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Sensitivity Analysis in Surveillance Performance Monitoring for ATM

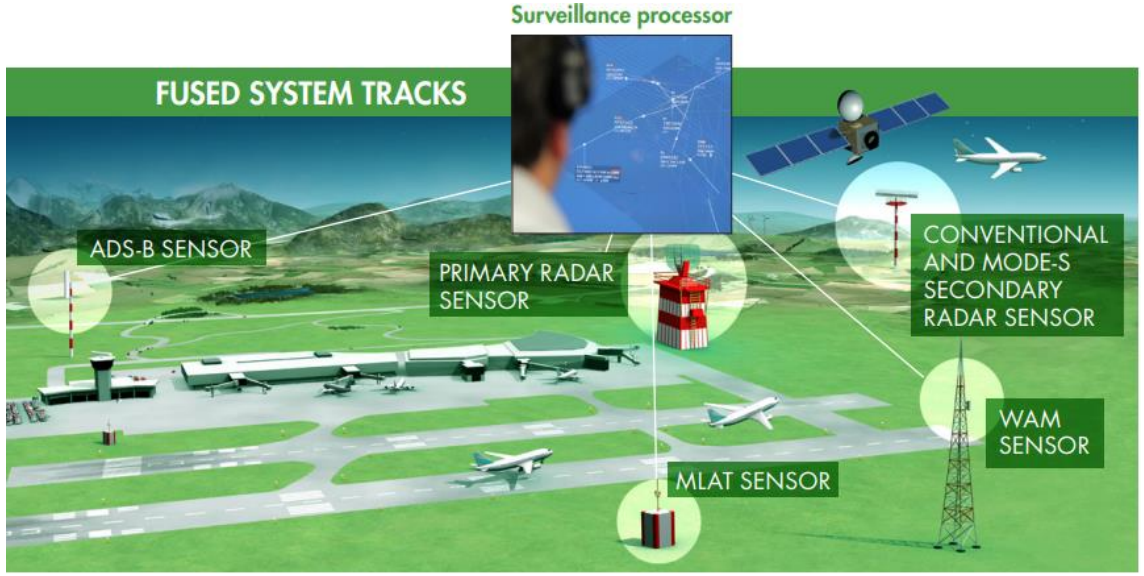
Nicolas Honoré
Clément Bénard
Christophe Labreuche

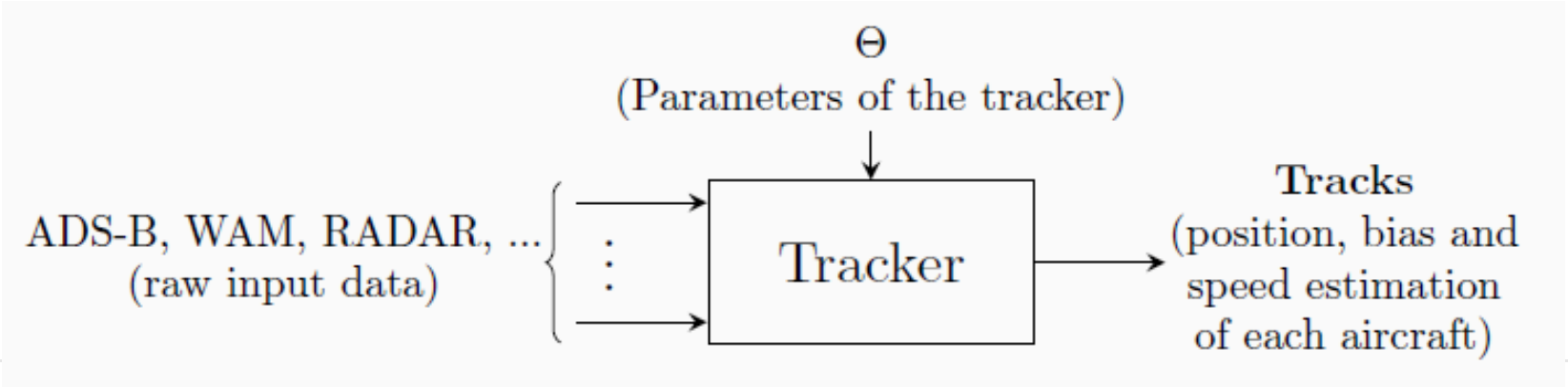
www.thalesgroup.com

I. ATM Context

Product perspective

> Multi Sensor Tracking System (MSTS)





