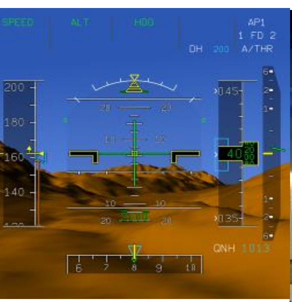
Using Complexity Science in Analyzing Safety/Capacity of ATM Designs

Henk Blom





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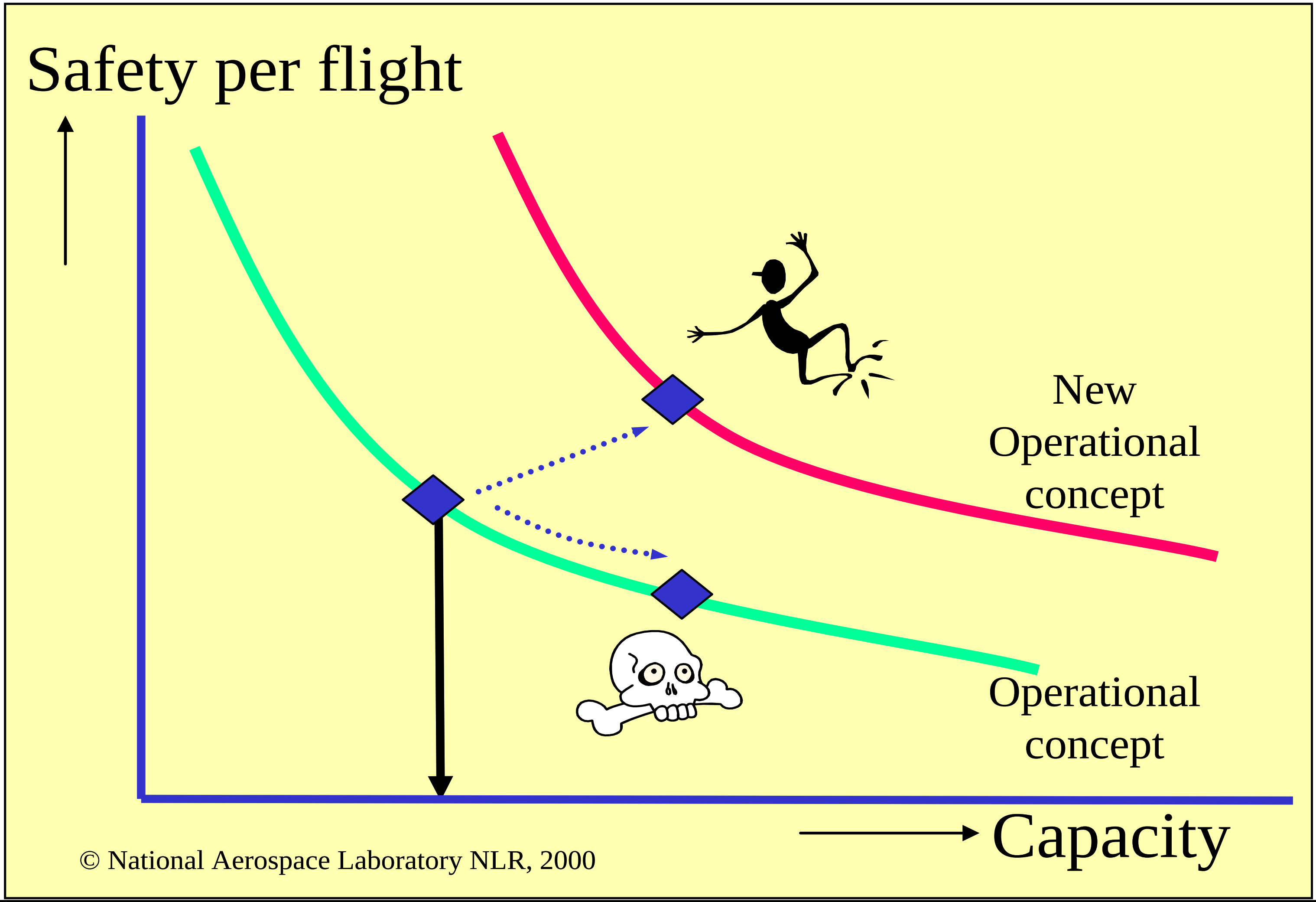
- <u>Motivation and background</u>
- Complexity Science methods Part 1
- Complexity Science methods Part 2

