB 3749	54	-1.94	-2829	-37	17	-296	2532.17
LC2 2373	57	-1.14	-1852	-13	44	-1097	755.24
LC2 532	58	-1.2	-2018	-16	42	-1042	976.55
OA5 108	61	-1.28	-2381	-28	33	-687	1694.53
OA1 192	54	-1.33	-1939	-15	39	-1033	905.68
OA1 1714	52	-1.12	-1514	-5	47	-1227	287.01
OA6 7277	40	-1.01	-808	-12	28	-408	400.04
HUB 3535	43	-0.98	-906	-8	35	-587	319.37
HUB 8114	36	-1.94	-1257	-19	17	-296	960.77
LC2 6219	39	-2	-1521	-14	25	-625	895.89
OA8 356	40	-0.72	-576	18	58	-1205	-628.93
HUB 6065	42	-0.71	-626	6	48	-810	-183.51
OA6 1107	38	-0.72	-520	2	40	-572	-52.44
HUB 4033	41	-1.07	-899	-9	32	-537	362.03
HUB 8308	41	-0.99	-832	-7	34	-581	251.38
OA1 414	32	-1.75	-896	-2	30	-785	110.57
HUB 6072	32	-1.29	-660	-6	26	-446	214.81
HUB 5723	28	-1.19	-466	0	28	-483	-16.64
HUB 8639	30	-0.88	-396	9	39	-653	-257.31
HUB 5622	29	-0.87	-366	10	39	-661	-294.98
LC1 1844	30	-1.82	-819	-13	17	-257	561.55
OA1 824	29	-1.66	-698	3	32	-828	-129.98
LC2 1052	28	-1.82	-713	-1	27	-687	26.50
HUB 8374	31	-1.42	-682	-7	24	-405	277.44
LC2 9998	33	-0.53	-289	32	65	-1120	-831.04
HUB 8498	30	-0.76	-342	15	45	-756	-414.46
HUB 8214	30	-1.4	-630	-6	24	-411	219.35
OA4 8655	33	-1.49	-811	0	33	-811	0.00
HUB 8635	27	-1.29	-470	-1	26	-446	24.54
HUB 1729	30	-0.72	-324	17	47	-795	-471.24
OA2 101D	27	-1.12	-408	0	27	-408	0.00
HUB 5815	30	-1.39	-625	-6	24	-414	211.89
OA6 955	21	-1	-220	8	29	-412	-191.54
OA5 680D	21	-0.75	-165	5	26	-254	-88.13
OA6 2033	14	-1.12	-110	2	16	-143	-33.60
HUB 771	13	-0.8	-68	1	14	-78	-10.80
OA8 8223	11	-0.55	-33	0	11	-33	0.00

Figure 10: Schedule list with delay, costs, and optimal delay requested per flight (case study 1).

Table 2: Distribution of flights and delay per AU.

Minutes of delay	Low cost flight ($\varepsilon = -0.5$)	High cost flight ($\varepsilon = -2$)
1st minute	0.25€	1€
10 minutes	25€	100€
20 minutes	100€	400€
30 minutes	225€	900€
40 minutes	400€	1600€
50 minutes	625€	2500€
60 minutes	900€	3600€
70 minutes	1225€	4900€

quantifying the potential benefits of flexibility for the LVUCs and for the rest of the AUs.

Table 1 shows the baseline delay and baseline costs per AU. Note that since the elasticities were randomly assigned to flights it was already expected that AUs had a proportion of costs similar to the share of delay.

5. Case Studies and Results

The following three case studies were simulated and analysed with the purpose of generating early empirical evidence about the potential feasibility and limitations of the FCL method. Case study 1 answers the question of whether the FCL feature can be used by all the AUs and for all the flights in a hotspot; case study 2 sheds light on whether the FCL mechanism could generate acceptable outcomes with a reduced number of flights using the mechanism in a single hotspot (3 flights was considered appropriate by a panel of AUs experts as a starting point for the analysis); case study 3 illustrates an example similar to case study 2 but including delay credits that are assumed to be transferred from past hotspots.

5.1. Case Study 1: All the AUs Using the FCL System. A first question that seems relevant to answer is whether the high flexibility conditions given by FCL could be used by all the AUs and not only by those considered LVUCs in a given hotspot. This question was preliminary discussed by S. Ruiz *et al.* in [11]. After that, several AU experts showed interest in exploring the possibility of using FCL by all the AUs, i.e., not only for LVUCs. This case study explores this idea.

Figure 10 shows the requested optimal delay changes (*taus*) calculated with UDOM, as well as the impact of the delay change on each flight. For convenience, it has been assumed that only the flights in and after the position of flight LC1 2612, a flight that has 9 minutes of delay, could be included in the FCL optimisation; i.e., the AUs could not use FCL to change the position of those flights earlier than flight LC1 2612.

Table 3 shows the aggregated impact on the costs per AU. Note that in relative terms all the AUs can optimise

Table 3: Potential cost reductions per AU using UDOM (case study 1).

AU name	Total flights	Baseline delay	Baseline cost	Optimal cost	Diff. Cost	% Reduc.
HUB	52	1316	-29283	-23007	6276	21.43%
LC1	8	248	-4735	-3799	936	19.78%
LC2	12	421	-12471	-10863	1608	12.90%
OA1	6	227	-7178	-5951	1227	17.09%
OA2	2	27	-425	-425	0	0.00%
OA3	2	59	-1131	-1131	0	0.00%
OA4	1	33	-811	-811	0	0.00%
OA5	3	73	-2632	-1679	953	36.21%
OA6	4	99	-1658	-1536	122	7.39%
OA7	0	0	0	0	0	0.00%
OA8	6	197	-4691	-4136	555	11.83%
	96	**2700**	**-65017**	**-53339**		

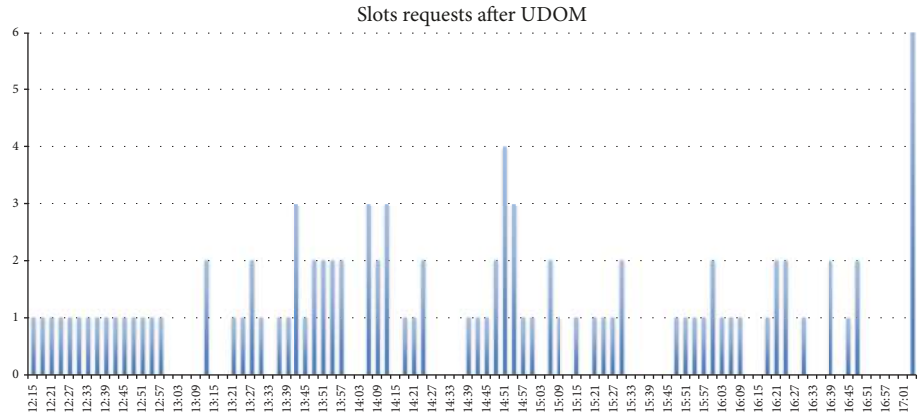

Figure 11: Slots requested by AUs after using UDOM (case study 1).

their costs in similar proportions, and it is worthy to point out that the AU with more potential for cost reduction has only 3 flights (an LVUC). The potential for cost reduction in this scenario for the AUs has been found within the range of approximately 7% up to 36% (average cost reduction of around 17%). The potential for cost reduction depends on the cost structure of the flights in the hotspot, and on the amount of delay allocated by the baseline sequence to each of the flights. Also it must be observed that some AUs—OA2, OA3, OA4, and OA7—cannot minimise their costs. In the case of OA2, OA3, and OA4, they have indeed just one of their flights in the hotspot (OA2 and OA3 have another flight but were not candidates for using FCL, since they are considered to be out of the hotspot); thus they cannot exchange delay between their flights. The use of credits with validity over the time could be used for giving flexibility to those AUs.

Figure 11 shows the slots demanded by the AUs with the aim of optimising their own costs. It can be observed in the figure that the demand is more or less evenly distributed. The presence of holes (slots not demanded), which are also spread more or less evenly along the sequence, is a consequence of the random distribution of cost structures (with different epsilons randomly assigned), together with the effect of the equity rule that forces the AUs to release slots in exchange of better slots for their relatively more expensive flights. Nevertheless, due to the need to allocate one flight to each available sequence position, the flights have been sorted by requested slot time and then they have been compressed to avoid empty slots and to optimise capacity.

