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

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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)
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 (3)
Introduction (4)

- 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.

- A part of this platform – **Risk Assessment (RA)** 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.
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Safety Performance Indicators (1)

• **Safety Performance Indicators (PIs)** are part of the wider APACHE performance framework.

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

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

- TAs/RAs, NMACs occur very often. So, count of those occurrences could be a good **proxy** of what could happen in the airspace.

- 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**).
Safety Performance Indicators (3)

• Apart from those indicators, there is also separation violation situations (SAF-4), i.e. conflicts, determination of which is based on actual distance between two aircraft and depends on separation minima applied.

• **Duration** of separation violation (SAF-5) situation is measured as a time period in which actual separation is lower than separation minima, while **Severity** (SAF-6) presents a measure of how close the difference between actual separation and separation minima is to zero.

• **Risk of conflict** (SAF-7) represents a combination of duration and severity of separation violation.
Safety Performance Indicators (4)

Horizontal separation violation

Vertical separation violation

\[ \phi_2(t) \quad \psi_2(t) \]

\[ \phi_1(t) \quad \psi_1(t) \]

\[ S_{\text{min}} \]

\[ t_1 \quad t_2 \quad t_3 \quad t_4 \]

\[ H_{\text{min}} \]

\[ x_{h,t}^k = \phi(t) \]

\[ x_{z,t}^k = \psi(t) \]

\[ \Delta t_h \]

\[ \Delta t_z \]

\[ \Delta t_c \]
Safety Performance Indicators (5)

- 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 (6)

<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><strong>SAF-1.1: Traffic Alerts warnings</strong></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><strong>SAF-2.1: Resolution Advisors issued</strong></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><strong>SAF-3.1: Near Mid Air Collisions</strong></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><strong>SAF-4.1: Separation violations</strong></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>[\frac{[(\text{Separation minima}) - (\text{Actual separation})]}{\text{(Separation minima)}}]</td>
</tr>
<tr>
<td><strong>Remark:</strong> 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><strong>Remark:</strong> 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>
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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 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)

- 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 (4)

• 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.

• 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.

\[
R = \frac{\sum_{i=1}^{n} R_i^*}{T}
\]

\[\text{Separation} \quad S_{\text{min}} \quad \varphi(t) \quad \text{t} \quad t_1 \quad t_2 \quad T\]
Modelling Approach (5)

- 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

Risk Assessment (RA)

- Separation violation detection module
- TCAS activation module

Output from Traffic and Capacity Planner (TCP)

- SAF-1, SAF-2, SAF-3
- SAF-4, SAF-5, SAF-6
- SAF-7

Safety PIs
Modelling Approach (6)

• 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.
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Numerical example (1)

• 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 without the SESAR Solutions that are the subject of the validation. This scenario has been named as Scenario S1.
  • The Solution scenarios are the scenarios including traffic and environment together with SESAR operational improvements that are the subject of the validation. These scenarios are named S2, S3 and S5.
Numerical example (2)

• **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).
Numerical example (3)

• Within those scenarios, several Case Studies have been proposed, each considering different level of air traffic demand, as gathered from Eurocontrol’s DDR2 service:
  
  • **Low demand** (24h of operations on February 20th 2017 with 13000+ flights).
  
  • **Medium demand** (24h of operations on July 28th 2016 with 15000+ flights).
  
  • **High demand** (24h of operations on July 21st 2023 with 19000+ flights, generated by Eurocontrol’s STATFOR tool configured to give the maximum amount of demand for that representative day).
Numerical example (4)

- The geographical scope of all the simulation results is limited to FABEC.
- En-route scheduled traffic above FL195 only, with helicopters and piston engine aircraft discarded has been considered for each Case Study.
Numerical example (5)

- Inputs were 4D flight trajectories presented as a series of points between origin and destination airport, with known latitude and longitude, flight level and time on each point.
  - Also, information about ground speed, course, flight status (climb, cruise, descent) and rate of climb or descent between two successive points were included.

- FABEC airspace is modelled as a set of connected boundary points with known latitude and longitude.
Numerical example (6)

• A deterministic simulation was performed using RA with the following parameters: \text{time increment} – 10 sec; \text{horizontal separation} – 5 NM; \text{vertical separation} – 1000 ft.

