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ECAC Use Case of Optimised Pre-tactical Time of Arrival Adjustments to Reduce Probability of Separation Infringements

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Abstract: Currently, a maximum allowable number of aircraft (A/C) entering and or within a sector for a given period is fixed. Anytime this threshold is reached, involved A/C are regulated by Air Traffic Flow and Capacity Management (ATFCM) to maintain an acceptable Air Traffic Controllers' (ATCOs') workload. This threshold is determined regardless of particular expected air traffic complexity, which may result from potential conflicts inherently in aircraft flight plans that may greatly affect the ATCOs' workload. This paper proposes a new ATFCM Demand and Capacity Balancing (DCB) methodology, applied to mitigate potential conflicts between A/C's trajectories at pre-flight level, in order to reduce the current ATCO's workload attributed to Separation Management (SM) interventions. This purpose is achieved through minor adjustments on A/C's Times of Arrival (TOAs) at conflicted en-route junctions. The adjustments of A/C's TOAs are implemented through minor changes on A/C's speed profile, applied before and after each conflicted junction, while maintaining each A/C's departure and Targeted Time of Arrival(TTA) at destination. The paper postulates that these TOA adjustments could be easily transformed into pre-tactical ATFCM DCB measures, assuming that ATFCM will issue Reference Business Trajectories (RBTs) containing time constraints at junctions, introduced to reduce the probability of conflicts. A case study of European Civil Aviation Conference (ECAC) air traffic network using real flight plan data is presented to show the validity of the methodology.

Keywords: ATFCM, TBO, ECAC, CD&R, DCB, junction, TOA

1. INTRODUCTION

According to ICAO Doc.9858, the Air Traffic Flow and Capacity Management (ATFCM) Demand and Capacity Balancing (DCB) function, shall be undertaken at strategic, pre-tactical and tactical levels. At these three levels, all members of the Air Traffic Management (ATM) community will collaboratively participate in providing a methodology, intended to increase the ATM operational effectiveness and efficiency. The last of the above DCB function levels "the tactical DCB level", will be focussed on the following specific objectives:

1. To perform through a collaborative decision-making (CDM) process, dynamic adjustments to the organization of airspace, in order to balance capacity;
2. To perform dynamic changes to the entry/exit times for aerodromes and airspace volumes, and adjustments to the users' schedules.

This paper focuses on the second objective above, which has today, led to several other research initiatives as briefly discussed below.

The Single European Sky ATM Research (SESAR) dynamic DCB (dDCB) project PJ09, is one of these initiatives. This project aims to improve the ATFCM, by reducing the complexity of the expected traffic peaks through the implementation of Short-Term ATFCM Measures (STAM), in order to streamline Air Traffic Controller's (ATCO's) workload.

In the above project, traffic peaks are monitored by Flow Management Positions (FMPs), through parallel use of sector entry counts and occupancy counts. The STAM measures applied, includes short ground delays and minor re-routings that are applied to a limited number of flights, in order to remove the expected demand and capacity imbalance in ATC sectors.

Other initiatives such as SESAR 1 solutions 19, 17, 18 and 57, are also in line with the second objective above (SESAR 2020 Multi-annual Work Programme (2015)).

In all the above research initiatives, strategic de-confliction at hot spots has not been considered. In addition, the applied methods to balance between demand and the system's resources to avoid the overload of ATC workload, still relies on limiting the maximum expected hourly entry count and or the occupancy of the expected traffic into the ATC sectors, irrespective of the potential interdependencies (potential conflicts).

DCB initiatives that are still based on sector entry count and or occupancy count are still anchored in the conventional ATM operations "the airspace based operations concept", and it is broadly recognised that they are no longer efficient to

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deal with sustained increasing traffic levels. It is then necessary, to reformulate ATFCM DCB processes, in order to align them with the new Trajectory Based Operations (TBO) concept (European ATM Master (2012).

Currently, a few initiatives have considered strategic de-confliction, the "En-Route Air Traffic Soft Management Ultimate System (ERASMUS) project, developed a tool to improve aircraft (A/C) strategic de-confliction. The ERASMUS tool generates a conflict-free trajectory segment of 15 minutes look-ahead time for each flight (Rey et al., 2016; Averty et al., 2016). This is achieved through its Trajectory Control by Speed Adjustment (TC-SA) function, which proposes real-time in-flight adjustments of the Reference Business Trajectory (RBT) by applying minor A/C speed adjustments, in order to remove detected conflicts and reduce the current ATC workload (Averty et al., 2016).