Figure 12 is an evidence of complex dynamics and inter-AUs demand incompatibilities emerging after trying to join all the individual requests in a single sequence. The figure shows at each sequence position the difference in minutes between the allocated position and the one requested. In general, it can be expected that less delay than the one requested (negative values in the chart) will have positive impact on AUs, which is advantageous for those flights. In the middle of the sequence, due to the limited capacity with respect to new demand for slots, some flights can be found that requested less delay but that will receive more delay than requested (they will be placed at later positions). Therefore, due to the incompatibilities of the many AUs requests, some flights are getting less delay (and less cost) and some more delay (and more cost). Table 4 shows the total effect in the total cost supported by the AUs, while Table 5 shows the new distribution of delay per AU. It can be noted that some AUs are significantly worse-off in terms of delays and costs after trying to optimise their costs through the FCL mechanism.

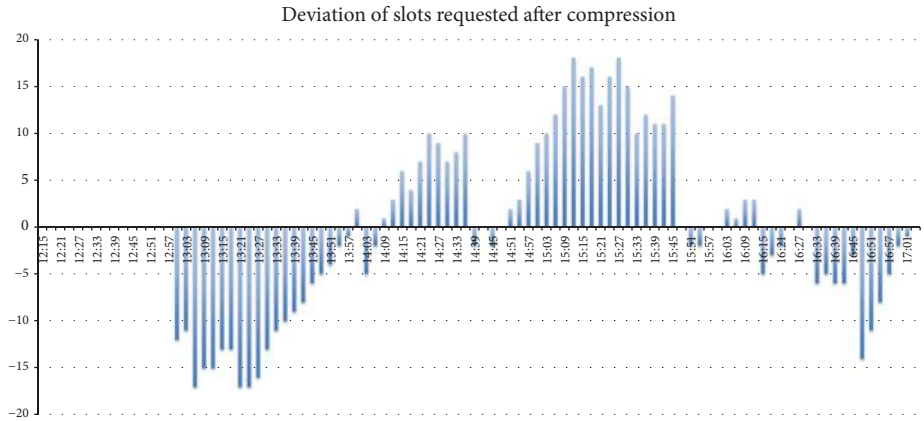

Figure 12: Deviation of slots requested after compression (case study 1).

Table 4: Effect of sequence compression on the AUs actual costs (case study 1).

AU name	Baseline cost	Optimal cost	Diff. (optim.-base)	% Reduc.	Actual cost	Diff. (actual - base)	% Reduc.
HUB	-29283	-23007	6276	21.43%	-21624	7659	26.15%
LC1	-4735	-3799	936	19.78%	-4361	374	7.90%
LC2	-12471	-10863	1608	12.90%	-14785	-2314	-18.56%
OA1	-7178	-5951	1227	17.09%	-7999	-821	-11.44%
OA2	-425	-425	0	0.00%	-340	86	20.14%
OA3	-1131	-1131	0	0.00%	-1927	-796	-70.32%
OA4	-811	-811	0	0.00%	-543	268	33.06%
OA5	-2632	-1679	953	36.21%	-1783	849	32.25%
OA6	-1658	-1536	122	7.39%	-1706	-48	-2.91%
OA7							
OA8	-4691	-4136	555	11.83%	-4678	13	0.27%

5.2. Case Study 2: LVUCs with up to 3 Flights in the Hotspot (Single Hotspot Optimisation). In this case study, the purpose is to assess the benefits of enabling FLC mechanism only for LVUCs that have up to three flights. The impact to others is also assessed. As shown in Figure 13, only OA2, OA3, O4, and OA5 are LVUCs in this hotspot scenario. Note that OA3 and OA4 have 1 flight each in the hotspot (OA3 has another flight in the scenario, but is placed before the hotspot), OA2 has 2 flights, and OA5 has 3 flights. In the figure, they can be found highlighted with different colours. The optimal delay requests found with UDOM for those AUs can also be found in the figure, together with the cost variation for those flights.

In this case study, optimisation is only allowed within the hotspot; i.e., AUs cannot optimise their delay throughout multiple hotspots. Thus, the LVUCs with one single flight, OA3 and OA4, will not have flexibility to minimise the impact of their baseline delay.

Figure 14 shows the changes in the sequence after the implementation of the LVUCs requests. It can be observed that the maximum impact on individual flights of other AUs has been 3 minutes (corresponding in this scenario to one sequence position).

Table 6 shows the aggregated variation of delay for the different AUs, which in the light of the figures and after consultation with a panel of operational experts (which included AUs representatives) it can be considered as negligible impact. Note that LC2 is the AU receiving more delay, i.e., 9 minutes, with no more than 3 minutes per flight. Note as well that OA2 and OA5 have the same delay as the baseline (no impact).

In terms of costs, Table 7 shows that OA2 and OA5 could potentially optimise their costs to figures that are quite close to what UDOM found, i.e., 22.34% of cost reduction for OA2 (who expected a 25.61% of cost reduction) and 38.38% of cost reduction for OA6 (who aimed at reducing the cost in 36.21%).

Regarding the impact on the rest of the AUs, some relatively small variations can be observed in Table 7. It must be pointed out that variation of 1-2% of cost could be considered as very huge impacts in reality; however to interpret the results of this simulation exercises it must be reminded that flights typically operate with some tolerances that makes the flight costs to be typically not so sensitive to an extra minute of delay (the quadratic cost structure is most likely not representing well the impact to

Table 5: Effect of sequence compression on the distribution of delay (case study 1).

AU name	Total flights	Baseline delay	Assigned delay	Difference	Avg. Delay
HUB	52	1385	1283	102	26.63
LC1	8	250	259	-9	31.25
LC2	12	461	524	-63	38.42
OA1	6	227	260	-33	37.83
OA2	2	32	29	3	16.00
OA3	2	59	77	-18	29.50
OA4	1	33	27	6	33.00
OA5	3	94	79	15	31.33
OA6	4	113	110	3	28.25
OA7	0	0	0	0	0.00
OA8	6	208	214	-6	34.67
	96	**2862**	**2862**	**0**	

