An innovative safety-neutral slot overloading technique to improve airspace capacity utilisation

Towards innovative enhancements for the Computer Assisted Slot Allocation system

Sergio Ruiz, Hamid Kadour and Peter Choroba
ATM/RDS/NET
EUROCONTROL Experimental Centre (EEC)
Bretigny-sur-Orge, France
sergio.ruiz@eurocontrol.int; hamid.kadour@eurocontrol.int: peter.choroba@eurocontrol.int

***Abstract*—This paper presents a new air traffic flow and capacity management (ATFCM) technique that uses some of the rules and mechanisms that are already existing in the computer-assisted slot allocation (CASA) system, such as the slot overloading and the compensation of overloaded slots, in a new innovative manner that could potentially increase the effective use of the airspace capacity, and consequently reduce the network delay and the impact of ATFCM delays on the airspace users (AUs) schedules and costs.**

Such a new ATFCM technique has been named Resourceful Overloading of Slots (ROS). The early validation of ROS has been made through fast-time simulations using the R-NEST tool –an ATFCM simulation developed by the EUROCONTROL Experimental Centre–, and using a realistic scenario of 28 days (i.e., an AIRAC) from Summer 2018 in which more delay was recorded. The simulation results indicate that the ATFCM delay in that period could have been 23% lower, and the impact of delay 27% lower, compared to the same scenario simulated with the baseline CASA (i.e. default CASA simulated without including the new ROS technique).

The new ROS technique has been also analysed in combination with a former innovative ATFCM technique, i.e., the Mitigation of Interacting Regulations (MIR), that has been recently proposed in a previous paper for enhancing CASA. The figures found in the simulations when the two techniques were activated jointly are promising, showing that the delay could be reduced, at least in the simulation setting, by 41% on average and the impact of delay by 55% on average. *(Abstract)*

Keywords: slot overloading; air traffic flow and capacity management; computer asisted slot allocation; CASA; SESAR

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I. Introduction

In the European air traffic management (ATM) system the Network Manager (NM) is responsible of the traffic flow and capacity management (ATFCM) functions at network level. Among other tasks, the NM has the responsibility to facilitate the different local demand and capacity balancing (DCB) processes and coordinate all the relevant actors to ensure that the air traffic demand never exceeds the capacities at any particular sector or airport of the network, while procuring the maximum operational efficiency and quality of service for the airspace users (AUs) [1][2][3].

When an imbalance between the capacity and the demand is foreseen at a particular sector or airport, the NM works in close cooperation with the air navigation service providers (ANSPs) to provide a DCB solution. A widely used solution, when no other better alternatives are possible, is to apply 'ATFCM regulations' to the traffic demand that is expected to enter the in sector or in the airport during the period of imbalance. For each active regulation in the network, the NM uses the computer-assisted slot allocation (CASA) to calculate departure delays for the regulated flights, until the demand matches the capacity.

The application of ATFCM delays to flights is a pragmatic solution to solve the network imbalances, and it worked efficiently in the past, when the ATM system was much less congested than nowadays. However, due to the current traffic levels in the network, today many sectors and airports have reached their capacity limits and, as a result, the DCB processes are becoming more frequent, more difficult to manage, and more costly for the airspace users and the society [4].

For that reason, there is an urgent need to either increasing the capacities in the system or reducing the latent ones, in order to improve the cost-efficiency of the current operations and also to guarantee access for the high levels of traffic demand that are forecasted for the next incoming decades [7]. In recent years, plenty of research efforts have been done to better understand and manage the factors and drivers of the ATM system capacity, e.g. new advanced ATM concepts such as the traffic complexity, the dynamic configuration of sectors, higher levels of automation in some processes, or others [11].