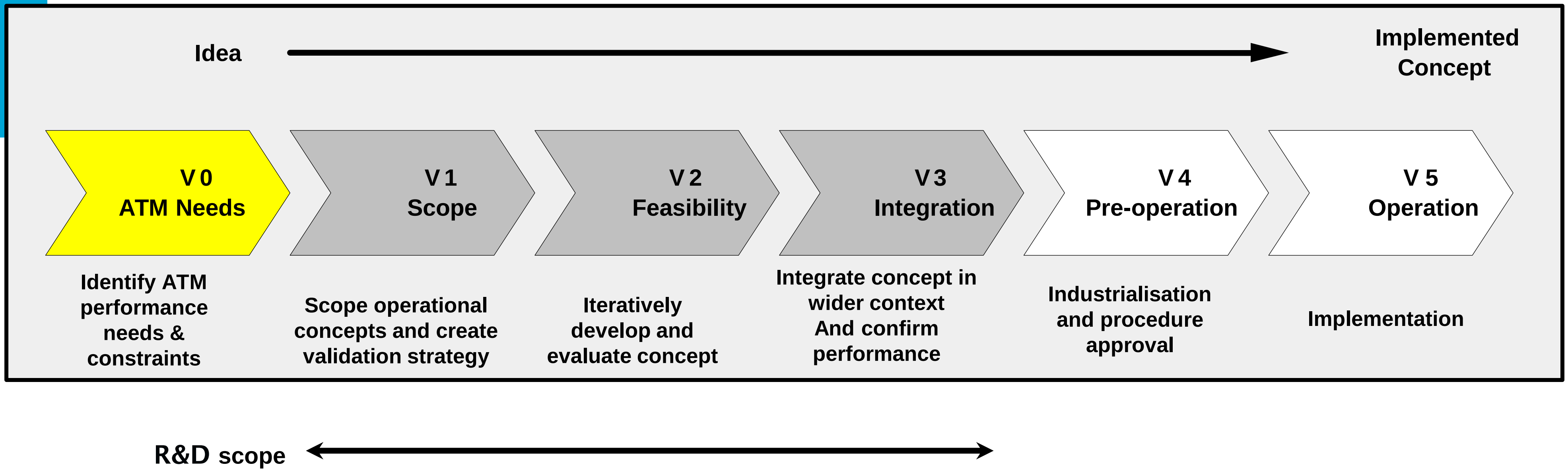
Future ATM design requires safety/capacity analysis