Flights	Baseline delay	Epsilon	Baseline cost	Optimal tau	Delay request	Optimal cost	Diff
OA3 5896D	0	-1.34	0	0	0	0	0
HUB 8384	2	-1.5	-3	0	2	-3	0
Empty	0	-1.85	0	0	0	0	0
LC2 2213	0	-1.35	0	0	0	0	0
Empty	0	-1.86	0	0	0	0	0
HUB 9757	0	-0.51	0	0	0	0	0
LC1 311	2	-1.55	-3	0	2	-3	0
HUB 6068	0	-1.63	0	0	0	0	0
HUB 5701	0	-0.97	0	0	0	0	0
HUB 6612	6	-1.69	-30	0	6	-30	0
HUB 5229	7	-1.95	-48	0	7	-48	0
LC2 6426	7	-0.7	-17	0	7	-17	0
HUB 1988	5	-1.39	-17	0	5	-17	0
OA2 320D	5	-1.38	-17	9	14	-142	-125
HUB 4325	6	-1.54	-28	0	6	-28	0
LC1 2612	9	-1.44	-58	0	9	-58	0
HUB 3422	7	-1.93	-47	0	7	-47	0
HUB 8106	10	-1.23	-61	0	10	-61	0
HUB 9359	7	-1.31	-32	0	7	-32	0
HUB 9293	9	-1.7	-69	0	9	-69	0
OA8 6731	10	-1.59	-79	0	10	-79	0
OA5 727D	12	-1.19	-86	23	35	-739	-653
HUB 5126	15	-1.62	-182	0	15	-182	0
LC1 4740	18	-0.81	-131	0	18	-131	0
HUB 9649	20	-0.88	-176	0	20	-176	0
OA1 5626	14	-1.01	-99	0	14	-99	0
HUB 9173	16	-1.02	-131	0	16	-131	0
HUB 9423	18	-1.13	-183	0	18	-183	0
HUB 5366	20	-1.82	-364	0	20	-364	0
HUB 4009	23	-1.42	-376	0	23	-376	0
HUB 8488	24	-0.71	-204	0	24	-204	0
HUB 4025	26	-1.04	-352	0	26	-352	0
HUB 1723	25	-2	-625	0	25	-625	0
HUB 5084	27	-1.39	-507	0	27	-507	0
HUB 4624	29	-0.58	-244	0	29	-244	0
HUB 1654	32	-1.33	-681	0	32	-681	0
OA8 4205	30	-1.65	-742	0	30	-742	0
HUB 9873	32	-1.57	-804	0	32	-804	0
HUB 3784	31	-1.71	-822	0	31	-822	0
LC2 2413	33	-1.43	-779	0	33	-779	0
HUB 5912	29	-0.87	-366	0	29	-366	0
LC1 1592	32	-0.55	-282	0	32	-282	0
HUB 1746	35	-1.5	-919	0	35	-919	0
LC2 2315	38	-0.79	-570	0	38	-570	0
LC1 6825	40	-1.15	-920	0	40	-920	0
HUB 6434	43	-1.6	-1479	0	43	-1479	0
OA1 318	46	-1.92	-2031	0	46	-2031	0
HUB 4321	48	-1.12	-1290	0	48	-1290	0
HUB 761	51	-0.51	-663	0	51	-663	0
HUB 6242	51	-1.05	-1366	0	51	-1366	0
HUB 8150	54	-2	-2916	0	54	-2916	0
LC2 2119	54	-0.84	-1225	0	54	-1225	0
HUB 591	56	-0.61	-956	0	56	-956	0
HUB 5618	54	-0.66	-962	0	54	-962	0
LC2 8387	55	-1.12	-1694	0	55	-1694	0
OA8 8611	56	-0.94	-1474	0	56	-1474	0
LC2 5206	59	-1.03	-1793	0	59	-1793	0
LC1 7103	60	-0.56	-1008	0	60	-1008	0
OA3 2151	59	-0.65	-1131	0	59	-1131	0
OA8 8667	61	-0.96	-1786	0	61	-1786	0
LC1 1105	59	-0.87	-1514	0	59	-1514	0
HUB 3749	54	-1.94	-2829	0	54	-2829	0
LC2 2373	57	-1.14	-1852	0	57	-1852	0
LC2 532	58	-1.2	-2018	0	58	-2018	0
OA5 108	61	-1.28	-2381	-28	33	-687	1695
OA1 192	54	-1.33	-1939	0	54	-1939	0
OA1 1714	52	-1.12	-1514	0	52	-1514	0
OA6 7277	40	-1.01	-808	0	40	-808	0
HUB 3535	43	-0.98	-906	0	43	-906	0
HUB 8114	36	-1.94	-1257	0	36	-1257	0
LC2 6219	39	-2	-1521	0	39	-1521	0
OA8 356	40	-0.72	-576	0	40	-576	0
HUB 6065	42	-0.71	-626	0	42	-626	0
OA6 1107	38	-0.72	-520	0	38	-520	0
HUB 4033	41	-1.07	-899	0	41	-899	0
HUB 8308	41	-0.99	-832	0	41	-832	0
OA1 414	32	-1.75	-896	0	32	-896	0
HUB 6072	32	-1.29	-660	0	32	-660	0
HUB 5723	28	-1.19	-466	0	28	-466	0
HUB 8639	30	-0.88	-396	0	30	-396	0
HUB 5622	29	-0.87	-366	0	29	-366	0
LC1 1844	30	-1.82	-819	0	30	-819	0
OA1 824	29	-1.66	-698	0	29	-698	0
LC2 1052	28	-1.82	-713	0	28	-713	0
HUB 8374	31	-1.42	-682	0	31	-682	0
LC2 9998	33	-0.53	-289	0	33	-289	0
HUB 8498	30	-0.76	-342	0	30	-342	0
HUB 8214	30	-1.4	-630	0	30	-630	0
OA4 8655	33	-1.49	-811	0	33	-811	0
HUB 8635	27	-1.29	-470	0	27	-470	0
HUB 1729	30	-0.72	-324	0	30	-324	0
OA2 101D	27	-1.12	-408	-9	18	-175	234
HUB 5815	30	-1.39	-625	0	30	-625	0
OA6 955	21	-1	-220	0	21	-220	0
OA5 680D	21	-0.75	-165	5	26	-254	-88
OA6 2033	14	-1.12	-110	0	14	-110	0
HUB 771	13	-0.8	-68	0	13	-68	0
OA8 8223	11	-0.55	-33	0	11	-33	0

Figure 13: Schedule list with delay, costs, and optimal delay requested per flight (case study 2).

others). In addition, it is assumed that the AUs that are not LVUCs may participate in other UDPP features (e.g., through Enhanced Slot Swapping, FDR/SFP, or others), thus optimising their costs and most likely compensating the relatively small impacts received from LVUCs that used FCL.

5.3. Case Study 3: LVUCs with up to 3 Flights in the Hotspot (Multiple Hotspot Optimisation). To illustrate the impact of LVUCs optimising over the time (multiple hotspots) let us assume that OA3 and OA4 can reduce the delay of their flights because they made efforts in other hotspots (i.e., they increased the delay for some of their flights, thus reducing the delay to flights of other AUs). In the paper of S. Ruiz *et al.* [11], the reader can find examples of how the UDOM can be adapted to optimise the costs of operations by managing delay over the time across multiple hotspots.

For the purpose of this case study, let us assume that in the same situation as shown in previous case study 2, the LVUCs OA3 and OA4 want to reduce the delay of their flights in 18 minutes each (six sequence positions in this hotspot scenario). It is assumed that proportional efforts were done by such AUs in the past in order to have the right for reducing their delay in this occasion.

Figure 15 shows the new sequence situation after the implementation of all the LVUCs requests. It can be noted that in this case a maximum delay impact of 6 minutes has been found in some flights (the flight of OA3 and the flight OA5 108 overcome the same three flights, thus generating an