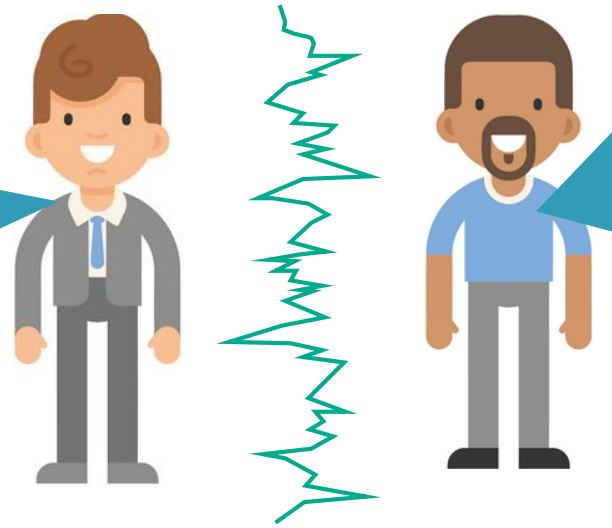
Modern *Air Traffic Control* (ATC)

Air Controller (AC)

- Visual check on tracking quality

When a problem is raised by AC

Report



Technical Supervisor

- don't really know how the technical issues impact AC's mission
- don't know what to do when ACs complain but no technical issue

Expert a posteriori analysis

- Separation model
- ESASSP Eurocontrol STANDARD for accuracy and integrity

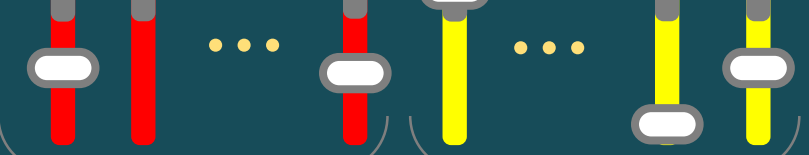
Operational Context: Supervision of Topsky Tracking System

Air Controller
- ensures aircraft separation

Technical Supervisor
- ensures equipment proper functioning

online | offline

Expert a posteriori analysis
- Separation model from Eurocontrol



Idea: Online Simplified Expert Analysis

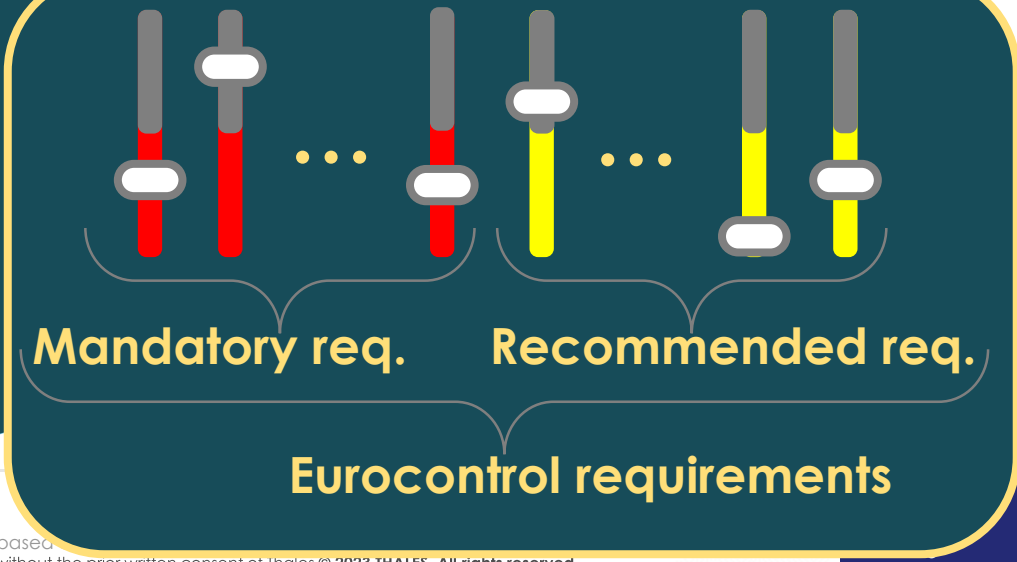
Overall Quality of Service (QoS)