ATM performance improvement targets of SESAR programme

- Capacity: 3 x
- Safety: 10 x
- Economy: 2 x
- Environment: 10%

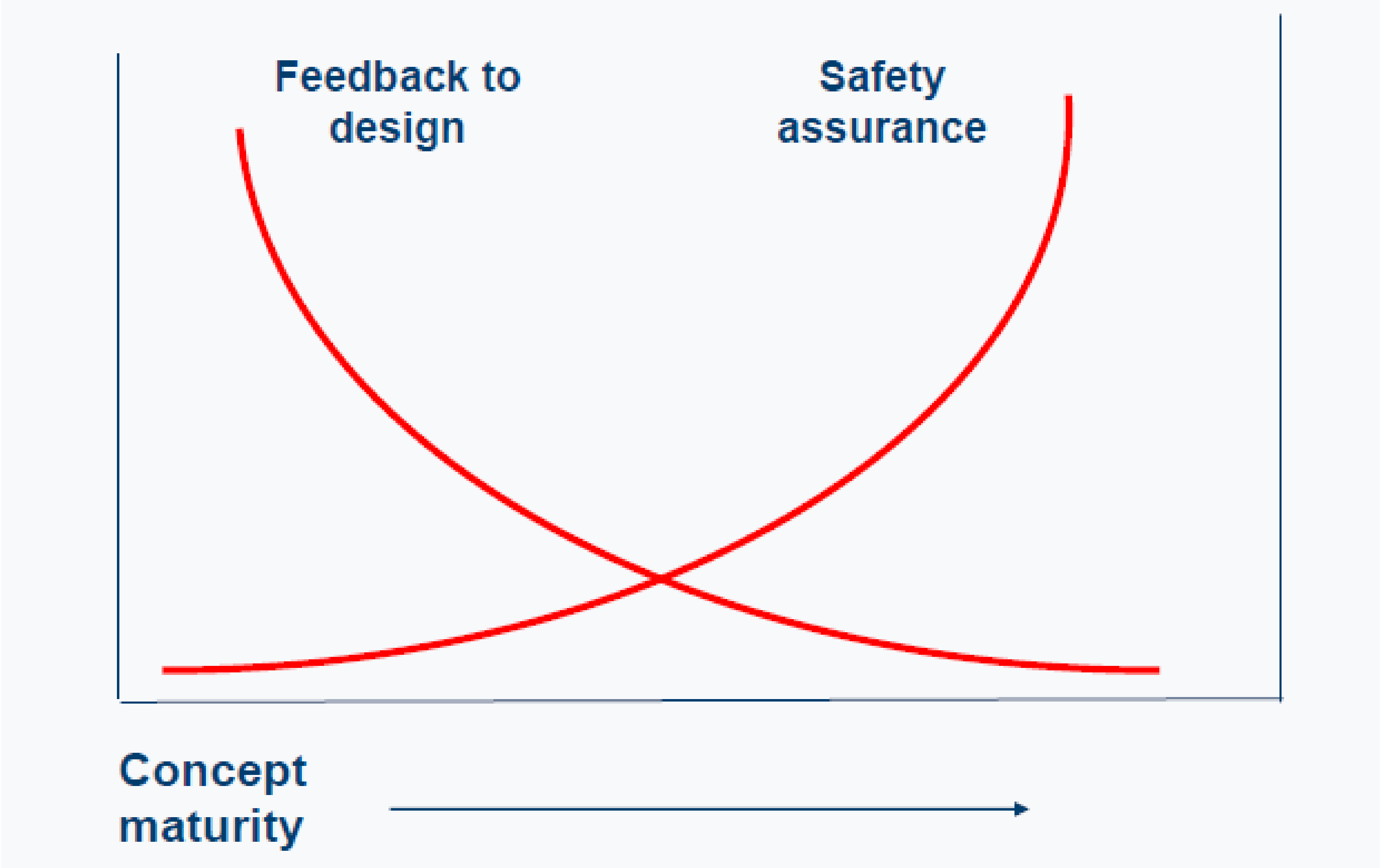


Advanced ATM development life-cycle