In this paper we propose a new technique called Resourceful Overloading of Slots (ROS) that aims at utilising the available airspace capacities in a more effective manner, thus reducing the latent capacities in the system. ROS is an innovative and pragmatic new concept because it re-uses some of the rules and mechanisms that already exist in the current CASA system, and proposes a certain amendments (overloads) for some of the slots calculated by CASA to improve the efficiency of the ATFCM regulations. Early simulation results will be discussed in this paper, showing that the proposed innovative enhancement for CASA could reduce significantly the impact of ATFCM delays to the airspace users.

The rest of the paper is organised as follows: section II describes the state of the art. Section III explains the new technique proposed to improve CASA. Section IV discusses the simulations results. Section V presents the conclusions and future work foreseen.

II. State of the Art

The following state-of-the-art subsections discuss: a) the most important factors affecting the airspace capacity; b) the ATCFM techniques used today to protect the airspace capacities; c) the shortcomings and limitations of the current methods; and d) the recent CASA developments to overcome some of the current system limitations. The contributions and relevance of this research paper to the state of the art are identified as well, in the last sub-section.

A. *Airspace capacity*

Airspace capacity is a term used to indicate the maximum number of flights that the Air Traffic Management (ATM) system can safely and efficiently control over a period of time [1][3]. Many different factors can potentially limit the airspace capacity (e.g., weather, separation standards, CNS infrastructure, etc.), but it is widely accepted that the major bottleneck today at the airspace sectors (especially at en-route sectors) is the ability of the air traffic control officers (ATCOs) to safely handle the traffic at each air traffic control (ATC) sector [12]. In other words: the airspace capacity is nowadays constrained by the maximum number of flights that the ATCOs can manage safely with an *acceptable/sustainable level of workload*.

The NM and the ANSPs need to accurately assess and protect the airspace capacities across the network, and to achieve such the use of objective metrics together with the proper tools is needed. However, a standard manner to quantify and estimate the *ATCOs' cognitive workload,* i.e. the actual sectors capacities, has still not been, in part because it is not easy to objectivise and to quantify. Airspace capacity depends on a mix of objective and subjective factors, such as the traffic complexity, the ATCOs skills and experience, their cognitive and physical conditions at the moment of the operations, or the decision support tools available, among other factors [15][14][12][13].

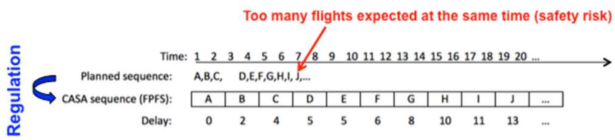

Figure 1: Schema of a CASA sequence during a regulation period

B. *Current ATFCM operations to protect ATC capacities*

In today's operations, when a potential demand-capacity imbalance is foreseen a few hours in advance with a certain level of confidence, the NM starts a DCB process to ensure that the demands and the capacities in the network are well balanced at any time with the lesser impact as possible to the airspace users. The first attempt of the NM, working closely with the ANSPs, is to adapt/increase the capacities at the congested sectors. If more capacity cannot be allocated to a congested airspace region, then the NM will start acting on the traffic demand. To minimise the costs for the AUs and the impact on the subsequent ATM operations, the DCB solutions try to re-plan the demand, typically in close collaboration with the airspace users. However, quite often is not possible to find alternate flight plans that can easily solve the DCB problems (e.g. due to several congestion problems occurring simultaneously at many network sectors). When this happens the Network Manager can activate, on request by the local ANPSs, a process to regulate the sector of interest. As soon as the sector is regulated, the CASA system issues 'ATFCM slots', which are new calculated departure slots for the flights affected by the regulation, with the aim of applying a tactical time-based separation between flights until the demand matches the capacity available

Figure 1 illustrates a high-level model of a CASA sequence of slots, and shows how the flights are delayed because of the regulation. In the example a certain number of flights (identified in the figure with letters, A,B,C...), have been scheduled to enter in a certain sector. In the example, the local flow management position (FMP) of that sector has assessed foreseen traffic situation in the sector, and decided to trigger a regulation to protect the ATCOs from receiving too many flights simultaneously. Attending the request of the FM, the NM triggers CASA to smooth the traffic and balance the situation. The flights are then sequenced in first-plan first-served order (FPFS) and their delay is calculated with respect to the time in which these flights were scheduled. The resulting calculated delay is carried out to the departure time of the affected flights (flights that are airborne are exempted from this process).