The ERASMUS project's key concept, was adopted by SESAR under the "Trajectory Adjustment through Constraint of Time (TRACT) service project" (ICAO ATMRPP, WP636 (2014)). It is expected that TRACT will be developed to manage early (within 25 minutes look-ahead time) conflicts. Similar to the TC-SA function, TRACT assesses the expected conflicts within its look-ahead time. It then tries to resolve them, by automatically issuing Controlled Time Over (CTO) constraints at the conflicted points to the appropriate A/C in real time. Minor A/C speed adjustments are applied to meet the CTO constraints. It was concluded however, that a TRACT solution is only possible to conflicts involving i4D-capable A/C and thus, it is well known that several enablers for TRACT are not yet available.

The above-discussed strategic de-confliction tools are automated tools that provide strategic detection and resolution of 4D-trajectory conflicts, at execution/in-flight phase. They are claimed to provide strategic detection of conflicts only because they can detect conflicts at a longer look-ahead time horizon than a typical detection look-ahead time used by the ATCOs.

This paper proposes a closed, but different approach for identifying, as far in advance as possible, during the pre-flight dynamic DCB timeframe, the expected traffic demand that produce soft and tight trajectory interdependencies at en-route junctions, which are likely to require ATC's tactical interventions. It also assesses the links among all the identified A/C potential conflicts and the ATCs' tactical interventions, as well as the up/downstream impact of these potential conflicts on the ATM network, and it computes the optimal solution for their integrated statistical minimization. This is achieved, by including time constraints' specifications into the initial RBT to remove strategically and proactively, potential conflicts at the crossing and merging points (junctions) through minor adjustments in A/C' Time of Arrival (TOA) at conflicted junctions. A/C' TOA adjustments, are achieved through minor adjustments on A/C' speed profile, applied before and after each conflicted junction, while at the same time, maintaining each A/C's departure and A/C's Targeted Time of Arrival (TTA) at destination.

The ultimate goal of this paper, similar to the conventional DCB procedures, is to maintain the number and complexity of the expected required ATC Traffic Synchronization (TS) and Separation Management(SM) interventions at reasonable levels, from the ATCOs' workload perspective. This paper formulates how to deal with flight plans in the future ATM, assuming that ATFCM will issue RBTs containing TTA/TTO constraints, that reduces significantly the probability of ATC's interventions. These RBTs shall be issued at Short-Term Air Traffic Flow and Capacity Management (STAM) timeframe, with an impact on both the regional Network Manager (NM) and the Flight Management Positions (FMPs).

2. SCOPE AND METHODOLOGY

2.1 Problem Scope

This paper deals with the en-route phase of flight, with a scope limited to solving potential conflicts involving A/C in cruise flights, where two or more A/C share an "active junction". Active junctions are here defined as points in the airspace, where a set of two or more A/C are expected to converge with their minimum required "safe" separation potentially infringed. Fig.1 illustrates the topology of an active junction. Links in Fig.1 represent planned A/C trajectory tracks, and their physical intersection characterises the topology of the junction (Gatsinzi et al., 2016; iFly Project Deliverable D3.1, 2016). When a junction has m incoming links and n outgoing links, then for $n=m$, it is referred to as a crossing point and when $m>n$, it is referred to as a merging point.

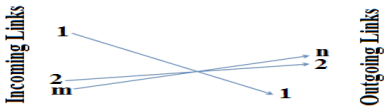


Fig. 1. Junction topology.

From the above definition of an active junction, this paper then deals with crossing and merging conflicts between aircraft in cruise flight. Understanding the geometry of a potential conflict is crucial in determining the most suitable technique to resolve it. It is therefore, understood that the proposed method, could not be a distinctive technique to produce a conflict free airspace. Other collaborative and coordinated actions, such as adjusting and swapping departing times at the departing airports (SESAR JU Report on PARTAKE, 2016), offsetting some flights from nominal route, and allowing multi-agent separation management while A/C are in flight, should be applied together with this method to solve other potential conflict geometries (evolving, parallel and opposite).

