In search of positive emergent behaviour in Time Based Operations

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***Abstract*— Thanks to decades of evolutionary developments, within conventional air traffic control, the collaboration between the planning controller and the tactical controller has been optimized. Under the forthcoming paradigm shift to Time Based Operations (TBO), there is need for a novel optimization of the collaboration of these two layers. Through agent based modelling and simulation it has recently been shown how these two layers can collaborate remarkably well under very high en-route traffic demand within an airborne self separation TBO concept. The aim of this paper is to make a further study of the collaborative behaviour between the layers of this airborne self separation TBO concept, as a preparation to optimizing the collaboration between similar layers in SESAR's TBO concept.**

Keywords: Free flight; Monte Carlo; rare events; safety risk assessment; airborne self separation, Time Based Operation, 4D trajectory plans

I. INTRODUCTION

In conventional ATM, medium term planning is provided by the planning controller, flight crews and their Flight Management Systems (FMS), whereas the tactical loop is formed by the tactical controller and flight crews. Thanks to decades of evolutionary developments, the collaboration between these two layers has been optimized. The SESAR concept of operations beyond 2020 [22], shortly referred to as SESAR2020+, involves a series of changes. Central to these changes is the paradigm shift to Time Based Operations (TBO). In SESAR2020+ terminology this means that aircraft should fly according to agreed conflict-free 4D trajectory plans which are made known to all actors involved as Reference Business Trajectories (RBT's).

A big unknown in this SESAR2020+ TBO framework is how everything works under various kinds of uncertainties, as a result of which one or more aircraft may not realize their 4D trajectory plans. There are several categories of uncertainties that cannot be totally avoided, such as meteorological uncertainties, data related uncertainties, human related uncertainties and technical systems related uncertainties.

In principle the SESAR2020+ ConOps has been designed to take care of these kinds of uncertainties through the possibility to revise 4D trajectory plans, and also to allow air traffic control to issue tactical flight instructions to pilots if the 4D planning layer has ran out of time. Although these tactical instructions are quite similar to the established way of working by an air traffic controller, there also are significant differences. For example, under SESAR2020+ an air traffic controller is expected to handle significantly more aircraft in its sector. Therefore the SESAR2020+ ConOps also foresees dedicated tactical decision support tools for air traffic controllers. The key issue is how to optimize the socio-technical collaboration between the 4D planning layer and the tactical layer in order to manage air traffic most effectively while taking into account the various uncertainties. Because the collaboration between these layers involves dynamic interactions between human decision makers, technical support systems, aircraft evolution, weather and other uncertainties, the combined effects result in types of emergent behaviours that cannot be predicted from the sum of the elemental behaviours.

The kind of emergent behaviour questions that are of special interest are:

1. How good is the tactical layer in managing uncertainties that are not timely resolved by the 4D planning layer?
2. What distances should be used between the centrelines of 4D trajectory plans in order to safely manage the various uncertainties?
3. At which traffic demands are phase transitions starting to happen and what are the consequences?

Through a series of agent based modelling and simulation studies [3,4] the socio-technical collaboration between a 4D trajectory planning layer and a tactical layer has been studied for an airborne self separation TBO concept. These studies showed that under this airborne self separation TBO, the integration of the 4D trajecory planning layer and the tactical layer is such effective that very high en route traffic demand can safely be accommodated. The aim of this paper is to address the above three questions for this airborne self separation TBO concept, with the expectation to learn from this for the benefit of SESAR2020+.

The paper is organized as follows. Section II introduces the airborne self separation TBO concept considered. Section III explains the agent based simulation model developed. Section IV reviews the main simulation results in [3,4].

Section V develops additional simulation results and addresses the three questions posed above. Finally, section VI draws conclusions and sketches the plan in taking advantage of these results for the investigation of positive emergent behaviour for the SESAR2020+ ConOps.

II. AIRBORNE SELF SEPARATION

A. *Autonomous Mediterranean Free flight ConOps*

The free flight "invention" [1] has motivated the study of multiple airborne self separation operational concepts and requirements, e.g. [5-8]. Although all studies assume some ASAS onboard an aircraft, there are large differences, e.g. regarding the coordination of conflict resolution between aircraft. Both [5] and [6] assume all aircraft to be equipped with an ASAS that broadcasts aircraft information to other aircraft and supports pilots with conflict resolution using an implicit form of coordination. Using this approach, a full ConOps has been developed for conducting state-based airborne self separation over the Mediterranean area [9-10]. For this Autonomous Mediterrranean Free Flight (AMFF) ConOps in-depth human in the loop simulations have shown that pilots are very well able to manage high traffic demands [11-12]. However, through agent based modelling and rare event Monte Carlo (MC) simulation, [13] has identified that in some infrequent cases the state based conflict resolution approach of AMFF asks too much trial and error by which rare multi aircraft conflicts may pose a too high safety risk.

B. *NASA's Airborne self separation TBO concept*

In [14-16], NASA has developed a TBO type of advanced ConOps that is aimed to accommodate both ASAS equipped as well as unequipped aircraft. Each ASAS equipped aircraft broadcasts both its state and its 4D trajectory intent. Conflict resolution between ASAS equipped aircraft works at a TBO layer and a tactical layer, exploits state and 4D intent information of other aircraft, and uses an implicit form of coordination. Through standard Monte Carlo simulation [17] showed that under nominal conditions, the TBO layer resolves all medium term conflicts well, also under very high en-route traffic demand. In follow-up studies [18-19] the effects of pilot response delays on the performance of the TBO layer have been studied using standard Monte Carlo and human in the loop simulations. Recently [20] has evaluated the effect of systematic wind prediction errors on the TBO layer using standard Monte Carlo simulations. These results show that under significant systematic wind prediction errors, aircraft may deviate too much from their 4D trajectory intents. In order to mitigate for these cases, [20] suggests to increase the horizontal separation minimum between 4D trajectory intents from 5Nm to a significantly higher value (i.e. 8Nm).