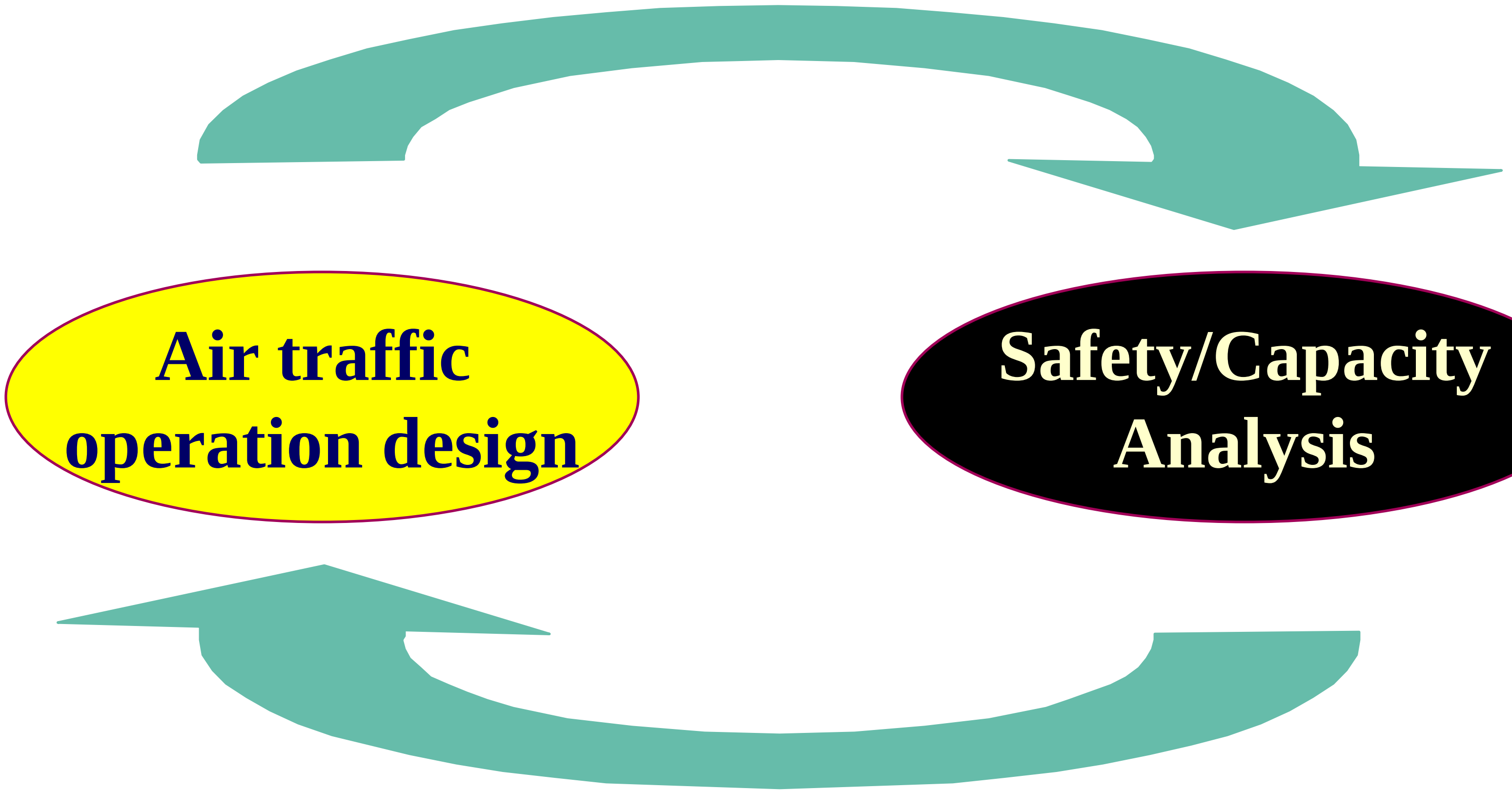


- Current safety validation is focused on regulatory approval in V4/V5
- Safety analysis in R&D (V1-V3) to provide understanding of the problem