The issuing of ATFCM slots is used to smooth the rate of flights that will enter or arrive into a sector or airport during the execution phase, thus reducing the density and complexity of the traffic, and preventing the ATCOs from excessive workload. Due to the high levels of congestion that exist today in the European ATM system, thousands of ATFM slots are calculated and allocated to flights per day (around 30% of the flights operated daily in Europe are regulated), thus generating high levels of delay and costly impacts to the airspace users [5] [6].

C. *Limitations of the DCB mechanism and research needs*

To facilitate the strategic and pre-tactical DCB measures of NM, as well as the proper coordination between all the actor during the day of operations, the ANSPs must declare to the NM, well in advance, their sector configuration plans and the estimated capacities. As argued before, a major difficulty of that process is to estimate the actual capacities of the ATCOs that will be on duty at each specific sector. Due to that, and because the ANSPs must be conservative when declaring their capacities, some safety buffers are added to the capacity estimations, meaning that the capacities declared are lower than the actual capacities [12][16][17]. These buffers represent a latent capacity in the ATM system, which should be minimised to reduce the levels of congestion and the delays in the network.

Another consequence of the buffers is that, when a regulation is triggered, the ATCOs of many sectors often experiment less workload than in the absence of a regulation. In other words, normally the ATCOs could deal with more traffic when the traffic is regulated and smoothed (i.e., time-separated) than when the traffic is not regulated. This is paradoxical, since it means that the ATCOs capacities are often underused during periods of congestion when precisely a more efficient use of capacity is desired [16][17]. Increasing the predictability of the traffic monitored by the FMPs could help to reduce the capacity buffers, since the FMPs could do a more accurate and reliable assessment of the congestion levels in their sectors, and thus they could identify any potential demand-capacity imbalance in a more effective way [11][12][17]. *Entry counts* (EC) is an objective metric traditionally used by the ANPSs to measure the number of flights entering in a sector within a certain period (e.g., 1 hour). EC is a relatively simple metric that has worked very well in the DCB context until recent years, when the traffic congestion has notably increased in the system. Today, some ANSPs need to complement the EC information with another metric called *occupancy counts* (OC), which takes into consideration the period in which each flight entering in a sector will remain monitored and controlled by the ATCOs. Thus, the OC is a better estimator of ATC workload than the EC. When the OC is monitored, two monitoring thresholds are normally used, i.e. the *peak capacity* and the *sustainable capacity*. The former expresses the maximum number of flights that an ATCO can manage at a certain short period (peak), while the second expresses the level of traffic that an ATCO can manage under acceptable levels of workload in a prolonged period of time [11]. Therefore, monitoring and managing well the OCs by the FMPs is key to better setup their regulation requests (starting time, duration, rates,…) so that the ATCOs do not operate below their sustainable workload levels (spare capacity), especially during a regulation period. Other advanced capacity metrics and techniques are today under research, such as the metrics of *traffic complexity*. Nevertheless, all these metrics and techniques share the aim of reducing the ATC latent capacities [11][14][15].

On the other hand, some of the capacity inefficiencies of the today's system can be directly attributed to the slot allocation process itself. For instance, past studies showed that some of the slots available during a regulation are unused, due to diverse reasons that affect the CASA processes, e.g. the lack of demand scheduled at certain sub-periods of a regulation, flights missing their slots, interactions with other regulations, and others, [18]. Therefore, new improvements for CASA should be developed to minimise such a waste of capacities. In this sense, the ROS technique proposed in this paper aims at improving the current CASA slot allocation process to have a better control on the capacities available, and to potentially reduce the presence of undesired unused slots (a kind of 'idle times' for ATC) during periods of regulation.