However, the simulation results [17-20] do not provide a complete picture of the capability of advanced airborne self separation. By studying the impact of systematic wind prediction errors on the TBO layer alone, it remains unclear what the conflict resolution power is of the combined effect of the TBO layer and the tactical layer. Maybe the tactical conflict resolution layer can resolve the remaining conflicts? If this would be the case, then there might be no need to increase the separation between 4D trajectory intents.

C. *iFly's Airborne self separation TBO concept*

During the first part of the iFly project, NASA's ConOps [14] has gratefully been used as starting point for the development of an advanced airborne self separation concept for en-route traffic under the name A^3 ConOps [2]. This A^3 ConOps intentionally addresses the hypothetical situation of 100% well equipped aircraft, and assumes no support at all from air traffic control on the ground. The full details of the A^3 ConOps and a corresponding A^3 Operational Services and Environmental Description (OSED) are in [2] and [21] respectively. Here we give a high level description of the A^3 ConOps only.

Similar to the SESAR2020 ConOps [22], the A^3 ConOps adopts TBO in the sense that each aircraft maintains a 4D trajectory intent that is shared with all other aircraft. According to SESAR2020 terminology [22], the 4D trajectory intent of an aircraft is referred to as a Reference Business Trajectory (RBT). In contrast to SESAR2020, however, RBT management in the A^3 ConOps is done by each aircraft without any support from air traffic control at the ground. Each aircraft is assumed to be equipped with the same dedicated ASAS system which is monitoring the surroundings and helps the flight crew to detect and resolve conflicts. Similar as in NASA's ConOps [14], A^3's ASAS uses two layers in the detection and resolution of potential conflicts: Medium Term Conflict Resolution (MTCR) and Short Term Conflict Resolution (STCR). Both MTCR and STCR are assumed to use implicit coordination only.

MTCR aims to identify ownship 4D trajectories which are free of planning conflict with the RBT's of higher priority aircraft over a time horizon of at least 15 minutes (and centrelines stay 5Nm or 1000 ft apart). Once a proposed 4D trajectory is accepted by the crew it is adopted as the aircraft's RBT, and it is broadcasted to the other aircraft. When a Medium Term Conflict with an RBT of another aircraft is detected, then the aircraft having lowest priority has to resolve the medium term conflict. The aircraft with higher priority simply sticks to its RBT. The priority of an aircraft is primary determined by the remaining distance to destination. The lower priority aircraft should adapt its RBT in order to resolve the conflict as well as not creating a conflict with an RBT of any of the other aircraft that have higher priorities.

STCR forms the next line of defense with a time horizon of at least 3 minutes and separation criterion of 3Nm and 900ft. When STCR detects a potential infringement of these separation criteria, then it is obliged to resolve this through a tactical manoeuvre, i.e. the priority rules do not apply anymore.

III. Agent Based Modelling

A. Multi Agent model of A[3] ConOps

In order to perform rare event Monte Carlo simulations for the A^3 ConOps, it is needed to develop a mathematical model of the operation which captures both nominal and non-nominal behaviour. The TOPAZ modelling approach [23,24] has been used to develop such a model. The first step is to develop an agent based model of the A^3 ConOps which allows to be used for rare event Monte Carlo simulation. Powerful rare event Monte Carlo simulation [25,26] requires that the agent based model satisfies specific mathematical conditions. In order to satisfy these conditions, the A^3 model is developed in the framework of Stochastically and Dynamically Coloured Petri Nets (SDCPN) [27].

In the A^3 model the following types of agents are taken into account:

- Aircraft state
- Pilot-Flying (PF)
- Pilot-Not-Flying (PNF)
- Airborne GNC (Guidance, Navigation and Control)
- Communication / Navigation / Surveillance systems
- Airborne Separation Assistance System (ASAS)

It should be noticed that the A^3 model developed is an initial one which does not yet incorporate environment/weather, Airborne Collision Avoidance System (ACAS) and Airline Operations Centre (AOC). Moreover, our current ASAS model is restricted to horizontal conflict detection and resolution, which implies that for the time being only aircraft flying at the same flight level are considered.

B. Velocity Obstacles in conflict resolution

Because the A^3 ConOps description in [3,21] leaves details of conflict resolution algorithms open, it was needed to adopt specific approaches for MTCR and STCR. The review of specific approaches in [28] and the results in [29] show a large variety of conflict resolution approaches available for potential use within the A^3 ConOps. In order to perform a risk assessment using rare event Monte Carlo simulation, one of these approaches had to be selected. Because computational load is a critical issue in rare event Monte Carlo simulation, we have selected Velocity Obstacles based conflict resolution [30-31]. Within the ASAS context, Velocity Obstacles based conflict resolution means that an aircraft stays away from the set of courses and velocities that lead to a predicted conflict with any other aircraft. In airborne self-separation research, such Velocity Obstacles approach has been referred to as Predictive ASAS [6].

