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A novel air traffic flow management model to optimise network delay

Towards innovative enhancements for computer-assisted slot allocation (CASA)

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***Abstract* – This paper describes the interacting regulations problem and a new method is presented to analyse and optimise network delay. The aim of this research is to contribute to the enhancement of the computer-assisted slot allocation (CASA) mechanism used today in Europe for assigning air traffic flow and capacity management (ATFCM) slots.**

The interacting regulations problem appears during periods of congestion owing to the non-smoothed coordination of multiple ATFCM constraints applied locally in different sectors. Flights affected by multiple regulated sectors may change their default first-plan-first-served (FPFS) sequence position in certain regulated sectors, which may generate complex 'interactions' – positive or negative – between those regulations, and this can typically increase total delay in the network.

An enhanced slot allocation method referred to as enhanced CASA (ECASA) is proposed in this paper, which consists in optimising – with heuristics– the default CASA sequences by applying small slot amendments to certain selected flights. Early benchmarking of the ECASA performance shows that the optimisation strategies introduced could significantly reduce network delay (by 27% on average in the simulated period of summer 2018). The proportion of flights delayed by more than 15 minutes could also be significantly reduced (by 42%), thus reducing the cost of operations. *(Abstract)*

Keywords: interacting regulations; air traffic flow and capacity management; ATFCM; computer-aisted slot allocation; CASA; delay optimisation

Foreward *– This work is envisaged as a part of the SESAR 2020 Industrial Research project PJ09 "Demand Capacity Balancing". PJ09's main objective is to develop and validate concepts and systems which complement the Network Management Function with network intelligence based on shared situational awareness, a common set of values and rules, and highly interconnected local network management functions.*

I. Introduction

In today's operations, if a potential demand-capacity imbalance is foreseen a few hours in advance with a certain level of confidence, the Network Manager activates a regulation scenario and issues 'ATFM slots' to smooth the rate of flights which in execution phase will enter or arrive in a sector or at an airport. The aim is to guarantee that the traffic levels in/at the sector/airport will at all times remain within acceptable and controllable levels for the air traffic controllers in charge [1][2].

Those ATFM slots impose controlled take-off times (CTOs) on certain flights whose plan is to cross a sector or to use an airport during a regulation period. Flights affected by regulation will often be significantly delayed with respect to the original slots scheduled for those flights, for example by more than 15 minutes, and it is well known that such a delay imposed on flights typically has a major *impact* (costs) on airspace users (AUs) [3]. Since profitability in the air transport industry is very low (1-5% of incomes [4]), it is extremely important that the ATFM slot allocation processes minimise the delay generated in the network in order to increase quality of service and operational cost-efficiency for AUs.

In Europe, ATFM slots are allocated by the computer-assisted slot allocation (CASA) [1] on the basis of a transparent

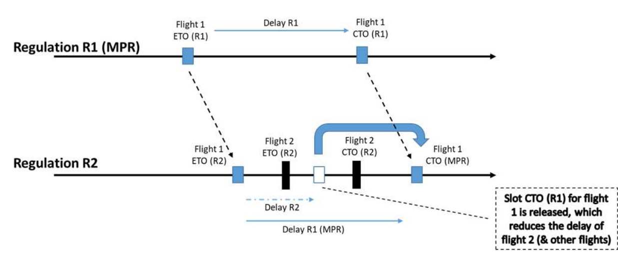

Figure 1: Interaction with a positive impact on Flight 2

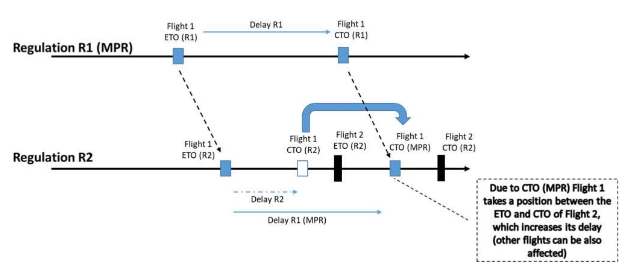

Figure 2: Interaction with a negative impact on Flight 2

set of rules and policies previously agreed and accepted by all the relevant ATM stakeholders, including AUs. The policy used today to allocate delay –when no other more constraining rule or operational policy applies – is first planned, first served (FPFS), which sorts the flights by the estimated time of arrival at or over (ETA/ETO) the constrained airport or sector, in accordance with the information present in the filed flight plans, and assigns the slots in this sequential order. In the US, the default slot allocation mechanism is also based on FPFS, though often referred to as *ration by schedule* (RBS) [5][6].

FPFS is widely accepted by AUs because it preserves the original sequence of flights (which is considered fair), and it is well accepted today in ATFM operations, because it is assumed to minimise the total delay in a regulation [5] [7].

In this paper, however, we will show that, as a consequence of the complex dynamics emerging in the network in the presence of multiple regulations, the FPFS policy does not minimise the overall delay in the network. In a tightly connected network, flights may often cross more than one regulated sector or airport. When this happens, the CASA mechanism changes the FPFS policy for some flights in some regulations: first, it finds the *most penalising regulation* (MPR) for each flight, i.e. the one which generates the most delay for the flight, and then it allocates the slot of the MPR to the flight. Finally, CASA calculates the new entry times for that flight in other regulations crossed, and 'forces' a slot in each regulation corresponding to the new calculated entry times for that flight. The new sequence position imposed by the MPR typically has an impact (either positive or negative) on other flights in the sequences of other regulations.

Figure 1 shows an example of a single *flight interaction* with a *positive impact* (PI): Flight 1 crosses two regulations, R1 and R2. Owing to R1 (the MPR for Flight 1), the flight is pushed to a later position in R2. Flight 2, which originally was in a later position than Flight 1, can now take a better position in the sequence (thus reducing its delay), since Flight 1 has released the original CTO position which corresponded to the default FPFS sequence in R2 (the white slot in the figure).

Similarly, Figure 2 shows an example of a single *flight interaction* with a *negative impact* (NI): Owing to its MPR, Flight 1 is pushed between the ETO and the CTO positions of Flight 2, thus forcing Flight 2 to take a later position (thus increasing its delay).