D. Another recent innovative CASA enhancement: the Mitigation of Interacting Regulations (MIR) mechanism

Another source of inefficiencies in the system come from a known problem referred in the literature to as the *interacting regulations problem* [9][10]. When the network is highly congested, as it happens today, the traffic delayed by some local regulations can often be involuntarily pushed in time to other congested and already-regulated sectors, thus starting a 'resonant domino effect' that can substantially increase the overall levels of congestion and delays in the network. To mitigate the interacting regulations problem and optimise the overall delay in the network, a new concept was recently developed at the EUROCONTROL Experimental Centre (EEC), i.e. the Mitigation of Interacting Regulations (MIR), which has been implemented in a prototype called Enhanced CASA (ECASA), which is today under validation in the NM [9][10].

In short, the MIR optimisation technique consists in preventing the flights that are delayed by their most penalising regulation (MPR) from entering in the beginning of large *tension zones* –sub-periods within a CASA sequence in which the delay is generated– of other regulations. To do so, the MIR component applies amendments to some targeted identified flights of the default CASA sequences. Figure 2 shows a realistic typical situation which was often observed in the archived data. In the example, flight F is delayed 5 positions (typically 10 or 15 minutes) by R1, which is its MPR. Note that the original ETO position of flight F in regulation R1 was the current position of flight B, and in R2 it was the current position of flight J. Owing to the delay allocated by R1 the flight is forced in R2 to the beginning of the tension zone TZ2b, and it also enters in R3, at the beginning of TZ3a. Due to this, each flight placed after F in TZ2b and in TZ3a will be pushed one position, thus increasing the delay of all those flights, typically by around 2 or 3 minutes. Note that tension zones may often include tens or hundreds of flights , thus the total delay could increase several hours in total due to such regulation interactions. The proposed MIR strategy consists in detecting such situations and applying less delay to flight F in R1 to prevent the extra delay. In addition, in this example, at 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 been used. 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. Important delay reductions can therefore be achieved if the proposed allocation strategy is applied to the flights that are found multiple times daily in similar situation than flight F, i.e. flights pushed by their MPRs at the beginning of tension zones of other regulations.

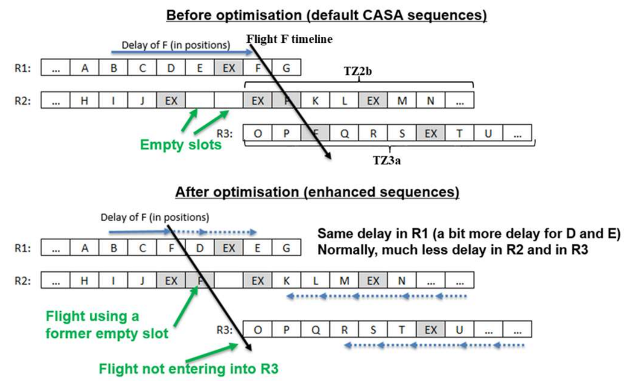

Figure 2: Mitigation of Interacting Regulations (MIR) technique

The early simulation results validating the MIR solution confirmed significant potential benefits for the network: around 27% less network delay on average and 42% less impact to AUs.

E. Contributions of this paper

This research paper contains two major contributions:

1. A new innovative technique called Resourceful Overloading of Slots (ROS) is proposed to enhance the slot allocation process of CASA by avoiding the waste of capacity (empty slots) at regulated sectors, thus making better exploitation of the available ATC capacities during periods of congestion.
2. We provide quantitative evidence based on fast-time simulations to preliminary validate the ROS technique. The results of two ECASA prototype configurations will be discussed, one in which only ROS was activated and assessed during the simulations, and a second one in which both ROS and MIR were activated as a combo to optimise the default CASA sequences.