• APACHE Framework in pre-ops \textit{does not simulate the tactical layer}, i.e. the air traffic controllers behavior in separating traffic.

• \textit{The numerical experiments have been run on a HP Compaq Elite 8300 PC, 64-bit Intel Core i5-3470 CPU @ 3.20 GHz computer with 8 GB of RAM memory.}

• \textit{Duration of computer runs ranges between 1h 45 min for low traffic demand and up to 2h 15 min for high traffic demand scenarios.}
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Results (1)

Comparing S2 with S1, it can be seen that all PIs are significantly reduced (more than half of the value in S1). Without consideration of other factors and the tactical ATC actions, it could be concluded that the application of enhanced FRA concept (S2) has a positive influence on safety.

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 (S3) also has a positive influence on safety.

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 (S5), although positive from the air traffic flow and capacity management point of view, does not show a positive effect on safety.
Results (2)

• Comparing different diagrams, it becomes evident that only a small amount of separation violations triggers TA warnings (in S1 it is roughly 1/4 to 1/6 cases, depending on traffic demand, in S2: 1/6, in S3 and S5: 1/4 to 1/5).

• Similarly, not all TAs trigger RAs (in S1: 1/3 to 1/4, S2: 1/6, S3: 1/5 to 1/10 and in S5 1/3). Finally, not all RA after resolution lead to possible NMACs (in S1: 2/3 to 3/4, S2: 3/4 to 4/5, S3 1/2, S5 2/3).

• Severity of conflicts in all scenarios is roughly the same, but its duration notably changes (in S2 and S3 it is shorter compared to S1), leading to final conclusion that the resulting conflict risk also notably fluctuates.
Results (3)

![Graph showing risk of conflicts across different scenarios]

- **Legend**:
  - High
  - Medium
  - Low

- **Axes**:
  - Y-axis: Risk of conflicts
  - X-axis: Scenario (S1, S2, S3, S5)

- **Observations**:
  - Scenario S1 has the highest risk for high level.
  - Scenario S5 has the highest risk for low level.
  - Scenario S3 has the lowest risk across all levels.
Results (4)

• Additionally, from figures it can be seen that S3 provides slightly better SPIs then S2, so one can argue that their combination could provide even better results.

• At the end, we can conclude that S2 and S3 have shown positive effects on Safety (according to their sole effect), while S5 caused deterioration of the safety PIs relative to S1.

• However, higher values of SPIs do not necessarily mean less safe operations.

• By comparing SPI values one can estimate the influence of different SESAR solutions on ATM safety performance.
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Conclusion and Further research (1)

• RA model brings new functionalities into safety performance assessment of the current and future ATM system.

  • **Firstly**, it allows **pre-ops** assessment (proactive and predictive functionality) of SPIs based on simulation, enabling evaluation of new concepts before their implementation and deployment using planned flight trajectories as inputs.

  • **Secondly**, it brings the possibility of **post-ops** assessment (retroactive functionality) based on new set of SPIs using flown trajectories as inputs.
Conclusion and Further research (2)

• New SPIs are proven to be useful for evaluation of concepts and their scenarios because they are closer to the real operations and are not dependant on incidents/accidents investigation reports.

• The question of SPIs importance remains open. Namely, in this research an equal importance of all SPIs is assumed, but one can argue that some of them are more important than the others.
Conclusion and Further research (3)

• SPIs can be used for safety characterization of certain airspaces (smaller units, e.g. sectors) which is not demonstrated in this research (one big airspace is considered), but is seen as one of the further research steps.

• Further research will cover the validation of RA component against real-life safety data in order to build the thrust in its outputs.
APACHE project

Thank you for your attention!

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### Back-up

<table>
<thead>
<tr>
<th>Scenario</th>
<th>TP</th>
<th>ASP</th>
<th>TCP</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</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>S2</td>
<td>Full free route operations and current FL allocation/orientation scheme</td>
<td>Static sectorisation</td>
<td>Computer assisted slot allocation (CASA)</td>
</tr>
<tr>
<td>S3</td>
<td>Current route network and Continuous Cruise Climbs</td>
<td>Static sectorisation</td>
<td>Computer assisted slot allocation (CASA)</td>
</tr>
<tr>
<td>S5</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>
</tbody>
</table>