Assessment of the Future Air Traffic Management System Safety Performance using Network-based Simulation Model

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***Abstract*— This paper presents a Network Based Simulation Model developed with the objective of assessing new safety performance indicators of the future air traffic management system within APACHE project (SESAR Exploratory Research project). The model represents a part of the APACHE System – a platform consisting of simulation, optimization and performance assessment tools. Developed model contains three modules: separation violation detection module, TCAS activation module and risk of conflict assessment module. The model application is illustrated by four scenarios: one referent and three solution scenarios (each involving the application of a certain SESAR solution). Three traffic demand levels were used, each containing planned flight trajectories crossing the FABEC airspace during 24 hours. Simulation results show capabilities to calculate certain safety performance indicators and to provide valuable safety feedback to traffic and airspace planners. Also, benefits of different SESAR solutions have been estimated.**

Keywords- Safety Indicators; Safety Performance; Air Traffic Management; Modeling; Simulation

I. INTRODUCTION

Air transport demand often exceeds available air transport system capacity, resulting in a series of negative consequences (flight delays, flight cancelations, etc.). On the other hand, the expectations of the air traffic management (ATM) community and the whole society are much bigger and primarily related to increase in safety, environmental protection, reduction in delays and ticket prices, etc. In such circumstances, the existing ATM system has to undergo certain changes that will allow it to meet these often-contradictory requirements in the future [1].

In the 1980s, ATM community has recognized this complex problem. A need to create a more efficient, safer and ecologically sustainable system at the global, regional and national levels was defined, which will make the maximum use of numerous possibilities of modern technical and technological achievements. It was recognized then that one of the main pillars of the future ATM system should be an efficient Performance Management System, which should enable managers to assess progress in various fields such as (in the context of air traffic) safety, capacity, accessibility, cost-efficiency, environment etc., with a significantly greater reliability [1).

In 1998, EUROCONTROL founded the "Performance Review Commission" (PRC) with the aim of establishing an independent and transparent performance management system within the European ATM system. The PRC is supported in its work by the "Performance Review Unit" (PRU), which is directly involved in collecting and analyzing performance data in collaboration with airspace users, air navigation service providers, airports, etc. [2]. Since then, every year the PRC issues “Performance Review Reports” (PRR [3]) which provide information on air traffic demand (expressed as a total number of IFR flights) and performance of the European ATM system in the four main Key Performance Areas (KPAs): safety, capacity, environment and cost-efficiency.

The APACHE project proposes a new framework to assess European ATM performance based on simulation, optimization and performance assessment tools that will be able to capture the complex interdependencies between KPAs at different modeling scales (micro, meso and macro). The specific objectives of the Project are [4]:

- to propose new metrics and indicators capable of effectively capturing European ATM performance under either current or future concepts of operation;
- to make an (initial) impact assessment of some SESAR 2020 solutions using the new APACHE Performance Scheme in different KPAs; and
- to analyze the interdependencies between the different KPAs by capturing the Pareto-front of ATM performance, finding the theoretical optimal limits for each KPA and assessing how the promotion of one KPA may actually reduce (and in which proportion) the performance of other KPAs.

The APACHE System is a platform (Figure 1), consisting of different software components and implementing a wide set of Performance Indicators (PIs) across several KPAs. It can be used for two different purposes: on one hand, to synthesize aircraft trajectories and airspace sectorization, in line with the SESAR 2020 scope, simulating different operational contexts and enabling in this way the possibility to perform what-if assessments (”Pre-ops” ATM performance assessment); on the other hand, to provide advanced models and optimization tools that can support the implementation of novel and more accurate PIs, which can be used both for ”Pre-ops” and also for ”Post-ops” (monitoring) purposes [5], [6].