2.2 Criteria for Achieving the Required Probability of ATC Intervention (PC)

The required TOA adjustments at active junctions are established at pre-flight DCB level, and achieved by applying minor changes on A/C speed profile. To be effective, these TOA adjustments should reduce the probability of ATC tactical intervention by limiting the probability of A/C simultaneous arrival to the junction (P_C), in order to provide estimated conflict free flight plans.

Given that the proposed method is applied at pre-flight level, the accuracy of the TOA interval constraints between any two consecutive A/C at an active junction, issued within the RBTs to achieve a certain required P_C value, will depend on the degree of the adherence of the actual trajectory to the planned trajectory. The planned trajectory may suffer from various sources of uncertainties, which cause errors in A/C's TOA at a junction. These uncertainties involve vertical, lateral (cross-track) and longitudinal (along-track) deviations. Additionally, uncertainties due to initial time or schedule deviations also affect the A/C's TOA at junction.

A comprehensive analysis has been performed in order to quantify all different sources of these uncertainties, when they are transferred into TOA uncertainties of A/C*i* and A/C*j* trajectories at the junction (Gatsinzi et al., 2017), and assuming that they are statistically uncoupled. A complete derivation of these uncertainties is provided by Gatsinzi et al., 2017, where it is shown that in order to achieve a realistic total TOA standard deviation value, specific operational and A/C capability conditions are required.

Assuming Gaussian distribution for all the aforementioned uncertainties, then the minimum required TOA interval at junction (τ_p) required to obtain any P_C value, can be computed by convolving the two associated probability density functions (pdfs) for A/C (*i, j*) time of arrival to the junction, such that:

If $\tau_p = \mathrm{TOA_i} - \mathrm{TOA_j}$, where $\mathrm{TOA_i}$ and $\mathrm{TOA_j}$ are the TOAs at junction for A/C*i* and A/C*j* respectively. Let σ_{Ti} and σ_{Tj} be the total standard deviation of uncertainties for A/C*i* and A/C*j* respectively.The required τ_p to achieve a desired P_C is the given by:

$$\tau_p = \sqrt{-2(\sigma_{Ti}^2 + \sigma_{Tj}^2) Ln[P_C \times \sqrt{2\pi(\sigma_{Ti}^2 + \sigma_{Tj}^2)}]} \qquad (1)$$

If the expected (nominal) TOA interval at junction (τ_0) is equal or greater than the above computed τ_p value, there will be no additional time interval required at junction. Otherwise, the demanded time increment shall be:

$$\tau = \tau_p - \tau_0 \qquad (2)$$

Fig.2 shows the required τ_p values for different P_C values, when computed using the total TOA standard deviation of σ_T =1.5minutes obtained in Gatsinzi et al., 2016. From Fig.2 for instance, to achieve $P_C=10^{-5}$, τ_p of approximately 9.4 minutes is required. This implies permitting the junction's inbound traffic flow capacity ($J_{IC}=1/\tau_p$) of up to 6A/C an hour.

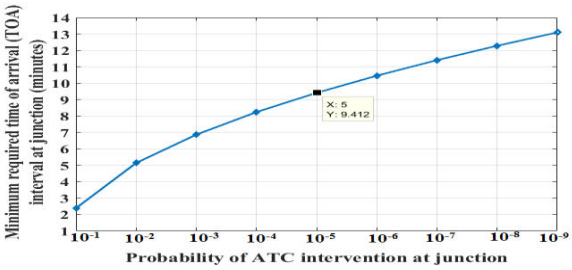


Fig. 2. TOA interval for different probabilities of ATC Intervention at Junction.

2.3 Computation of speed/TOA changes

The new speed/TOAs to the junctions for all A/C that removes potential conflicts, and applied to solve the DCB problem at pre-flight level to achieve the required P_C value, are computed using a novel basic Linear Programing (LP) optimization tool, where the total amount of distance-weighted speed changes is minimised. The new basic LP tool removes the scalability problem inherent in the existing sophisticated ATFCM optimisation methods, especially when applied to high traffic environments such as the ECAC airspace. Additionally, as a basic LP is applied, the algorithm execution time is not a limiting factor.