It is essential to note that flight interactions may affect (and they typically do so) several flights in the sequence through a chain reaction (the domino effect), for instance Flight 2, by changing its position in the example, may generate PIs or NIs on other flights in the sequence, which in turn may change the positions of other flights in the same or other regulations (for example if some affected flights cross other regulations).

Flight interactions are generated by the presence of multiple regulations which are linked by flights, and the interactions can change the delay for other flights, and as a consequence *total delay* and *throughput* (i.e. the number of flights entering the

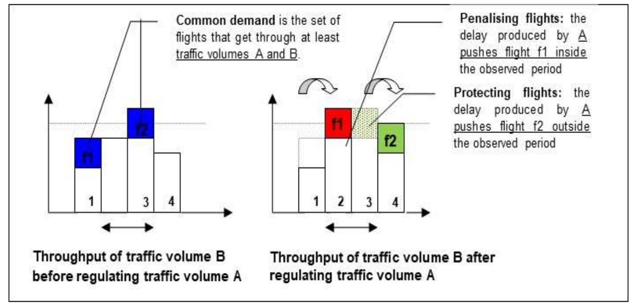

Figure 3: Illustration of network effects (throughput variation)

sector in a specific period) in other regulations. This is referred to in this paper as the *interacting regulations* problem. Such interactions generate complex network effects which can significantly increase the delay in the network (as be seen later).

This research shows that the slot allocation processes triggered during periods of congestion could be substantially enhanced by applying minor amendments to the CASA default sequences such that the interacting regulations problem is minimised. As a result, the total delay generated globally in the network can be minimised and the impact on AUs reduced. To verify this hypothesis, a simulation model (R-NEST) together with optimisation heuristics have been developed and integrated. The new optimisation model is referred to in this paper as enhanced CASA (ECASA), and the main goal of the proposed method is to make it rapidly deployable in the European Network Manager in order to improve the performance of network operations. The simulation results of ECASA have been benchmarked against CASA and discussed in terms of *capacity* (the delay and efficiency-of-use of the available capacity), *AU operational efficiency* (the impact of delay) and *network stability*. *Safety* is assumed to remain neutral, since no significant changes in operational procedures are proposed.

The rest of the paper is structured as follows. Section II covers the state of the art. Section III explains the research methods and tools. Section IV analyses the interactions between regulations. Section V describes the optimisation model proposed. Section VI covers the conclusions and future steps.

II. STATE OF THE ART

A. Network delay optimisation

The aim of ATFM is to ensure that air traffic controllers are never overloaded (safe operations) while attempting to maximise the accommodation of traffic demand (ATM capacity) and minimise the costs associated with delay (AU operational efficiency).

The network delay optimisation problem is a complex one involving emergent system dynamics referred to as network effects [8]. Figure 3 shows an example of the so-called network effects. Bars in the figure represent the traffic demand (throughput) expected to enter to a traffic volume in four different periods. The figure illustrates an example of how modifying the time dimension of a trajectory (for example after allocating a CASA delay to solve a congestion problem in a traffic volume A) may generate more demand at some periods (referred as the penalisation effect) in another traffic volume B, or may reduce the demand for some periods (referred as protection) in a traffic volume B. The impact on network stability (network effects) must therefore be checked when minimising delay.

In the scientific literature, the network delay optimisation problem has been typically approached through classical optimisation methods, and this has led to a better and formalised understanding of the problem principles. A first optimisation approach to the ATFM problem was provided by Odoni in 1987 [9], who presented a simplified static and deterministic approach for a single airport. After this work, several problem extensions have been developed, incorporating multi-airport and en-route capacity constraints with static-deterministic, static-stochastic, and dynamic-stochastic versions of the problem, e.g. [10][11][12][13][14][15], altogether aiming to move gradually from purely academic scenarios to the large-scale problems faced in real operations.

However, two major difficulties have up to now been present in the classical mathematical approaches, namely a) the computational intractability of finding real-time solutions when the solution space of the problem is large (as is the case in real operations), and b) the acceptability of the solutions found from the point of view of equity.

With regard to the computational efficiency handicap, it is paramount in real operations to be able to rely on a slot allocation mechanism which is able to find acceptable solutions at network level in a few seconds or minutes (owing to the high level of dynamicity of real ATM operations in Europe, the sequences should ideally be calculated in less than a minute).

With regard to equity, for the slot allocation mechanism to be accepted, it needs to be perceived as "fair" by the stakeholders, especially by AUs. In this sense, the FPFS (or *ration-by-schedule*) policy, which is implemented by CASA, enjoys widespread acceptability and a broad consensus among the key stakeholders, i.e. AUs and ANSPs, because it is easy to understand, effective, and is considered fair. According to Lulli and Odoni [18], the problem of finding equitable and efficient solutions seems to be especially complex in European ATM, while as discussed by Barnhart et al. [17], solutions based on FPFS policy have better chances of acceptance by AUs.

Some modern approaches have also been under development in recent decades based on collaborative decision-making (CDM) principles. Some of the approaches have sought to minimise changes to the current system, thus adopting an innovative approach, e.g. [19][20], whereas others have sought fundamental changes in the system, thus proposing more disruptive solutions in the management of ATFM slots, e.g. [21][22], or in line with trajectory-based operations which may take longer to bring into real operation, e.g. the concepts of the Collaborative Trajectory Options Project [23] or the strategic de-confliction of 4D trajectories [24]. Some of these approaches are promising, but since they require significant changes in the operational environment, they do not seem suitable for short-term implementation.

B. Contributions of this paper

The major contribution of this paper is its innovative approach, in which a minimum change is applied to the system and large benefits are achieved. The CASA mechanism used today in European operations has been taken as a baseline and small amendments have been applied to the sequences to generate substantial delay reductions with significantly less impact on AUs. The optimisation model proposed is not based on classical optimisation methods but on a powerful heuristic, which is supported by a novel formal analysis of the interactions between flights and between regulations (the formal analysis is also summarised and presented in this paper).