Figure 1 shows the overall concept of the APACHE framework. First, several scenarios to be studied are defined, setting up different options regarding the traffic demand, airspace capacities and eventual restrictions; the SESAR solution(s) to be enabled; and the level of uncertainty to be considered (Figure 1, Scenario Configuration). The APACHE-TAP (trajectory and airspace planner), which could be seen as a small prototype of an ATM simulator (Figure 1, APACHE Framework), has a double functionality in the project [6]: a) to synthesize traffic and airspace scenarios representative enough of current operations; or emulating future operational concepts in line with the SESAR 2020 ConOps, and b) to support the implementation of novel ATM PIs, which require some advanced functionalities (such as optimal fuel trajectories considering real weather conditions, optimal airspace opening schemes, large-scale conflict detection, etc.). Then, the ATM Performance Analyzer (PA) component (Figure 1) implements all the PIs of the APACHE performance framework, including as well some indicators from the current performance scheme for benchmarking purposes [6].

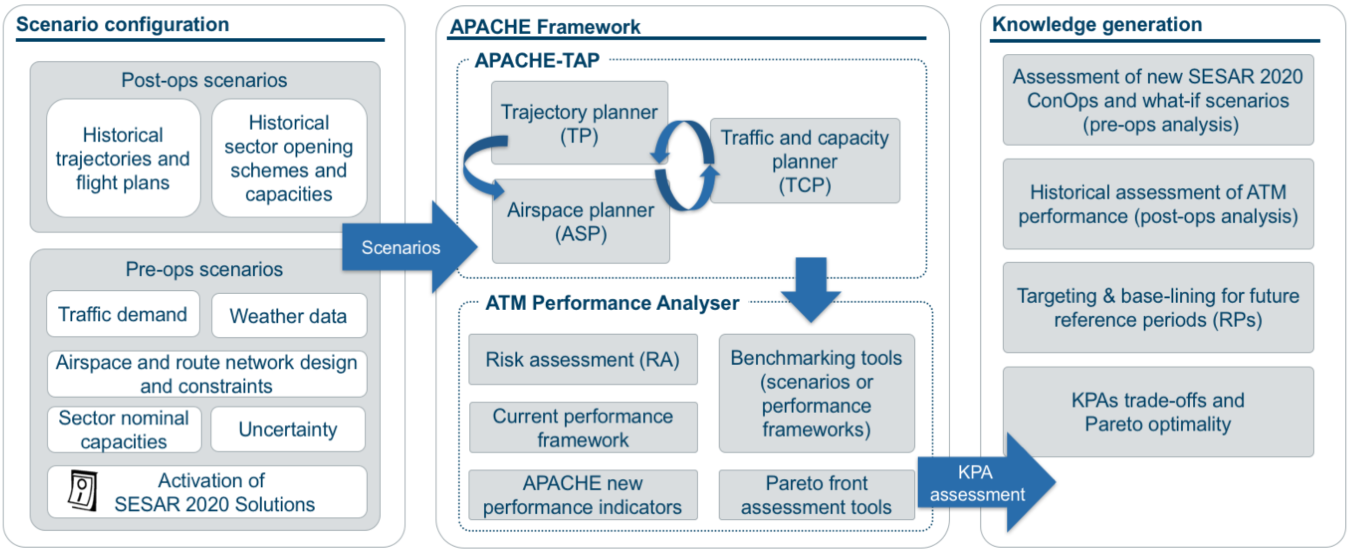

Figure 1. The APACHE framework

In this paper we present a part of this platform – Risk Assessment (RA) component belonging to the ATM Performance Analyzer (Figure 1) and conducting the assessment of Safety Performance Indicators (Safety PI or SPI) of the future ATM system. RA is meant to be used by system planners/designers, Network Manager and PRU in order to assess contributions of different SESAR solutions to safety. Second section presents Safety PIs proposed. The RA modeling approach is described in third section. The results of a numerical example are presented in section four, while fifth section concludes the paper.

II. SAFETY PERFORMANCE INDICATORS

In order to evaluate the success of any system it is necessary to have information on the current situation of the system, or the so-called “performance”. Therefore, performance is a term which can refer to the variables (indicators, characteristics) describing the status of the system in a certain area.

Nowadays performance is usually related to the economic aspect of the success of a system, but more and more attention is given to safety and environmental protection, which are the areas where it is very difficult to reach an agreement on the methods and parameters for performance management.