Within the ATFCM DCB function, the speed/TOA changes shall be issued by the Network Manager (NM), by including them within the RBT in a form of requested Targeted Time Over (TTO) for en-route junctions and Targeted Time of Arrival (TTA) to junctions in TMAs entry points. A brief description of the main elements of the linear optimisation model developed for this method is provided in this section. This LP model contains four main constraints:

1. The global time performance at each active junction is maintained to keep the entropy of the traffic in the route network;
2. The minimum required TOA interval (τ_p) to achieve the required probability of simultaneous arrival to the junction (P_C) defined in (1) shall be achieved for any two consecutive A/C at any active junction;
3. The departure and Targeted Time of Arrival (TTA) at final destination is maintained for each A/C;
4. The Maximum allowable speed change is fixed.

To maintain the global time performance, a set of computed new TOAs (t^+_{mi}) at each junction (*m*), shall have the same mean time (t_{m0}) same as the one for the set of TOAs before applying speed changes (t^-_{mi}), that is to say:

$$t_{m0} = \frac{\sum_i t^-_{mi}}{N_m} = \frac{\sum_i t^+_{mi}}{N_m}$$, then for all A/C and all junctions:

$$t^{+}_{m1} + t^{+}_{m2} + t^{+}_{m(n-1)} = nt_{m0} \quad (3)$$

To compute the new TOAs at any junction that respects the minimum required TOA interval defined in (2) for any two consecutive A/C at any junction, the junction equation provided in (4) is used. In this equation, each A/C is assigned with a subscript with the number of the order they arrive to the junction (e.g.1,2…n) such that:

$$\left.\begin{aligned} t^{+}_{m2} - t^{+}_{m1} &= \tau_{m21} \\ t^{+}_{m3} - t^{+}_{m2} &= \tau_{m32} \\ t^{+}_{mn} - t^{+}_{m(n-1)} &= \tau_{m(n-1)n} \end{aligned}\right\} \quad (4)$$

The above junction equation provides the new TOAs for each junction (m) and each A/C (i). These equations have to be solved over all active junctions in the network.

Additionally, to respect the aforementioned third constraint, the total flight time shall be maintained such that for the last junction (k) of each flight (i), the initial targeted time of arrival (TTA) is maintained. Therefore, for all affected A/C (i), the following condition applies.

$$t^{+}_{ki} = t^{-}_{ki} \quad (5)$$

Furthermore, all relative speed changes (δV^{m+1}_{im}) between junction m and $m+1$ shall be below a given maximum threshold (X %) such that.

$$\delta V^{m+1}_{im} \leq 0.0X \times V^{m+1}_{im} \quad (6)$$

To formulate the objective function, the following variables are defined:

V^{m+1}_{im}; A/C speed between junction m and $m+1$,

d^{m+1}_{im}; A/C flight distance between junction m and $m+1$,

Δt^{m+1}_{im}; A/C travel time between junction m and $m+1$.

The relationship between the variations on the A/C speed between junctions and the variations on the A/C travel time is given by:

$$\delta V^{m+1}_{im} = -\frac{d^{m+1}_{im}}{(\Delta t^{m+1}_{im})^2}\delta(\Delta t^{m+1}_{im})$$

Given that the variations on travel time between junctions (m) and (m+1) are given by:

$\delta(\Delta t^{m+1}_{im}) = (t^{+}_{m+1} - t^{-}_{m+1}) - (t^{+}_{m} - t^{-}_{m})$, then:

$$\delta V^{m+1}_{im} = -\frac{d^{m+1}_{im}}{(\Delta t^{m+1}_{im})^2}[(t^{+}_{m+1} - t^{-}_{m+1}) - (t^{+}_{m} - t^{-}_{m})]$$

The flight efficiency of the involved A/C will be affected by the distance along which the speed change is applied. Then, the "cost" for a particular perturbed trajectory can be modelled by the product of $\delta V^{m+1}_{im} \times d^{m+1}_{im}$, which leads to a global cost function obtained as a sum of these elementary contributions given by:

$$J = \sum_i \sum_m \delta V^{m+1}_{im} \times d^{m+1}_{im} = \sum_i \sum_m [\frac{d^{m+1}_{im}}{(\Delta t^{m+1}_{im})}]^2 = \sum_i \sum_m [V^{m+1}_{im}]^2 [(t^{+}_{m+1} - t^{-}_{m+1}) - (t^{+}_{m} - t^{-}_{m})] \quad (7)$$

The cost function in (7), with its associated constraints defined in (3) to (6), provides an optimised set of proposed speed changes to achieve the required TOA changes that removes all the potential conflicts at any required probability of A/C simultaneous arrival to the junction or in other words, required probability of ATC intervention to resolve conflicts. While, at the same time maintaining all A/C departure times, TTA at final destination, and the overall time performance at all active junctions.