The fact that ECASA uses the sequences of CASA, together with its rules and principles, ensures that ECASA will be well adapted to operate in real time to cope with the dynamic changes and uncertainties of the operational environment. With regard to equity, the same philosophy applies, i.e. small amendments to the equitable CASA sequences are expected to lead also to 'equitable-enough' sequences (although this is an assumption to be verified in future validation exercises). Finally, the scope of this research has been focused on ATFM slot allocation only. Nonetheless, the optimisation mechanism proposed does not exclude – and indeed is compatible with – other ATFM control mechanisms applied to flights, such as flight-level capping, horizontal re-routings, linear holdings or others.

C. Current CASA rules (simplified)

For the analysis of interactions between regulations, it is important to understand how the current CASA rules contribute to the phenomenon and propagation of interactions between flights. The following points present a (simplified) set of rules used in CASA [1].

FPFS policy: A flight *i* subject to regulation R1 will be sequenced in accordance with FPFS policy.

Exempted flights: Some flights are exempted from the CASA sequencing, e.g. airborne flights or flights proceeding from non-ECAC airports, medical emergency flights, amongst others. For such flights, a position in the sequence is reserved/forced at the closest position corresponding to their ETA/ETO.

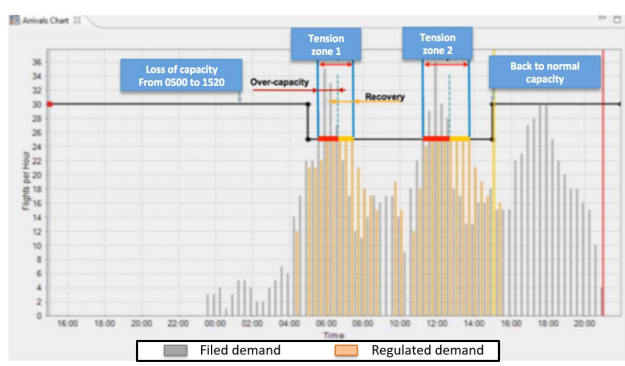

Figure 4: Illustration of a regulation and tension zones

True revision process: The CASA sequences are re-calculated and updated every certain number of minutes (currently once a minute). Any change in the network (e.g. activation of new regulations, changes in the actual airspace capacities, etc.), or in flight status (for example a flight is airborne, cancellations, non-ATFCM delays, etc.), may lead to sequences which are different from the previous true revision processes.

Most penalising regulation (MPR): If a flight i is crossing more than one regulation, the one allocating the greatest delay will be the MPR. A position will be forced (blocked) for that flight in other regulations taking into consideration the updated ETA/ETO of the flight due to the CTA/CTO allocated by the MPR.

Compression: To optimise the use of available capacity and minimise the impact on AUs, any empty position will be filled whenever possible with the closest non-blocked flight placed later in the sequence. This mechanism is referred to in the literature as *compression* [5] [6] and it will be applied to the earliest flight if it is not blocked and its ETO plus a tolerance (typically around 2 minutes) is earlier than or the same as the CTO associated with the empty slot. The FPFS policy is preserved.

Capacity of slots: Only one flight per slot is allowed in general. There are exemptions to this rule (see *overloaded slots*).

Overloaded slots: On certain special occasions the FMPs may accept up to two flights allocated in the same slot. This is then referred to as an overloaded slot. In practice, overloaded slots are compensated for by leaving an empty slot in the sequence, close to the slot which was overloaded. The compression mechanism cannot use the empty slots which compensate for nearby overloads.

Manual slot amendments: CASA rules include the possibility for the human ATFM operators to apply amendments to the default CASA sequences, for operational reasons such as to preserve safety or to optimise network performance. This rule will be exploited by ECASA, which will identify flights to be amended in order to reduce network delay.

III. METHODOLOGY AND TOOLS TO ANALYSE THE REGULATION INTERACTION PROBLEM

In this section the methodology to quantify the interactions between flights and between regulations is described.

A. Definitions

Linked regulations: A set of two or more regulations in which one or more flights are planned to enter (note: regulations are linked by flights).

Interaction between flights: Direct or indirect increase or reduction in delay which one flight regulated in one regulation (MPR) may cause to certain flights in another regulation.

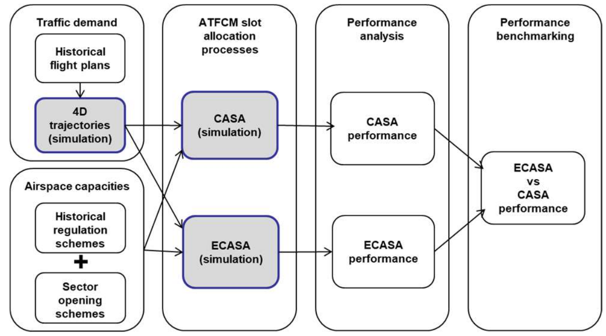

Figure 5: Research methodology

Interaction between regulations: Increase or reduction in throughput and delay in a regulation as a consequence of the flight interactions between it and another regulation.

Tension zone (TZ): Sub-sequence of positions within a regulation sequence in which compression can be applied to some flights if one of the positions in the zone is released. During the allocation process, some flights will be allocated slot times which are later than those planned, thus generating delay (or 'tension'). Flights in a TZ will typically be delayed, with the exception of the first flight(s) (at least one flight will have zero delay at the beginning of a TZ). However, flights may sometimes be in a tension zone (and take earlier positions) while not being delayed at all. This may be the case for flights with no positive delay and with some tolerance for early departure (formally, 'negative delay'). Note that regulation sequences may – and indeed typically do – have several TZs. See Figure 4.

B. R-NEST simulation tool

R-NEST is a model-based simulation tool [25], sharing the same core as the EUROCONTROL NEST tool [26], and it is dedicated to research activities to evaluate advanced ATM concepts. The tool combines dynamic ATFCM simulation capabilities with powerful airspace design and capacity planning analysis functionalities.

