Agent-based safety risk analysis of Trajectory Based Operation in the Terminal Manoevring Area

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***Abstract*—In 2004 the European Commission initiated the Single European Sky ATM Research (SESAR) programme to meet future capacity and safety needs. The current architecture of ATM services needs to be changed in order to comply with the continuously growing demand for air transport. This paper presents the results of a safety assessment of SESAR developed Trajectory Based Operation (TBO) in the Terminal Manoeuvring Area (TMA) in which pilots are allowed to make tactical decisions themselves rather than having to await controller instructions. The separation assurance responsibility is distributed between the pilots and the controller. The safety risk assessment is conducted using the TOPAZ safety assessment methodology. The results suggest that the pilots have a major contribution in detecting and solving potential conflicts in the TMA.**

Keywords- Airborne Separation Assistance System (ASAS); Single European Sky ATM Research (SESAR); Terminal Manoeuvring Area (TMA); TOPAZ; Agent-based modelling; Stochastically and Dynamically Coloured Petri Nets; Monte Carlo simulations

I. INTRODUCTION

As a step towards increasing future Air Traffic Management (ATM) capacity, the Single European Sky ATM Research (SESAR) proposed the SESAR 2020 Concept of Operations (ConOps). The concept is a Trajectory Based Operation (TBO) using a four-dimensional (4D) trajectory planning, which is implemented through the exchange of Reference Business Trajectories (RBTs) [2]. According to [3] such RBT based approach is supported by aircraft equipment to better follow assigned trajectories with fewer controller tactical interventions, and automatic detection and timely resolution of any deviation that impacts loss of separation.

An earlier agent-based safety risk study [1] focuses on whether reduction of lateral distance between centrelines of en route lanes/Standard Instrument Departure routes (SIDs) and Standard Terminal Arrival Routes (STARs) can safely be done in a future Terminal Manoeuvring Area under a ground-based TBO concept of operations, which is referred to as TMA-T1 ConOps [4]. The TMA-T1 concept of operation aims to reduce the nominal lateral distances (the spacing) between en route lanes, SIDs and STARs from 8 Nautical Miles (NM) to 5 NM [1]. This reduction would allow significant capacity increase for complex or constrained TMAs.

In this TMA-T1 ConOps there are two layers of control: one is the TBO layer, which determines conflict-free 4D trajectory plans. The other layer is the tactical control loop, which consists of Air Traffic Control (ATC) providing tactical manoeuvre instructions to aircraft in case of an unexpectedly remaining conflict. The study [1] has shown that under this TMA-T1 ConOps a safe reduction between centrelines of route structures is feasible if significant safety objectives are satisfied.

The objective of this paper is to evaluate the impact in terms of safety and safety objectives of partially shortening the tactical control loop by giving pilots some tactical self-separation control support. To accomplish this, the paper evaluates the safety risk of a modified version of the TMA-T1 operation in which pilots actively make tactical conflict resolution decisions with support of an Airborne Separation Assistance System (ASAS). This modified TMA-T1 operation is referred to as TMA-T1-ASAS. In order to evaluate safety risk the Traffic Organization and Perturbation Analyzer (TOPAZ) methodology was used [5]. This is a safety assessment method developed by researchers at NLR.

This paper is organised as follows. Section II describes the TMA-T1-ASAS operation. Section III presents the development of an agent-based model of the TMA-T1-ASAS operation. Section IV presents the rare event MC simulation results based on this model. Section V discusses the MC simulation results. Section VI draws conclusions.

II. TMA-T1-ASAS OPERATION

For the TMA-T1-ASAS operation, a high density TMA is considered, accommodating several airports. In this TMA various closely spaced SIDs and STARs may be defined, and also several en route lanes at a lower flight level.

Similar to the TMA-T1 ConOps, TMA-T1-ASAS aims to reduce lateral distances (the spacing) between en route lanes, SIDs and STARs to 5 NM. Reducing the separation distance between centrelines of route structures potentially increases capacity. There are no new constraints on radar separation minimum, hence these can be assumed to stay as today, i.e. at 3 NM.

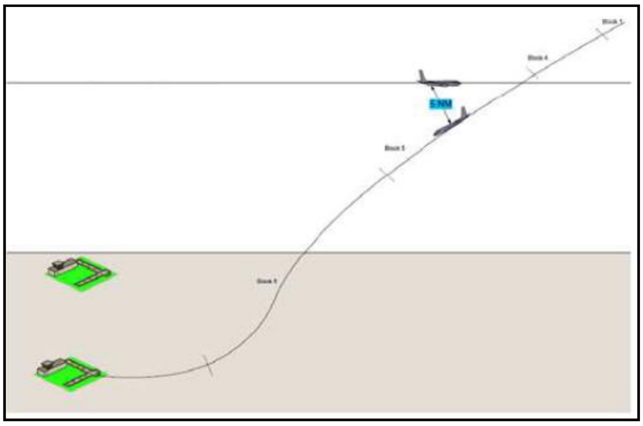

Figure 1. Conflict scenario TMA-T1-ASAS operation [6]

The conflict scenario considered in this paper is the same as in the study of [1]: An aircraft flying en route and aircraft flying on a STAR, on paths which are spaced laterally by 5 NM, see Figure 1. The aircraft on the STAR are flying a Continuous Descent Approach (CDA). In the TMA-T1-ASAS operation the separation assurance responsibility is distributed between the controller and the pilots. This means that the controllers are still responsible for the safe and orderly operation of flight in compliance with the ICAO Rules of Air, other relevant ICAO and CAA/JAA provisions, and within standard operating procedures. But the pilots are allowed to act themselves in case of a significant deviation from the conflict free intended 4D trajectory plans.