C. MTCR and STCR implementation principles

Complementary to the choice of Velocity Obstacle based conflict resolution, various implementation principles have been adopted for MTCR and STCR respectively. The specific implementation principles adopted for MTCR are:

- MTCR detects planning conflicts (5Nm&1000ft) 10 min. ahead, and resolves 15 min. ahead.
- Aircraft nearest to destination has priority over other.
- Aircraft with lowest priority has to make its 4D plan conflict free (15 min ahead) with all other plans.
- If there is no feasible conflict free plan then rather than doing nothing, it is better to identify a plan that has a minimal undershooting of the 5Nm/1000ft criterion and does not create a short term conflict.
- Upon approval by the crew, the aircraft broadcasts a non-conflict-free 4D plan together with a message of being “Handicapped” (which is priority increasing and forces other aircraft to help resolving the initial undershooting).

Using the above principles, the MTCR part of ASAS computes an RBT advisory by determining a sequence o Trajectory Change Points (TCP’s) with minimum turning angles (to the left or to the right) such that there are no predicted conflicts remaining with any aircraft which has higher priority than ownship aircraft and which is within the MTCR horizon. If there is no minimum turning angle possible below a certain value $\varphi_{M, max}$, then the turning angle below $\varphi_{M, max}$ is identified which does not create a short term conflict and provides the lowest undershooting of the minimum spacing criteria of 5Nm and 1000ft between the RBT’s. In that case the ownship aircraft names itself handycapped. As soon as the advised MTCR advisories and the corresponding advisories have been implemented in the Airborne GNC agent of the ownship aircraft, then these are broadcasted together with a handycap message.

The specific implementation principles adopted for STCR are:

- STCR detects conflicts (3Nm&900ft) 3 min. ahead and resolves 3 min. plus 10 s ahead through course changes.
- When an aircraft detects a short term conflict it is obliged to resolve the conflict without waiting for any of the other aircraft
- If there is no feasible alternative, then rather than doing nothing it is better to choose a tactical maneuver which minmizes the undershooting of the minimum tactical separation criterion.
- Upon approval of the crew, the aircraft broadcasts its new course, which will trigger other aircraft to help resolving in case of an initial undershooting.

Using the above principles the STCR part of ASAS determines a resolution course as the minimum turning angle (to the left or to the right) such that there are no predicted conflicts remaining with any aircraft and which is within the short term horizon. If there is no minimum turning angle possible below a certain value $\varphi_{S, max}$, then the turning angle below $\varphi_{S,\ max}$ is identified which provides the lowest undershooting of the minimum separation criteria.

D. Model parameter values

The A^3 simulation model has a total of 164 scalar parameters. For each of these 164 parameters, a baseline value has been adopted in [32]. As an illustration, Table I gives the baseline values for the key dependability parameters of the A^3 enabling technical systems. Similarly, Table II gives the baseline values for the MTCR and STCR parameters. In addition to baseline parameter values, we also identified various non-baseline parameter values. This allows us to evaluate the sensitivity of the assessed safety risk level to changes in parameter value(s). Non-baseline parameter values have been identified for the following seven (groups of) parameters:

1. Crew response delay parameters
2. ASAS dependability parameters
3. Actual Navigation Performance (ANP) parameter
4. MTCR horizontal separation parameter
5. STCR horizontal separation parameter
6. Groundspeed parameter
7. Systematic Wind Prediction Error.

Table III specifies the non-baseline values identified for these seven (groups of) parameters.

IV. RARE EVENT MONTE CARLO SIMULATION RESULTS

A. Scenarios considered

The Agent Based Model of section III has been implemented in Delfi simulation code. Subsequently this simulation code is used to conduct rare event MC simulations for the following three scenarios:

- Two aircraft encounter
- Eight aircraft encounter
- Random traffic scenarios.

For each of these scenarios, rare event Monte Carlo (MC) simulations have been conducted for the baseline parameter values and for each of the seven (groups of) parameter changes in Table III. During each rare event MC simulation various safety related events have been assessed, including:

- Minimum Separation Infringement (MSI)
- Loss Of Separation (LOS) = ⅔rd of MSI
- Near Mid Air Collision (NMAC) (<1 Nm and <400 ft)
- Mid Air Collision (MAC) (<100 m and < 131 ft)

Full simulation results are given in [32,3,4]. Here the focus is on the results obtained for the random traffic scenarios using Periodic Boundary Condition [33] to mimic a large airspace.

TABLE I. BASELINE VALUES OF KEY DEPENDABILITY PARAMETERS OF A^3 ENABLING SYSTEM

Model parameters of A^3 enabling technical systems	Baseline dependability
Probability of GNSS down	1.0 $\times 10^{-5}$
Probability of Global ADS-B down[1]	1.0 $\times 10^{-6}$
Probability of Aircraft ADS-B Receiver down	5.0 $\times 10^{-5}$
Probability of Aircraft ADS-B Transmitter down	5.0 $\times 10^{-5}$
Probability of Aircraft ASAS performance corrupted	5.0 $\times 10^{-5}$
Probability of Aircraft ASAS System down	5.0 $\times 10^{-5}$

TABLE II. BASELINE VALUES OF A^3 CONOPS MODEL BASED MTCR AND STCR PARAMETERS

	Look ahead time	Horizontal separation	Vertical separation	Info used	Max turn angle $\varphi_{M,\ max}$
STCR	3 min + 10 sec	3Nm	900ft	State & Intent	$\varphi_{S,\ max} = 60^0$
MTCR	15 min	5Nm	1000ft	Intent	$\varphi_{M,\ max} = 60^0$