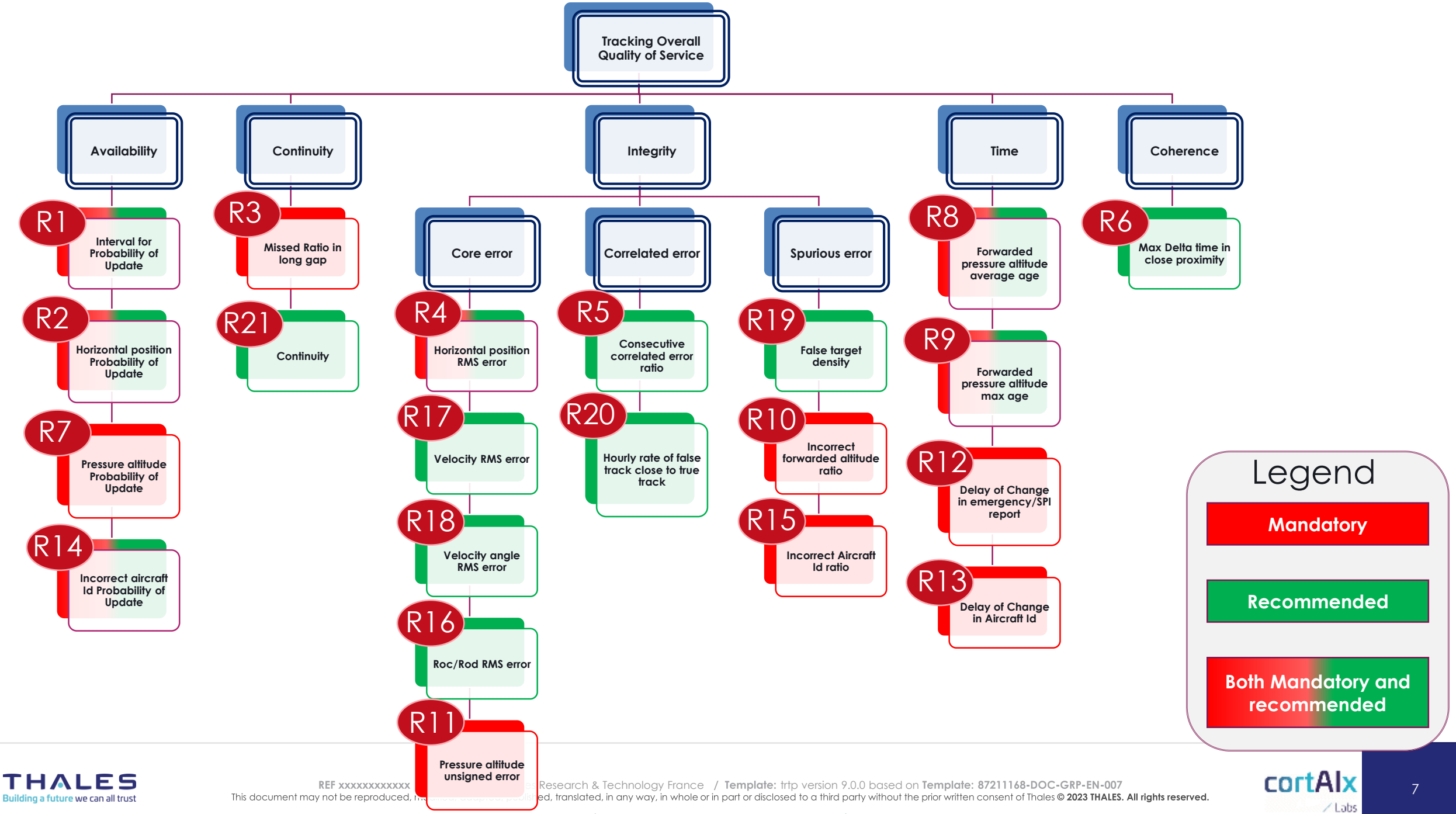
online

offline

Expert a posteriori analysis

- Separation model from Eurocontrol

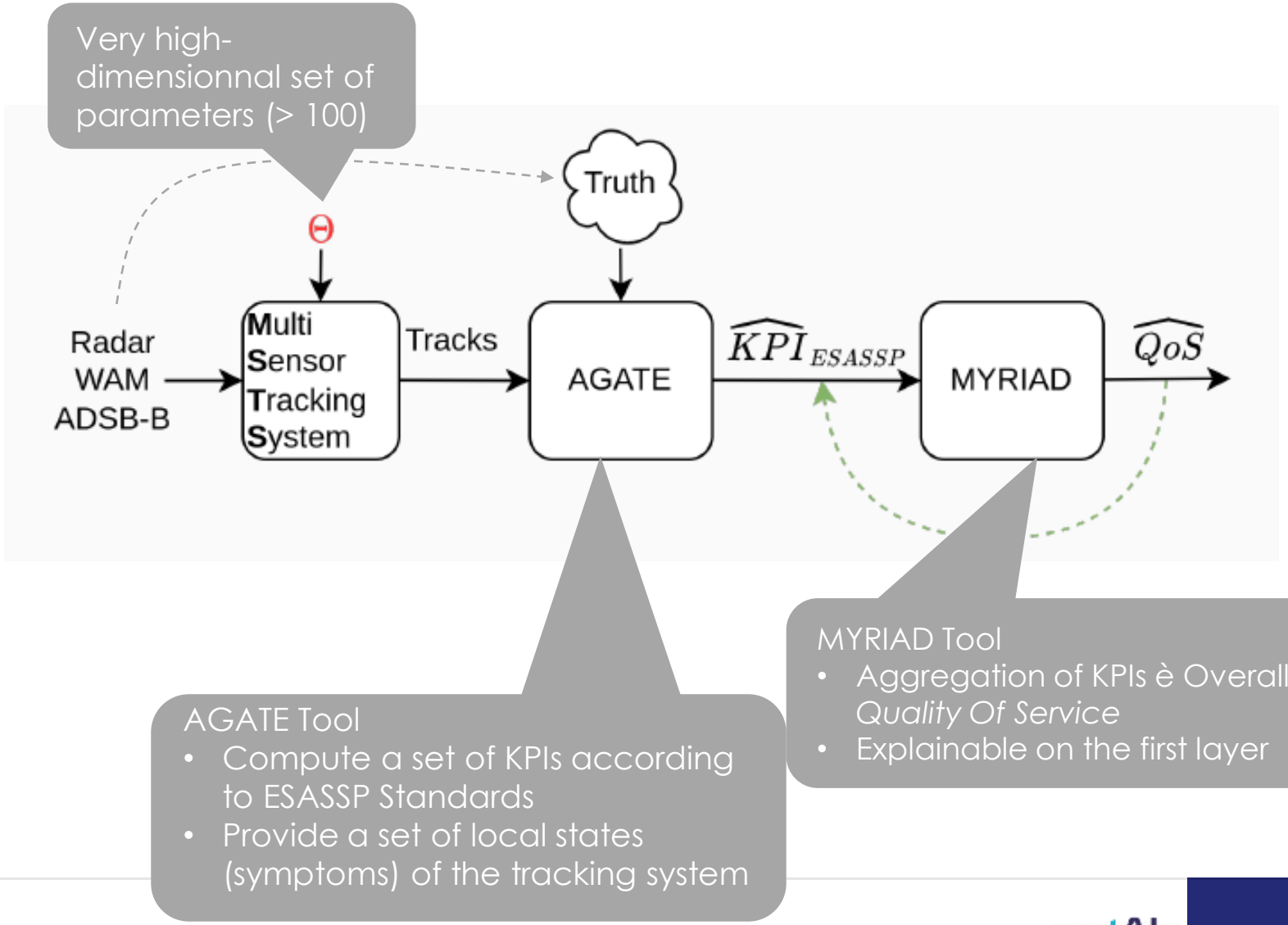




Use case perspective: the tuning problem

> Solution: *tuning actions*

- Change MSTS parameters
  - Noise assumptions