III. AGENT-BASED MODEL OF TMA T1-ASAS

A. *Agent-based modelling*

An ‘agent’ typically is any entity such as a human operator or a technical system, which may possess situation awareness of the environment [7]. Agent-based modelling is a way to model the dynamics of complex systems and complex adaptive systems. According to [8] agent-based models can integrate cognitive models of human performance, physical models of technology behaviour and descriptions of their operating environment. Simulation of these individual models acting together can predict the result of completely new transformations in procedures and technologies.

In [1] the agent-based model of the TMA-T1 operation is described. This paper focuses on the effect when pilots are allowed to make tactical decisions themselves rather than having to await controller instructions. The model in [1] should therefore be extended with an Airborne Separation Assistance System (ASAS) to assist the pilot in detection and resolution of potential conflicts.

In the TMA-T1-ASAS model the following types of agents are taken into account:

- Aircraft evolution
- Air Traffic Control (ATC) system
- Air Traffic Controller (ATCo)
- Pilot Flying
- Airborne Separation Assistance System (ASAS)

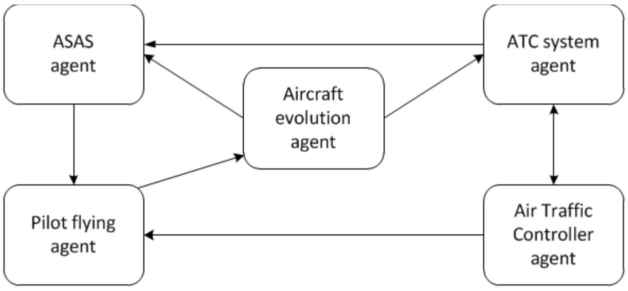

Figure 2. Agents and their interactions

Figure 2 depicts the agents and their interactions. Note that for the Aircraft evolution agent, the Pilot flying agent and ASAS agent there is one agent per aircraft in the model. Moreover there is only one Air Traffic Controller agent and one ATC system agent in the model.

B. *Agent-level Petri Nets*

Next, the agent-based model is specified using the formalism of Stochastically and Dynamically Coloured Petri Net (SDCPN), [9], [10], [11], [12]. SDCPN is a very powerful formalism to model air traffic operations, such as the future TMA-T1-ASAS operation. It covers the modelling of various discrete modes of operation as well as continuous modes of operation such as the position and velocity of aircraft, which influence each other. The model is stochastic, meaning that the various events may happen at random times, and the continuous values may have randomness as well.

For all agents one or more Local Petri Nets (LPNs) can be defined, where each LPN is an SDCPN-based submodel describing an agent-specific process. In the model for TMA-T1-ASAS there is one aircraft flying level (ac_0) and there are multiple aircraft flying on a STAR (ac_j is introduced *m* times, for j=1, .., *m*). Each LPN consists of Places, which represent discrete states or modes, and Transitions, which represent mode switches, connected by arcs (arrows).

Table 1 presents the LPNs for the agents in the TMA-T1-ASAS operation. Next to this table, a description of the Local Petri Nets is given for each of these agents.

TABLE I. LOCAL PETRI NETS IN THE TMA-T1-ASAS MODEL; LPN’S WHICH DIFFER FROM TMA-T1 ARE MARKED BY *

Agent	Local Petri Net
1. Aircraft evolution	Aircraft evolution ac_0
	Aircraft evolution ac_j
2. Pilot flying	Pilot flying ac_0 and ac_j
3. ASAS	ASAS processing ac_0 and ac_j *
	ASAS surveillance ac_0 and ac_j *
	ASAS system mode ac_0 and ac_j *
	ADS-B transmitter ac_0 and ac_j *
	ADS-B receiver ac_0 and ac_j *
4. Air Traffic Controller	Air Traffic Controller
5. ATC system	ATC system
	ADS-B global*

Aircraft evolution as agent

The aircraft evolution agent contains two LPNs. One is LPN Aircraft evolution ac_0 which denotes the flight path flown by the aircraft flying en route. The three places of LPN Aircraft evolution ac_0 represent the following modes:

- *On lane:* aircraft ac_0 flies level.
- *Sharp turn left*: aircraft ac_0 makes a sharp turn left.
- *Back to lane*: aircraft ac_0 flies back to his lane.