3. DISCUSSION & RESULTS

3.1 Case Study

It is generally acknowledged, that air traffic density has one of the largest correlations with ATCO's workload, associated to tactical interventions due to potential conflicts. Considering that, ECAC is one of the busiest airspaces in the world, a high-density traffic scenario of the whole ECAC airspace is considered in this paper. In order to build the ECAC air traffic scenario, flight plan data is extracted from Eurocontrol Demand Data Repository 2 (DDR 2).

According to Eurocontrol, in 2016, the network air traffic in ECAC reached an all-time record of 10,190,903 flights, with a daily average traffic of 27,844 flights, surpassing the former record set in 2008. The busiest day of the year was the 9th September with 34,594 flights (Eurocontrol Performance Review Report, 2016). However, these Eurocontrol records are based on the actual flown trajectories. When DDR2 planned trajectories (flight plans) are used to re-analyse the above traffic distribution in this paper, since the proposed STAM measure is considered at pre-flight level, 9th September remains the busiest day in 2016, with 35,703 planned flights, and a peak 30 minutes time window between 8:00am-8:30am GMT of 1169 flights. In this preliminary study, the planned traffic in the above peak 30 minutes time window is used. However, for each active flight in this time window, its whole trajectory in the ECAC airspace is considered for potential conflict identification and mitigation process.

3.2 Identification of Potential Conflicts

The Eurocontrol Network Strategic Tool (NEST) is used to analyse and identify potential conflicts (Eurocontrol NEST facts sheet, 2012). In this paper, the Terminal Manoeuvring Areas (TMAs) are considered as boundary condition of the problem. In other words, only traffic in the ECAC airspace beyond the limits of the TMAs' borders is considered in the proposed DCB method. Consequently, ECAC en-route airspace reduced vertical separation minima (RVSM) rules of 1000ft vertical separation at flight levels (FL290-410), and the 5NM horizontal separation minimum are applied for potential conflict identification. In addition, as discussed in

the scope of the paper, cruise-cruise crossing type of conflicts are considered in this preliminary analysis, whilst evolving and parallel conflicts are not considered.

Fig.3 shows the total number of conflicts identified (right y-axis), and the distribution of number of cruise-cruise crossing type of conflicts in percentage of total conflicts identified (left y-axis) at and above different minimum flight levels (FLs).

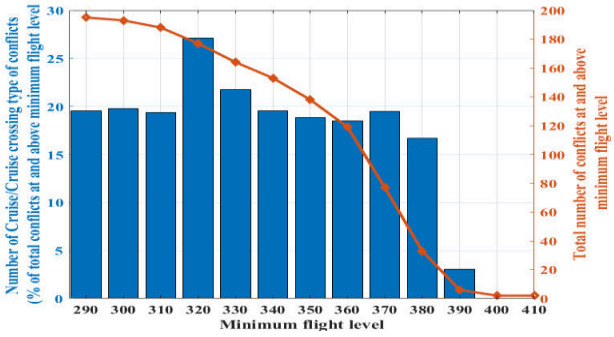


Fig.3.Total number of conflicts (right y-axis) and distribution of number of cruise-cruise crossing type of conflicts at and above different minimum flight levels (left y-axis).

In Fig.3, high numbers of total potential conflicts at and above low minimum FLs (FL290-FL310), are in part attributed to high numbers of flights flying at these FLs, but are also significantly attributed to potential conflicts between evolving aircraft in climb/descent to/from different TMAs in ECAC area and A/C already established in cruise flight. The number of A/C that fly at very high FLs (FL390-410) within ECAC area is very low, exhibiting predominantly parallel conflicts in cruise flights.

