Potential Safety Occurrences as Indicators of Air Traffic Management Safety Performances

A Network Based Simulation Model

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Abstract—This paper presents a Network Based Simulation Model developed with objective to assess new safety performance indicators of future air traffic management system within APACHE project (a SESAR Exploratory Research project). This model presents a part of 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. Developed model was tested on 24 hour planned flights crossing the French airspace covering three test cases. It shows capabilities to calculate certain safety performance indicators and to provide valuable safety feedback to traffic and airspace planners.

Keywords- Safety Indicators, Safety Performances, Air Traffic Management, Modelling, 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 him 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 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 modelling 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 along different KPAs; and
- to analyse 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 the platform (Figure 1), build up with different software components implementing a wide set of Performance Indicators (PIs) across several KPAs. It can be used with 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 demand of traffic, 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 from 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) module (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].

In this paper a part of this platform – Risk Assessment (RA) belonging to the ATM Performance Analyzer (Figure 1) related to assessment of Safety PIs of future ATM system is presented and illustrated. 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. Section II presents proposed Safety PIs. In Section III an RA modelling approach is presented. Section IV contains results of numerical examples, while Section V concludes paper.

II. SAFETY PERFORMANCE INDICATORS

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].

All PIs and KPIs are based on accident/incident investigation reports (post operation analysis, reactive safety approach) and are aggregated on annual level. 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, listed in Table I: Traffic Alert (TA) warnings (SAF-1), Resolution Advisories (RA) issued (SAF-2), Near Mid Air Collisions (NMAC) (SAF-3).

Similarly, number of potential separation violations (SV) could be used to indicate safety (SAF-4).

All these indicators could be also given as rates of specific occurrences, i.e. as 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 duration of conflict situations (SAF-6). Based on these two indicators (different combinations of conflict duration and severity) it is possible to calculate a risk of conflicts (SAF-7) in a given airspace (shaded areas in Figure 2).

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAF-1: Number of Traffic Alerts warnings</td>
<td># TAs</td>
<td>Count of TAs</td>
</tr>
<tr>
<td>SAF-1.1: Traffic Alerts warnings</td>
<td>TAs/flight (hour)</td>
<td>Number of TAs / Number of flights or flight hours</td>
</tr>
<tr>
<td>SAF-2: Number of Resolution Advisories issued</td>
<td># RAs</td>
<td>Count of RAs</td>
</tr>
<tr>
<td>SAF-2.1: Resolution Advisories issued</td>
<td>RAs/flight (hour)</td>
<td>Number of RAs / Number of flights or flight hours</td>
</tr>
<tr>
<td>SAF-3: Number of Near Mid Air Collisions</td>
<td># NMACs</td>
<td>Count of NMACs</td>
</tr>
<tr>
<td>SAF-3.1: Near Mid Air Collisions</td>
<td>NMACs/flight (hour)</td>
<td>Number of NMACs / Number of flights or flight hours</td>
</tr>
<tr>
<td>SAF-4: Number of separation violations</td>
<td># SVs</td>
<td>Count of separation violations</td>
</tr>
<tr>
<td>SAF-4.1: Separation violations</td>
<td>SVs/flight (hour)</td>
<td>Number of separation violations / Number of flights or flight hours</td>
</tr>
<tr>
<td>SAF-5: Severity of separation violations</td>
<td>-</td>
<td>[(Separation minima) – (Actual separation)] / (Separation minima)</td>
</tr>
<tr>
<td>SAF-6: Duration of separation violations</td>
<td>sec</td>
<td>Time during which separation minima is violated.</td>
</tr>
<tr>
<td>SAF-7: Risk of conflicts</td>
<td>-</td>
<td>Compound PI which value depends on SAF-5 and SAF-6</td>
</tr>
</tbody>
</table>

TABLE I. NEW SAFETY PIS PROPOSED [1]

Each portion of airspace can be characterized by those indicators in order to find out a “hot spots” 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 distribution of each absolute indicator during given period of time in order to find out the moment of time in which the highest values are expected [1].

TAs/RAs, NMACs occur very often. According to [7] in average three TCAS-related events occur in German airspace every day. So, 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 closest point of approach (CPA) between two aircraft when this anticipation is time-based.

Apart from those indicators, there is also separation violation situations, i.e. conflicts, determination of which is based on 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 presents a measure of how close the difference between actual separation and separation minima is to zero (Figure 3). Risk of conflict represents a combination of duration and severity of separation violation [8].

Normalized values of counts present 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].
III. MODELLING APPROACH

In order to assess safety of future ATM system within APACHE framework a Risk Assessment (RA) component is proposed.