  - Tolerance threshold
  - Trigger threshold
  - Many more …
- Tuning these parameters is a black art magic.

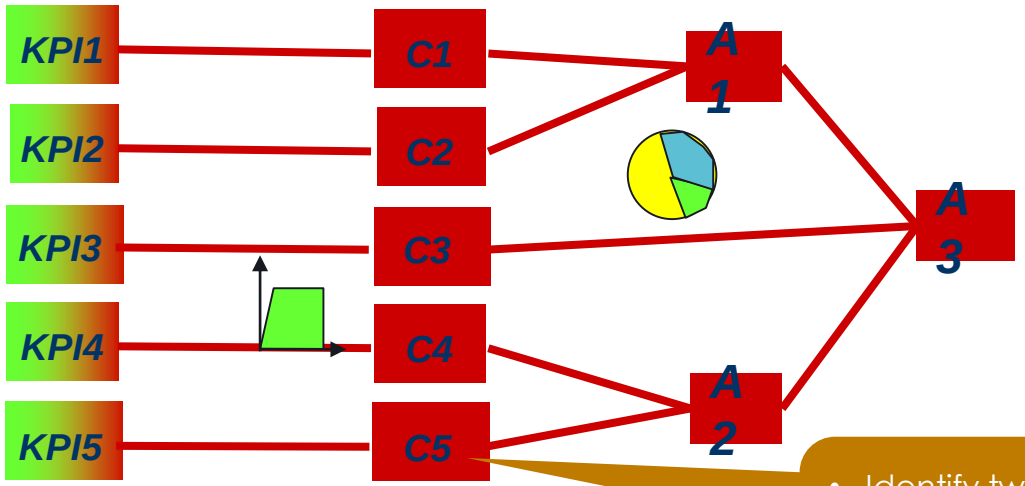


II. Multicriteria Decision Model

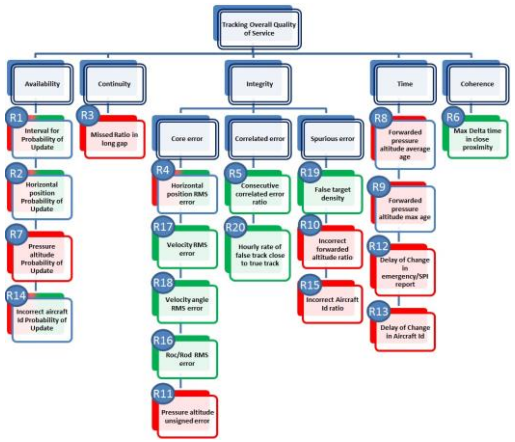
Multi-Criteria Decision Making for the QoS