Flights	ETA	CTA FPFS	Baseline delay	UCTA FCL	Delay UDPP	Diff. Delays
OA3 5896D	12:16	12:15	0	12:15	0	0
HUB 8384	12:16	12:18	2	12:18	2	0
Empty	12:21	12:21	0	12:21	0	0
LC2 2213	12:26	12:24	0	12:24	0	0
Empty	12:27	12:27	0	12:27	0	0
HUB 9757	12:31	12:30	0	12:30	0	0
LC1 311	12:31	12:33	2	12:33	2	0
HUB 6068	12:36	12:36	0	12:36	0	0
HUB 5701	12:36	12:39	0	12:39	0	0
HUB 6612	12:36	12:42	6	12:42	6	0
HUB 5229	12:38	12:45	7	12:45	7	0
LC2 6426	12:41	12:48	7	12:48	7	0
HUB 1988	12:46	12:51	5	12:51	5	0
HUB 4325	12:51	12:57	6	12:54	3	3
LC1 2612	12:51	13:00	9	12:57	6	3
OA2 320D	12:49	12:54	5	13:00	11	-6
HUB 3422	12:56	13:03	7	13:03	7	0
HUB 8106	12:56	13:06	10	13:06	10	0
HUB 9359	13:02	13:09	7	13:09	7	0
HUB 9293	13:03	13:12	9	13:12	9	0
OA8 6731	13:05	13:15	10	13:15	10	0
HUB 5126	13:06	13:21	15	13:18	12	3
LC1 4740	13:06	13:24	18	13:21	15	3
HUB 9649	13:07	13:27	20	13:24	17	3
OA1 5626	13:16	13:30	14	13:27	11	3
HUB 9173	13:17	13:33	16	13:30	13	3
HUB 9423	13:18	13:36	18	13:33	15	3
HUB 5366	13:19	13:39	20	13:36	17	3
OA5 727D	13:06	13:18	12	13:39	33	-21
HUB 4009	13:19	13:42	23	13:42	23	0
HUB 8488	13:21	13:45	24	13:45	24	0
HUB 4025	13:22	13:48	26	13:48	26	0
HUB 1723	13:26	13:51	25	13:51	25	0
HUB 5084	13:27	13:54	27	13:54	27	0
HUB 4624	13:28	13:57	29	13:57	29	0
HUB 1654	13:28	14:00	32	14:00	32	0
OA8 4205	13:33	14:03	30	14:03	30	0
HUB 9873	13:34	14:06	32	14:06	32	0
HUB 3784	13:38	14:09	31	14:09	31	0
LC2 2413	13:39	14:12	33	14:12	33	0
HUB 5912	13:46	14:15	29	14:15	29	0
LC1 1592	13:46	14:18	32	14:18	32	0
HUB 1746	13:46	14:21	35	14:21	35	0
LC2 2315	13:46	14:24	38	14:24	38	0
LC1 6825	13:47	14:27	40	14:27	40	0
HUB 6434	13:47	14:30	43	14:30	43	0
OA1 318	13:47	14:33	46	14:33	46	0
HUB 4321	13:48	14:36	48	14:36	48	0
HUB 761	13:48	14:39	51	14:39	51	0
HUB 6242	13:51	14:42	51	14:42	51	0
HUB 8150	13:51	14:45	54	14:45	54	0
LC2 2119	13:54	14:48	54	14:48	54	0
HUB 591	13:55	14:51	56	14:51	56	0
HUB 5618	14:00	14:54	54	14:54	54	0
LC2 8387	14:02	14:57	55	14:57	55	0
OA5 108	14:26	15:27	61	15:00	34	27
OA8 8611	14:04	15:00	56	15:03	59	-3
LC2 5206	14:04	15:03	59	15:06	62	-3
LC1 7103	14:06	15:06	60	15:09	63	-3
OA3 2151	14:10	15:09	59	15:12	62	-3
OA8 8667	14:11	15:12	61	15:15	64	-3
LC1 1105	14:16	15:15	59	15:18	62	-3
HUB 3749	14:24	15:18	54	15:21	57	-3
LC2 2373	14:24	15:21	57	15:24	60	-3
LC2 532	14:26	15:24	58	15:27	61	-3
OA1 192	14:36	15:30	54	15:30	54	0
OA1 1714	14:41	15:33	52	15:33	52	0
OA6 7277	14:56	15:36	40	15:36	40	0
HUB 3535	14:56	15:39	43	15:39	43	0
HUB 8114	15:06	15:42	36	15:42	36	0
LC2 6219	15:06	15:45	39	15:45	39	0
OA8 356	15:08	15:48	40	15:48	40	0
HUB 6065	15:09	15:51	42	15:51	42	0
OA6 1107	15:16	15:54	38	15:54	38	0
HUB 4033	15:16	15:57	41	15:57	41	0
HUB 8308	15:19	16:00	41	16:00	41	0
OA1 414	15:31	16:03	32	16:03	32	0
HUB 6072	15:34	16:06	32	16:06	32	0
HUB 5723	15:41	16:09	28	16:09	28	0
HUB 8639	15:42	16:12	30	16:12	30	0
HUB 5622	15:46	16:15	29	16:15	29	0
LC1 1844	15:48	16:18	30	16:18	30	0
OA1 824	15:52	16:21	29	16:21	29	0
LC2 1052	15:56	16:24	28	16:24	28	0
HUB 8374	15:56	16:27	31	16:27	31	0
LC2 9998	15:57	16:30	33	16:30	33	0
HUB 8498	16:03	16:33	30	16:33	30	0
HUB 8214	16:06	16:36	30	16:36	30	0
OA4 8655	16:06	16:39	33	16:39	33	0
OA2 101D	16:21	16:48	27	16:42	21	6
HUB 8635	16:15	16:42	27	16:45	30	-3
HUB 1729	16:15	16:45	30	16:48	33	-3
HUB 5815	16:21	16:51	30	16:51	30	0
OA6 955	16:33	16:54	21	16:54	21	0
OA6 2033	16:46	17:00	14	16:57	11	3
HUB 771	16:48	17:01	13	17:00	12	1
OA5 680D	16:36	16:57	21	17:01	25	-4
OA8 8223	16:51	17:02	11	17:02	11	0

Figure 14: Impact of LVUC decision-making on the sequence and on the delay of flights (case study 2).

Table 6: Effect of sequence compression on the distribution of delay (case study 2).

AU name	Total flights	Baseline delay	Assigned delay	Difference	Variation
HUB	52	1385	1375	10	0.72%
LC1	8	250	250	0	0.00%
LC2	12	461	470	-9	-1.95%
OA1	6	227	224	3	1.32%
OA2	2	32	32	0	0
OA3	2	59	62	-3	-5.08%
OA4	1	33	33	0	0
OA5	3	94	92	2	2.13%
OA6	4	113	110	3	2.65%
OA7	0	0	0	0	0.00%
OA8	6	208	214	-6	-2.88%
	96	**2862**	**2862**	**0**	

impact of two sequence positions, i.e., 6 minutes, for some flights).

Tables 8 and 9 show similar figures as in case study 2 for delay and cost impacts. After consultation in an expert panel workshop (which included AUs representatives), it was concluded the impact on delay caused by LVUCs using FCL could again be considered negligible, whereas the impact to other in terms of costs is not conclusive due to the simplifications done in the cost curves of flights. OA2 and OA5 could optimise their costs in the same order of magnitude as calculated by UDOM. The figures shown for OA3 and OA4 are not taking into account the cost of the efforts done in the past hotspots to have flexibility in the studied hotspot. It is expected however that they should be able to reduce their