The other LPN of aircraft evolution agent is LPN Aircraft evolution ac_j which denotes the flight path flown by one aircraft on a STAR. In the operation there are multiple aircraft *m* flying on a STAR. Therefore LPN Aircraft evolution ac_j is introduced *m* times in the model, for j=1, .., *m*. The three places of LPN Aircraft evolution ac_j represent the following modes:

- *CDA*: aircraft ac_j on the STAR flies a Continuous Descent Approach (CDA).
- *Climb*: aircraft ac_j is climbing.
- *Level*: aircraft ac_j flies level.

Pilot flying as agent

The pilot flying as agent contains LPN Pilot flying. The LPN Pilot flying denotes the cognitive tasks of the pilot. The pilot is always busy with exactly one of the generic tasks. Note that LPN Pilot flying is introduced *m+1* times in the model, for j=0,..,*m*. The places in the LPN Pilot Flying represent the following modes [13]:

- *Monitoring*: The state in which the pilot collects, gathers and integrates information on the current goal.
- *Monitoring and Decision-making*: Using information provided by systems and, possibly, by other human operators and depending on his (intent) situation awareness, the pilot makes up his mind about: whether co-ordination is required, and if so, with whom and what, and whether a particular action is required, and if so when and which specific action.
- *Execution*: The state in which the pilot is actually operating the aircraft, activating functions by means of a human-machine interface.
- *Execution Monitoring*: The state in which the pilot monitors events and developments expected from an action.
- *Monitoring and Goal Prioritisation*: The state in which the pilot collects information and decides what goal requires his attention next.

ASAS as agent

This agent contains five LPNs: LPN ASAS processing, LPN ASAS surveillance, LPN system mode, LPN ADS-B transmitter and LPN ADS-B receiver. LPN ASAS processing ac_0 detects possible conflicts of aircraft ac_0 with other aircraft in the operation. LPN ASAS processing ac_j detects possible conflicts of aircraft ac_j with aircraft ac_0. LPN ASAS surveillance ac_0 receives the state information of all aircraft *m* flying on a STAR. LPN ASAS surveillance ac_j receives the state information of all other aircraft *k* in the model, where k=0,1,..,*m*; k≠j. LPN ASAS system mode ac_0 and ac_j denotes if ASAS is working or not. The three places of LPN ASAS system mode ac_0 and ac_j represent the following modes:

- *Working:* ASAS is working correctly.
- *Failure:* ASAS fails.
- *Corrupted*: ASAS is corrupted.

LPN ADS-B transmitter ac_0 and ac_j denotes if the ADS-B transmitter of the aircraft is working or not. The LPN has two places that represent the following modes:

- *Working*: ADS-B transmitter is working correctly/ No ADS-B transmission failure.
- *Not working*: ADS-B transmitter is not working / ADS-B transmission failure.

LPN ADS-B receiver ac_0 and ac_j denotes if the ADS-B receiver of the aircraft is working or not. The LPN has two places that represent the following modes:

- *Working*: ADS-B receiver is working correctly/ No ADS-B receiver failure.
- *Not working*: ADS-B receiver is not working / ADS-B receiver failure.

Air Traffic Controller as agent

The Air Traffic Controller as agent contains LPN Air Traffic Controller. The LPN Air Traffic Controller denotes the cognitive tasks of the controller. The controller is always busy with exactly one of the generic tasks. Note that there is only one LPN Air Traffic Controller in the model. The places in the LPN Air Traffic Controller represent the following modes [13]:

- *Monitoring*: The state in which the air traffic controller collects, gathers and integrates information on the current goal.
- *Monitoring and Decision*: Using information provided by systems and, possibly, by other human operators and depending on his (intent) situation awareness, the air traffic controller makes up his mind about: whether co-ordination is required, and if so, with whom and what, and whether a particular action is required, and if so when and which specific action.
- *Execution:* The state in which the air traffic controller gives an instruction to a pilot to resolve a conflict.
- *Execution Monitoring:* The state in which the air traffic controller overlooks the events and developments resulting from an action.

ATC system as agent

The ATC system as agent contains two LPNs. LPN ATC system with one place which represents the following mode:

- *Info*: receives state information of all aircraft in the model, conflict detection and alerting and flight plan performance monitoring of aircraft ac_0.

The other LPN is LPN ADS-B Global. LPN ADS-B Global represents the following two modes:

- *Not-Occupied*: ADS-B Global is not occupied.
- *Occupied*: ADS-B Global is occupied.

C. *Specification of agent interactions*

The above specification means that each aircraft in the model is represented by seven LPNs: LPN Aircraft evolution, LPN Pilot flying, LPN ASAS processing, LPN ASAS surveillance, LPN ASAS system mode, LPN ADS-B transmitter and LPN ADS-B receiver. Moreover there is one LPN Air Traffic Controller, one LPN ATC system and one LPN ADS-B global. Hence, since there are *m* aircraft on a STAR and one aircraft on level, there are 7(*m*+1)+3 Local Petri Nets in the TMA-T1-ASAS model.

Subsequently interactions between these LPNs are specified. Connections between LPNs are realised using the Compositional Specification principles presented in [11]. Two types of basic interconnections between nodes in different LPNs are used [11]:

- Enabling arc (or inhibitor arc) from one place in one LPN to one transition in another LPN. These types of arcs have been used widely in Petri net literature.
- Interaction Petri Net (IPN) from one (or more) transition(s) in one LPN to one (or more) transition(s) in another LPN.