Parmenter [7] is distinguishing between four types of performance measures:

- Key Result Indicators (KRIs): provide “overall summary of how the organization is performing”,
- Result Indicators (RIs): tell “how teams are combining to produce results”.
- Performance Indicators (PIs): tell “what teams are delivering”.
- Key Performance Indicators (KPIs): tell “how the organization is performing in its critical success factors”.

Performance Indicators (PIs) or Key Performance Indicators (KPIs) in business environment are mostly quantitative information; and according to Parmenter [7] there are seven characteristics of KPIs.

They should be non-financial, timely (measured frequently), CEO focused, simple to understand, “team” based; they should reflect significant impact and encourage appropriate action. Above all, KPIs are current- or future-oriented measures.

A. Background

ATM system plays an important role in ensuring the overall safety of air traffic. Safety is one of the main Key Performance Areas [8]. Following ICAO's Performance Based Approach [9], SESAR identifies in its Master Plan the "need for a single, simplified European ATM System coupled with a performance-based approach that will satisfy all stakeholders' requirements". This need is recognized as the importance of defining metrics for all involved stakeholders [10]). Similar vision is defined in the U.S. NextGEN programme [11].

The problem of measuring safety performance has been a topic for discussion for at least 50 years [12]. According to Roelen and Klompstra [13] the "development and measurement of proper safety performance indicators is not straightforward, so many important issues are still very much open, e.g. which indicators represent the true safety performance?" They also stated that "traditionally, accident rates were used to measure the performance of aviation safety, but when safety increased accidents became rare events and a larger statistical base was required" [13].

Tarrents [14] proposed "incidents as a basis for safety performance indicators." Heinrich developed a theory (so-called injury pyramid, or 1:600 Rule) showing that the number of incidents is significantly greater than the number of accidents [15]. Rockwell [16] identified the following characteristics of a good measure of safety performance: quantifiable, representative to what is to be measured, sensitive to change in environmental or behavioral conditions, provide minimum variability when measuring the same conditions.

According to [10] a long list of previous work exists presenting different performance metrics and indicators of the ATM system (safety performances among them). In order to detect loss of separation and predict dynamics of disturbance propagation Pozzi et al. [17] combine big-data processing systems with operational expertise. Gaydos et al. [18] measure the increase of the number of medium-term conflict resolution advisories produced by trajectory-based descends. Di Gravio et al. [19] build synthetic and user-friendly safety-related indicators applying analytic hierarchy process and combining safety events over time. Further on, they have proposed a statistical model of safety events (accidents, incidents and issues) in order to predict overall safety performance of ATM System [20]. Similarly, Chen and Li [21] proposed a method of safety performance measurement with a series of safety performance indicators.

Ehliar and Wagner [22] developed for LFV (Swedish ANSP) a set of 27 safety performance indicators and recommended 6 as potential KPIs. Panagopoulos et al. [23] have proposed "a conceptual framework that could improve aviation safety performance" and stated that "proper safety PIs or safety metrics should provide an indication of the likelihood of an accident (i.e. defect) and should assist enterprises detect and respond to potential problems and variation from the standard (i.e. non-conformities) before an accident occurs".

B. Safety PIs in APACHE

Safety Performance Indicators (SPIs) are part of the wider APACHE performance framework. Related to the scope of APACHE project, the PRU is currently assessing a range of PIs in the field of safety, e.g. number of accidents and serious incidents, number of reported unauthorised penetrations of airspace, number of reported separation minima infringements, etc., among which two are used as KPIs: total commercial air transport accidents; and the number of accidents with air navigation service contribution [1]. Similar situation is observed in USA [11]. Namely, all PIs and KPIs are based on accident/incident investigation reports (post operation analysis, reactive safety approach) and are aggregated on annual level.

APACHE proposed some new indicators compliant with the Performance Objective One stated in [3]: "Reduction of loss of separation incidents both horizontally and vertically by focusing on system risk, which can be estimated in pre-tactical phase in order to identify hotspots on the network and take measures to increase safety". APACHE proposes SPIs which are measurable in simulations of "Pre-ops" or "Post-ops" operations and could be measured in a real system on a daily or hourly level, but are not dependent on accident/incident reporting (proactive safety approach) [1].