III. An Innovative Slot Allocation Technique to Reduce Network Delay: The ROS Mechanism

To minimise the network delay, a new optimisation mechanism referred in the paper to as Resourceful Overloading of Slots (ROS) is proposed. One of the main goals of the suggested method is to make it rapidly deployable in the CASA system of the European Network Manager.

In a nutshell, the ROS mechanism takes the default slot sequences calculated by CASA as an input, and identifies opportunities in which a particular slot could be allocated to two flights instead of one (*slot overloading*), thus increasing the capacity utilisation. The major constraint imposed is not to exceed the capacities declared at sectors. Some argued assumptions can be made with regards to such constraint.

The concept of slot overloading is not new. In current CASA system, only one flight per slot is allowed in general. However, in some especial circumstances that are justified by operational reasons, up to two flights can be allocated in a same slot, e.g., when two flights are forced by their MPRs in a same slot of a third regulation. When this happens, the slot is said to be *overloaded*. According to the current ATFCM practices [1], overloaded slots are accepted, but must be 'compensated' from the point of view of the ATCOs workload. For that purpose, an empty slot needs to be forced in the sequence in a position as close as possible to the overloaded slot. The *compensation slot* (i.e., the forced empty slot) cannot be used by any flight, since it aims at compensating the extra workload required by the ATCO to control the two flights that were allocated overloading a slot. This practice is considered as safety-neutral under normal circumstances, and thus it is well accepted today by ATCOs, FMPs and the NM because: a) during periods of regulation the traffic complexity is smoothed by the CASA slots, thus normally requiring significantly less ATC workload; b) the probability of traffic bunching does not change significantly when a slot is overloaded (due to traffic uncertainties); and c) any potential risk of workload increase is considered compensated by the introduction of the compensation slot (an empty slot).

The new ROS technique consists in re-using the slot overloading principles and mechanisms discussed above, but inverting the operational logic to use them in favour of reducing latent capacities: if a non-forced empty slot is identified in the sequence, then a nearby non-overloaded slot could be overloaded with an extra flight. Figure 3 shows two examples of non-forced empty slots that were often observed in many CASA regulation sequences, i.e. at the beginning of the sequences and/or in the middle of the sequences. Both cases may occur e.g. due to the lack of traffic demand scheduled to such specific periods (an average of 10 non-demanded/unused slots per regulation was found in simulated scenarios of Summer 2018).

The ROS technique has the advantage that the flights selected can be allocated to earlier slots that are compatible with their schedules (i.e., not 'too early' slots), while from the point of view of capacity the solution is equivalent to allocate the unused slots to those selected flights. Consequently, less wasted capacity and less delay impact to AUs are expected. From the ATCO workload perspective, the new ROS slot sequences should be acceptable, since any slot overload generated by the ROS technique could have appeared in the sequence as a result of other operational reasons, or by chance. Thus, as far as the overloaded slots are duly compensated, the ROS sequences can be argued to be safety-neutral with respect the CASA ones.

Regarding the integration of the new ROS feature with the default CASA process, it just requires the addition of two additional steps on the top of the normal CASA process, to be executed at each True Revision Process (i.e. every 1 minute):

1. Run CASA as usual ('normal' CASA is the core).
2. Identify empty stots and near-by slots that could be overloaded by close-by flights
3. Change the position of the earliest flight that could overload the targeted slot. Note: that flight will release its position and thus the flights placed after will take a better position in the next true revision process (step 1), when the sequence will be compressed, and the delay optimised.