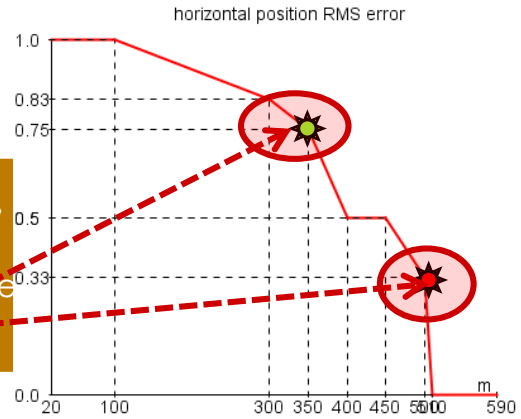
> Decomposable model:

$$u(x) = F\left(u_1(x_1), \ldots, u_n(x_n)\right)$$



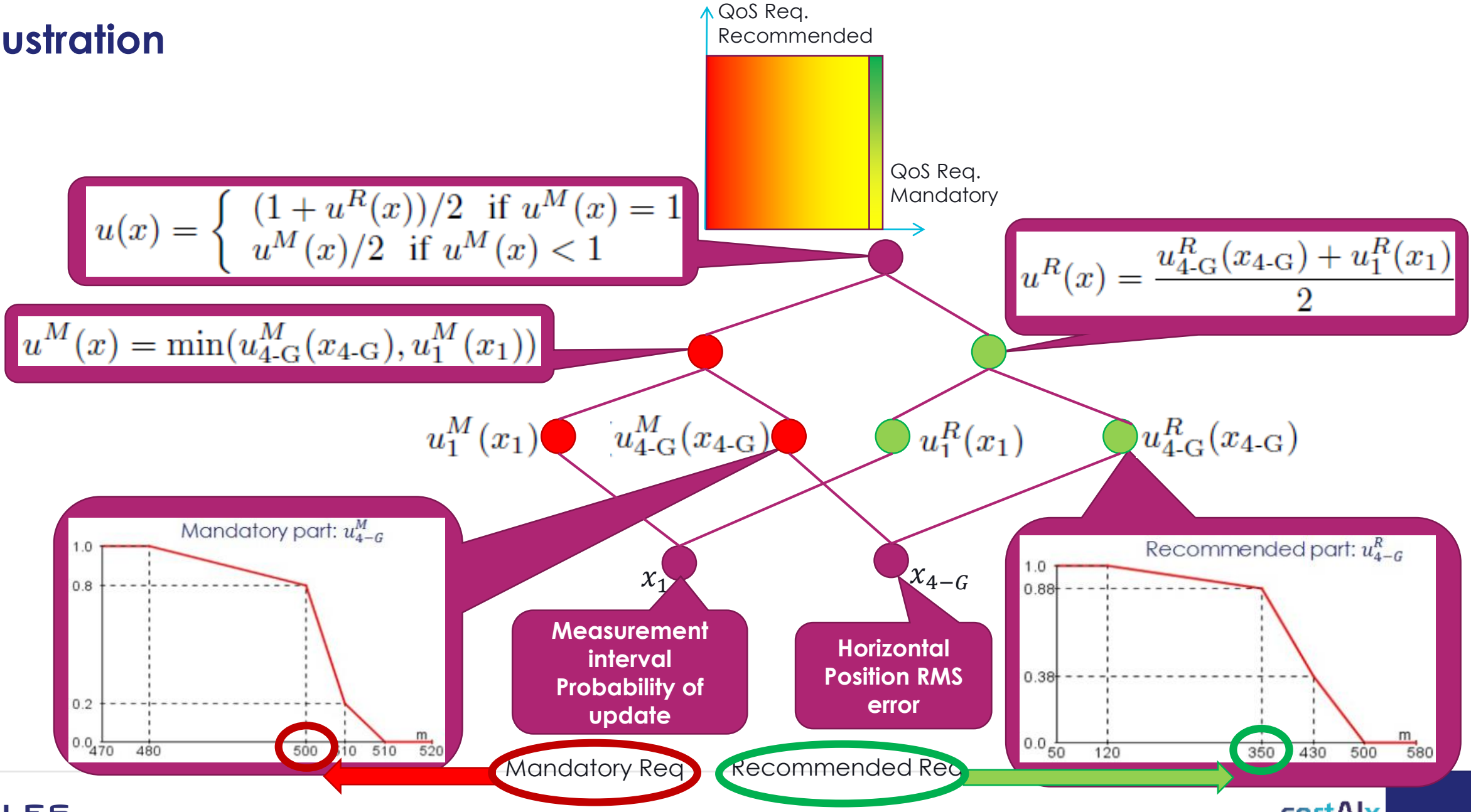
QoS model





- Identify two « reference levels » on the metric
  - Recommended Requirement
  - Mandatory Requirement