R-NEST can calculate 4D flight trajectories for a given route network, taking into account aircraft performance data, route restrictions and flight level constraints, SIDs and STARs and military area opening times. The dynamicity of network operations can be simulated to measure and analyse the delays which degrade network performance. ATFCM delays are calculated with an emulation of the CASA (Computer Assisted Slot Allocation) algorithm used by the Network Manager in real operations to respond to network constraints.

C. General research approach (steps)

The methodology used in this research is presented in Figure 5. The simulation steps are shown in shadowed boxes. The first step of the research method consists of the preparation of the simulation inputs, i.e. the traffic demand and the airspace capacities. The traffic demand used is based on the historical records available in the the EUROCONTROL's Demand Data

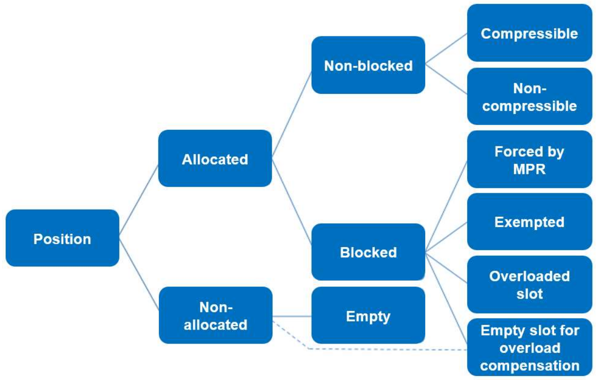

Figure 6: Ontology of sequence position uses and statuses

Repository (DDR2),, which contain the flight routes as planned before any ATM intervention (files m1). From the flight plans, the 4D trajectories are generated using the functionalities included in R-NEST. The airspace capacities are determined by the historical records for the day of operations simulated, i.e. the historical regulation scheme (the final snapshot of the regulations actually applied), and the sector opening schemes registered for that day. Since the regulation schemes are not simulated but reproduced, there is no need to obtain the actual sector capacities on the day of operations.

Two different sets of simulation outputs will be obtained from the CASA and ECASA modules in different simulations. As a final step for the purpose of this research, the sequence solutions and performances of each of the CASA and ECASA mechanisms will be compared in terms of the delay produced, the impact on AU operational efficiency, and the impact on network stability.

IV. ANALYSIS OF INTERACTIONS

To identify the origin/causes of the interactions and quantify their impact on flights and regulations, it is important to understand how the interactions are propagated and spread by chain reactions across the sequences.

Interactions are caused by changes in the positions of flights in a regulation sequence due to the delay allocated by the MPRs for those flights. Any change in position of one flight always generates two events: 1) *releasing* of the position previously allocated, and 2) *taking* of the new position. These two events may generate a direct impact on other flights, such as a) *pushing* the flights towards later positions, thus increasing the delay for those flights (*negative impact*); this typically is the impact caused by a *taking* event; or b) *compressing* the flights towards earlier positions, thus typically reducing their delay (*positive impact*); this typically is the impact caused by a *releasing* event.

Any change in the position of the affected flights can in turn have an impact on other adjacent flights (an indirect impact of the causing interaction), which may propagate the initial direct impact (caused by an external regulation) through the sequence via a *chain reaction/domino effect*.

To understand how the interactions are propagated by chain reactions through the sequences, all the possible combinations of direct and indirect impacts for the various cases have been analysed in the following sub-sections.

a) Ontology of sequence position uses and statuses

Figure 6 identifies all possible uses and statuses of the slots/positions in a sequence as considered in our analysis. This ontology has been derived from the simplified CASA rules as detailed in Section II.

In the context of this paper (note that some terms could have different meanings outside the context of this paper), positions in a sequence may have the status *allocated* (used by flights) or *non-allocated* (empty). If a flight using a certain position is forced by a most penalising regulation, or if a flight is exempted, then the position is considered *blocked*. Flights which have the status *non-blocked* may be *compressible*, meaning that they can take positions before their current position (i.e. flights with delays and/or with some tolerance to operate slightly earlier than planned), or they may be *non-compressible*, meaning that they cannot be allocated earlier slots. Two special cases have also been considered in the analysis: the case of *overloaded slots*, where two flights are allocated the same slot in a sequence, and that of *compensation slots*, where blocked empty slots are placed near overloaded slots to avoid too much traffic entering a sector or airport.

b) Propagation of interactions

Figure 7 and Figure 8 respectively illustrate two simplified examples of how positive and negative impacts are propagated, with the aim of summarising, without any loss of generality, the fundamentals of the micro-analysis conducted.

In Figure 7, a regulation sequence is presented in its initial state S0. Positions 6 to 16 are in tension (i.e. with compressible flights). In the example, flight G releases its position (assume that its MPR removes flight G from this regulation). The