The resulting SDCPN-based model for TMA-T1-ASAS, including all interconnections and other mathematical details is presented in [14]. The key addition of the SDCPN-based model for TMA-T1-ASAS, compared to the one in [1] for TMA-T1, is the model for the agent ASAS. This model is added to support pilots with conflict detection and resolution in the TMA-T1-ASAS operation. The remainder of this subsection illustrates the SDCPN-based model developed for ASAS on-board each aircraft, including the interconnections between the LPNs. For ASAS a distinction is made between j=0, referring to the aircraft en route, and j=1,..,*m*, referring to aircraft on a STAR. ASAS for aircraft ac_j is modelled through the SDCPN-based model depicted in Figure 3.

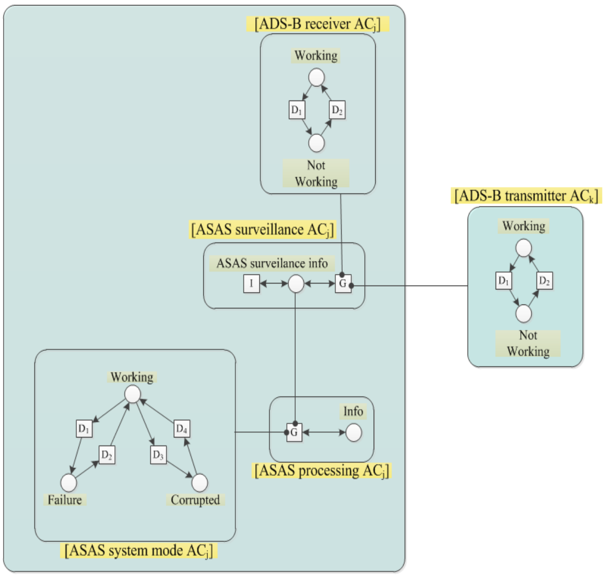

Figure 3. The agent in the TMA-T1-ASAS operation is modelled by five LPNs and a number of ordinary and enabling arcs. In this figure ac_j represents an aircraft on level (j=0) or an aircraft on a STAR (j=1,..,*m*), and k≠j.

The ADS-B information from another aircraft ac_k (where k=0,1,..,.*m*; k≠j) is received by LPN ASAS surveillance ac_j if three conditions are satisfied:

1. LPN ADS-B receiver ac_j is working;
2. LPN ADS-B transmitter ac_k of aircraft ac_k is working,
3. LPN ADS-B global (part of ATC System agent) is not occupied.

Under these three conditions, LPN ASAS processing ac_j uses the state information of the own aircraft and the other aircraft ac_k available from the respective Aircraft evolution LPNs, to detect potential conflicts between ac_j and ac_k. Furthermore, if LPN ASAS system mode ac_j is working, the Pilot flying will be alerted by ASAS if potential conflicts occur. This clarifies that the ASAS agent is further connected to the Aircraft evolution agent, the ATC system and the Pilot flying agent (not drawn in Figure 3).

D. *Implementation and verification*

The SDCPN model specification has been implemented in an object oriented programming language; in this study Delphi XE3 was used. The SDCPN specification was implemented in four steps: The first step is the translation of the formal SDCPN structure into software code per LPN component. The second step is the development of the software code at the agent level. The third step is the software implementation at agent interactions level. And the fourth and final step is the implementation of the software code that supports running Monte Carlo simulations of the implemented SDCPN.

During the implementation of the SDCPN model specification in Delphi code, the software was also tested. This was done through conducting the following sequence of tests: common functions, each Local Petri Net implementation, each agent implementation, interactions between agents, full Monte Carlo simulation. Also the graphical user interface was tested. This was to verify that the input and output of data works well. This was followed by parameterization, through search of literature and complemented by conducting expert interviews.

In addition, model verification has been performed by running Monte Carlo simulations of the TMA-T1-ASAS model under the same conditions as in [1], i.e. by disabling the ASAS component. As expected, under the same condition (no ASAS support to pilots) the Monte Carlo simulation results of the TMA-T1-ASAS operation were similar to the Monte Carlo simulation results of the TMA-T1 operation. After this, Monte Carlo simulations have been run with specific parameters, and the results obtained have been compared with prior expectations. It appeared that the prior expectations were met.

IV. MONTE CARLO SIMULATION

A. *Non-nominal encounter conditions*

The next step is to perform an analysis of relevant non-nominal scenarios that potentially happen within the TMA-T1-ASAS operation. A non-nominal scenario analysis of the TMA-T1 operation is performed in [6]. This study considers the same non-nominal encounter conditions as in [6] in order to analyse the effect of allowing pilots to make tactical decisions themselves. These non-nominal encounter conditions are referred to as “No ATC”, “Short Term Conflict Alert (STCA) only" and "Flight Plan Conformance Monitoring (FPCM) and/or STCA".