Flights	ETA	CTA FPFS	Baseline delay	UCTA FCL	Delay UDPP	Diff. Delays
OA3 5896D	12:16	12:15	0	12:15	0	0
HUB 8384	12:16	12:18	2	12:18	2	0
Empty	12:21	12:21	0	12:21	0	0
LC2 2213	12:26	12:24	0	12:24	0	0
Empty	12:27	12:27	0	12:27	0	0
HUB 9757	12:31	12:30	0	12:30	0	0
LC1 311	12:31	12:33	2	12:33	2	0
HUB 6068	12:36	12:36	0	12:36	0	0
HUB 5701	12:36	12:39	0	12:39	0	0
HUB 6612	12:36	12:42	6	12:42	6	0
HUB 5229	12:38	12:45	7	12:45	7	0
LC2 6426	12:41	12:48	7	12:48	7	0
HUB 1988	12:46	12:51	5	12:51	5	0
HUB 4325	12:51	12:57	6	12:54	3	3
LC1 2612	12:51	13:00	9	12:57	6	3
OA2 320D	12:49	12:54	5	13:00	11	-6
HUB 3422	12:56	13:03	7	13:03	7	0
HUB 8106	12:56	13:06	10	13:06	10	0
HUB 9359	13:02	13:09	7	13:09	7	0
HUB 9293	13:03	13:12	9	13:12	9	0
OA8 6731	13:05	13:15	10	13:15	10	0
HUB 5126	13:06	13:21	15	13:18	12	3
LC1 4740	13:06	13:24	18	13:21	15	3
HUB 9649	13:07	13:27	20	13:24	17	3
OA1 5626	13:16	13:30	14	13:27	11	3
HUB 9173	13:17	13:33	16	13:30	13	3
HUB 9423	13:18	13:36	18	13:33	15	3
HUB 5366	13:19	13:39	20	13:36	17	3
OA5 727D	13:06	13:18	12	13:39	33	-21
HUB 4009	13:19	13:42	23	13:42	23	0
HUB 8488	13:21	13:45	24	13:45	24	0
HUB 4025	13:22	13:48	26	13:48	26	0
HUB 1723	13:26	13:51	25	13:51	25	0
HUB 5084	13:27	13:54	27	13:54	27	0
HUB 4624	13:28	13:57	29	13:57	29	0
HUB 1654	13:28	14:00	32	14:00	32	0
OA8 4205	13:33	14:03	30	14:03	30	0
HUB 9873	13:34	14:06	32	14:06	32	0
HUB 3784	13:38	14:09	31	14:09	31	0
LC2 2413	13:39	14:12	33	14:12	33	0
HUB 5912	13:46	14:15	29	14:15	29	0
LC1 1592	13:46	14:18	32	14:18	32	0
HUB 1746	13:46	14:21	35	14:21	35	0
LC2 2315	13:46	14:24	38	14:24	38	0
LC1 6825	13:47	14:27	40	14:27	40	0
HUB 6434	13:47	14:30	43	14:30	43	0
OA1 318	13:47	14:33	46	14:33	46	0
HUB 4321	13:48	14:36	48	14:36	48	0
HUB 761	13:48	14:39	51	14:39	51	0
HUB 6242	13:51	14:42	51	14:42	51	0
HUB 8150	13:51	14:45	54	14:45	54	0
LC2 2119	13:54	14:48	54	14:48	54	0
HUB 591	13:55	14:51	56	14:51	56	0
OA3 2151	14:10	15:09	59	14:54	44	15
HUB 5618	14:00	14:54	54	14:57	57	-3
LC2 8387	14:02	14:57	55	15:00	58	-3
OA5 108	14:26	15:27	61	15:03	37	24
OA8 8611	14:04	15:00	56	15:06	62	-6
LC2 5206	14:04	15:03	59	15:09	65	-6
LC1 7103	14:06	15:06	60	15:12	66	-6
OA8 8667	14:11	15:12	61	15:15	64	-3
LC1 1105	14:16	15:15	59	15:18	62	-3
HUB 3749	14:24	15:18	54	15:21	57	-3
LC2 2373	14:24	15:21	57	15:24	60	-3
LC2 532	14:26	15:24	58	15:27	61	-3
OA1 192	14:36	15:30	54	15:30	54	0
OA1 1714	14:41	15:33	52	15:33	52	0
OA6 7277	14:56	15:36	40	15:36	40	0
HUB 3535	14:56	15:39	43	15:39	43	0
HUB 8114	15:06	15:42	36	15:42	36	0
LC2 6219	15:06	15:45	39	15:45	39	0
OA8 356	15:08	15:48	40	15:48	40	0
HUB 6065	15:09	15:51	42	15:51	42	0
OA6 1107	15:16	15:54	38	15:54	38	0
HUB 4033	15:16	15:57	41	15:57	41	0
HUB 8308	15:19	16:00	41	16:00	41	0
OA1 414	15:31	16:03	32	16:03	32	0
HUB 6072	15:34	16:06	32	16:06	32	0
HUB 5723	15:41	16:09	28	16:09	28	0
HUB 8639	15:42	16:12	30	16:12	30	0
HUB 5622	15:46	16:15	29	16:15	29	0
LC1 1844	15:48	16:18	30	16:18	30	0
OA4 8655	16:06	16:39	33	16:21	15	18
OA1 824	15:52	16:21	29	16:24	32	-3
LC2 1052	15:56	16:24	28	16:27	31	-3
HUB 8374	15:56	16:27	31	16:30	34	-3
LC2 9998	15:57	16:30	33	16:33	36	-3
HUB 8498	16:03	16:33	30	16:36	33	-3
HUB 8214	16:06	16:36	30	16:39	33	-3
OA2 101D	16:21	16:48	27	16:42	21	6
HUB 8635	16:15	16:42	27	16:45	30	-3
HUB 1729	16:15	16:45	30	16:48	33	-3
HUB 5815	16:21	16:51	30	16:51	30	0
OA6 955	16:33	16:54	21	16:54	21	0
OA6 2033	16:46	17:00	14	16:57	11	3
HUB 771	16:48	17:01	13	17:00	12	1
OA5 680D	16:36	16:57	21	17:01	25	-4
OA8 8223	16:51	17:02	11	17:02	11	0

Figure 15: Impact of LVUC decision-making on the sequence and on the delay of flights (case study 3).

Table 7: Effect of sequence compression on the AUs actual costs (case study 2).

AU name	Baseline cost	Optimal cost	Diff. (optim. - base)	% Reduc. (optim. - base)	Actual cost	Diff. (actual - base)	% Reduc. (actual - base)
HUB	-29283	-29283	0	0.00%	-29438	-155	-0.53%
LC1	-4735	-4735	0	0.00%	-4924	-189	-3.99%
LC2	-12471	-12471	0	0.00%	-13072	-601	-4.82%
OA1	-7178	-7178	0	0.00%	-7140	38	0.53%
OA2	-425	-317	109	25.61%	-330	95	22.34%
OA3	-1131	-1131	0	0.00%	-1249	-118	-10.43%
OA4	-811	-811	0	0.00%	-811	0	0.00%
OA5	-2632	-1679	953	36.21%	-1622	1010	38.38%
OA6	-1658	-1658	0	0.00%	-1616	42	2.53%
OA7							
OA8	-4691	-4691	0	0.00%	-5033	-342	-7.29%

total—over the time—costs in the same order of magnitude as OA2 and OA5.

6. Discussion of the Simulation Results

With the current FCL rules, and due to the complex interactions and emergent dynamics between the different AUs prioritisations, it cannot be guaranteed that the resulting FCL sequence will have a positive or neutral impact on the AUs costs. In the light of the results (see case study 1), it seems quite unlikely that all the AUs can use FCL in its current form. Further research needs to be done to investigate new strategies and rules that will allow to develop solutions with positive cost reduction for all the AUs. The FCL feature seems

Table 8: Effect of sequence compression on the distribution of delay (case study 3).

AU name	Total flights	Baseline delay	Assigned delay	Difference	Variation
HUB	52	1385	1387	-2	-0.14%
LC1	8	250	253	-3	-1.20%
LC2	12	461	482	-21	-4.56%
OA1	6	227	227	0	0.00%
OA2	2	32	32	0	0
OA3	2	59	44	15	25.42%
OA4	1	33	15	18	54.55%
OA5	3	94	95	-1	-1.06%
OA6	4	113	110	3	2.65%
OA7	0	0	0	0	0.00%
OA8	6	208	217	-9	-4.33%
	96	**2862**	**2862**	**0**	

Table 9: Effect of sequence compression on the AUs actual costs (case study 3).

AU name	Baseline cost	Optimal cost	Diff. (optim. - base)	% Reduc. (optim. - base)	Actual cost	Diff. (actual - base)	% Reduc. (actual - base)
HUB	-29283	-29283	0	0.00%	-29890	-607	-2.07%
LC1	-4735	-4735	0	0.00%	-5033	-297	-6.27%
LC2	-12471	-12471	0	0.00%	-13674	-1203	-9.65%
OA1	-7178	-7178	0	0.00%	-7292	-114	-1.59%
OA2	-425	-317	109	25.61%	-330	95	22.34%
OA3	-1131	-1131	0	0.00%	-629	502	44.38%
OA4	-811	-811	0	0.00%	-168	644	79.34%
OA5	-2632	-1679	953	36.21%	-1758	874	33.20%
OA6	-1658	-1658	0	0.00%	-1616	42	2.53%
OA7							
OA8	-4691	-4691	0	0.00%	-5204	-513	-10.93%

to be a good mechanism to give access for LVUCs with 3 flights or less. In addition, it deserves special mention that, for those LVUCs with only 1 flight, the FCL mechanism was able to give access to UDPP (i.e., flexibility) through multiple hotspots, thus guaranteeing access and equity of UDPP.

For a reduced number of LVUCs using the FCL, the expected impact to other AUs can in general be considered negligible (to be further confirmed with operational experts after the analysis of many more cases), while the benefits for the LVUCs using FCL may be notably large. In addition, it can be assumed that the—negligible—impact that LVUCs in a hotspot could generate to other non-LVUCs flights could be easily compensated by the important cost reductions that such non-LVUCs could achieve through access to other UDPP features (e.g., Enhanced Slot Swapping). In addition, according to the results of the statistical analysis (Figure 3), most of the AUs are LVUCs quite often: in 85% of the hotspots that affect their flights; therefore, the AUs that are not LVUCs in a specific hotspot scenario could potentially be benefited from the FCLs feature in other hotspots in which they might be LVUCs.

The hotspot scenario used in the simulated case studies is quite typical in terms of duration, severity, and number of AUs and LVUCs affected; therefore, it is expected that a certain degree of extrapolation of the results to other hotspot situations is possible.

Finally, the case studies considered that LVUCs are the AUs with a maximum number of flights caught in the hotspot equal to three. Such definition of LVUC was preliminary agreed through discussion with a panel of AUs and operational experts. However, in the light of this early results, a sensitivity analysis should be conducted with multiple realistic scenarios in different conditions and with different AUs involved to determine which should be the number of flights that could use FCL in each hotspot while preserving equity over time.