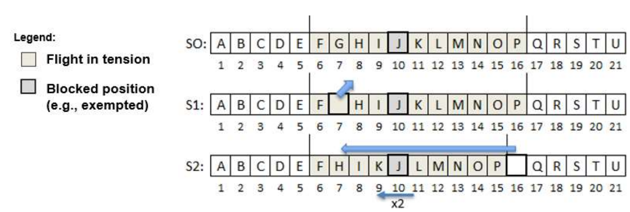

Figure 7: Propagation of positive impacts

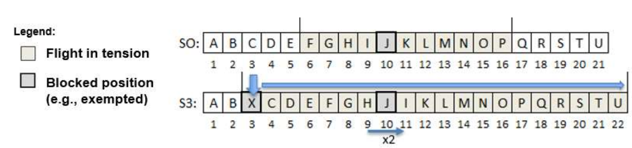

Figure 8: Propagation of negative impacts

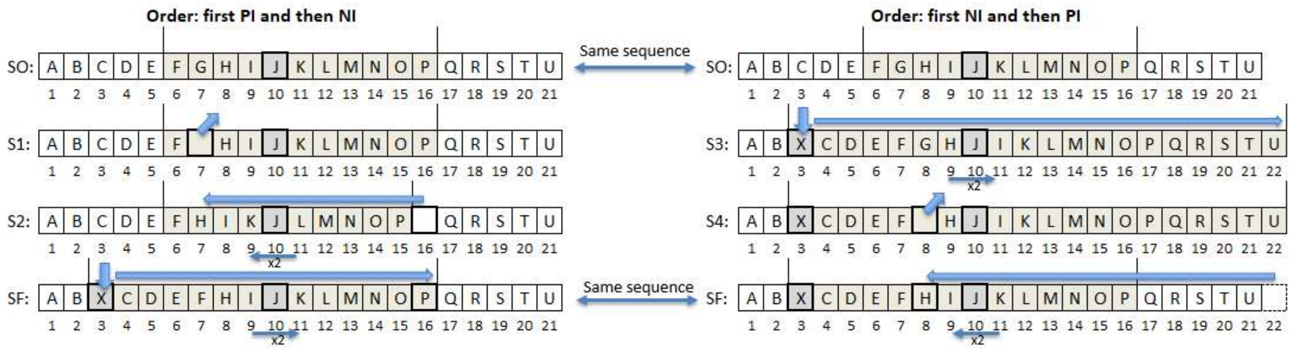

Figure 9: Accumulative and commutative properties of flight interactions

sequence status S1 shows that an empty slot is generated as a consequence in position 7. After the application of compression by CASA, flight H, which is compressible, will take position 7, and will release position 8 as a consequence. Via a chain reaction, flights H to P will take earlier positions, except for flight J, which is in a blocked position (exempted flight or position forced by MPR). Note that flight K, adjacent to J, takes the slot in position 9, thus reducing its delay in two positions. This is a *collateral positive impact* caused by the blocked position of J. After compression, the empty slot is 'displaced' to position 16, where no later flight can use it since they are all non-compressible (cannot take earlier positions). Note that the length of the tension zone is reduced in one position since one flight has been released.

Figure 8 shows the same initial status S0 as in Figure 7. In this example, flight X enters the sequence taking position 3 (it is assumed that flight X enters the sequence owing to the delay allocated by its MPR). Since X is forced by CASA into position 3, flight C is 'pushed' to the next available position, in this case position 4. Via a chain reaction/domino effect, all the non-blocked flights after X are pushed to the end of the sequence or to where an empty slot is found. Note that flight H, adjacent to blocked flight J, is pushed to position 11, thus increasing its delay in two positions owing to the *collateral negative impact* of J. Note that all the flights which were pushed at least one position are now in tension, i.e. they are compressible because they could now take earlier positions. Thus flights Q to U are in tension in sequence S3, while sequence S3 is one position longer (there is one more flight in the sequence).

From the analysis of flight interactions the following lemmas can be derived:

Lemma I. *A release of a slot will always generate a hole (empty slot) in a sequence.*

Lemma II. *Compression is applied if and only if there is a hole in a tension zone (where flights are in tension, i.e. compressible).*

Lemma III. *There cannot be any holes (empty slots) in tension zones. If a release occurs within a TZ, then the hole will be occupied and 'displaced' by chain reaction owing to the compression process until the hole appears in the final position in the original TZ (note: the resulting new TZ will be one position shorter owing to the release of one flight).*

Lemma IV. *Compression does not alter the position of blocked flights in a sequence.*

Lemma V. *Compression does not change the order of non-blocked flights in a sequence (FPFS policy is preserved).*

Lemma VI. *A taking of a slot will always fill a hole (empty slot) in a sequence. If the hole does not exist (it is occupied by another flight), the allocated flight will be forced ('pushed') to take the next non-blocked position. Other later flights may also be pushed by a chain reaction.*

Lemma VII. *The chain reaction of a taking will only be stopped when a hole is found (sometimes at the end of a sequence).*

Lemma VIII. *Chain reactions of takings do not alter the position of blocked flights in a sequence.*

Lemma IX. *Chain reactions of takings do not change the order of non-blocked flights (the FPFS policy is preserved).*

c) Accumulative and commutative properties

With the lemmas derived from the micro-analysis above, it is possible to prove that flight interactions have two properties, i.e. accumulative and commutative properties. The proof of the properties is important in the paper to show the appropriateness of both the methodology and the strategy proposed for optimisation.

Accumulative: *The total net impact on a flight is the direct sum of all the impacts received:*

$$TI_i = \sum NI_i - \sum PI_i = NFSB_i - EFSB_i + \Delta ESSB_i \quad (1)$$

Equation 1 states that the *total impact* (*TI*) on a flight *i* is the net sum of the *negative impacts* (*NI*) and *positive impacts* (*PI*), which can be determined by counting how many *new flights in the sequence before its position* (*NFSB*) appear with respect the original sequence, and then subtracting the *exiting flights in the sequence before its position* (*EFSB*), and taking into account the variation of *empty slots in the sequence before its position* (*ESSB*): a filled former empty slot cancels a NI, a new empty slot in the sequence cancels a potential PI.

Commutative: *The order of the impacts does not alter the final sequence.*

This property is indeed a consequence of the accumulative property. To prove the property, a simplified example without loss of generality is illustrated in Figure 9. Note that the intermediate sequence statuses and impacts may evolve differently with the change of order, but the final sequence status will be the same irrespective of the order in which the interactions are applied.

V. HEURISTIC OPTIMISATION MODEL

A. Fundamentals of the optimisation model proposed

Analysis of the interactions showed that removing a flight from a TZ can reduce the delay of the flights allocated afterwards. The closer to the beginning of the TZ, the larger the number of flights which benefited and the greater the reduction in the delay.

