Potential Safety Occurrences as Indicators of Air Traffic Management Safety Performances
A Network Based Simulation Model

Fedja Netjasov, Dusan Crnogorac
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)

This project has received funding from the SESAR Joint Undertaking under the European Union’s Horizon 2020 research and innovation programme under grant agreement No 699238
Outline

• Introduction
• Safety Performance Indicators
• Modelling Approach
• Numerical example
• Results
• Conclusion and Further research
Introduction (1)

• 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 Key Performance Areas (KPAs) at different modelling scales (micro, meso and macro).

• The APACHE System is the platform, build up with different software components (existing and newly developed) implementing a wide set of performance indicators across several KPAs.
Introduction (2)
• The specific objectives of the APACHE:
  • 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.
Introduction (4)

• The APACHE System is the platform, 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:
  • 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);
  • 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.
Introduction (5)

• The ATM **Performance Analyzer (PA)** module implements all the PIs of the APACHE performance framework, including as well some indicators from the current performance scheme for benchmarking purposes.

• In this paper a part of this platform – **Risk Assessment (RA)** belonging to the ATM PA 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.
Outline

• Introduction
• **Safety Performance Indicators**
• Modelling Approach
• Numerical example
• Results
• Conclusion and Further research
Safety Performance Indicators (1)

• **Safety Performance Indicators (PIs)** 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, but two safety KPIs are used: *total commercial air transport accidents*; and the *number of accidents with air navigation service contribution*.

• APACHE proposes performance indicators which are measurable in simulation and could be measurable in a real system as well, but are not dependent on accident/incident reporting.
Safety Performance Indicators (2)

- Two categories of PIs are proposed in APACHE based on their values: **absolute** and **relative** one.

- Indicators with absolute values are given as counts of specific occurrences (listed in table) by ascending severity: Traffic Alert (TA) warnings (**SAF-1**), Resolution Advisories (RA) issued (**SAF-2**), Near Mid Air Collisions – NMACs (**SAF-3**).

- 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.

- Similarly, number (or rate) of separation violations could be used to indicate safety (**SAF-4**).
Safety Performance Indicators (3)

- TAs/RAs, NMACs occur very often. 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.
Safety Performance Indicators (4)

- Apart from these indicators, and related to SAF-4, it is proposed to measure severity of separation violation 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 it is possible to calculate a risk of conflicts in a given airspace (SAF-7).
Safety Performance Indicators (5)

- **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.

- **Risk of conflict** represents a combination of duration and severity of separation violation.
Safety Performance Indicators (6)

• Normalized values (relative PIs) 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.
## Safety Performance Indicators (7)

<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 Advisors issued</td>
<td># RAs</td>
<td>Count of RAs</td>
</tr>
<tr>
<td>SAF-2.1: Resolution Advisors 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>[{(\text{Separation minima}) - (\text{Actual separation})} / (\text{Separation minima})]</td>
</tr>
<tr>
<td>Remark: It is computed by simulation of traffic within given airspace.</td>
<td></td>
<td></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>Remark: It is computed by simulation of traffic within given airspace.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAF-7: Risk of conflicts</td>
<td>-</td>
<td>Compound PI which depends on SAF-5 and SAF-6</td>
</tr>
</tbody>
</table>
Safety Performance Indicators (8)

• 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 (time series) in order to find out the moment of time in which the highest values are expected.
Outline

• Introduction
• Safety Performance Indicators
• Modelling Approach
• Numerical example
• Results
• Conclusion and Further research
Modelling Approach (1)

• **The Risk Assessment (RA)** component 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)*) crossing an optimal airspace configuration (*output from Airspace Planner (ASP) component*) 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.
Modelling Approach (2)

• Generally, RA is a network based simulation model consisting of three modules:
  
  ▪ **Separation violation detection module** (dynamic conflict detection model based on known flight intentions),
  
  ▪ **TCAS activation module** (stochastically and dynamically coloured Petri Net model) and
  
  ▪ **Risk of conflict assessment module**.

• 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.
Modelling Approach (3)

Output from Traffic and Capacity Planner (TCP)

Set of optimal flights trajectories
(horizontal trajectories + vertical profile)

Optimal sector configurations, i.e. set of sectors with optimal shape

Output from Airspace Planner (ASP)

Risk Assessment (RA)

Separation violation detection module

TCAS activation module

Risk of conflict/accident assessment module

SAF-1, SAF-2, SAF-3

SAF-4, SAF-5, SAF-6

SAF-7

Safety PIs
Modelling Approach (4)

• 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.

• 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).
Modelling Approach (5)

- The **Risk of conflict assessment module** is based on calculation of "**elementary risk**" which is defined as the area between the minimum separation line and the function representing the change of aircraft separation.
Modelling Approach (6)

- The risk of conflict is then defined as the ratio between the "elementary risk" and the observed period of time.
- Based on risk between specific aircraft pairs, an assessment of the total risk (SAF-7) in a given sector is performed.

\[
R = \frac{\sum_{i=1}^{n} R_i}{T}
\]
Modelling Approach (7)

- 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.
Modelling Approach (8)

• Based on the RA architecture a specific computer program (written in Python language) is developed containing following phases:
  
  ▪ **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 conflicts and calculation of risks and other safety indicators;
  
  ▪ **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.
Modelling Approach (9)

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[i]-FL[j]<1000ft
                IF Lat[i]-Lat[j]<5NM or Lon[i]-Lon[j]<5NM
                    CALCULATE distance(Flight[i], Flight[j])
                    IF distance(Flight[i], Flight[j])<5NM
                        WRITE pairData (Flight[i], Flight[j], DateTime[i], FL[i], FL[j], dFL, Lat[i], Lon[i], Lat[j], 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[i], FL[i], FL[j], dFL, Lat[i], Lon[i], Lat[j], Lon[j], minimum_distance, separation_violation_duration, risk
Outline

- Introduction
- Safety Performance Indicators
- Modelling Approach
- Numerical example
- Results
- Conclusion and Further research
Numerical example (1)

- Three integration and verification test cases, 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.