From Fig.3, the number of cruise-cruise crossing conflicts are highest at FL320 with 27.12% of the total 177 potential conflicts identified at and above this FL (equivalent to 48 conflicts). Therefore, given that this paper is concerned with solving this type of potential conflicts, all the identified A/C in cruise/cruise crossing potential conflicts at and above FL320 are chosen to be the subject of TOA/speed changes for potential conflict removal, while other conflict types can be considered for further work.

The above 48 identified conflicts in NEST, involves 86A/C of which 77A/C have a single active junction, 8A/C have two active junctions and 1A/C have three active junctions along trajectory, where TOA/speed changes are required.

3.3 Potential Conflicts Removal at a Required Probability of Simultaneous Arrival to the Junction of 10^{-5}

To remove the identified potential conflicts, $P_C=10^{-5}$ is first set as the required probability of simultaneous arrival to the junction. This probability value is considered low enough to significantly reduce the current actual probability of ATC tactical intervention. It then follows that if $P_C=10^{-5}$ is set as the target, from Fig.2, then the minimum required TOA interval between any two consecutive A/C at any active junction is 9.4 minutes.

The LP optimization model is applied to obtain the optimal speed changes for each A/C before and after each active junction, in order to achieve the above-required minimum TOA for all 48 identified conflicts. The optimal speed changes before active junctions are required to remove potential conflicts for all A/C, while the optimal speed changes after active junctions are required to maintain the TTA at destination in the case of A/C with a single active junction along trajectory. For A/C with multiple active junctions along trajectory, speed changes are applied to each trajectory segment before/after each active junction to remove conflicts and to the trajectory segment after the last junction to maintain the TTA.

Fig.4 shows the computed optimal speed changes before and after each junction, per each conflict for A/C*i* and A/C*j* in percentage of nominal A/C speed. The computed required optimal speed changes ranges between [-8.9%, +9.1%] of the nominal A/C speed, with only 16.7% above ±6% speed change range, 83.3% within ±6% speed change range and 19.8% within ±3% speed change range.

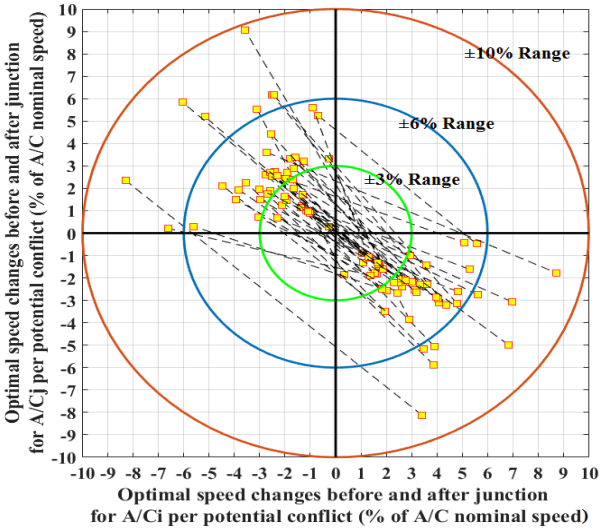


Fig.4.Computed optimal speed changes before and after junction per each identified conflict for A/C*i* and A/C*j*

When the above optimal speed changes are applied to the A/C's nominal flight speed profiles, the same percentage of A/C's TOA at that junction is modified. For instance; for an A/C flying at 400 knots for a flight distance of 134NM, if a speed change of 5% is applied to this flight, the A/C's TOA at junction will be also modified by 5% ; equivalent to one minute for every 20 minutes of A/C's flight time.

To test the performance of this method, the computed optimal speed/TOA changes are applied to the A/C's nominal flight speed profiles in the initial flight plans of the 86A/C involved in potential conflicts. This result into flight plans optimised for potential conflict removal at pre-flight DCB level. These optimised flight plans, are then introduced back into the same whole ECAC network sample. The resulting scenario containing all the 1169 flights is re-analysed in NEST conflict detection tool, where all the 48 cruise/cruise crossing conflicts involving 86A/C with TOA/Speed adjustments are successfully removed. Only three conflicts are induced to

other A/C that were not initially considered for speed/TOA changes.