RA is intended for "Pre-ops" simulation of air traffic consisting of optimal flights trajectories (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].

Generally, RA is a network based simulation model consisting of three modules (Figure 4) [9]:

- Separation violation detection module (dynamic conflict detection model based on known flight intentions [8]),
- TCAS activation module (stochastically and dynamically coloured Petri Net model [10]) and
- Risk of conflict assessment module [8].

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

If the situation worsens then TCAS activation module is started. 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 on 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 [5, 8].

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 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, see pseudo code) is developed containing following phases [9]:

- PHASE 1: Reduction of traffic input (triage) eliminating flights that can not come into conflict (divergent trajectories, different FLs, different entry times, etc.);
- PHASE 2: Determination of flights in conflicts and calculation of risks and other safety indicators, based on [8];
- 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 [10].

![Diagram](image-url)
Figure 4. RA module architecture [5]

Pseudo Code

// Step 1: Reading input data (Flight ID, Date, Time, FL, Latitude, Longitude)
READ: Flight ID, Date, Time, Flight Level (FL), Latitude, Longitude

// Step 2: Filtering data to match criteria (excluding data that do not belong to observed interval and FL<190)
IF FL>190 and IntervalStart<DateTime<IntervalEnd THEN
    WRITE filtered_input_file: Flight ID, Date, Time, FL, Latitude, Longitude

// Step 3: Sorting data by DateTime, FL, Latitude, Longitude
SORT filtered_input_file: DateTime, FL, Latitude, Longitude

// Step 4: Pairing (with optimization) flights that meet criteria (dFL<10 and distance<5NM)
FOR i=1 TO (length(filtered_input_file)-1)
    FOR j=i+1 TO length(filtered_input_file)
        IF DateTime(i)=DateTime(j)
            IF FL(j)-FL(i)<1000ft
                IF Lat(j)-Lat(i)<5NM or Lon(j)-Lon(i)<5NM
                    CALCULATE distance(Flight(i), Flight(j))
                    IF distance(Flight(i), Flight(j))<5NM
                        WRITE pairData (Flight(i), Flight(j), DateTime, FL(i), FL(j), dFL, Lat(i), Lon(j), Lat(i), Lon(j), distance)
                    ELSE break
                ELSE break
            ELSE break
    ELSE break

// Step 5: Calculating duration of separation violation (for each pair subtract separation violation beginning time from separation violation ending time)
READ pairData
SORT pairData: Flight(i), Flight(j)
CALCULATE separation_violation_duration

// Step 6: Finding Closest Point of Approach (CPA) for each pair of flights
DETERMINE minimum_distance for each pairData
CALCULATE severity for each pairData

// Step 7: Deleting all other occurrences of Separation Violation than CPA
DELETE all_occurrences but minimum_distance for pairData

// Step 8: Calculating risk for all pairs observed
CALCULATE risk for each pairData

// Step 9: Running TCAS module
DETERMINE type of alert (TA or RA) and NMAC occurrence for each pairData

// Step 10: Forming output file
WRITE output_file: Flight(i), Flight(j), DateTime, FL(i), FL(j), dFL, Lat(i), Lon(j), Lat(i), Lon(j), minimum_distance, separation_violation_duration, risk
IV. NUMERICAL EXAMPLE

Three integration and verification test cases (Table II), involving the full workflow of the APACHE System have been performed. In those cases the APACHE-TAP was used to synthesize trajectories and airspace configurations for “pre-ops” assessment purposes.

The traffic demand and AIRAC cycle are taken from February 20th 2017, covering 24h and considering only those flights crossing the French airspace. Demand data has been obtained from Eurocontrol’s DDR2, including the aircraft type, departure time and origin/destination airports. Airspace data, consisting of elementary/collapsed sectors and airspace configurations definition, as well as, capacities of the sectors were also taken from the AIRAC data from the DDR2 supplemented by French national data repository.

DDR2 files contained an initial demand of 7375 flights. Nevertheless, since the APACHE Project focuses in the en-route phase, all flights with a requested flight level below FL195 were discarded from the simulations. Moreover, helicopters and piston engine aircraft were also discarded, leading to a total of 6895 scheduled flights analyzed in this test case [6]. For each flight a detailed 4D trajectory was available following both structured and free routing (Figure 5).