7. Conclusions and Future Work

The FCL mechanism has shown good properties to give effective access for LVUCs to UDPP. In particular, it has been found that (a) a LVUC can find for each of his flights the optimal amount of delay minutes that should be increased or decreased in order to minimise his total costs; (b) a LVUC can obtain delay credits by accepting extra delay (amount of extra delay controlled/decided by the LVUC) and use the

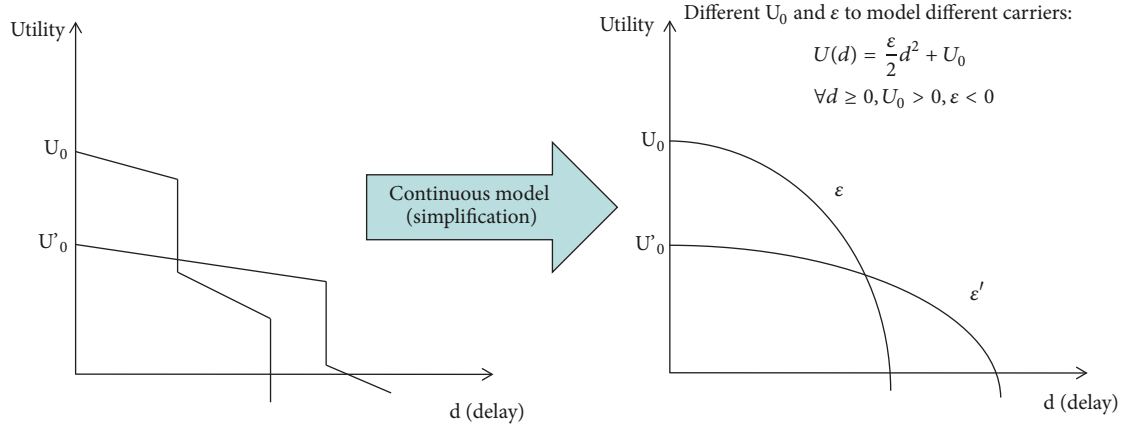

Figure 16: Approximation of the utility function as a continuous quadratic function.

credits in the same hotspot (if the LVUC has more than one flight) or save the credits and use them in future hotspots (i.e., LVUCs are able to optimise their operations over the time); and (c) the FCL rules are simple and the level of coordination required is very efficient, so the LVUCs and the rest of the AUs can concentrate on optimising their own operations.

FCL cannot be used—in its current form of baseline rules and principles—by AUs in a hotspot that are not LVUCs due to the likeliness of emerging inequities. However, early evidence showed that equity could be preserved over the time if the number of flights being prioritised with FCL and the maximum negative impact allowed to other flights is limited at each hotspot. The precise definition of these parameters to control the trade-off between flexibility and equity requires further research. Three flights could be recommended as a starting point to determine whether an AU is an LVUC in a hotspot, while six minutes of additional negative impact at some flights could be considered in principle negligible by the AUs.

For the flights that are not allowed to use FCL in a hotspot, the AUs could use the other UDPP features based on slot swapping, since such mechanisms can guarantee full equity over the time ("equity" understood as no direct negative delay impact to others) and may likely provide enough flexibility to the AUs when they are not LVUCs. Nevertheless, all the AUs are often LVUCs—even the largest airlines—in many regulations that occur every day. Therefore the possibility to include all the AUs—irrespective of the number of flights operated per day—using FCL when they are LVUCs in a hotspot is recommended, since it may contribute to reduce the cost for all the AUs and possibly increase the predictability and robustness of fleet schedules (e.g., for a hub carrier a single flight delayed in a remote/non-hub airport could have a knock-on impact on the hub connections and cause disruption on the full-day's operations). Further research is needed to determine whether special rules may apply for AUs that are always LVUCs, e.g., Business Aviation.

Further research and validation is required to determine the exact number of flights that could use FCL in any hotspot without jeopardising equity over the time and to bring the FCL concept towards higher levels of maturity.

Appendix

A. User Delay Optimisation Model (UDOM)

A.1. Definitions and Assumptions. One of the main assumptions in UDOM is that the AUs taking part in the system can be modelled as utility maximising; i.e., the major objective of each AU is to maximise its utility function. Therefore, AUs are assumed to have a utility function, which is depending on several variables, such as the delay cost structure of each flight.

Utility is an important concept in economics and game theory, because it represents satisfaction experienced by the consumer of a good (see H. Varian [28]). In the context of this document, the concept of "utility" will be understood as the value perceived by a particular AU if a given slot is allocated to a particular flight operated. Without loss of generality, in this document it is assumed that utility is directly related to economic profits obtained by the AUs for operating their flights; however the concept of utility may also include any type of operational constraints known by the flight dispatcher, and any indirect economic or non-economic type of benefits or costs.

Table 10 describes all the mathematical symbols that will be used in the model formulation.

A.2. Mathematical Representation of the Utility or Delay Cost Functions for Flights. A utility function for a single flight, U(t), can be represented analytically as a continuous quadratic function, as it can be observed in Figure 16. If negative delay is not considered (simplification), the *utility* as a function of the delay, d, assigned to a flight can be expressed as

$$U(d) = \frac{\varepsilon}{2}d^2 + U_0, \quad \forall d \geq 0$$

$$\frac{\partial' U}{\partial' d} = \mu_d = \varepsilon d \leq 0 \tag{A.1}$$

$$\frac{\partial'' U}{\partial'' d} = \varepsilon < 0,$$

Table 10: Description of model parameters and variables.

Symbol	Range	Description
d	$[0, +\infty)$	*Delay* of a flight (d_0 means $d=0$)
U_0	$[0, +\infty)$	Max *utility* of a flight when its $d=0$
N	$[0, +\infty)$	Number of flights operated by an AU in the reference period
ε_i	$(-\infty, +\infty)$	*Elasticity* of the utility function of flight i. Used to model in a simplified way (continuous model) different operational flight margins
ρ_i	$[0, 1]$	Probability of a flight i for being affected/delayed by a hotspot
δ_i	$[0, +\infty)$	*Average delay expected* for flight i in the route operated (i.e., typical delay from hotspots on that route)
$\widetilde{d_i}$	$[0, +\infty)$	*Baseline (random) delay* for flight i
τ_i	$(-\infty, +\infty)$	*Delay shift,* to increase or reduce the delay of flight i
d_i^*	$[0, +\infty)$	*Optimal delay* for flight i in the actual hotspot
d_i'	$(-\infty, +\infty)$	*Shifted delay*, i.e., delay difference between the optimal delay and the baseline delay, for flight i

where ε is the elasticity of the utility function, μ_d the marginal utility, and U_0 the maximum utility in case of no delay allocated to that flight. It is assumed for the sake of simplicity that every single flight has a maximum utility when the delay, d, *is* zero, at a certain slot, and the utility is then progressively decreasing as far as the delay is increasing. Since the elasticity is negative, any delay incurred by a flight will cause a reduction on the utility perceived by the AU for this flight. Utility will be negative if the cost of delay has become greater than the maximum economic value expected for that flight if operated on time. Different revenue and cost structures can be modelled by changing the parameters; thus they can be adapted to different types of AUs' type of activity (low cost, HUB, business aviation, or others).

In reality, utility functions are unknown and may be nonlinear and nonconvex (the cost functions as well). However, in this document it is assumed for the sake of simplicity that every single flight has a maximum utility when the delay, d, *is* zero, at a certain slot, and the utility is then progressively decreasing as far as the delay is increasing. Utility will be negative if the cost of delay has become greater than the maximum economic value expected for that flight if operated on time.

A.3. UDOM for N Flights and Multiple Hotspots. The used delay optimisation model can be expressed for N flights of the same AU, each of those flights characterised by a different elasticity ε_i and affected by delays with different probabilities ρ_i and with a particular and different expected delay δ_i for each of them:

$$\max_{\tau_1,\ldots,\tau_N} \quad \overline{U} = \sum_{i=1}^{N} U_i\left(d_0\right)\left(1-\rho_i\right) + \sum_{i=1}^{N} U_i\left(\delta_i+\tau_i\right)\left(\rho_i\right)$$
$$\text{s.t.} \quad \sum_{i=1}^{N} \tau_i = 0 \tag{A.2}$$

After some mathematical development (e.g., using multipliers of Lagrange), the optimal delay shift for each flight i can be expressed by

$$\tau_i^* = \frac{\sum_{j=1}^{N} \delta_j}{\sum_{j=1}^{N} \left(\varepsilon_i \rho_i / \varepsilon_j \rho_j\right)} - \delta_i \tag{A.3}$$

Further explanations about how this equation has been developed can be found in Section A.4 where the UDOM model will be extended with inequality constraints to consider the duration of the hotspot.