Considering the above-discussed results, then the total number of conflicts at and above FL320 in ECAC area, between 8:00am-8:30am on 9th Sep 2017, is reduced from 177 conflicts to 132 conflicts by removing only crossing conflicts in cruise flight with the proposed method. The proposed method therefore provides the expected results and its performance can be said to be as expected. In addition, since linear programing is applied, the expected execution times will not be a limiting factor for scenarios covering the ECAC's current and foreseen air traffic levels.

3.4 The feasibility of the Proposed ATFCM DCB method in ATCO's and Airspace User's perspective

Even with the above-discussed performance, the proposed method will be only adopted, if the computed speed/TOA changes are realistic in terms of both ATCOs' daily operations and Airspace Users' (AU) perspective.

Concerning the ATCOs' perspective, previous studies have concluded using fast-time simulation tools, that A/C speed modifications that are within a range of ±10%, could be applied without being noticed by the ATCOs (Averty et al., 2007). The obtained optimal speed changes in this paper are all below this range. In addition, Human in the Loop (HIL) experiments, have shown that speed changes in the range of ±6% were not noticed by ATCOs, even when ATCOs were informed of the ongoing covert speed change experiment (Drogoul et al., 2009). In this paper, 83.3% of the computed required optimal speed changes are within this ±6% range. Furthermore, in the above HIL experiments, it was concluded that even for greater speed changes of up to ±12%, ATCOs did not notice 50% of them. The main observation from the above experiments was that, for en-route flights, the absolute values of A/C speed changes are only sporadically considered and memorized by ATCOs (Drogoul et al., 2016).

Based on the above references, then the speed changes computed in this paper could be introduced in the flight plans and implemented by A/C, while keeping ATCOs unaware of the ongoing conflict resolution process. This resolution process can then be conceived in such a way that it can be considered at strategic level, and integrated with tactical ATC procedures to reduce the probability of ATC tactical intervention to specific desired levels.

When the required probability of A/C simultaneous arrival to the junction (P_C) was set to 10^{-5}, requiring a minimum time interval of approximately τ_p=9.4 minutes between consecutive A/C at junction, the maximum inbound traffic flow at the junction (the frequency of traffic) was then bounded to approximately $J_{IC}=1/\tau_p = 6$A/C per hour. Therefore, this probability determines the maximum number of A/C that can safely transverse a given airspace volume which affects the controllers workload per flight, and in turn, largely determining the available airspace capacity/ATC resources. Then, depending on the available ATC workforce, different required probability of simultaneous arrival to the junction (P_C) can be used to remove the expected potential conflicts.

Given that the identification of potential conflicts was based on the conventional en-route separation minima (5NM and 1000ft), it can be realistically assumed that ATC tactical intervention is very likely for each of the potential conflicts identified in this paper, if no mitigation action is taken at pre-flight level. Therefore, even by increasing the desired probability of simultaneous arrival to the junction (P_C) value from 10^{-5} to higher values, the resulting smaller speed/TOA changes will still significantly reduce the current probability of ATC TS/SM tactical intervention.

Fig.5 shows the required optimal speed changes before and after an active junction for different A/C at the 48 identified active junctions, for different required probability of A/C simultaneous arrival to the junction (P_C). From Fig.5, it can be seen that when P_C value is increased, the required speed/TOA changes are considerably reduced. For instance, considering the worst case; the highest of all computed speed changes (9.1%) required of A/Ci before junction 37 (counting from bottom-up in Fig.5), when P_C is increased from 10^{-5} to 10^{-4} and subsequently to 10^{-3} , 10^{-2} and 10^{-1} , the required speed change before junction is decreased to 7% and subsequently to 5.4%,4.1% and 3.2% respectively. This is equivalent to about a reduction in speed change by a factor of 1.3% when P_C is increased by a factor of 10; and this trend applies to all computed speed changes.

Therefore, from the above results, it follows that depending on the required probability of simultaneous arrival of A/C to the junction (P_C), the amount speed/TOA changes required to remove potential conflicts is significantly different, but all could result in the reduction of the current ATC tactical intervention.