Illustration



III. Sensitivity Analysis

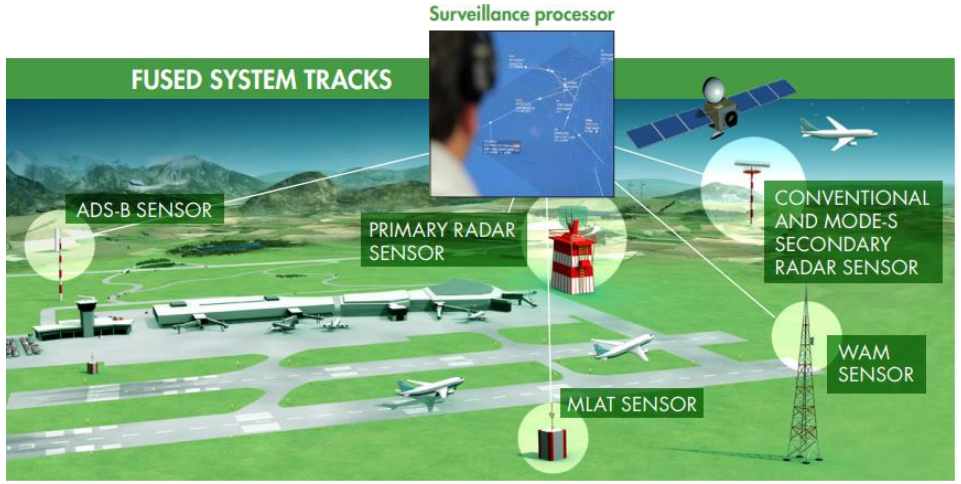
Objective

> MCDA model can be analyzed as a multivariate black-box model

$$u(x) = F\left(u_1(x_1), \ldots, u_n(x_n)\right)$$

> Sensitivity analysis (SA) of the MCDA model can identify metrics involved in a QoS degradation

> SA is performed with a data sample collected by Thales systems



Data

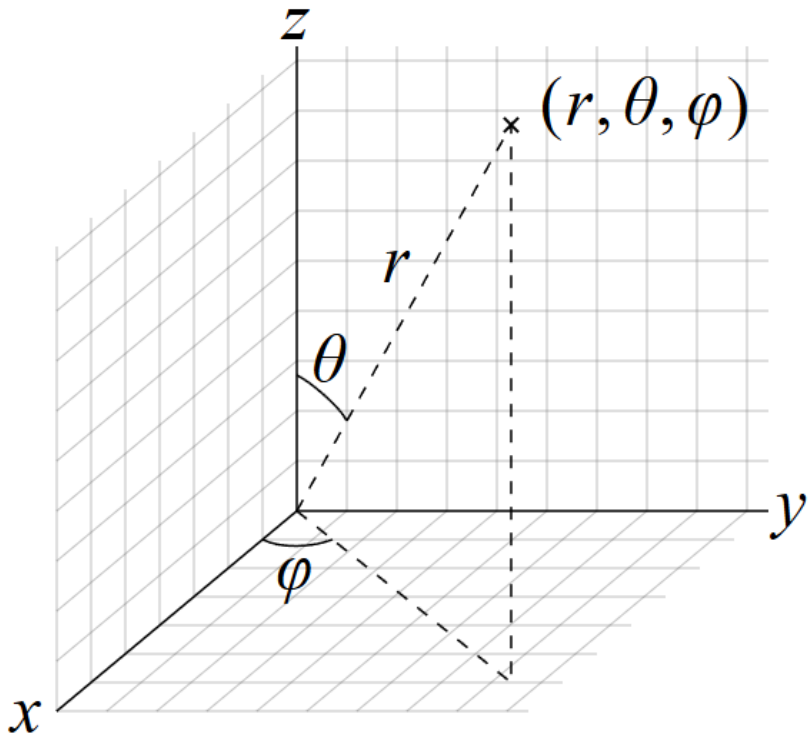
> Data sample collected by Thales systems

> 3 days of recordings in February 2025 over a large airspace area

> QoS is computed every 30 minutes (106 QoS values)

> Simulated degraded QoS: noise is manually introduced over 5 hours

- Gaussian noise is introduced on the range and azimuth values of the polar coordinates.
- Range: noise standard deviation is 30 meters for the first 30 minutes, and is increased by 20 meters for each data batch, to finally reach 210 meters.
- Azimuth: noise standard deviation is constant at 5 milliradian.