Figure 17 illustrates an example in which an LVUC has 3 flights, F1, F2, and F3, each one with a maximum utility of 500 monetary units if they were not delayed. The three flights have been originally allocated to some ATFCM slots that generate to them 5, 12, and 20 minutes of delay, respectively. Each of the flights has different cost structure and thus different sensitivity/elasticity to delay, i.e., $\varepsilon_{f1} = -2$, $\varepsilon_{f2} = -10$, and $\varepsilon_{f3} = -9$. The baseline delay utility can be calculated as

$$\begin{aligned} U_{BD} &= U_{f1}(5) + U_{f1}(12) + U_{f1}(20) \\ &= 474 - 220 - 1300 = -1045 \end{aligned} \tag{A.4}$$

After computing the optimal delay allocation with UDOM, the LVUC would request a slot with 21 minutes of extra delay for flight F1 and a delay reduction of 7 and 14 minutes for flights F2 and F3, respectively. Note that the total delay for the LVUC is the same. The optimised utility is

$$\begin{aligned} U_{UD}^* &= U_{f1}(5+21) + U_{f1}(12-7) + U_{f1}(20-14) \\ &= -176 + 375 + 338 = +537 \end{aligned} \tag{A.5}$$

illustrating the change in utility for the AU, and comparing the maximum utility affordable (no delay), Figure 18 expected utility if the baseline FPFS sequence is applied and the optimised sequence if the LVUC is allowed to use FCL.

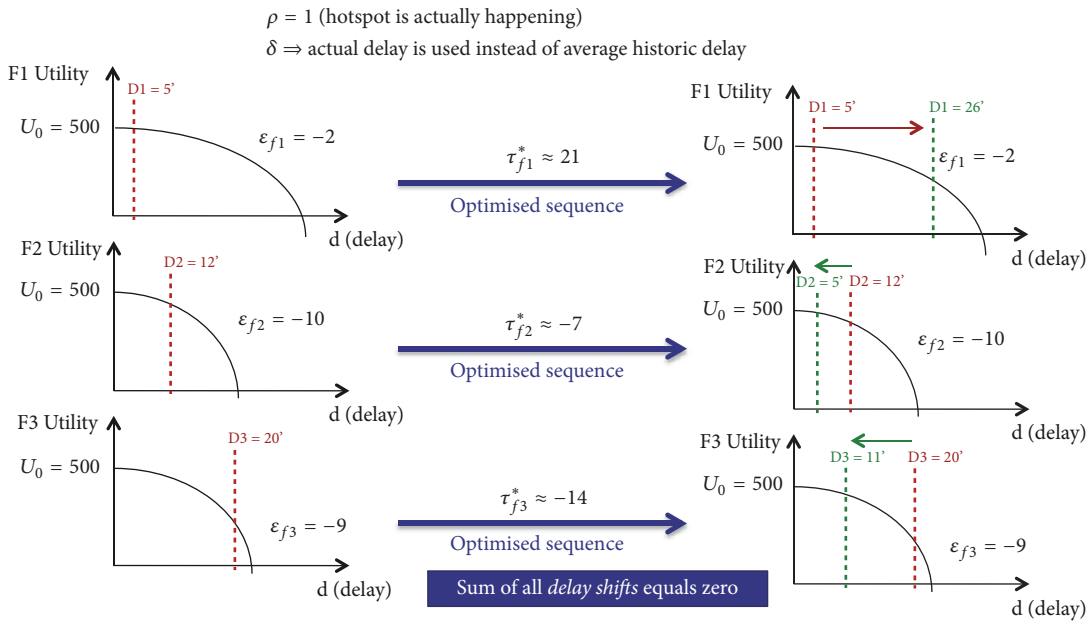

Figure 17: Example of optimal delay redistribution using UDOM.

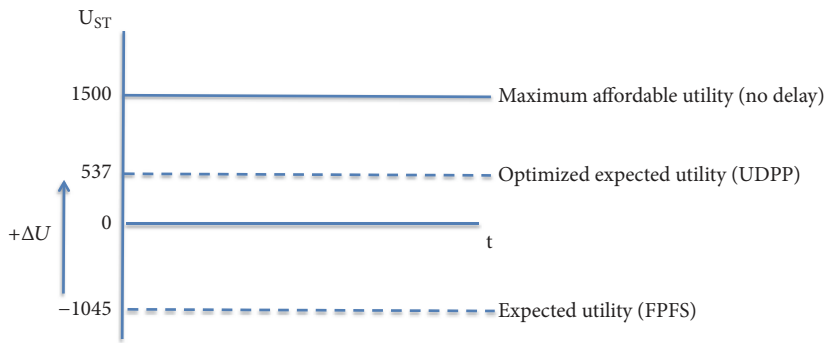

Figure 18: Change in utility after optimisation.

A.4. Implementation Aspects and Generalisation of UDOM with Inequality Constraints (KKT Conditions). The method of Lagrange multipliers allows solving convex optimisation problems subject to equality constraints, as presented in (A.3). However, for implementing and running simulations with realistic hotspot scenarios some extra inequality constraints are needed, in particular the hotspot time-window boundaries. If these constraints are not included in the model, in some cases, the AUs with flights close to the boundaries of the hotspot could request, after optimising their delay with UDOM, slots that were beyond these boundaries, thus leading to nonfeasible results in practice. In order to incorporate the hotspot boundary constraints, a new set of inequality constraints is needed.

The mathematical model to optimise becomes

$$\max_{\tau_i} \quad f(\tau) = \sum_{i}^{N} U_i(\delta_i + \tau_i)\rho_i$$

$$s.t. \quad g(\tau) = \sum_{i}^{N} \tau_i = 0$$

$$\begin{aligned} &\mathrm{h1}_i(\tau): \ -\tau_i \le IT_i \\ &\mathrm{h2}_i(\tau): \ \tau_i \le FT_i, \end{aligned} \tag{A.6}$$

where U_i is the utility function of flight i ($U(d) = (\varepsilon/2)d^2 + U_0$), δ_i, τ_i and ρ_i are, respectively, the delay allocated to flight i, the delay shift (variable of control) that the AU can decide to optimise his costs, and the probability of that flight for being delayed. IT_i and FT_i are the new parameters with respect to the basic UDOM shown in the paper, which are IT_i, the distance in time between the slot allocated to flight i, and the initial time of the hotspot, and FT_i, the distance in time between the slot allocated to flight i, and the final time of the hotspot.

The Karush-Kuhn-Tucker (KKT) conditions allow generalising the method of Lagrange multipliers to include inequality constraints. Let a generic optimisation problem be expressed as follows (vector form):

$$\begin{aligned} \max_{x} \quad & f(x) \\ s.t. \quad & g(x) = 0 \\ & \mathrm{h}(x) \leq 0 \end{aligned} \tag{A.7}$$

Any optimal solution for the above problem must fulfil the following four KKT conditions:

(1) Stationarity

$$\nabla f(x) + \lambda g(x) + \mu h(x) = 0 \tag{A.8}$$

(2) Primal Feasibility

$$\begin{aligned} g(x^*) &= 0 \\ \mathrm{h}(x^*) &\leq 0 \end{aligned} \tag{A.9}$$

(3) Dual Feasibility

$$\lambda \geq 0 \tag{A.10}$$

(4) Complementary Slackness

$$\lambda g(x^*) = 0 \tag{A.11}$$

In practice, the resolution of problems with KKT conditions are often solved with recursive algorithms. The fourth condition forces the solution to be at the boundary of an inequality constraint when an optimal solution would be beyond such boundary in case that such inequality constraint would not be present in the problem.