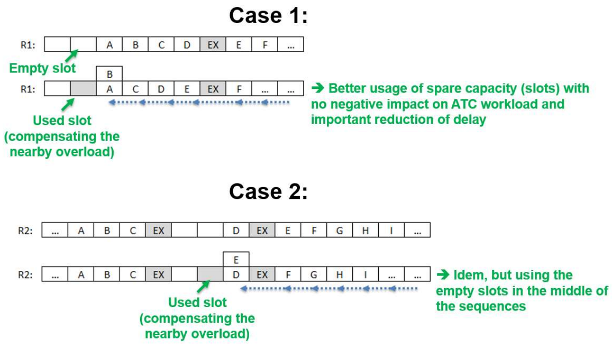

Figure 3: Resourceful Overloading of Slots (ROS) technique

IV. SIMULATION RESULTS

A. *Experimental setup*

The hypothesis of this research is that the ROS mechanism proposed could contribute to reduce the total network delay generated by ATFCM regulations. To verify such hypothesis a simulation model has been developed and integrated in R-NEST, a tool developed at the EEC that incorporates an ATFCM simulation model with a slot allocation process based on real CASA [19][20].

Figure 4 illustrates the methodology followed to simulate and benchmark the new ECASA features (i.e., ROS and MIR) against the reference scenario in which only the normal simulated CASA system is active (i.e. not enhanced). The simulation scenarios used correspond to real scenarios from the most congested 28-days period in Summer 2018 (i.e. AIRAC cycle 1808). The flights plans and regulation schemes have been extracted from the repository Digital Data Repository (DDR2). The simulation results of ECASA and CASA have been benchmarked in terms of network delay and impact to AUs.

Two different simulation analyses have been performed. In the first one, only the ROS mechanism has been activated on ECASA and benchmarked against CASA. In the second one, both ROS and MIR mechanisms were coupled and activated for working jointly as a combo. The goal was to check if these two optimisation mechanisms could be complementary and, if so, to quantify how much the combo could reduce the network delay and the impact of delay to AUs with respect the CASA baseline. To ensure a fair comparison, both the ECASA and the CASA sequences were simulated with R-NEST under the same conditions.

B. *Network delay optimisation potenial*

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. These figures correspond to the simulation outputs from R-NEST, which is around 10-15% higher than the real delay officially reported. This bias is due to some limitations and simplifications of the simulation environment (e.g. some operational events were not simulated in our experiments, like flight cancellations, re-routings, level capping, or others).

Figure 5 shows the distribution of delay reductions achieved in the period of analysis with the simulation environment. According to the figure, the ROS technique achieved 23.4% delay reduction on daily average with respect the baseline CASA. The MIR mechanism achieved 26.6% reduction on average. Therefore, both mechanisms could achieve substantial delay reductions of similar order of magnitude.

The figure also shows the distribution of delay reductions achieved by the ECASA system with the two mechanisms activated as a combo, i.e. ROS and MIR acting one after the other at each true revision process (note: MIR was acting first, and then ROS). The results show that the delay of the AIRAC 1808 could potentially have been 41% lesser on average, while at some days the delay reduction could have been almost the half (47.3%). Note that the powerful delay reduction of the combined mechanisms indicate that both mechanisms are quite independent from each other and therefore largely compatible and complementary.