Data

> Illustration of the obtained Mandatory QoS

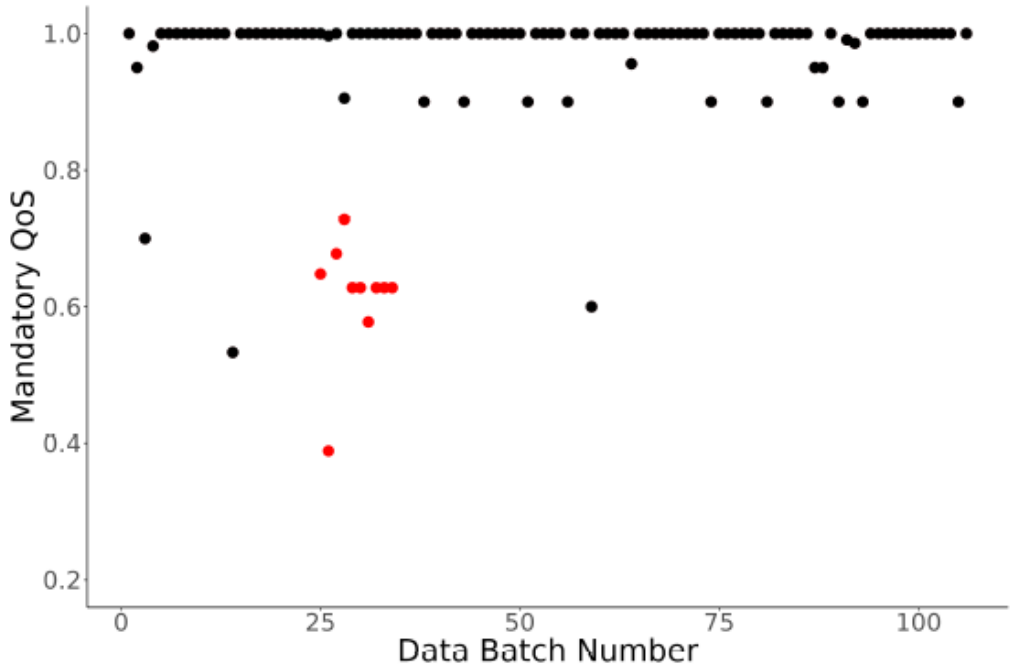


Fig. 4. Evolution of the mandatory QoS over the three days of recorded data. The QoS of the original data is displayed in black, and the QoS with the introduced noise on the positions measured by the radar systems is in red.

Methodology

> Perform global (GSA) and local (LSA) sensitivity analysis for the Mandatory QoS model

> Assumptions

- In nominal settings, Mandatory QoS is expected to be close to 1, with a variability close to 0
- Time dependence is neglected

> Data

- Collected operational data with the introduced noise

> Sensitivity indices

- Shapley effects (GSA) & SHAP (LSA)

> Algorithms

- SHAFF based on random forests (GSA) & TreeSHAP based on xgboost (LSA)

Definitions of Shapley Values

> Global Sensitivity Analysis (GSA)

- Inputs $\mathbf{X} = (X^{(1)}, \ldots, X^{(m)}) \in \mathcal{X}$ (m=26 metrics)
- Value function $v(U) = \frac{\mathbb{V}[\mathbb{E}[u(\mathbf{X})|\mathbf{X}^{(U)}]]}{\mathbb{V}[u(\mathbf{X})]}$
- Shapley values $\mathrm{Sh}_j = \sum_{U \subset M \setminus \{j\}} w(U) \frac{\mathbb{V}[\mathbb{E}[u(\mathbf{X})|\mathbf{X}^{(U\cup\{j\})}]] - \mathbb{V}[\mathbb{E}[u(\mathbf{X})|\mathbf{X}^{(U)}]]}{\mathbb{V}[u(\mathbf{X})]}$ with $w(U) = \frac{1}{m}\binom{m-1}{|U|}^{-1}$

> Local Sensitivity Analysis (LSA)

- Value function $v_{\mathbf{x}}(U) = \mathbb{E}[u(\mathbf{X})|\mathbf{X}^{(U)} = \mathbf{x}^{(U)}]$
- Shapley values $\mathrm{SHAP}_j(\mathbf{x}) = \sum_{U \subset M \setminus \{j\}} w(U)\big(\mathbb{E}[u(\mathbf{X})|\mathbf{X}^{(U\cup\{j\})} = \mathbf{x}^{(U\cup\{j\})}] - \mathbb{E}[u(\mathbf{X})|\mathbf{X}^{(U)} = \mathbf{x}^{(U)}]\big).$
- Efficiency $u(\mathbf{x}) = \sum_{j=1}^{M} \mathrm{SHAP}_j(\mathbf{x})$