The proposed optimisation heuristic thus consists in preventing flights delayed by their MPR from entering (large) tension zones of other regulations. Figure 10 shows a realistic situation which was often observed in the archived data. The ETO position of flight F corresponds to the current position of B in regulation R1 and to the current position of J in R2. Flight F is delayed 5 positions (typically 10 or 15 minutes) by R1, which is its MPR. Owing to this delay the flight is forced in R2 to the beginning of a tension zone, and it also enters R3. Tension zones may often include tens or hundreds of flights, which will each be pushed one position, thus increasing the delay of all those flights, typically by around 2 or 3 minutes, and several hours in total. Note that in some positions just before the forced position of flight F in R2 there are two empty slots. This is a waste of capacity which could have spared a good deal of delay if it had ben used. The proposed strategy consists in detecting such situations and applying less delay to flight F in R1. In the example, if flight F was delayed three positions instead of five, F would not enter the tension zone of R2 and would also not enter R3, and thus F would be removed from the periods of actual congestion and better use of the available capacity could be achieved. In R1 a few flights (D and E) would be slightly more delayed, while the total delay in R1 would remain the same (the delay is exchanged between the flights). In R2 and R3, the delay reductions could be quite large, often of the order of hours in each regulation. Note that several flights are often forced by their MPR in the beginning of tension zones, in similar situation

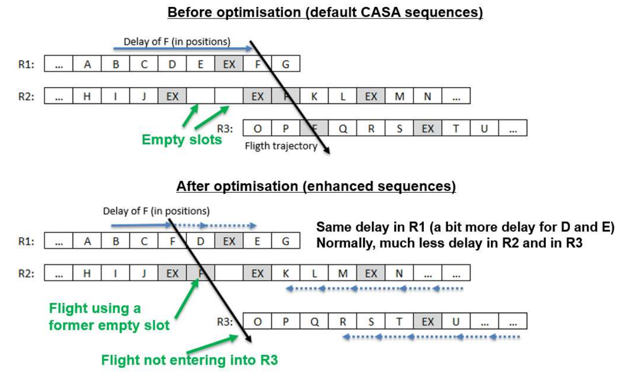

Figure 10: Example of the optimisation strategy proposed

than flight F in the example. Thus, important delay reductions can be achieved per flight and per regulation if the proposed allocation strategy is applied.

B. Implementation aspects

In order to facilitate the compatibility with CASA (fast innovation approach), a very simple heuristic optimisation model has been implemented: first, the flights which generate more negative interactions are identified (e.g. flight F in Figure 10), and then highest priority is given to those flights so that a new position for that flight can be found in the next true revision process of CASA (1 or 5 minutes later). Selected flights will be typically allocated their delay-zero position or close to it.

The integration with the default CASA process is as follows (note that ECASA is in steps 2 and 3 of the process):

1. CASA generates slot sequences with the most updated information in the system.
2. ECASA identifies flights which are delayed by their MPR and generate large negative impacts on other regulations.
3. ECASA increases the priority of those flights identified in the previous step.
4. A new position for the amended flights will be found by CASA in the next true revision process.

It is worth pointing out that changing the position of those selected flights will also require changing the position of other flights (chain reaction), which in some cases could lead to new negative interactions in the network. Nevertheless, any new interaction which may occur because of these amendments will be identified in subsequent loops of the true revision process and, owing to its iterative nature, the algorithm will typically converge in a few iterations to solutions with de-coupled regulations (delay reductions). In some rare situations the ECASA algorithm might not be able to de-couple some of the regulations (e.g., a regulation pushing a lot of its traffic into the beginning of another regulation); in those particular regulations the delay might be slightly reduced or not reduced at all.

VI. RESULTS: CASA VS ECASA BENCHMARKING

A. Simulation scenarios and conditions

To benchmark ECASA against CASA, the 28 days of the Aeronautical Information Regulation And Control (AIRAC) cycle 1808 available in DDR2 were simulated, corresponding to the period of highest delay in 2018 (mid-July to mid-August). To ensure a fair comparison, both the ECASA and the CASA sequences were simulated with R-NEST under the same conditions. See Section 4 for more details of the methodology followed.

B. Network delay in the period

Figure 11 shows a box diagram summarising the delay statistics for the period. The average delay per day in the busiest period of summer 2018 was around 200,000 minutes of delay per day, with a minimum of 100,000 and a maximum of 340,000 minutes of delay in a single day. This figure corresponds to the simulation outputs from R-NEST. In comparison with the delay figures available in DDR2 (figures for which can also be seen in the Network Manager delay reports [27]) the delay simulated is around a 15% higher than that reported, which is congruent with the fact that some operational events were not simulated in our experiments, e.g. flight cancellations, re-routings, level capping, or others.

Figure 12 confirms that the delay in the network shows a high level of correlation, as expected, with the number of regulations on each day of operations.

C. Network delay reduction

Figure: 13 shows a box diagram of the relative delay reduction achieved by ECASA in comparison with CASA for the same AIRAC 1808. As observed in the figure, after the application of the amendments to the CASA sequences (around 1,500 flights were amended by ECASA), the delay could be reduced by 27% on average in the period, with a peak delay reduction of 35% in one of the most congested days of the 2018. An 18% delay reduction in a day was the minimum case observed in the period analysed.

Figure 14 shows that the optimisation potential increases with the amount of delay, which suggest that the greater the number of regulations activated, the greater the number of delay inefficiencies generated.

D. Impact on airspace users

Figure 15 shows that the number of flights delayed is 13.7% lower in the ECASA sequences than in the CASA sequences (9,161 flights were delayed by ECASA as against the 10,616 delayed by CASA).

Figure 16 shows the number of delayed flights broken down into delay ranges of 15 minutes. Distributions for CASA and ECASA and the difference between ECASA and CASA are shown in the figure. It is worth noting that flights are typically operated with some tolerance to delay, and it is therefore commonly accepted that the cost of up to 15 minutes of delay is negligible in practice for most flights. The figure shows that the number of flights delayed by up to 15 minutes (flights with no impact) increased with ECASA, whereas flights delayed more than 15 minutes (flights with costly delay) were considerably reduced (a 42% reduction on average).

It should also be noted that ECASA increased slightly the number of flights with more than 90 minutes of delay, from 77 flights in CASA (0.7% of the flights delayed) to 137 in ECASA (1.5% of the flights delayed). Those flights –when not cancelled by the airlines– could be candidates for applying other ATFCM measures, such as re-routing, level capping or others.

In the light of these results, it can be concluded that ECASA has great potential for reducing the impact of ATFCM measures on AUs and increasing the quality of ATFCM services.