Two categories of SPIs are proposed in APACHE based on their values [1]: absolute and relative ones. Indicators with absolute values are given as counts of specific occurrences, as listed in Table I: Traffic Alert (TA) warnings (SAF-1), Resolution Advisories (RA) issued (SAF-2), Near Mid Air Collisions (NMAC) (SAF-3). Similarly, the number of potential separation violations (SV) could be used to indicate safety (SAF-4).

All of these indicators could also be given as rates of specific occurrences, i.e. counts normalized by the number of flights or total flight hours through the given airspace, showing in such a way demand and complexity level in a given airspace.

Apart from these indicators, and related to SAF-4, it is proposed to measure separation violation severity for aircraft in conflict (SAF-5), in situations when either horizontal, vertical or both separation minima are violated, as well as the duration of conflict situations (SAF-6). Based on these two indicators (different combinations of conflict duration and severity) it is possible to calculate the risk of conflict (SAF-7) in a given airspace (shaded areas in Figure 2).

Each portion of airspace can be characterized by those indicators in order to identify "hotspots" in the airspace (portion of airspace with the highest values of most serious occurrences). Apart from finding the geographically most safety jeopardized location it is also possible to follow the distribution of each absolute indicator during a given period of time in order to identify the moment of time in which the highest values are expected [1].

TAs/RAs, NMACs occur very often. According to [24], in average three TCAS-related events occur in German airspace every day.

TABLE I. NEW SAFETY PIS PROPOSED

Indicators	Unit	Description
SAF-1: Number of Traffic Alerts warnings	# TAs	Count of TAs
SAF-1.1: Traffic Alerts warnings	TAs/flight (hour)	Number of TAs / Number of flights or flight hours
SAF-2: Number of Resolution Advisories issued	# RAs	Count of RAs
SAF-2.1: Resolution Advisories issued	RAs/flight (hour)	Number of RAs / Number of flights or flight hours
SAF-3: Number of Near Mid Air Collisions	# NMACs	Count of NMACs
SAF-3.1: Near Mid Air Collisions	NMACs/flight (hour)	Number of NMACs / Number of flights or flight hours
SAF-4: Number of separation violations	# SVs	Count of separation violations
SAF-4.1: Separation violations	SVs/flight (hour)	Number of separation violations / Number of flights or flight hours
SAF-5: Severity of separation violations	-	[(Separation minima) – (Actual separation)] / (Separation minima) *Remark:* It is computed by simulation of traffic within given airspace.
SAF-6: Duration of separation violations	sec	Time during which separation minima is violated. *Remark:* It is computed by simulation of traffic within given airspace.
SAF-7: Risk of conflicts	-	Compound PI which value depends on SAF-5 and SAF-6

Therefore, count of those occurrences could be a good proxy of what could happen in the airspace. Of course, TAs/RAs, NMACs are based on anticipation of distance at the closest point of approach (CPA) between two aircraft, where this anticipation is time-based.

Apart from these indicators, there are also separation violation situations, i.e. conflicts, determination of which is based on the actual distance between two aircraft and depends on separation minima applied. Duration of separation violation situation is measured as a time period in which actual separation is lower than separation minima, while severity represents a measure of how close the difference between the actual separation and separation minima is to zero (Figure 3). Risk of conflict represents a combination of duration and severity of separation violation [25].

Normalized values of counts show how frequent mentioned occurrences are relative to the number of flights passing through a given airspace or relative to total flight time of all flights passing through the same airspace [1].