GSA Results

- Shapley effects computed with SHAFF for the Mandatory QoS model
- The two metrics with the highest impact on the QoS variability are x_4^{G}, x_4^{F}
- x_4^{G}, x_4^{F} quantify the horizontal position error, strongly degraded by the noise
- x_2^{F} is the update probability of position, also degraded by the noise through the loss of tracks
- x_8 and x_{10} are also impacted though worse data age with the loss of tracks

KPI	Sh_j
x_4^{G}	0.19
x_4^{F}	0.17
x_{10}	0.14
x_2^{F}	0.12
x_8	0.12
x_9	0.02
x_3	0.01
x_{14}^{G}	0.01
x_7^{G}	0
x_{11}^{SF}	0
x_{11}^{CDF}	0
x_{12}	0
x_{13}	0
x_{14}^{F}	0

TABLE II
SHAPLEY EFFECTS OF THE INPUT KPIS FOR THE MANDATORY QOS MODEL.

LSA Results

> TreeSHAP is computed for the Mandatory QoS model

> The obtained values are consistent with utility functions

> For example, the violation of the requirement for the horizontal position error ($x_4^{(F)}$ < 550 m) generates a decrease of 0.2 in the global Mandatory QoS

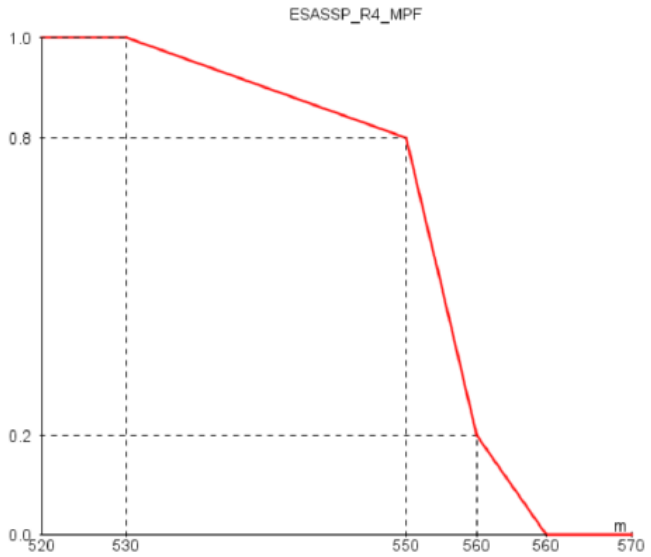


Fig. 6. Utility function of $x_4^{(F)}$ for the mandatory QoS model.

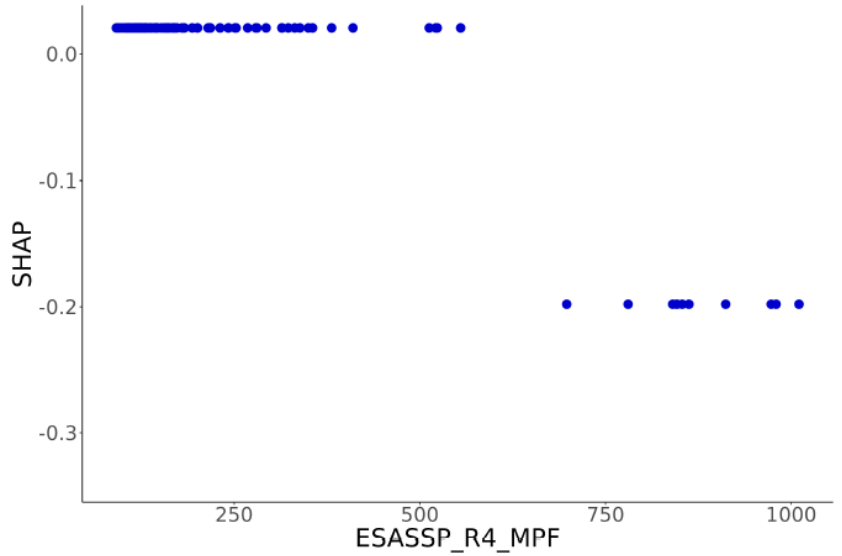


Fig. 5. SHAP values of $x_4^{(F)}$ for the mandatory QoS model, computed with TreeSHAP and xgboost [26].

Conclusion

> **Sensitivity analysis (SA) seems promising to analyze QoS degradations and identify the involved metrics**

> **SA can provides useful information to Technical Supervisor to lead investigations and fix problems**

> **Future improvements**

- Uncertainty quantification of sensitivity indices
- Improved functional decompositions for local analysis (TreeSHAP has limitations)
- Handle time dependence

END

Thank you for your attention !