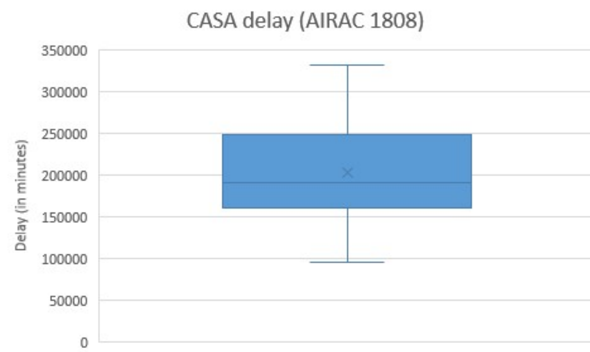

Figure 11: Delay in the period (mid-July to mid-August 2018)

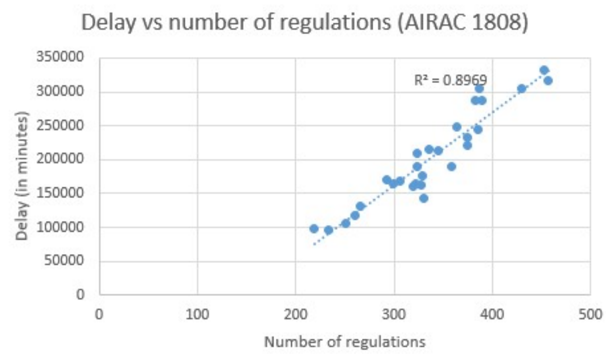

Figure 12: Delay vs number of regulations

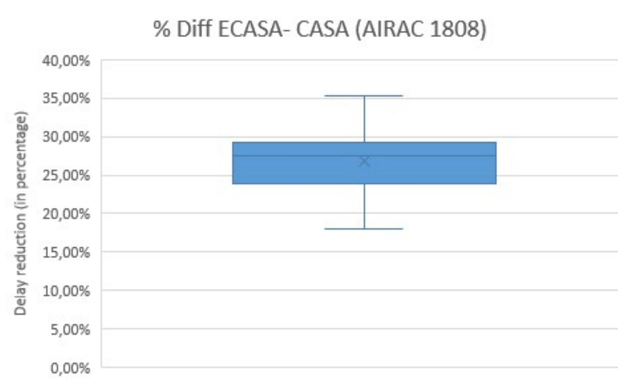

Figure: 13 Relative delay reduction achieved by ECASA

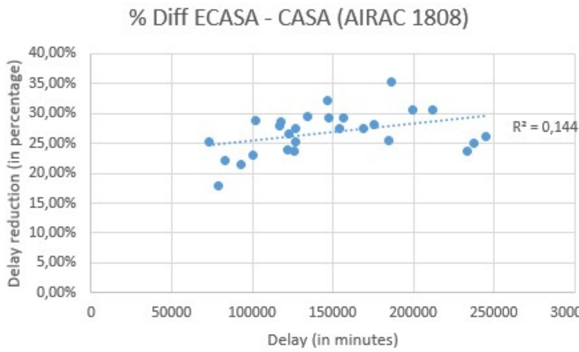

Figure 14: The delay reduction potential increases with delay

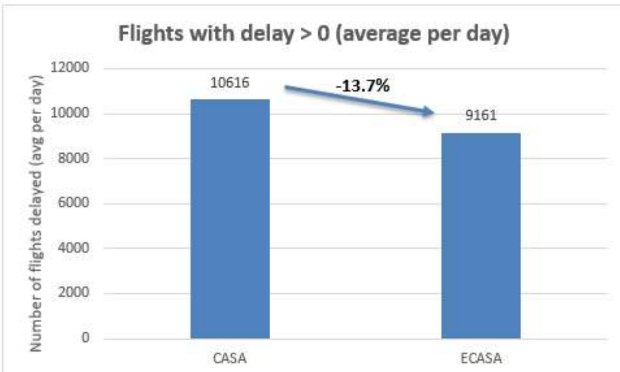

Figure 15: Number of flights delayed

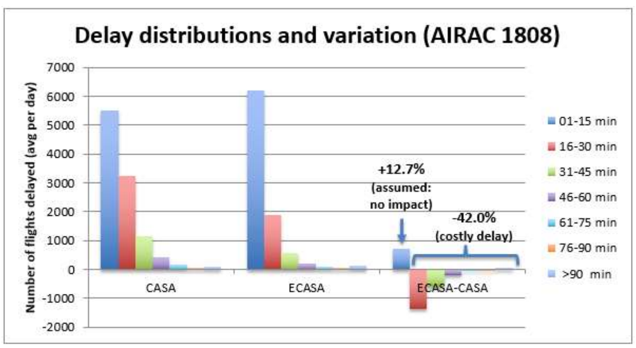

Figure 16: Delay distributions and variation

E. Impact on network stability

It is important to have a measure of the potential impact of ECASA on network stability, i.e. its impact on the throughput of traffic volumes in the network. Since the traffic demand of the analyses has been simulated, the actual capacities and sector opening schemes are not a good reference for assessing the impact on stability. A measure relative to CASA will be used instead.

Table I shows an analysis of traffic volumes (TVs), the throughput of which, observed in slices of 10 minutes throughout the day of operations, was increased by ECASA in comparison with CASA. Around 9% of the TVs used by CASA (i.e. 875 out of 9,857 TVs) were penalised by ECASA with 1 more flight, while 3% (315 TVs) were penalised with more than 2 flights. In this experiment, it is not possible to know whether receiving 1 or 2 additional flights in a period of 10 minutes would be acceptable for the TVs affected (it should be acceptable if they are not saturated), but even if the TVs affected were saturated, the additional flights could sometimes be accepted by the FMPs if safety were not compromised. Only 1.4% (140) of the TVs were affected with more than 3 additional flights in a period of 10 minutes after the application of the ECASA amendments. The analysis of the throughput reduction (i.e. fewer flights in a 10-minute slice) is symmetrical with the results shown in the table (i.e. < -1 flights ➔ 8%; < -2 flights ➔ 3%; < 1.5%, etc.). It is worth noting that FMPs typically have some margin to adapt capacities and sector opening schemes to the traffic expected in the sectors under their control. The impact on network stability must be further explored in future research, but these figures show quite promising results.