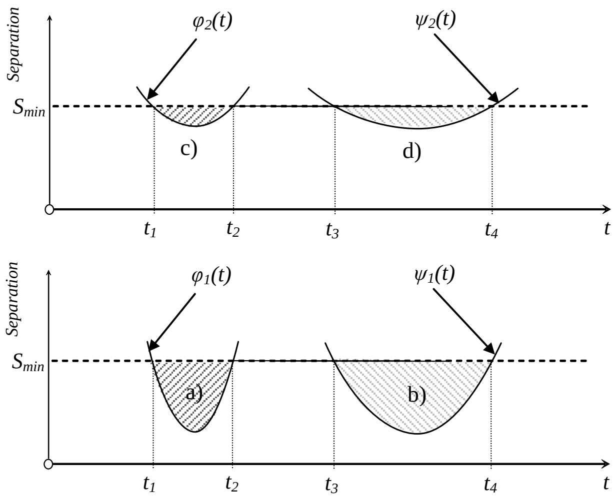

Figure 2. Different combinations of the potential conflict duration and severity resulting in smaller or higher risk: a) short and more severe, b) long and more severe, c) short and less severe and d) long and less severe (φ, ψ - separation functions, S_{min} – separation minima)

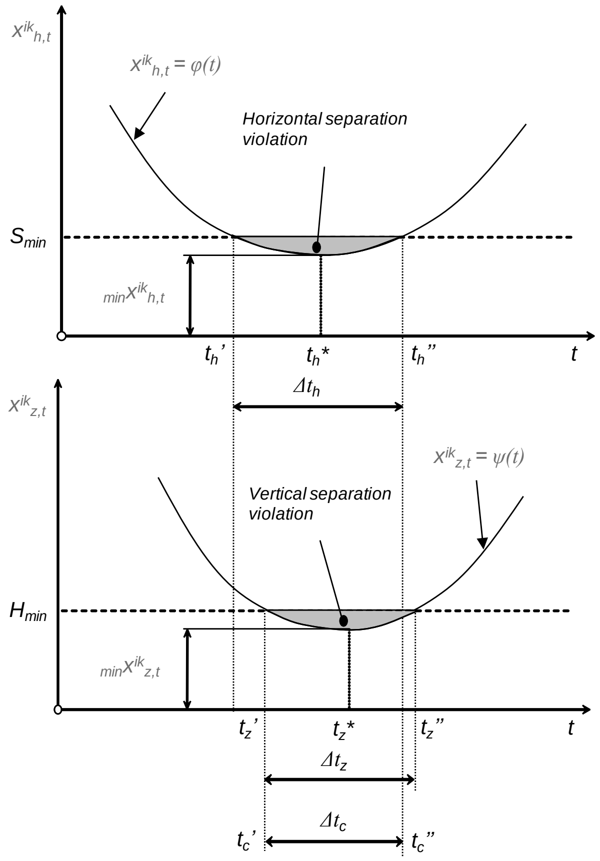

Figure 3. Representation of potential conflict duration and severity (S_{min} and H_{min} are horizontal and vertical separation minima respectively, Δt_c is conflict duration, $_{min}X^{ik}_{h,t}$ and $_{min}X^{ik}_{z,t}$ are minimal separations in horizontal and vertical plane respectively)

III. MODELLING APPROACH

In order to assess safety of future ATM system within APACHE framework a Risk Assessment (RA) component is developed. RA is intended for "Pre-ops" simulation of air traffic consisting of optimal flights trajectories (4D trajectories given as output of Trajectory Planner (TP) and Traffic and Capacity Planner component (TCP), Figure 1) crossing an optimal airspace configuration (output from Airspace Planner (ASP) component, Figure 1) with aim to assess safety performances and to provide outputs in form of SPIs as well as safety feedback (which could be considered by TCP and ASP components in case that proposed flight trajectories and sector boundaries are not suitable from the safety point of view) [5].

Similarly to some previous research efforts [26], [27], [28] an RA is developed as network based simulation model consisting of three modules (Figure 4) [29]:

- Separation violation detection module (dynamic conflict detection model based on known flight intensions [25],
- TCAS activation module (stochastically and dynamically coloured Petri Net model [30]) and
- Risk of conflict assessment module [25].

The RA component is based on the assumption that conflict between a pair of aircraft exists when either horizontal and/or vertical separation minima are violated. The Separation violation detection module compares the actual separation of aircraft (both in horizontal and vertical plane) with a given separation minima in order to detect a potential conflict. Once conflicts are detected, this module counts them (SAF-4) and then for each conflict it calculates its severity (SAF-5) and duration (SAF-6) under given circumstances (Figure 4) [5].