Non-nominal encounter condition "No ATC"

Non-nominal encounter condition "No ATC" considers a situation in which the controller does not, or is not able to give a conflict recovery instruction to an aircraft in conflict. In this situation, we assume that the aircraft en route makes a turn away from its lane; the aircraft on the STAR maintains a straight line. However, no instruction from the controller is given to resolve any conflict. This situation may occur, e.g. due to failing communication or failing ground surveillance equipment. Studying this situation helps to understand the effect of controller actions on reducing collision risk, and to set Safety Objectives on failure of communication and surveillance equipment.

Moreover, in this non-nominal encounter condition the pilot flying is monitoring the positions and velocities of all aircraft that are available to him through the Cockpit Display of Traffic Information (CDTI). About two minutes before a conflict is due to occur (i.e. two minutes before separation is less than 3 NM), the ASAS alerting system warns the pilot for a conflict. If a conflict occurs the pilot should make a resolution manoeuvre. ASAS gets as input only position information, from which it derives velocity information.

Non-nominal encounter condition "STCA only"

Non-nominal encounter condition "STCA only" considers a situation in which the aircraft makes a turn, while the controller and the ATC system have the intent situation awareness that the turn can be safely made. Here, we make the assumption that the aircraft en route makes this turn, i.e., the aircraft on the STAR maintains a straight line. This means, according to the ATC system, the aircraft on approach has an RBT according to the STAR, and the aircraft en route has an RBT that is making a turn away from the en route lane.

The controller is monitoring the positions and velocities of all aircraft that are available to him through surveillance equipment and the traffic situation display. In this scenario, about two minutes before a conflict is due to occur (i.e. two minutes before separation is less than S_{radar} = 3NM), the Short Term Conflict Alert (STCA) system warns the controller of a conflict. Upon this, after a (random) reaction time, the controller takes action: he uses R/T to give the flight crew of one of the aircraft an avoidance instruction. R/T is assumed to be working properly. One option is to give the aircraft on the STAR an instruction to level off, thus ensuring vertical separation. Another option is to send the aircraft en route back to the en route lane. In the simulation model, STCA gets as input only position information, from which it derives velocity information. After a (random) reaction time, the pilot-flying of the aircraft that has been given the instruction, reacts and follows the instruction.

Moreover, in this non-nominal encounter condition the pilot flying is monitoring positions and velocities of all aircraft that are available to him through CDTI. About two minutes before a conflict is due to occur (i.e. two minutes before separation is less than 3 NM), the ASAS alerting system warns the pilot for a conflict. If a conflict occurs the pilot should make a resolution manoeuvre. ASAS gets as input only position information, from which it derives velocity information.

Non-nominal encounter condition "FPCM and/or STCA"

Non-nominal encounter condition "FPCM and/or STCA" considers a situation in which the aircraft makes a turn, and the controller has the situation awareness that the turn can be safely made. However, the ATC system has the intent situation awareness that the aircraft should continue to fly in a straight line. This means, according to the ATC system, the aircraft on approach has an RBT according to the STAR, and the aircraft en route has an RBT according to the en route lane. Again, we make the assumption that the aircraft en route makes this turn, i.e., the aircraft on the STAR maintains a straight line.

The controller is monitoring the positions and velocities of all aircraft that are available to him through surveillance equipment and the traffic situation display. In this scenario, at some point, the flight plan conformance monitoring (e.g. Monitoring Aids, MONA) detects that the aircraft is making a turn away from its intent RBT. The controller is alerted to this deviation, and after a (random) reaction time, the controller takes action: he uses R/T to give the flight crew of one of the aircraft a recovering instruction. R/T is assumed to be working properly. One option is to give the aircraft on the STAR an instruction to level off, thus ensuring vertical separation. Another option is to send the aircraft en route back to the en route lane. It is assumed that MONA gets as input precise state information (position, velocity) of aircraft, e.g. through ADS-B or Mode S.

In addition, about two minutes before a conflict is due to occur STCA warns the controller of a conflict. Upon this, after a (random) reaction time, the controller takes action, by using R/T to give the flight crew of the aircraft on the STAR an instruction to level off, or to send the aircraft en route back to the en route lane. After a (random) reaction time, the pilot-flying of the aircraft that has been given the instruction, reacts and follows the instruction.

Moreover, in this non-nominal encounter condition the pilot flying is monitoring the positions and velocities of all aircraft that are available to him through the CDTI. About two minutes before a conflict is due to occur (i.e. two minutes before separation is less than 3 NM), the ASAS system warns the pilot for a conflict. If a conflict occurs the pilot should make a resolution manoeuvre. ASAS gets as input only position information, from which it derives velocity information.

B. Monte Carlo simulation results

Figures 4, 5 and 6 show the conditional collision risk results for the three non-nominal encounter conditions considered. The (upper) blue line shows the results of the TMA-T1 operation and the (lower) red line shows the results of the TMA-T1-ASAS operation in which pilots are making tactical decisions themselves rather than having to await controller instructions.