<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>
Numerical example (2)

- The traffic demand and AIRAC cycle are taken from February 20th 2017, covering 24h and considering only those flights crossing the French airspace.
Numerical example (3)

- 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.
Numerical example (4)

- 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.

- A total of 6895 scheduled flights analyzed in this test case.
- For each flight a detailed 4D trajectory was available following both structured and free routing.
- An RA deterministic simulation was performed with the following parameters: time increment – 10 sec; horizontal separation – 5 NM; vertical separation – 1000 ft.
Numerical example (5)

Synthesised trajectories crossing French airspace: left - Current route structure and free route areas, right - Full free-route from origin to destination airports
Outline

• Introduction
• Safety Performance Indicators
• Modelling Approach
• Numerical example
• Results
• Conclusion and Further research
Results (1)

- Resulting SPIs for all three test cases are given in Table:

<table>
<thead>
<tr>
<th></th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAF-1</td>
<td>361</td>
<td>420</td>
<td>197</td>
</tr>
<tr>
<td>SAF-2</td>
<td>146</td>
<td>93</td>
<td>3</td>
</tr>
<tr>
<td>SAF-3</td>
<td>107</td>
<td>73</td>
<td>1</td>
</tr>
<tr>
<td>SAF-4</td>
<td>1816</td>
<td>1400</td>
<td>829</td>
</tr>
<tr>
<td>SAF-5</td>
<td>0.523 ± 0.297</td>
<td>0.560 ± 0.302</td>
<td>0.470 ± 0.271</td>
</tr>
<tr>
<td>SAF-6</td>
<td>352.22 ± 754.45</td>
<td>303.14 ± 785.90</td>
<td>112.36 ± 299.21</td>
</tr>
<tr>
<td>SAF-7</td>
<td>7.3 · 10^{-3}</td>
<td>6.0 · 10^{-3}</td>
<td>3.0 · 10^{-3}</td>
</tr>
</tbody>
</table>
Results (2)

• **Case A** is representing current system and is serving as a benchmark.

• It is evident (from Table) 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) as well as more severe conflicts (0.560 vs. 0.523, Table).
Results (3)

• In **Case C** which combines implementation of ADCB with Free routing, values for all SPI are lower than in Case A and Case B (e.g. reductions of SAF-3, 6 and 7 are very significant, Table).

• So, Case C provides more contribution to safety than 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.
Results (4)

- Tendency that Case C produces lower values is evident among SAF-1 to SAF-4 values.

Combined effect of full free routing and ADCB is most beneficial from safety point of view.
Results (5)

- Median, first and third quartile as well as min and max values are given for SAF-5 and SAF-6:
  - 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).
Results (6)

<table>
<thead>
<tr>
<th>SAF-7</th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.00E-03</td>
<td>7.30E-03</td>
<td>6.00E-03</td>
<td>1.00E-02</td>
</tr>
</tbody>
</table>

Safety benefit of ADCB
Safety benefit of FRA
Results (7)

- Locations of all conflicts during the day in case of structured vs. free routing are also presented.

- 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.
Results (8)

Whole day distribution of separation violations – SAF 4 (CPA below 5NM) in case of Structured Routing (left, Case B) and Free Routing (right, Case C)

SAF-4 = 1400

SAF-4 = 829
Outline

- Introduction
- Safety Performance Indicators
- Modelling Approach
- Numerical example
- Results
- Conclusion and Further research
Conclusion and Further research (1)

• 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, a network based simulation model developed with aim to assess Safety Performance Indicators of future ATM system is presented.
Conclusion and Further research (2)

• 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.

• Results also shows safety benefits of certain SESAR solutions.
Conclusion and Further research (3)

• Further research will go in two directions:

  • one will cover **validation of RA** against real-life safety data in order to build the thrust 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.
Conclusion and Further research (4)

• Some preliminary results obtained in meantime:
Conclusion and Further research (4)

- Some preliminary results obtained in meantime:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>TP mode</th>
<th>ASP mode</th>
<th>TCP mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Current route network</td>
<td>FL allocation/orientation</td>
<td>Static sectorisation</td>
</tr>
<tr>
<td>S2</td>
<td>Enhanced FRA scenario</td>
<td>FL allocation/orientation</td>
<td>Static sectorisation</td>
</tr>
<tr>
<td>S3</td>
<td>Current route network</td>
<td>Continuous Cruise Climbs</td>
<td>Static sectorisation</td>
</tr>
<tr>
<td>S4</td>
<td>Current route network</td>
<td>FL allocation/orientation</td>
<td>Dynamic sectorisation</td>
</tr>
<tr>
<td>S5</td>
<td>Current route network</td>
<td>FL allocation/orientation</td>
<td>Static sectorisation</td>
</tr>
<tr>
<td>S6</td>
<td>Enhanced FRA scenario</td>
<td>FL allocation/orientation</td>
<td>Dynamic sectorisation</td>
</tr>
<tr>
<td>S7*</td>
<td>Enhanced FRA scenario</td>
<td>Continuous Cruise Climbs</td>
<td>Dynamic sectorisation</td>
</tr>
</tbody>
</table>
APACHE project

Thank you for your attention!