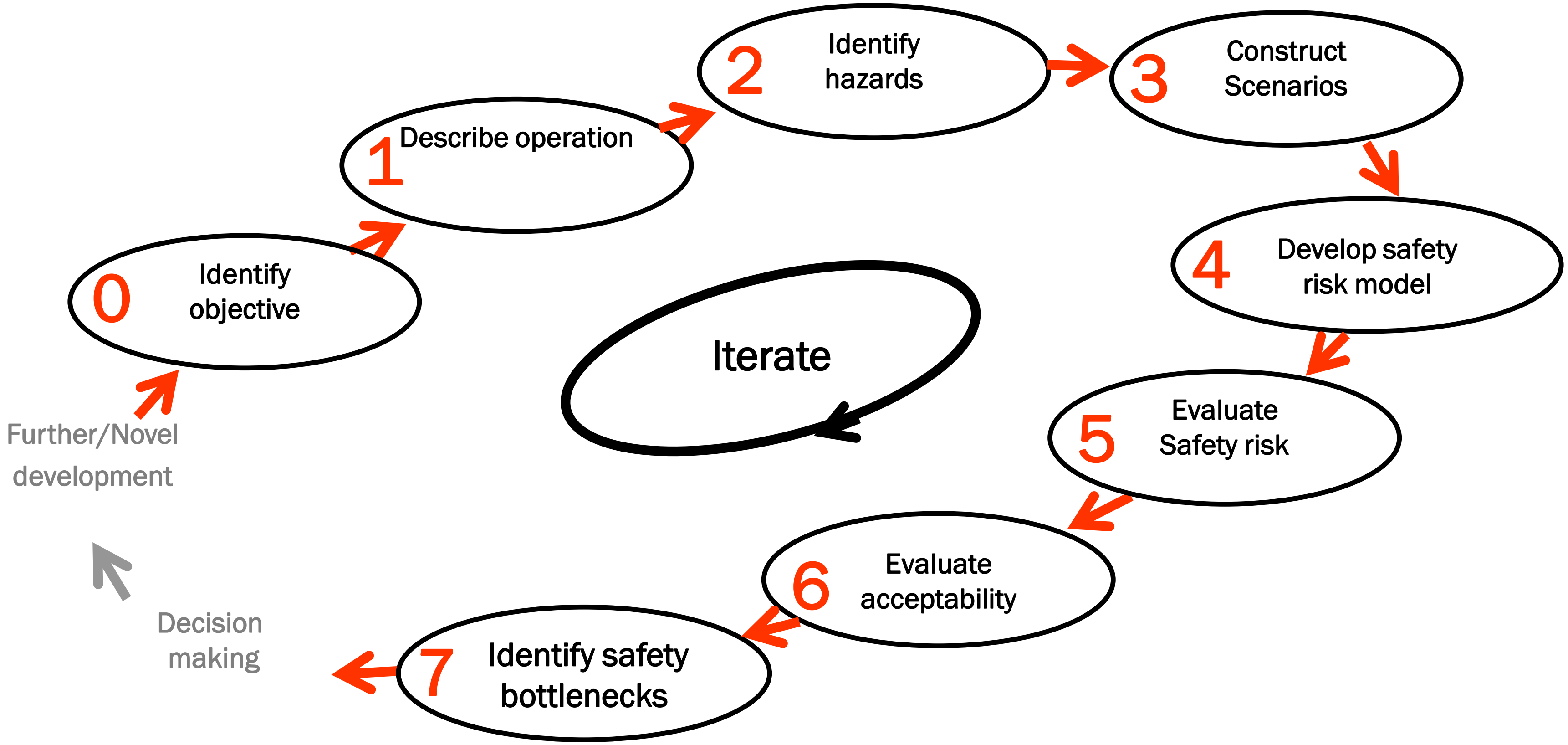
Feedback to Design vs. Safety Assurance