TABLE III. NON-BASELINE PARAMETER VALUES IDENTIFIED FOR SENSITIVITY ANALYSIS OF A^3 CONOPS MODEL

Id	Model parameter(s)	Specific setting(s)
1	Crew response delay	All crew response times are divided by 2
2	ASAS dependability	10x and 100x better than values in Table I
3	ANP	ANP0.5 and ANP2 versus baseline ANP1
4	MTCR	Horizontal separation 6Nm instead of 5Nm
5	STCR	Horizontal separation 5Nm instead of 3Nm
6	Groundspeed	300m/s instead of baseline 250m/s
7	Wind Prediction Error	10 m/s, 20 m/s, 30 m/s instead of 0 m/s

B. Simulation results for dense random traffic

The simulation results obtained are shown in Figure 1 for a 3x and a 6x high 2005 traffic demand. Figure 1 shows that for the baseline random traffic scenario, the effectiveness of the A^3 model follows the RNP1 kind of behaviour until it reaches MSI level. Subsequently, the A^3 model produces a factor 10^5 or more improvement between MSI and LOS. It is remarkable that in none of the rare event simulations a single event has been counted in which the miss distance was lower than 2.0 Nm. The 2.0 Nm value has been counted only once, and this was for the 6x high 2005 scenario.

Figure 2 shows that setting STCR separation value back from 3 Nm to 5 Nm has remarkable impact on the curves: the sharp reduction that occurred at 3 Nm is now already occurring at 5 Nm. The curves in Figure 2 show that the contribution of the RBT's is reduced by about slightly more than a factor 10. However, this loss is compensated for by an extra reduction by the tactical layer. Because of the very good results obtained for the A^3 ConOps with 5Nm STCR separation, Figure 3 combines this result with an estimated curve for the effect of baseline dependability of ASAS related systems. First the new curve is obtained by running MC simulations with initial condition that ADS-B global is down. Subsequently this curve is copied at a factor 10^{-6} lower values to complete the A^3 ConOps curve.

[1] Global ADS-B down refers to frequency congestion/overload of data transfer technology used by ADS-B.

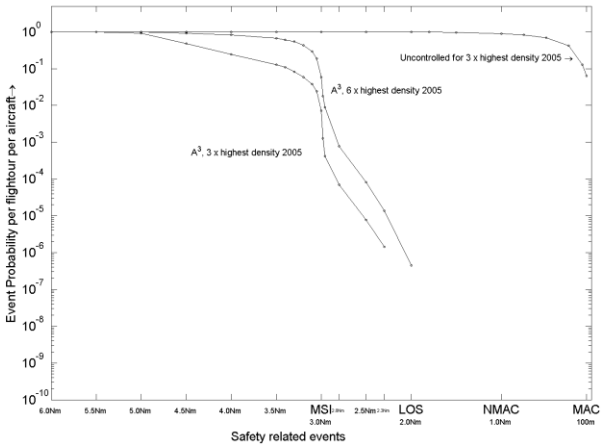

Figure 1. Estimated event probability per aircraft per flighthour for random traffic under A^3 model control and uncontrolled. Traffic densities are 3x and 6x high en-route traffic density in 2005.

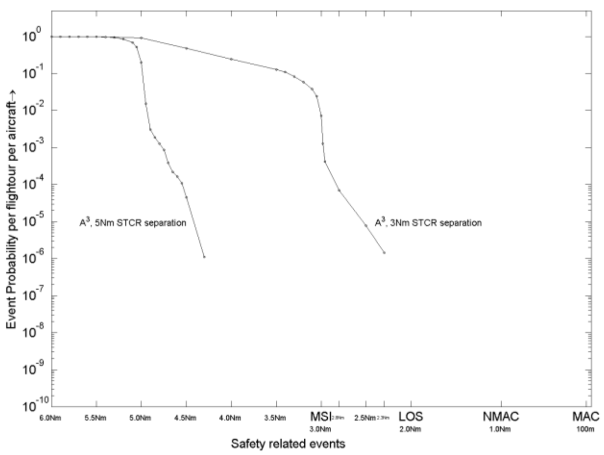

Figure 2. Estimated event probability per aircraft per flighthour for random traffic under A^3 model control at 3x high 2005 en-route traffic demand. Left curve shows effect of 5 Nm STCR separation.

Figure 3 also shows a reference point in the form of a bracket representing current events in controlled UK airspace for which the miss distance between aircraft underscores 66% of the applicable minimum separation criteria [34]. For the 3× highest denstiy in 2005, the A^3 ConOps with a 5Nm STCR separation minimum, is doing much better than the values in [34] for the current operation.

C. Systematic wind prediction errors

While the accuracy of wind forecasts has improved in recent years, it is known that occasional large errors can occur, which are known to significantly affect the performance of trajectory prediction tools [35]. Figure 4 shows the impacts upon the risk curve of systematic wind errors of 10 m/s, 20 m/s and 30 m/s (60 knots). Even for a systematic wind field error of 30 m/s the curve remains well away from the LOS frequency bracket, i.e. the current underscoring of 66% of the minimum separation value of 5Nm. A systematic wind prediction error of 60 knots eats away about 1Nm separation buffer at the 10^{-5} event probability level. This is much less than the 3Nm reported in [20] for the strategic conflict resolution layer only. Moreover, figure 4 shows that this 1Nm loss stays very well within the current LOS bracket at 66% of minimum separation. The results show that STCR is able to safely resolve the significant wind induced deviations from 4D trajectory intents (RBT's).