If the situation worsens then TCAS activation module is activated (Figure 4). It counts Traffic Alerts (SAF-1) and Resolution Advisories (SAF-2) warnings and, based on them, possible number of NMACs (SAF-3) [5].

The risk of conflict assessment module is based on calculation of "elementary risk" which is defined as the area between the surface limited by the minimum separation line and the function representing the change of aircraft separation (shaded area in Figures 2 and 3). The risk of conflict (SAF-7) is then defined as the ratio between the "elementary risk" and the observed period of time. Apart from the risk between specific aircraft pairs, an assessment of the total risk in a given sector is also performed (Figure 4) [5], [30].

The conflict risk between aircraft pairs and the total conflict risk depends on airspace geometry, traffic demand, aircraft velocities, spatial and temporal distribution of air traffic within the airspace, as well as the applied separation minima. As such, the risk values taken as a safety feedback could suggest changes in flight trajectories and/or changes in sector boundaries, i.e. sector geometry.

Based on the RA architecture (Figure 4), a specific computer program (written in Python language) has been developed, containing the following phases [29]:

- PHASE 1: Reduction of traffic input (triage), eliminating flights that cannot come into conflict (divergent trajectories, different FLs, different entry times, etc.);
- PHASE 2: Determination of flights in conflict and calculation of risk and other safety indicators, based on [25];
- PHASE 3: Checking whether TCAS will be activated and how (TA only, or TA with RA, or RA revision, etc), and counting of TCAS events. It is based on [30].

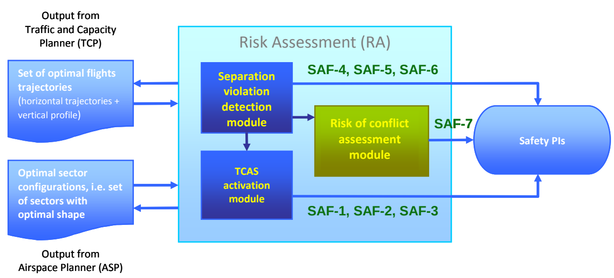

Figure 4. Risk Assessment component architecture

IV. NUMERICAL EXAMPLE

Aiming at showing the capabilities of the APACHE System, this section presents the comparison of safety PIs for several validation scenarios (Table II), involving the full workflow of the APACHE System. The APACHE-TAP was used in these scenarios to synthesize trajectories and airspace configurations for the "pre-ops" assessment purposes.

The objective of the pre-ops assessment is to compare the results of the different Solution scenarios with the Reference scenario, assessing the safety performance and applicability of the APACHE Framework safety PIs to evaluate various SESAR Solutions. The Reference scenario includes the traffic and environment, but without the SESAR Solutions that are the subject of validation. This scenario has been named as Scenario S1 (Table II). On the other side, the Solution scenarios are the scenarios including traffic and environment together with SESAR operational improvements that are the subject of validation [31]. These scenarios are named S2, S3 and S5 (Table II, note: scenarios S4, S6 and S7 also exist, but are not used in this research). Overall, three Solution scenarios have been used for the "pre-ops" assessment of the simulations results. Each of the scenarios implies the use of a specific SESAR Solution [31]:

- Scenario S2: Enhanced free-route area (FRA) scenario, assuming completely full free-route operations between origin and destination airports (i.e. assuming that the whole European airspace is a single FRA).
- Scenario S3: Continuous Cruise Climbs (CCC) scenario is pushing vertical flight efficiency to the theoretical limits by removing any constraint in the vertical trajectory (i.e. removing any level-off in climb/descent phases, but also removing current flight level allocation and orientation schemes).
- Scenario S5: Advanced demand and capacity balance (ADCB) scenario, implementing a prototype for future collaborative decision making strategies to deal with imbalances between demand and capacity (it is allowing the Network Manager to solve the DCB problem by using delays, re-routings and level capping in a single global optimization problem).