Taking the above into account, the UDOM model can be generalised with the KKT conditions by applying the following recursive algorithm:

(1) Let θ be the total excess delay of the AU out of the hotspot boundaries calculated as follows (note the inequality constraints are incorporated in the calculation of θ):

$$\theta = \sum_i \theta_i, \quad \forall \theta_i = \begin{cases} IT_i - \tau_i & \text{if } \tau_i < FT_i \\ \tau_i - FT_i & \text{if } \tau_i > FT_i \\ 0 & \text{otherwise} \end{cases} \tag{A.12}$$

The recursive algorithm must be initialised with $\theta = 0$ (assume no excess before the first trial/iteration).

(2) Find the optimal solution for the general UDOM-KKT problem, which can be expressed as

$$\begin{aligned} \max_{\tau_i} \quad & f(\tau) = \sum_i^N U_i (\delta_i + \tau_i) \rho_i \\ s.t. \quad & g(\tau) : \sum_i^N \tau_i = \theta \end{aligned} \tag{A.13}$$

(3) Calculate θ with (A.11).

(4) For any flight i with $\theta_i > 0$ (i.e., for each flight it checks if the optimal solution found in previous steps requires slots that are out of the hotspot boundaries), do the following:

(a) Set the solution/position for flights with excess at the boundary (i.e., they will request the first or the last slots in the hotspot).

(b) Remove these flights from the optimisation in the next iterations (they already have been assigned a solution).

(5) Repeat steps (2), (3), and (4) until $\theta = 0$ (θ must be zero for any feasible solution).

Note that the Lagrange condition for optimality, $\nabla f(x) = \lambda \nabla g(x)$, applied to the general UDOM-KKT problem in (A.12) generates the following system of equations (dual problem):

$$\begin{bmatrix} \varepsilon_1 (\delta_1 + \tau_1) \rho_1 - \lambda \\ \vdots \\ \varepsilon_n (\delta_n + \tau_n) \rho_n - \lambda \\ \tau_1 + \ldots + \tau_n - \theta \end{bmatrix} \tag{A.14}$$

Once the system of equations is solved, the optimal delay per flight can be found:

$$\tau_i^* = \frac{\sum_j^N \delta_j + \theta}{\sum_j^N \left(\varepsilon_i \rho_i / \varepsilon_j \rho_j \right)} - \delta_i \tag{A.15}$$

If $\theta = 0$ in the first iteration (i.e., all the optimal/requested slots are within the hotspot boundaries), the solution is exactly the same as in (A.3), i.e., the normal UDOM (no UDOM-KKT). And if $\theta > 0$ the delay excess generated by flights that have been assigned to the boundaries of the hotspot will be shared among the flights of the AU according to the relative importance/cost structure of each flight (indeed in the same proportion as the total delay is reallocated by the AU among his flights). Therefore, once the recursive algorithm converges to $\theta = 0$, the KKT conditions can be satisfied, meaning that an optimal solution for the AU has been found.

Data Availability

The flight list data and cost parameterisations used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] EUROCONTROL, "ATFCM Users Manual," Ed. 22.1, 2018.

[2] M. O. Ball, C. Chen, R. Hoffman, and T. Vossen, "Collaborative Decision Making in Air Traffic Management: Current and Future Research Directions," in *New Concepts and Methods in Air Traffic Management*, Transportation Analysis, pp. 17–30, Springer Berlin Heidelberg, Berlin, Germany, 2001.

[3] FAA, "Interface control document for substitutions during ground delay programs, ground stops, and airspace flow programs," Version 3.1, 2007.

[4] EUROCONTROL, "Performance Review Report, an assessment of air traffic management in Europe during the calendar year 2017," 2017.

[5] Univerity of Westminster, "European airline delay cost reference values - updated and extended values," Ed. 4.1. 2015.

[6] D. Xiaoxu, H. Minghua, W. Tian, and H. Liu, "Modeling congestion propagation in multistage schedule within an airport network," *Journal of Advanced Transportation*, vol. 2018, Article ID 6814348, 11 pages, 2018.

[7] IATA ECONOMICS, "Profitability and the air transport value chain," IATA ECONOMICS N◦10, 2013.

[8] IATA ECONOMICS, "Annual review 2018," 2018.

[9] "SESAR P.07.06.04. UDPP Step 2 V1 OSED. Partners: EUROCONTROL, AA, AF-Group, DLH-Group, EBAA, ELFAA, IAOPA, SAS, IATA," 2013.

[10] N. Pilon, S. Ruiz, A. Bujor, A. Cook, and L. Castelli, *Improved Flexibility and Equity for Airspace Users during Demand-Capacity Imbalance - An Introduction to The User-Driven Prioritisation Process*, Sixth SESAR Innovation Days, Delft, Netherlands, 2016.

[11] S. Ruiz, L. Guichard, and N. Pilon, *Optimal Delay Allocation under High Flexibility Conditions during Demand-Capacity Imbalance*, SESAR Innovation Days, 2017.

[12] T. Vossen and M. Ball, "Optimisation and mediated bartering models for ground delay programs," *Naval Research Logistics*, vol. 53, no. 1, pp. 75–90, 2006.

[13] L. Castelli, R. Pesenti, and A. Ranieri, "The design of a market mechanism to allocate air traffic flow management slots," *Transportation Research Part C: Emerging Technologies*, vol. 19, no. 5, pp. 931–943, 2011.

[14] N. Schefers, J. J. Ramos González, P. Folch, and J. L. Munoz-Gamarra, "A constraint programming model with time uncertainty for cooperative flight departures," *Transportation Research Part C: Emerging Technologies*, vol. 96, pp. 170–191, 2018.

[15] R. Jovanovic, O. Babic, V. Toic, and V. Tošic, "Pricing to reconcile predictability, efficiency and equity in ATM," in *Proceedings of the 11th USA/Europe ATM R&D Seminar*, vol. 2015, Lisbon.

[16] A. Harada, T. Ezaki, T. Wakayama, and K. Oka, "Air traffic efficiency analysis of airliner scheduled flights using collaborative actions for renovation of air traffic systems open data," *Journal of Advanced Transportation*, vol. 2018, Article ID 2734763, 14 pages, 2018.

[17] T. Kistan, A. Gardi, R. Sabatini, S. Ramasamy, and E. Batuwangala, "An evolutionary outlook of air traffic flow management techniques," *Progress in Aerospace Sciences*, vol. 88, pp. 15–42, 2017.

[18] A. R. Odoni, L. Bianco, and G. Szegö, "The flow management problem in air traffic control," in *Flow Control of Congested Networks*, Springer, Berlin, Germany, 1987.

[19] M. Ball, G. Donohue, and K. Hoffman, "Auctions for the safe, efficient and equitable allocation of airspace system resources," in *Combinatorial Auctions*, P. Cramton, Y. Shoham, and R. Steinberg, Eds., pp. 507–538, MIT Press, Cambridge, 2005.

[20] R. H. Coase, *The Problem of Social Cost*, 1960.

[21] N. Ivanov, F. Netjasov, R. Jovanović, S. Starita, and A. Strauss, "Air Traffic Flow Management slot allocation to minimize propagated delay and improve airport slot adherence," *Transportation Research Part A: Policy and Practice*, vol. 95, pp. 183–197, 2017.

[22] "Crown Consluting, Inc. (for NextGen). Flight Priority Deep Dive. Final Report," 2011.

[23] V. Krishna, *Auction Theory*, Academic Press, 2nd edition, 2009.

[24] R. Gibbons, *Game Theory for Applied Economists*, Princeton University Press, Princeton, NJ, USA, 1992.

[25] S. J. Rassenti, V. L. Smith, and R. L. Bulfin, "A Combinatorial Auction Mechanism for Airport Time Slot Allocation," *RAND Journal of Economics*, vol. 13, no. 2, p. 402, 1982.

[26] G. Stojković, F. Soumis, J. Desrosiers, and M. M. Solomon, "An optimization model for a real-time flight scheduling problem," *Transportation Research Part A: Policy and Practice*, vol. 36, no. 9, pp. 779–788, 2002.

[27] R. L. Hoffman, *Integer Programming Models for Ground- Holding in Air Traffic Flow Management*, Department ISR, 1997.

[28] H. Varian, *Intermediate Microeconomics: A Modern Approach*, W. W. Norton & Company, 2009.