The horizontal axes in the figures show various values for the spacing between the en route lane and the STAR, in Nautical miles. The vertical axis provides the conditional collision risk, i.e. the probability for an aircraft on the en route lane to collide with an aircraft on the STAR, for the situation described. Between 100 000 and 170 million Monte Carlo simulations were run for each point estimate on the graph, depending on the number of collisions counted per run. Lower collision risk requires more runs to obtain more accurate results. The small blue and green blocks in the figure indicate the upper bound and the lower bound of a 95% confidence interval for each conditional risk point.

Non-nominal encounter condition "No ATC"

The conditional collision risk results for non-nominal encounter condition "No ATC" are given in Figure 4. Figure 4 shows that for all spacing values the conditional collision risk results for the TMA-T1 operation are at a constant level of about 3.3E-3. This means that according to the model, each en route aircraft entering the sector has a probability of 3.3E-3 to collide with an aircraft on the STAR, under the conditions of the TMA-T1 operation and the encounter condition considered. For the TMA-T1-ASAS operation the conditional collision risk results are at a constant level of about 3.4E-6 with bounds 2.7E-6 and 4.3E-6 of the 95% confidence interval. This means that according to the model, each en route aircraft entering the sector has a probability of 3.4E-6 to collide with an aircraft on the STAR, under the conditions of the TMA-T1-ASAS operation and the encounter condition considered. One may notice that for all spacings the results of operation of the TMA-T1-ASAS operation are about a factor 971 better than those of the TMA-T1 operation.

Under the "No ATC" condition, it is assumed that a controller does not give instructions. The conditional collision risk per level aircraft passing a STAR in the TMA-T1 operation at a spacing of 5 NM is 3.3E-3. Hence for ten million encounters 33000 collisions have been counted because the controller could not give an avoidance instruction. In the TMA-T1-ASAS operation pilots are allowed to make tactical decisions themselves. In this case pilots are able to reduce the risk of collision to 34 collisions per ten million encounters (which is a factor 971 reduction with bounds 2.7E-6 and 4.3E-6 of the 95% confidence interval). This incorporates the probability that the ADS-B (global) frequency is occupied. If ADS-B global is occupied ASAS does not receive state information of other aircraft and cannot detect possible collisions. In such cases the pilots are not able to avoid the collision. In the model the probability of ADS-B global being occupied is 1E-3, which largely corresponds to the factor 971 reduction by going from TMA-T1 to TMA-T1-ASAS.

Non-nominal encounter condition "STCA only"

The conditional collision risk results for non-nominal encounter condition "STCA only" are given in Figure 5. The conditional collision risk in the TMA-T1 operation at a spacing of 5 NM is 6.0E-5 collisions per level aircraft passing a STAR and decreases to a level of about 2.5E-7 collisions per level aircraft passing a STAR at larger spacings. The conditional collision risk in the TMA-T1-ASAS operation at a spacing of 5 NM is 8.6E-8 collisions per level aircraft passing a STAR with bounds 4.9E-8 and 1.5E-7 of the 95% confidence interval. It appears that for spacing larger than 5 NM no collisions have been counted in 140 million Monte Carlo simulations. Hence,

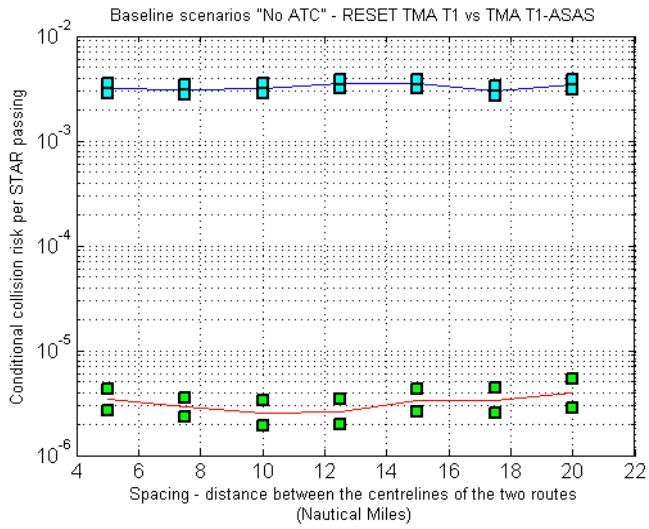

Figure 4. Monte Carlo simulation results for non-nominal encounter condition "No ATC" for TMA-T1 (upper, blue line) and TMA-T1-ASAS (lower, red line). The small blue and green blocks indicate the upper bound and the lower bound of a 95% confidence interval.