<table>
<thead>
<tr>
<th>Case</th>
<th>TP</th>
<th>ASP</th>
<th>TCP</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Current route network and current FL allocation/orientation scheme</td>
<td>Static sectorisation</td>
<td>Computer assisted slot allocation (CASA)</td>
</tr>
<tr>
<td>B</td>
<td>Current route network and current FL allocation/orientation scheme</td>
<td>Static sectorisation</td>
<td>Advanced demand and capacity balancing (ADCB)</td>
</tr>
<tr>
<td>C</td>
<td>Full free route and current FL allocation/orientation scheme</td>
<td>Static sectorisation</td>
<td>Advanced demand and capacity balancing (ADCB)</td>
</tr>
</tbody>
</table>

An RA deterministic simulation was performed with the following parameters: time increment – 10 sec; horizontal separation – 5 NM; vertical separation – 1000 ft. Resulting SPIs for all three test cases are given in Table III.

Case A is representing current system and is serving as a benchmark. It is evident (Table III) that implementation of ADCB (Case B) is decreasing risk of conflict in the airspace (SAF-7) as well as SAF-2, 3, 4 and 6 values. However, SAF-1 and SAF-5 values are higher leading to a conclusion that ADCB measures in certain situations can cause both increasing number of TAs (420 vs. 361, Table III) as well as more severe conflicts (0.560 vs. 0.523, Table III). In Case C which combines implementation of ADCB with Free routing, values for all SPI are lower then in Case A and Case B (e.g. reductions of SAF-3, 6 and 7 are very significant, Table III).

So, Case C provides more contribution to safety then Case B. But, higher values of SPIs do not mean less safe operations. Comparing SPIs values one can estimate influence of different SESAR solutions on ATM safety performances.

Figure 6 presents a distribution of SAF-1 to SAF-4 values during the day. Tendency that Case C produces lower values is evident among presented SPIs. Figure 7 summarises SAF-5 and SAF-6 values. Median, first and third quartile as well as min and max values are given for both SPIs. In case of SAF-5 (conflict severity) it is evident that smallest median value is in Case C (median: Case A – 0.69; Case B – 0.54; Case C – 0.39). Similarly is in case of SAF-6 (conflict duration) were the...
smallest median value is in Case C but also smallest dispersion of values (median: Case A – 70; Case B – 55; Case C – 50).

Figure 8 presents locations of all conflicts during the day in case of structured vs. free routing. Free routing is producing very distributed conflicts which could be harder for air traffic controllers to handle, despite the fact that is causing decrease of SPI values (positive effect). Those results should be understood as an illustration only, not as arguments that free routing is “safer” than the other cases.

Figure 6. Daily distribution of a) SAF 1, b) SAF 2, c) SAF 3, d) SAF 4 indicators

Figure 7. Comparison of SAF-5 (left) and SAF-6 (right) values (median, first and third quartile, max i min values),
V. CONCLUSION

Within the APACHE project a new framework to assess future European Air Traffic Management system performance based on simulation, optimization and performance assessment tools at different modelling scales (micro, meso and macro) is proposed. In this paper a Risk Assessment component is presented, a network based simulation model developed with aim to assess Safety Performance Indicators of future ATM system.

Risk Assessment component is consisting of three modules: separation violation detection module, TCAS activation module and risk of conflict assessment module. Modelling approach followed during development of this module is consisting of three phases: reduction of traffic input, determination of flights in conflicts and calculation of risks and TCAS activation checking. A dedicated computer programme written in Python language is developed. A model is tested on 24 hour planned flights crossing French airspace covering three test cases. Results show capabilities to calculate certain safety performance indicators and to provide valuable safety feedback to traffic and airspace planners.

Further research will go in two directions. One will cover validation of RA against real-life safety data in order to build the trust in its outputs, while other direction will aim to simulate different scenarios in order to determine benefits of certain SESAR solutions as well as to uncover interdependencies between different key performance areas, safety being one of them.

ACKNOWLEDGMENT

This paper is part of a project that has received funding from the SESAR Joint Undertaking under grant agreement No 699338 (APACHE - Assessment of Performance in current ATM operations and of new Concepts of operations for its Holistic Enhancement, http://apache-sesar.barcelonatech-upc.eu/en) under European Union’s Horizon 2020 research and innovation programme. The opinions expressed herein reflect the author’s view only. Under no circumstances shall the SESAR Joint Undertaking be responsible for any use that may be made of the information contained herein.

The authors would like to thank all colleagues from APACHE consortium: Technical University of Catalonia (UPC), Ecole Nationale de l’Aviation Civile (ENAC), Advanced Logistics Group (ALG) and University of Belgrade - Faculty of Transport and Traffic Engineering (UB-FTTE) for their contributions in the definition and implementation of new PIs as well as in development of APACHE Framework.

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