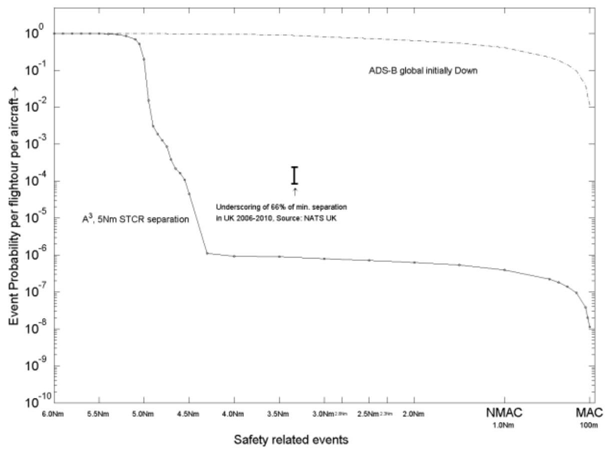

Figure 3. Estimated event probability per aircraft per flighthour for random traffic under A^3 model control at traffic demand of 3x high en-route traffic demand in 2005. The dashed curve at the top is obtained through running standard MC simulations for the A^3 ConOps model under the initial condition that ADS-B Global is Down. This curve has been used to construct a completion of the line curve for miss distance values below 4Nm.

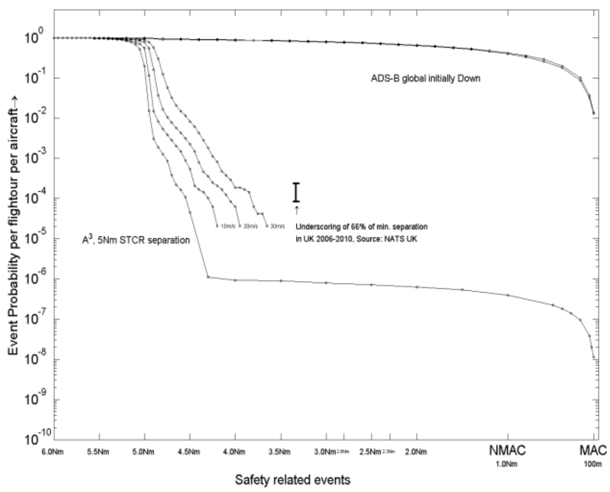

Figure 4. Effect of systematic wind field errors of 0, 10, 20 and 30 m/s.

D. Comparison against future TLS

In [4] a systematic comparison against future required TLS values has been provided. This shows that the airborne self separation TBO concept has the potential to realize SESAR very high future safety targets.

V. COMPLEMENTARY SIMULATION RESULTS

A. Flight efficiency

So far simulations with the agent based model of the airborne self-separation TBO concept has been used to evaluate the safety of the concept. However those simulations can as well be used to assess flight efficiency. More specifically we measure the mean loss in *effective distance travelled*, and the mean *lateral deviation* at the end point of the Monte Carlo simulation period of 20 minutes. As is depicted in Figure 5, the *effective distance travelled* eliminates any detours made to reach this end point, while the *absolute value of the lateral deviation* at this end point provides a measure of the net effect of these detours in terms of the lateral displacement at the end of the 20 minutes.

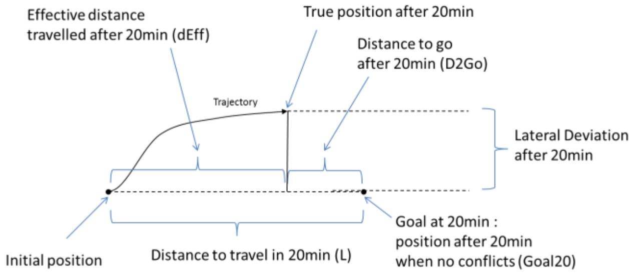

Figure 5. Flight efficiency measures.

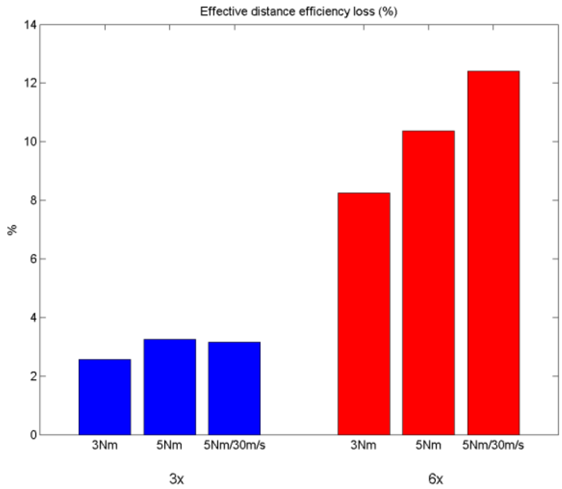

Figure 6. Mean loss in effective distance travelled for airborne self separation TBO concept under 3x and 6x high 2005 traffic demands.

In Figures 6 and 7 the results of flight efficiency evaluations are shown for two very high en route traffic demands: 3x and 6x high 2005 en-route traffic demands. The results in Figure 8 show that the mean loss in *effective distance travelled* is around 2% only under the 3x high 2005 en route traffic demand, though increases to values around 10% under 6x high 2005 traffic demand. Figure 7 shows that the mean of the *absolute value of the lateral deviation* tends to double with traffic demand.