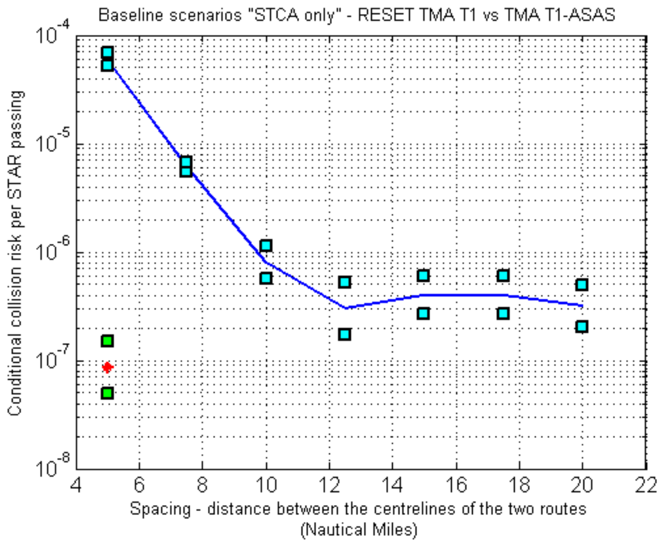

Figure 5. Monte Carlo simulation results for non-nominal encounter condition "STCA only" for TMA-T1 (upper, blue line) and TMA-T1-ASAS (lower, red dot). The small blue and green blocks indicate the upper bound and the lower bound of a 95% confidence interval.

the conditional collision risk for spacings larger than 5 NM is less than 1 in 140 million (i.e. less than 7.1E-9 collisions per level aircraft passing a STAR).

When comparing the conditional collision risk results of the TMA-T1 operation with the TMA-T1-ASAS operation (see Figure 5), one may notice that for a spacing of 5 NM, the results of operation of the TMA-T1-ASAS operation are a factor 698 better than those of the TMA-T1 operation.

Non-nominal encounter condition "FPCM and/or STCA"

The conditional collision risk results for non-nominal encounter condition "FPCM and/or STCA" are given in Figure

6. The conditional collision risk in the TMA-T1 operation at a spacing of 5 NM is collisions per level aircraft passing a STAR and at a spacing of 7.5 NM it is 3.3E-7 collisions per level aircraft passing a STAR. The conditional collision risk in the TMA-T1-ASAS operation at a spacing of 5 NM is 2.4E-8 collisions per level aircraft passing a STAR with bounds 6.4E-9 and 6.0E-8 of the 95% confidence interval. It appears that for spacing larger than 5 NM no collisions have been counted in 170 million Monte Carlo simulations. Hence the conditional collision risk for spacings larger than 5 NM is less than 1 in 170 million (i.e. which is less than 5.9E-9 collisions per level aircraft passing a STAR).

When comparing the conditional collision risk results of the TMA-T1 operation with the TMA-T1-ASAS operation (see Figure 6), one may notice that for a spacing of 5 NM, the results of operation of the TMA-T1-ASAS operation are a factor 458 better than those of the TMA-T1 operation. This shows that according to the model of the three non-nominal conditions, the pilots (which are allowed to make tactical decisions themselves), supported by ASAS, have a major contribution to solving conflicts.

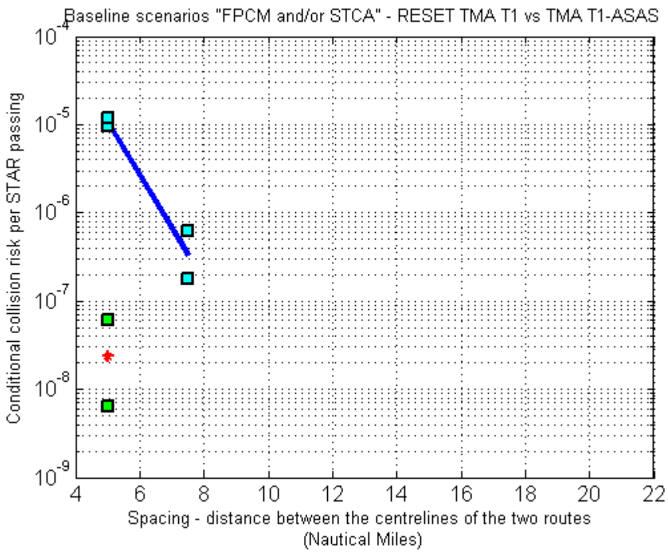

Figure 6. Monte Carlo simulation results for non-nominal encounter condition “FPCM and/or STCA” for TMA-T1 (upper, blue line) and TMA-T1-ASAS (lower, red dot). The small blue and green blocks indicate the upper bound and the lower bound of a 95% confidence interval.

TABLE II. SAFETY OBJECTIVES FOR THE THREE NON-NOMINAL ENCOUNTER CONDITIONS IN TMA-T1 [1] AND TMA-T1-ASAS [14].

Non-nominal encounter condition	**TMA-T1** [flight hour]$^{-1}$	**TMA-T1-ASAS** [flight hour]$^{-1}$
“No ATC”	1.1E-7	1.0E-4
“STCA only”	6.0E-6	4.0E-3
“FPCM and/or STCA”	3.4E-5	1.4E-2

V. INTERPRETATION OF SIMULATION RESULTS

A. *Safety Objectives*

Section IV.B explained that for TMA-T1-ASAS, factors of conditional collision risk improvement (relative to TMA-T1) have been measured for the conditions “No ATC”, “STCA only” and “FPCM and/or STCA” These factors straightforwardly reduce the Safety Objectives derived in [1] for the TMA-T1 ConOps; the resulting Safety Objectives for TMA-T1-ASAS are shown in Table II.