Within these scenarios, several Case Studies have been proposed, each considering different level of air traffic demand, as gathered from Eurocontrol's DDR2 service [31]:

- SX01: Medium demand (24h of operations on July 28th 2016 - with 15000+ flights).
- SX03: High demand (24h of operations on July 21st 2023 generated by Eurocontrol's STATFOR tool configured to give the maximum amount of demand for that representative day - with 19000+ flights).
- SX05: Low demand (24h of operations on February 20th 2017 - with 13000+ flights).

The geographical scope of all the simulation results is limited to FABEC (i.e. only trajectories crossing FABEC and only ATC sectors within FABEC have been considered). A full day of operations (24h, en-route scheduled traffic above FL195 only, helicopters and piston engine aircraft discarded) has been considered for each Case Study.

In order to determine safety PIs a deterministic simulation was performed using RA (although stochastic simulation was possible) with the following parameters: time increment – 10 sec; horizontal separation – 5 NM; vertical separation – 1000 ft. APACHE Framework in pre-ops is not simulating the tactical layer, i.e. the air traffic controllers behaviour in separating traffic.

Figures 5 and 6 show results for all the pre-ops Scenarios and Case Studies. As seen in the figures, the increase in traffic demand (mostly) leads to an increase of safety PI values in all observed scenarios, which seems to be logical. However, it is notable that this increase is not linear.

Comparing S2 with S1, it can be seen that all PIs are significantly reduced (more than half of the value in S1).

TABLE II. SCENARIOS CONSIDERED

Scenario	TP	ASP	TCP
S1	Current route network and current FL allocation/ orientation scheme	Static sectorisation	Computer assisted slot allocation (CASA)
S2	**Full free route operations and current FL allocation/ orientation scheme**	Static sectorisation	Computer assisted slot allocation (CASA)
S3	Current route network and **Continuous Cruise Climbs**	Static sectorisation	Computer assisted slot allocation (CASA)
S5	Current route network and current FL allocation/ orientation scheme	Static sectorisation	**Advanced demand and capacity balancing (ADCB)**

Without consideration of other factors and the tactical ATC actions, it could be concluded that the application of enhanced FRA concept has a positive influence on safety. This can be explained by a smaller amount of conflict situations, which are widely distributed in the airspace, and by the fact that conflict points are less concentrated on the crossing points observed in the case of S1 when flights are following existing airways.

A similar trend can be observed in the case of comparison between S3 and S1. Values of all PIs are significantly reduced (even more then in the case of S2), leading to conclusion that the introduction of continuous cruise climbs has a positive influence on safety too. Results can be explained by the fact that flights do not enter into conflict situations in vertical plane due to constant climb, i.e. they are "avoiding" each other more often than in the case of S1.

Finally, in the case of S5 vs. S1 comparison, it is evident that the values of all PIs in S5 are equal or higher compared to S1 (difference increases with the increase of traffic demand). These results lead to the conclusion that the application of ADCB, although positive from the air traffic flow and capacity management point of view, does not show a positive effect on safety. Therefore, it is possible that the resolution of certain congestion problems could lead to the occurrence of some safety-related issues.

At the end, we can conclude that S2 and S3 have shown positive effects on Safety, while S5 caused deterioration of the safety PIs. However, higher values of SPIs do not necessary mean less safe operations. By comparing SPIs values, one can estimate the influence of different SESAR solutions on ATM safety performance.