The results for the 3x high 2005 traffic demand show a modest sensitivity to switching the minimum separation minimum between 3 Nm and 5 Nm. Moreover, even a systematic wind prediction error of 30 m/s has a modest effect on flight efficiency. This is in sharp contrast to the sensitivities seen for the 6x high 2005 traffic demand.

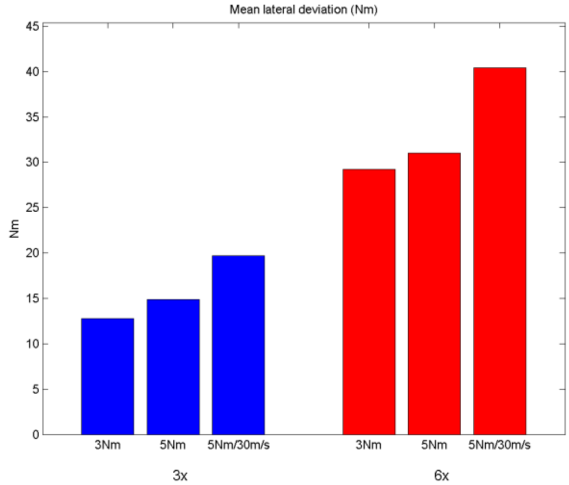

Figure 7. Mean absolute value of lateral deviation for airborne absolute self separation TBO concept under 3x and 6x high 2005 traffic demands.

Together with the safety results obtained in Section IV, this leads us to the conclusion that the airborne self separation TBO concept considered can safely and efficiently accommodate 3x high 2005 en route traffic demand, and is able to safely accommodate a two times higher traffic demand at the cost of reduced flight efficiency, i.e. some 10% loss in terms of the mean *effective distance travelled* and some doubling of the mean *absolute value of the lateral deviation*.

B. What happens without MTCR layer?

The very good results obtained under systematic wind prediction errors, mean that the STCR layer is very effective in resolving tactical conflicts. Hence the question is whether this power of the STCR layer is such good that there even is no need for the MTCR layer. A nice aspect of agent based modelling and simulation of an advanced ATM ConOps is the possibility to change the ConOps through some plug-and-play of the agent based model. In this section we consider the plug-and-play version which deletes the MTCR layer from the ConOps, by which the STCR layer only remains. The rare event MC simulation results are depicted in Figure 8. The simulation results are given for two versions:

- MTCR layer is deleted and STCR layer is same as before.
- MTCR layer is deleted and STCR layer includes a back to goal guidance

The curves for these two cases in Figure 8 clearly show that the sharp edge that applied under the original ConOps does no longer apply. This is a clear demonstration that the value of the MTCR layer still works when the intended conflict-free 4D plans appear to be not conflict-free in the end. In such case the STCR layer only has to identify some tactical deviations from the 4D plans in order to reconfigure the 4D trajectories of the aircraft involved in the conflict.

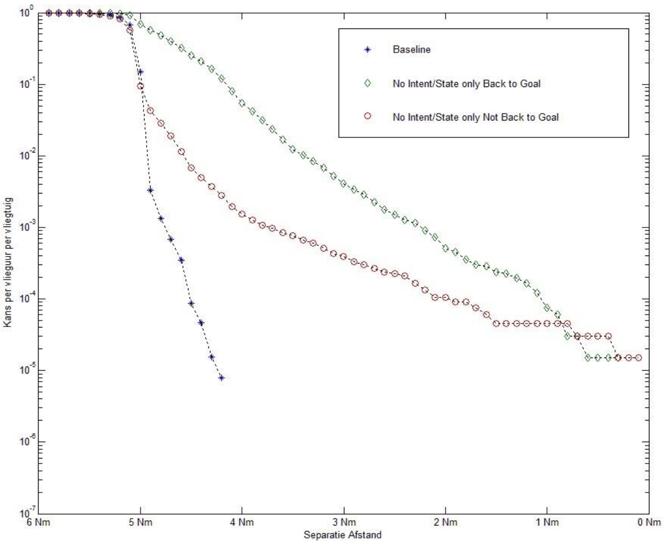

Figure 8. What happens when the MTCR layer is left out, by which the STCR layer has to do all conflict resolution. The curves show baseline results (+), STCR only (o) and STCR extended with a back to goal algorithm (diamonds).

C. *Answering the questions posed in the Introduction*

For the airborne self separation TBO concept we are now prepared to answer the three questions posed in the Introduction:

1. How good is the tactical layer in managing uncertainties that are not timely resolved by the 4D planning layer?

The results in figures 1-4 show that both under 3x and 6x high 2005 traffic demands, the tactical layer is very good in safely managing uncertainties that are not timely resolved by the 4D planning layer. This is a very positive emergent behaviour that clearly goes beyond the expectations of the designers of the airborne self separation TBO concept. The results in Figure 8 show that this powerful capability of the tactical layer works so well in combination with the broadcasting of the preparatory work by the 4D planning layer, even when this alone did not yield a fully safe solution. The conclusion is that in the airborne self separation TBO concept considered, the 4D and tactical layers play quite different roles that are both of great value, and which roles cannot be exchanged between these two layers

2. What distances should be used between the centrelines of 4D trajectory plans in order to safely manage the various uncertainties?