This reflects that non-nominal encounter condition “No ATC” in the TMA-T1-ASAS operation is allowed to occur about a factor 971 morFFPe often than in the TMA-T1 operation. The non-nominal encounter condition “STCA only” in the TMA-T1-ASAS operation is allowed to occur about a factor 698 more often than in the TMA-T1 operation. Furthermore the non-nominal encounter condition “FPCM and/or STCA” in the TMA-T1-ASAS operation is allowed to occur about a factor 458 more often than in the TMA-T1 operation.

The Safety Objectives provide valuable feedback to the design team. This allows them to significantly improve their understanding about the effect of allowing the pilots to make tactical decisions themselves in a modified TMA-T1 operation.

B. *Contribution of Air Traffic Controller*

It is important to notice that under TMA-T1-ASAS, the tactical role of the controller comes to help in case of STCA or FPCM. By using the simulation results obtained we quantify what factor in safety is due to these tactical controller roles.

In comparing the results obtained for the three encounter conditions of the TMA-T1-ASAS model in which pilots are allowed to make tactical decisions themselves, one may notice that for a spacing of 5 NM, the result of encounter condition “STCA only” is about a factor 40 better than the result of encounter condition “No ATC”. This shows that according to the model, the controller still has a major contribution to reducing the collision risk, even if the controller only reacts upon an STCA alert.

Moreover when comparing the results of encounter condition “FPCM and/or STCA” and “STCA only”, one may notice that for a spacing of 5 NM, “FPCM and/or STCA” is about a factor 3.6 better than “STCA only”. This shows that according to the model, the Flight Plan Conformance Monitoring has still a significant contribution in reducing collision risk, in addition to STCA.

C. *Sensitivity results*

Finally, a sensitivity analysis was conducted to analyse the sensitivity to risk of changes in values for a selection of key parameters in the Monte Carlo simulation model. The main conclusion that can be drawn from the sensitivity results is that according to the model, the conditional collision risk is highly sensitive to changes in any parameter that influences the time available to resolve a conflict between two aircraft. These parameter values are the average pilot reaction time, the average controller reaction time, the radar separation minimum, the angle of turn and the speed. For example, if the average reaction time of the pilot increases there is less time available to resolve a conflict. If the separation minimum used by ASAS decreases, ASAS will react later, leaving less time for the pilot to resolve a conflict.

Moreover the probability of ADS-B global being occupied is also sensitive. This can be explained by the fact that when ADS-B global is occupied the state information of other aircraft is not received. In that case ASAS could not detect possible conflicts and therefore the pilots are not able to avoid the collision. If the probability of ADS-B global being occupied decreases the pilots are able to resolve more conflicts.

VI. CONCLUDING REMARKS

The purpose of this study was to evaluate safety risk of a modified TMA-T1 operation in which pilots are making tactical decisions themselves rather than having to await controller instructions. This operation is called the TMA-T1-ASAS operation. The conflict scenario considered in this operation is the same as in [1], a stream of aircraft that are flying on a Standard Terminal Arrival Route (STAR) and an aircraft flying level in the TMA with a spacing of 5 NM.

In order to evaluate safety risk the Traffic Organization and Perturbation Analyzer (TOPAZ) methodology was used. The quantitative safety risk results were obtained through conducting rare event Monte Carlo simulations of a multi-agent stochastic dynamic risk model of the TMA-T1-ASAS operation. All mathematical details of the model were described in terms of Stochastically and Dynamically Coloured Petri Nets (SDCPN). The SDCPN-based specification was implemented in an object oriented programming language; in this study Delphi XE3 is used.

Comparison of the Monte Carlo results for the TMA-T1 operation with those for the TMA-T1-ASAS operation shows that pilots may have a major contribution in tactical resolution for the three non-nominal encounter conditions considered, i.e. “No ATC”, “STCA only” and “FPCM and/or STCA”.

The paper has also derived Safety Objectives, under the adopted agent-based model and the baseline values for its parameter values, regarding the allowable rate of occurrence of three selected conflict and resolution conditions. Due to allowing pilots to start tactical resolutions, for TMA-T1-ASAS the Safety Objectives are orders of magnitude more relaxed than they are for TMA-T1.

To gain further insight into potential directions in making the TMA-T1-ASAS operation sufficiently safe, also a sensitivity analysis has been performed regarding the effects of variations in parameter values on conditional collision risk. For the situations and conditions considered, the conditional risk appears to be sensitive to parameter values that influence the time available for the pilot or controller to resolve collisions. Moreover in the sensitivity analysis it is shown that the probability of ADS-B global being occupied has effect on the conditional collision risk results.

Follow up of the current research is to conduct a systematic bias and uncertainty analysis. Both for TMA-T1 and for TMA-T1-ASAS, there are differences between the models and the true operation. Various types of such differences exist, such as parameter value assumptions, numerical approximation assumptions, model structure assumptions, assumptions due to non-coverage of identified hazards, etc. Through a systematic bias and uncertainty analysis the effect of these differences on the assessed safety risk values can be analysed [15]. Such sensitivity analysis should also identify into which directions the TMA-T1-ASAS simulation model should be further improved, e.g. to improve the assessment of interactions between pilots and ATC.

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