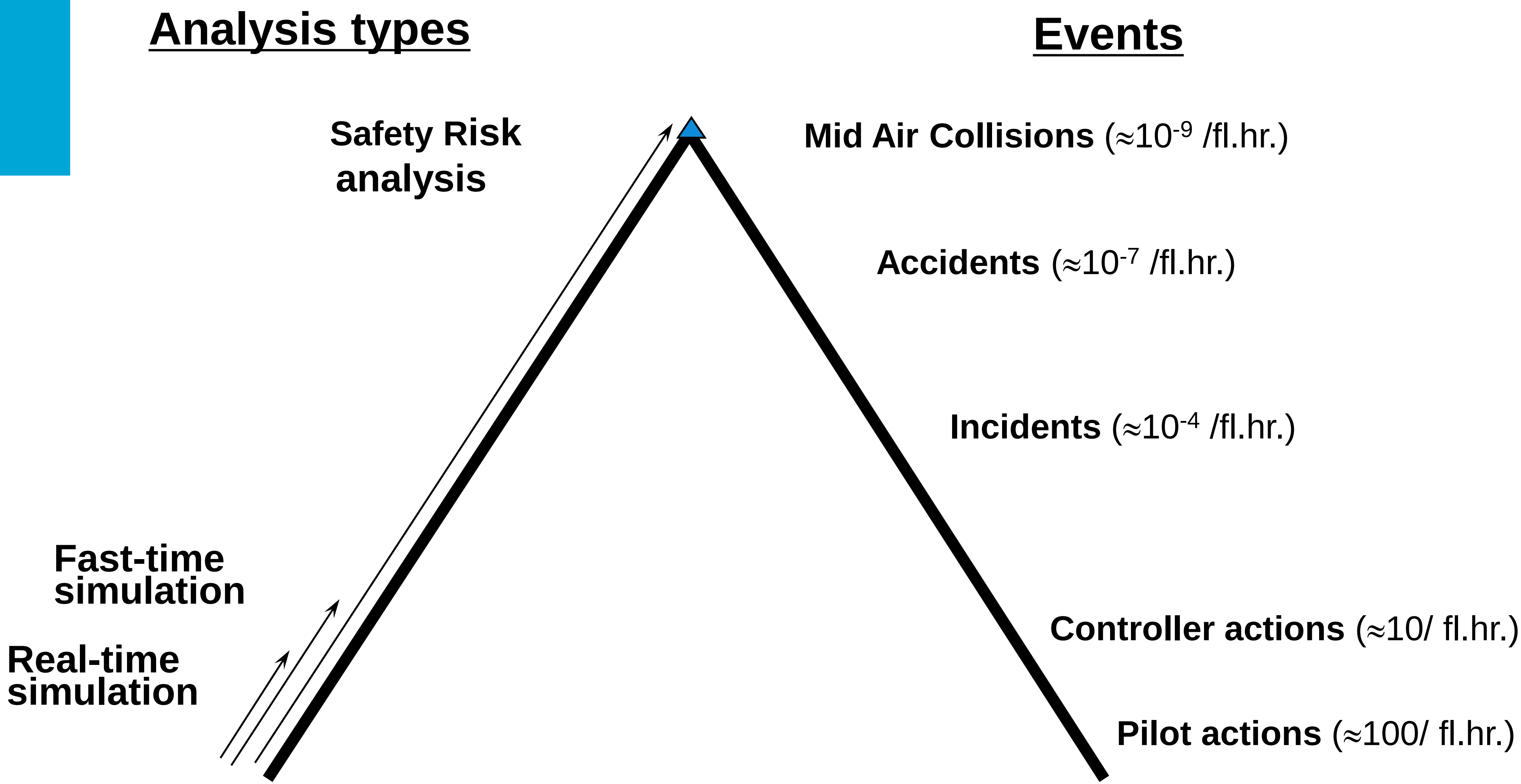
Safety/capacity analysis feedback to future ATM design