In ATM, standing practice is to take care that the distance between centrelines of 4D plans does not become smaller than the sum of the minimum separation + 2x the Required Navigation Precision (RNP). However, the safety curves in figure 2 clearly show that there is no need to account for the RNP values, i.e. the distance between centrelines of 4D plans may be the same as the minimum separation value. The efficiency measures in Figures 6 and 7 show that under 3x high 2005 traffic demand this has a minor influence on efficiency only. Only under 6x high 2005 traffic demand the influence is significant.

3. At which traffic demands is phase transition starting to happen and what are the consequences?

In road traffic a relative small increase of traffic demand may lead to a sudden decrease in travel velocity as a result of which the total traffic flow may suddenly decrease. From the results in figures 6 and 7 follows that such severe phase transition behaviour is not happening with the airborne self separation TBO concept, even not when traffic demand is increased from 3x high 2005 to 6x high 2005. Phase transition is entering very smoothly only, which is in large contrast with the abrupt behaviour in road traffic. A physical explanation for this difference is that road traffic starts to reduce velocity so much when local traffic density becomes too large that this reduces the total traffic flow. In air traffic however, the responses in case of too dense traffic consists of relative small course changes only instead of strong velocity reductions. This explains why *effective distance travelled* reduces slightly only, and *absolute value of lateral deviation* doubles when traffic demand doubles from 3x to 6x high 2005. In conclusion, 3x high 2005 en-route traffic demand can safely and efficiently be accommodated by the airborne self separation TBO concept considered.

VI. CONCLUDING REMARKS

A. *Positive emergent behaviours identified*

The agent based MC simulation results in Section IV-V reveal powerful positive emergent behaviours for the airborne self-separation TBO concept considered in [3,4]. The key emergent behaviours found can be summarized as follows:

- A proper tactical conflict detection and resolution layer makes it possible for the pilot to resolve tactical situations under which its 4D trajectory plan has lost the conflict-free quality.
- There appears to be no need to keep centrelines of conflict-free 4D plans further away from each other than the tactical separation minimum.
- In addition to safely accommodating 3x busy en-route 2005 traffic demand, phase transitions above this traffic demand level enter in a smooth and safe way.

It also is remarkable that each of these emergent behaviours goes beyond prior expectations of the designers of the airborne self-separation TBO concept considered.

B. *In search of positive SESAR2020+ emergent behaviour*

The follow-up research question is whether these positive emergent behaviours can also be made to work in the SESAR2020+ TBO concept. This follow-up research will be conducted through the recently started SESAR WP-E research project EMERGIA. This project is organized through the following series of investigations.

First, we will develop an agent based model of the SESAR2020+ ConOps. Subsequently this model is used to simulate and identify emergent behaviours at multiple time scales of the SESAR2020+ Concept of Operations in en-route airspace, and to learn understanding the underlying systemic interactions.

Next, differences will be identified between emergent behaviours for the SESAR2020+ ConOps and the positive emergent behaviours identified for the advanced airborne self-separation TBO concept. Any of the differences found can be used as valuable learning points for the improvement of the SESAR2020+ ConOps by a dedicated concept development team.

Finally, an agent based model will be developed for the improved SESAR2020+ ConOps. Subsequently this is used to identify emergent behaviours at multiple time scales of the improved SESAR2020+ Concept of Operations in en-route airspace, and to identify the improvements in emergent behaviours relative to SESAR2020+.

ACKNOWLEDGEMENT

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REFERENCES

[1] RTCA, "Final report of RTCA Task Force 3; Free Flight implementation", RTCA Inc., Washington DC, October 1995.

[2] iFly Deliverable D1.3, "Autonomous Aircraft Advanced (A3) ConOps", by G. Cuevas et al. January 2010.

[3] H.A.P. Blom, G.J. Bakker, "Safety of advanced airborne self separation under very high en-route traffic demand", Proc. SESAR Innovation Days, ENAC, Toulouse, 29 November-1 December 2011.

[4] H.A.P. Blom and G.J. Bakker, Can airborne self separation safely accommodate very high en-route traffic demand?, Proc. AIAA ATIO conference, 17-19 September 2012, Indianapolis, Indiana, USA

[5] V.N. Duong, E.G. Hoffman, "Conflict resolution advisory service in autonomous aircraft operations", Proc. 16th DACS Conf., 1997.

[6] J. Hoekstra, "Designing for Safety, Free Flight Air Traffic Management concept", PhD Thesis, Delft University of Technology, 2001.

[7] J. Krozel, "Free flight research issues and literature search". Under NASA contract NAS2-98005, 2000.

[8] RTCA, "DO-242a, Minimum aviation system performance standards for ADS-B", issued 25th June 2002

[9] Gayraud, F. Nacchia, J. Barff, R.C.J. Ruigrok, "Mediterranean Free Flight operational concept, requirements and procedures", Report MFF D220, 2005 (www.medff.it/public/index.asp).

[10] Maracich, "Flying free flight: pilot perspective and system integration requirements", Proc. 24th DASC, Washington, 2005.

[11] R.C.J. Ruigrok, N. de Gelder, H.J. Abma, B. Klein Obbink, J.J. Scholte, "Pilot perspective of ASAS self separation in challenging environments", Proc. 6th USA/Europe ATM R&D Seminar, 2005.

[12] R.C.J. Ruigrok, .J.M. Hoekstra, 'Human factor evaluation of free flight issues solved and issues remaining', Applied Ergonomics, Vol. 38 (2007), pp. 437-455.