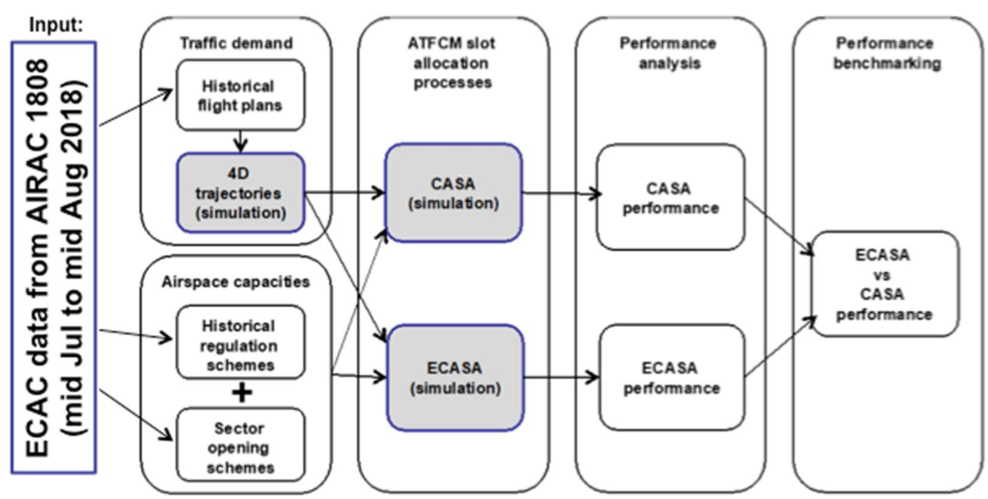

Figure 4 Research methodology with fast-time simulations

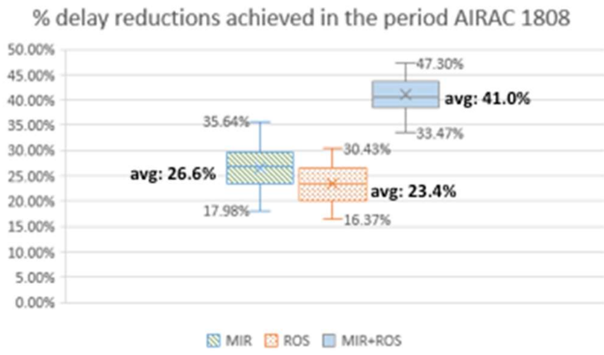

Figure 5: Distributions of network delay reductions achieved

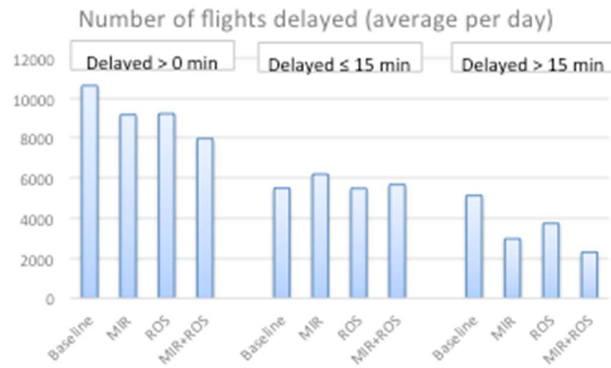

Figure 6: Average number of flights delayed per mechanism

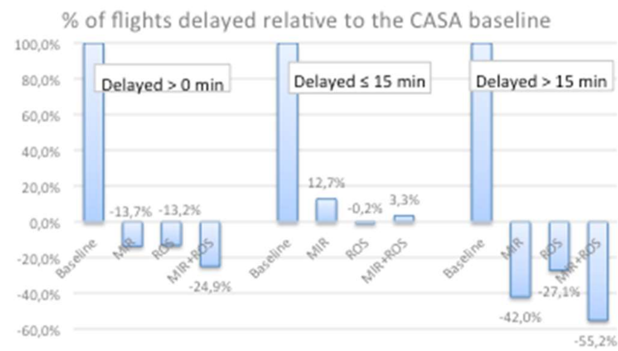

Figure 7: Reduction of delayed flights per mechanism compared to the CASA default sequences

C. Delay impact optimisation potential

It is well-known that the cost of delay is not linear and that it may impact differently to each flight [5][6]. In this paper it is assumed that flights are scheduled with some tolerance to delay, and only the flights with more than 15 minutes of ATFCM delay are considered to be at risk of suffering large operational disruptions and/or cause significant economical costs for the airspace users that operate them. Thus, flights with 15 minutes of ATFCM delay or less will be considered as not impacted, at least not significantly, by the slot allocation processes.

To assess the potential benefits, in terms of impact of delay, three key performance indicators have been calculated for each simulations set: a) the daily average number of flights with delay; b) the daily average number of flights delayed 15 minutes or less (i.e., flights delayed but not impacted significantly); and c) the daily average number of flights delayed more than 15 minutes (i.e., flights that could incur in significant costs).