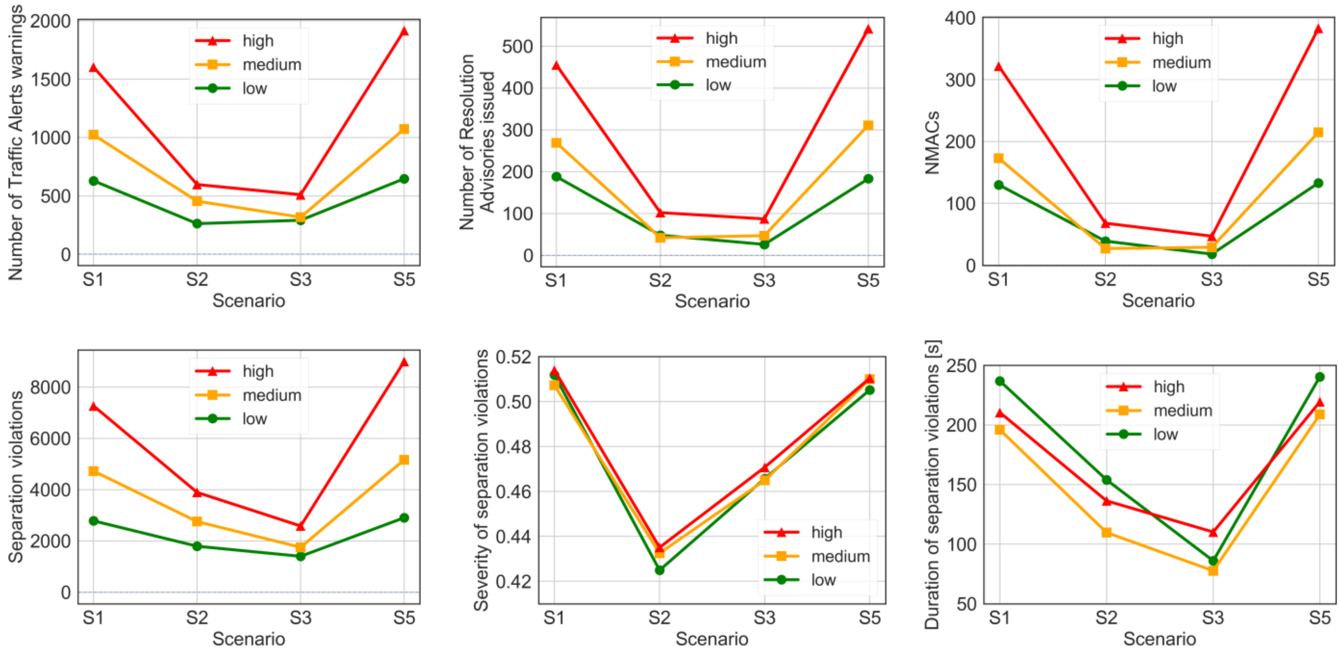

Figure 5. Pre-ops results for the safety PIs: SAF-1 to SAF-6

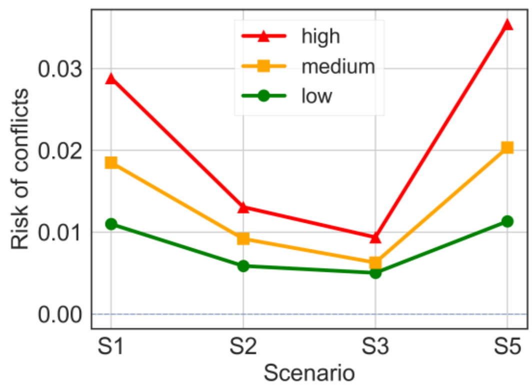

Figure 6. Pre-ops results for SAF-7

V. CONCLUSION

A new framework to assess the future European Air Traffic Management system performance based on simulation, optimization and performance assessment tools at different modeling scales (micro, meso and macro) is proposed within the APACHE project. In this paper, a Risk Assessment component is presented, i.e. network based simulation model developed with the aim of assessing Safety Performance Indicators of the future ATM system. RA component consists of three modules: separation violation detection module, TCAS activation module and risk of conflict assessment module. Modeling approach followed during development of this module consists of three phases: reduction of traffic input, determination of flights in conflict and calculation of risks and

TCAS activation checking. A dedicated computer programme written in Python language has been developed.

The model is applied on four scenarios: one referent and three solution scenarios. Three traffic demand levels were used, each containing planned flight trajectories crossing the FABEC airspace during 24 hours. Results demonstrate the capabilities to calculate certain safety performance indicators and to provide valuable safety feedback to traffic and airspace planners. Also, benefits of different SESAR solutions have been estimated.

Further research will go in two directions. One will cover the validation of RA component against real-life safety data in order to build the thrust in its outputs, while the other direction will aim at simulating different scenarios in order to uncover interdependencies between different key performance areas, safety being one of them.

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