[13] H.A.P. Blom, B. Klein Obbink, G.J. Bakker, "Simulated Safety Risk of an Uncoordinated Airborne Self Separation Concept of Operation", Air Traffic Control Quarterly, Volume 17 (2009) Number 1, pp. 63-93.

[14] NASA, "DAG-TM Concept element 5 en-route free maneuvering for user-preferred separation assurance and local TFM conformance operational concept description", AATT Project Milestone 8.503.10, NASA Airspace Systems Program Office, Washington D.C., 2004.

[15] D.J. Wing, W.B. Cotton, "For spacious skies: self-separation with "Autonomous Flight Rules" in US domestic airspace", Proc. 11th AIAA ATIO Conference 2011, Virginia Beach, VA, USA, September 2011.

[16] D.J. Wing, W.B. Cotton, 'Autonomous Flight Rules, A concept for self-separation in US domestic airspace", Report NASA/TP-2011-217174, NASA Langley Research Centre, Hampton, VA, November 2011.

[17] M. Consiglio, S. Hoadley, D. Wing and B. Baxley, "Safety Performance of Airborne Separation: Preliminary Baseline Testing", Proc. 7th AIAA ATIO Conf., Belfast, Ireland, 2007

[18] M. Consiglio, S. Hoadley, D. Wing, B. Baxley and D. Allen, "Impact of Pilot Delay and Non-Responsiveness on the Safety Performance of Airborne Separation", Proc. 8th AIAA ATIO Conf., September 2008.

[19] M.C. Consiglio, S.R. Wilson, J. Sturdy, J.L. Murdoch, D.J. Wing, "Human in the loop simulation measures of pilot response delay in a self-separation concept of operations", Proc. 27th Int. Congress of the Aeronautical Sciences (ICAS 2010), 2010.

[20] M. Consiglio, S. Hoadley and B.D. Allen, "Estimation of Separation Buffers for Wind-Prediction Error in an Airborne Separation Assistance System", Proc. USA/Europe ATM Seminar, Nappa, CA, 2009.

[21] iFly Deliverable D9.1, "Operational Services and Environmental Description (OSED) of Airborne Self-Separation Procedure (SSEP)", by E. Gelnarová, P. Cásek, August 2009.

[22] SESAR, "Concept of Operation, Sesar definition phase, Task 2.2.2, Milestome 3", Report DLT-0612-222-02-00, Version 2.0, 2007.

[23] H.A.P Blom, G.J. Bakker, P.J.G. Blanker, J. Daams, M.H.C. Everdij, M.B. Klompstra, "Accident risk assessment for advanced ATM", Eds: G.L. Donohue & A.G. Zellweger, Vol. 193 in Progress in Astronautics and Aeronautics, AIAA, 2001, pp. 463-480.

[24] H.A.P. Blom, S.H. Stroeve, H.H. De Jong, "Safety risk assessment by Monte Carlo simulation of complex safety critical operations", *Proc. 14th Safety-critical Systems Symposum*, Bristol, UK, Eds: F. Redmill and T. Anderson, Springer, London, 2006.

[25] H.A.P. Blom, J. Krystul, G.J. Bakker, M.B. Klompstra, B. Klein Obbink, "Free flight collision risk estimation by sequential Monte Carlo simulation", Eds: C.G. Cassandras and J. Lygeros, Stochastic hybrid systems; recent developments and research trends, Taylor & Francis/CRC Press, 2007, pp. 249-281.

[26] H.A.P. Blom, G.J. Bakker and J. Krystul, "Rare event estimation for a large scale stochastic hybrid system with air traffic application", Chapter in: G. Rubino and B. Tuffin (editors), Rare event simulation using Monte Carlo methods, Wiley, 2009.

[27] M.H.C. Everdij and H.A.P. Blom, Hybrid state Petri nets which have the analysis power of stochastic hybrid systems and the formal verification power of automata, Ed: P. Pawlewski, Petri Nets, Chapter 12, I-Tech Education and Publishing, Vienna, 2010, pp. 227-252.

[28] iFly Deliverable D8.1, "A3 ConOps refinement", Editors: L. BieScas and H.A.P. Blom, Final draft of October 2011

[29] iFly Deliverable D5.3, "Report on advanced conflict resolution mechanisms for A3 ConOps", by E. Siva, J.M. Maciejowski, G. Chaloulos, J. Lygeros, G. Roussos, K.Kyriakopoulos. August 2011.

[30] Y. Abe, M. Yoshiki, "Collision avoidance method for multiple autonomous mobile agents by implicit cooperation", Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS 01), pp. 1207–1212.

[31] P. Fiorini, Z. Schiller, "Motion planning in dynamic environments using velocity obstacles", *The International Journal of Robotics Research*, Volume 17 (1998), pp. 760–772.

[32] iFly Deliverable D7.4, "Final Report on Accident Risk Assessment of the A3 operation" by H.A.P. Blom and G.J. Bakker, September 2011.

[33] D.C. Rapaport, "The art of molecular dynamics simulation", Cambridge University Press, 2004.

[34] NATS presentation at FAA/Eurocontrol AP15 meeting, Washington DC, March 8-10, 2011.

[35] M. Paglione, H. Ryan, "Aircraft conflict probe sensitivity to weather forecast errors", *Proc. 26th IEEE/AIAA DASCe*, October 2007.