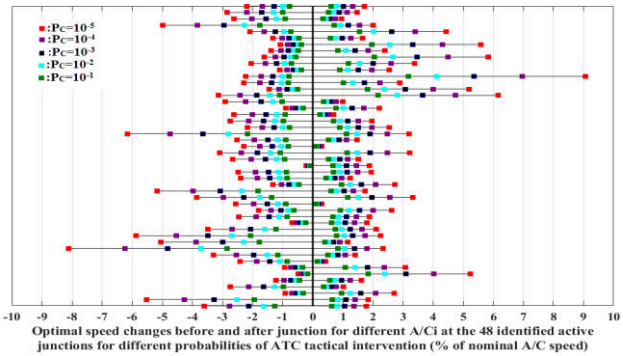


Fig.5.Optimal speed changes before and after an active junction for different A/C*i* at the 48 identified active for different required probability of A/C simultaneous arrival to the junction (P_C).

Concerning AUs perspective, if the computed optimal speed/TOA changes do not significantly affect the A/C's performance, AUs will accept them as constraints in the RBTs. On the contrary, when high speed/TOA changes are required, especially when computed at very low P_C values, other ATFCM measures such as the "Cooperative departures for a competitive ATM network service (PARTAKE)" (SESAR JU Report on PARTAKE, 2016), can be applied

together with the proposed method, in order to reduce the required speed/TOA changes to lower thresholds. Moreover, as previously discussed, the proposed method is not expected to be a distinctive technique to produce a conflict free airspace.

PARTAKE is being studied under SESAR 2020 exploratory research projects. It is focussing on improving the ATFCM dDCB process, through prompt identification of potential conflicts at network level and re-adjusting the Estimated Take-Off Times (ETOTs) of affected A/C within their assigned nominal Controlled Time of Take-off (CTOT) margins, and rearranging the departing sequence of aircraft at the involved airports to remove those potential conflicts.

The proposed method in this paper and PARTAKE project are then somehow complementary. That is, if there are some computed speed/TOA adjustments at junctions that are unrealisable by A/C, PARTAKE can help by adjusting the A/Cs' ETOTs for the involved A/C to increase their initial time separation at junction, in such a way that smaller speed/TOA adjustments at junction are required by the proposed method.

3. CONCLUSION

The current ATFCM DCB measures such as sector entry count and sector occupancy count are still anchored to the conventional ATM concept "the airspace based operations" rather than the new one based on "TBO" concept, and it is broadly recognised that they are no longer efficient to deal with the sustained increasing traffic density.

This paper postulates a new ATFCM DCB method, applied to reduce current ATC Traffic Synchronisation (TS) and Separation Management (SM) tactical interventions. It is based on the identification and mitigation of the expected traffic demand, that produce soft and tight trajectory interdependencies (potential conflicts) at en-route junctions, through minor adjustments on the A/C's Times of Arrival (TOA) at conflicted junctions applied at pre-flight DCB level. Potential conflicts are identified as a set of A/C involved in one or multiple conflicts, violating the minimum required separation at junction, and likely to require reactive ATCOs' corrective actions. At pre-flight DCB level, based on the initial RBTs, the Network Manager (NM) identifies these potential conflicts; this identification includes the expected TOAs at conflicted junction for the involved A/C. The ATFCM mitigation actions is based on computing the optimal TOA adjustments achieved through minor adjustments on A/C speed profile, applied before and after each conflicted junction for all involved A/C, considering spatial-temporal interdependencies of all identified conflicts as well as their upstream/downstream impacts on the ATM network.

The computation of new TOAs is based on a basic Linear Programing (LP) optimization model, which removes the scalability problem inherent in the existing sophisticated ATFCM optimisation methods. The results show a good performance in terms of the computed A/Cs' speed/TOA adjustments feasibility in both airspace users' and ATC perspectives. Moreover, the nominal potential conflicts with minimum cascading effects on initially non-conflicted traffic are removed. A high-density traffic ECAC network sample was used as the test case. The results show a good performance in terms of the computed A/C's speed/TOA adjustments feasibility in both airspace users' and ATC perspectives, and in the complete removal of nominal potential conflicts with minimum cascading effects on initially non-conflicted traffic, considering a high-density traffic ECAC network sample. The NM shall issue these new TOAs in form of time constraints' specifications into the A/Cs' initial RBTs, in order to achieve a certain desired level of ATC tactical intervention, depending on the available ATC workforce.

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ECAC use case of optimised pre-tactical time of arrival adjustments to reduce probability of separation infringements

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