TABLE I. TVs WITH CASA THROUGHPUT PENALISED BY ECASA

Throughput variation (in 10 min slices)	*Number of TVs*	*% of TVs (total #TVs: 9857)*
≥ 1 flights	817	8.29 %
≥ 2 flights	315	3.20 %
≥ 3 flights	140	1.42 %
≥ 4 flights	66	0.67 %
≥ 5 flights	32	0.33%

VII. Conclusions and Future Work

The interacting regulations problem has been presented, showing that the first-planned-first-served (FPFS) policy currently used in operations for slot allocation purposes cannot minimise the overall delay in the network. To minimise the delay, a new heuristic optimisation mechanism referred to in the paper as ECASA (Enhanced CASA) has been discussed. The main goal of the proposed method is to make it rapidly deployable in the European Network Manager. It therefore takes CASA as a baseline (including the FPFS policy) and applies targeted slot amendments to certain cherry-picked flights.

Despite the simplicity of the optimisation heuristic proposed, the ECASA vs CASA benchmarking has shown very promising results. For summer 2018 (a highly congested scenario), ECASA was able to potentially reduce the delay in the network by around 27% per day on average, with peaks of 35% less delay on some busy days. In addition, ECASA was able to reduce by on average 42 % the number of flights with more than 15 minutes of delay, thus significantly reducing the impact of the remaining delay. In terms of impact on network stability (variation in the throughput of traffic volumes across the network), promising results were also found, showing that a few number of traffic volumes were actually negatively affected with additional traffic. The actual impact of this additional traffic should be further assessed in a more realistic environment to validate the feasibility of ECASA in real operations.

The next step is to explore the potential benefits and challenges of the proposed enhancements for CASA in real Network Manager operations. A short lead-time to transfer the new concept into operations is expected. Future research will also include new optimisation strategies to make better use of the available capacities and to further reduce delays. Future traffic conditions (SESAR timeframes of 2025 and 2035) will also be simulated to explore the potential benefits and limits of the new slot allocation strategies.

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References

[1] EUROCONTROL, "ATFCM Users Manual", Ed. 22.1.18

[2] ICAO, "Procedures for air navigation services – Air Traffic Management" (doc 4444), 16th Edition, 2016

[3] University of Westminster, European airline delay cost reference values – Updated and extended values, Ed. 4.1.15

[4] IATA ECONOMICS, "Profitability and the air transport value chain", IATA ECONOMICS Nº10, 2013

[5] T.W. Vossen and M.O. Ball, "Optimisation and mediated bartering models for ground delay programs", Naval Research Logistics, 53, pp. 75-90, 2006

[6] FAA, "Traffic Flow Management in the National Airspace System", October 2009

[7] L. Castelli, R. Pesenti and A. Ranieri, "The design of a market mechanism to allocate Air Traffic Flow Management slots", Transportation Research Part C, 19 (5), pp. 931-943, 2011

[8] EUROCONTROL, "Assessment of ATFCM Network Effect", Technical Report, 2007

[9] A.R.Odoni, "The flow management problem in air traffic control", in Flow Control of Congested Networks, pp. 269-288, 1987

[10] M. Terrab and S. Paulose, "Dynamic strategic and tactical air traffic flow control", IEEE international conference on systems, man and cybernetics, 1992

[11] P. Vranas, D. Bertsimas and A. Odoni, "The multi-airport ground-holding problem in air traffic control", Operations research, 42(2), pp. 249-261, 1994

[12] S. Mukherjee and M. Hansen, "A dynamic stochastic model for the single airport ground holding problem. Transportation science, 41(4) pp. 444-456, 2007

[13] Ball, M. O., C. Barnhart, G. Nemhauser, A. Odoni, "Air transportation: Irregular operations and control". Handbooks in operations Research and Management Science, vol. 14, 2007

[14] Ball, M. O., R. Hoffman, A. Odoni, R. Rifkin, "A stochastic integer program with dual network structure and its application to the ground-holding problem. Oper. Res. 51(1) 167-171, 2003

[15] Bertsimas, D., S. S. Patterson, "The air traffic flow management problem with enroute capacities", Oper. Res. 46(3) 406-422, 1998

[16] Ball, M.O., C.Y. Chen, R.L. Hoffman, T. Vossen: Collaborative Decision Making Air Traffic Management: Current and Future Research Directions, to appear in New Concepts and Methods in Air Traffic Management, Bianco-Dell'Olmo-Odoni (eds.), Springer Verlag, 2001

[17] C. Barnhart, D. Bertsimas, C. Caramanis, and D. Fearing, "Equitable and Efficient Coordination in Traffic Flow Management", Transportation Science, 46, 2012

[18] G. Lulli and A. Odoni, "The European air traffic flow management problem", Transportation Sci. 41(4) 431-443, 2007

[19] K. Chang, K. Howard, R. Oiesen, L. Shishler, M. Tanino, and M. C. Wambsganns, "Enhancements to the FAA ground-delay program under collaborative decision making", Transportation Sci. 34(1) 57-76, 2001

[20] N. Pilon, S. Ruiz, A. Bujor, A. Cook & 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

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

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

[23] O. Rodionova, H. Arneson, B. Sridhar and A. Evans, "Efficient trajectory options allocation for the collaborative trajectory options program," *IEEE/AIAA 36th Digital Avionics Systems Conference (DASC)*, 2017

[24] S. Ruiz, "Strategic trajectory de-confliction to enable seamless aircraft conflict management", PhD thesis, 2013, available online: https://www.tdx.cat/bitstream/handle/10803/131454/srn1de1.pdf?sequence=1&isAllowed=y

[25] https://www.eurocontrol.int/publications/research-network-strategic-tool-r-nest-factsheet, accessible online in January 2019

[26] https://www.eurocontrol.int/services/nest-modelling-tool accessible online in January 2019

[27] EUROCONTROL, Monthly Network Operations Report – August 2018, 2018, available online (accessible in January 2019): https://www.eurocontrol.int/sites/default/files/publication/files/nm-monthly-network-operations-report-analysis-august-2018.pdf

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