Figure 6 shows the assessment in absolute terms and Figure 7 shows the relative assessment with respect the simulated CASA (i.e. the *baseline*). The daily average number of flights delayed by the simulated CASA in the AIRAC 1808 was about 10600 flights (out of 34600 flights operated daily on average). Both ROS and MIR techniques reduced the number of flights delayed in the same order, i.e. by 13% approx. (1500 less flights delayed approx.). However, MIR performed significantly better than ROS in terms of distribution and impact of delay, i.e. the frequency of 'innocuous' delays (15 minutes or less) augmented for MIR by 12% with respect CASA and ROS, and the number of flights with high risk of impact (i.e. flights with more than 15 min delay) decreased by 42% in the case of MIR and by 27% in the case of ROS, both compared to the CASA baseline.

It was also observed that the combination of both mechanisms, MIR+ROS, improved drastically the delay figures. Around 25% less flights were delayed (2600 less flights than the CASA baseline), and a reduction of 55% on average was achieved in the number of flights delayed more than 15 minutes. Nevertheless, it must be highlighted that such massively positive figures should be taken carefully at this stage, since they must be validated further before extrapolating the simulation results to the real –and much more complex– operational environment.

V. CONCLUSIONS AND FUTURE WORK

This paper has presented a new innovative slot overloading technique, i.e., the ROS technique, that could potentially contribute to improve significantly the performance of the CASA slot allocation process. According to the simulation results, the ROS technique could significantly reduce the delay in the network and the impact of delay on the airspace users. The ATM cost-efficiency/effectiveness is expected to improve too, as a result of to the expected increase of the ATCOs productivity (less empty slots in the regulation sequences) and the lesser direct costs of the ATFCM functions (less flights delayed and less impact of delay).

The ROS technique can potentially improve the use of the available capacity, thus reducing the number of unused ATFCM slots. The impact of the ROS technique on safety has been discussed and preliminary concluded that the slots sequences amended should in principle remain safety-neutral. In particular, it is not expected that the ROS technique can generate slots sequences that could be unacceptable for the ATC. Nonetheless, further validation is required to confirm or reject such preliminary conclusion.

The proposed method has been integrated to work in combination with another recently proposed innovate mechanism for CASA, i..e. the MIR technique, and large delay reductions have been achieved when both mechanisms where working jointly as a combo.

The largely positive results of these research are preliminary and based on simplified fast-time simulation models that are not exempted of limitations. Therefore, any exact figure of these preliminary results, either absolute or relative, should be taken with caution at this stage.

Next steps of this research will include the testing and validation of the new ECASA techniques in the operational NM systems, including shadow mode simulations and other exercises closer to real operations. The aim is to introduce these innovative techniques in real operations, and thus potentially contribute to improve the performance of the ATM system.

Acknowledgments

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Sergio Ruiz is an ATM validation expert and researcher at the EUROCONTROL Experimental Centre (EEC). He has more than 10 years of experience in developing and validating new ATM concepts in various SESAR exploratory and industrial projects, and is currently contributing to the development of advanced decision support systems for the Network Manager. He holds a PhD in telecommunication and system engineering from the Universidad Autónoma de Barcelona.

Hamid Kadour is an ATM network operations researcher at the EUROCONTROL Experimental Centre (EEC). He has 20 years of experience in developing and validating new ATM concepts related to air traffic flow management. He is currently participating in the concept development of the future European flow management system within the SESAR industrial research program.

Peter Choroba is R&D project leader at the EUROCONTROL Experimental Centre (EEC). He manages a project focused on improved ATM network prediction and performance in the context of advanced demand capacity balancing. He has 17 years of experience in ATM research, ranging from airport operations (wake vortices), ATM performance and air traffic flow management. He holds an MSc in air transport engineering and a PhD in transport and communication technologies from the University of Zilina.