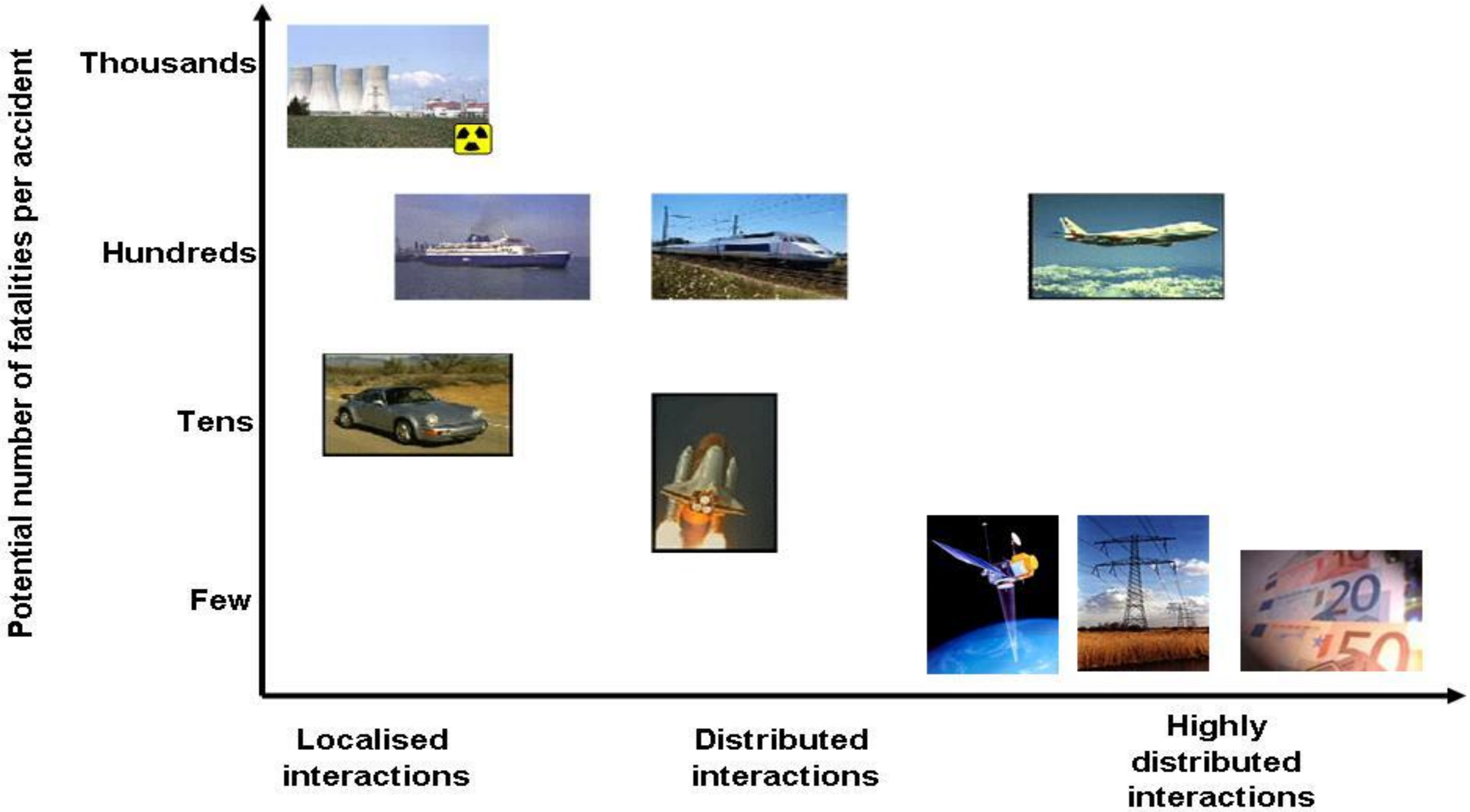
Safety risk assessment cycle



Air Traffic Safety Pyramid



ATM and other socio-technical systems



Emergent Behaviour

- Emergent behaviour is a result of interactions between local behaviours of many entities
- Emergent behaviour cannot be understood from the individual entity local behaviours alone

- Emergent behaviour examples in ATM:
    - Delay propagation over the traffic network due to a bad weather condition
    - Accidents due to combinations of events and misunderstandings in the socio-technical system
- Change in one part may change emergent behaviour unexpectedly

Emergent Behaviour and ATM Design

- Open and Socio- aspects of ATM are not well covered by established system engineering approach
- No theory that tells how to improve emergent behaviours of a complex socio-technical system (Holland, 2006)
- As long as emergent behaviour is not understood, then it is more likely to have a negative than a positive impact
- Hence early learning to understand potentially new emergent behaviours provide opportunities to improve ATM design:
  - to mitigate negative emergent behaviours found, and
  - to take advantage of any positive emergent behaviours.
- Agent-based Modelling and Simulation and Network Flow Modelling have the widest proven applicability in searching for potential emergent behaviours in complex critical infrastructure systems (Ouyang, 2014)

Safety Modelling and Analysis Approaches

- Sequential accident modelling (e.g. fault/event trees)
  - Accident = Sequence of ordered events, such as failures or malfunctions of humans or machines
- Epidemiological accident modelling (e.g. Bayesian Belief Network)
  - Accident = Like spreading of disease: combination of failures and latent / environmental conditions, leading to degradation of barriers an defences
- Systemic accident modelling (e.g. FRAM, STAMP)
  - Accident = Emergent from the performance variability of a joint cognitive system, as a result of complex interactions and unexpected combinations of actions
- Agent-based Safety Risk Analysis
  - Accident Risk = Influenced by positive and negative dynamic and emergent behaviour of a complex distributed and open socio-technical system

Agent-based Safety Risk Analysis in TOPAZ

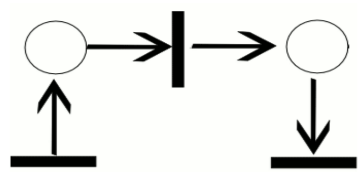
Human Performance Modelling

Mathematical model integrating state-of-the-art psychology in human cognition/performance modeling. Based on SA (Endsley, 1995), the multiple resources model (Wickens 1998), the contextual control mode model (Hollnagel 1993), and human error modelling (Kirwan 1994)

TOPAZ: Traffic Organization & Perturbation AnalyZer

Sensitivity, Bias, and Uncertainty Analysis

Assessment of the impact of potential differences between the true operation and the agent-based model such as errors in paramter values, model structure differences from reality, etc.



Agent-Based Modeling and Simulation

Capability to integrate hetregonous components of the ATM system such as cognitive models, technological models, and working procedures

Stochastically & Dynamically Colored Petri Net Formalism

Advanced Modelling language to develop the agent-based model in a compositional way, and conduct MC simulations enabling powerful stochastic analysis.

Rare Event Monte Carlo Simulation

Application of probabilistic reachability analysis to stochastic hybrid systems, providing a framework to capture uncertainty and dynamics of the ATM system,

Agent Based Safety Risk Analysis: TOPAZ applications

- Conventional ATM: Reduction of separation minima [1]
- Simultaneous use of converging runways [2]
- Active Runway Crossing [3],[4] (Part 1)
- Initial TBO operations in TMA [5],[6]
- Free Flight (Tutorial, Part 2)

[1] Blom et al., ECC2003 [2] Blom et al., ATC-Q 2003 [3] Stroeve et al., 2008
[4] Stroeve et al., 2013 [5] Everdij et al., 2012 [6] Teuwen et al., 2014

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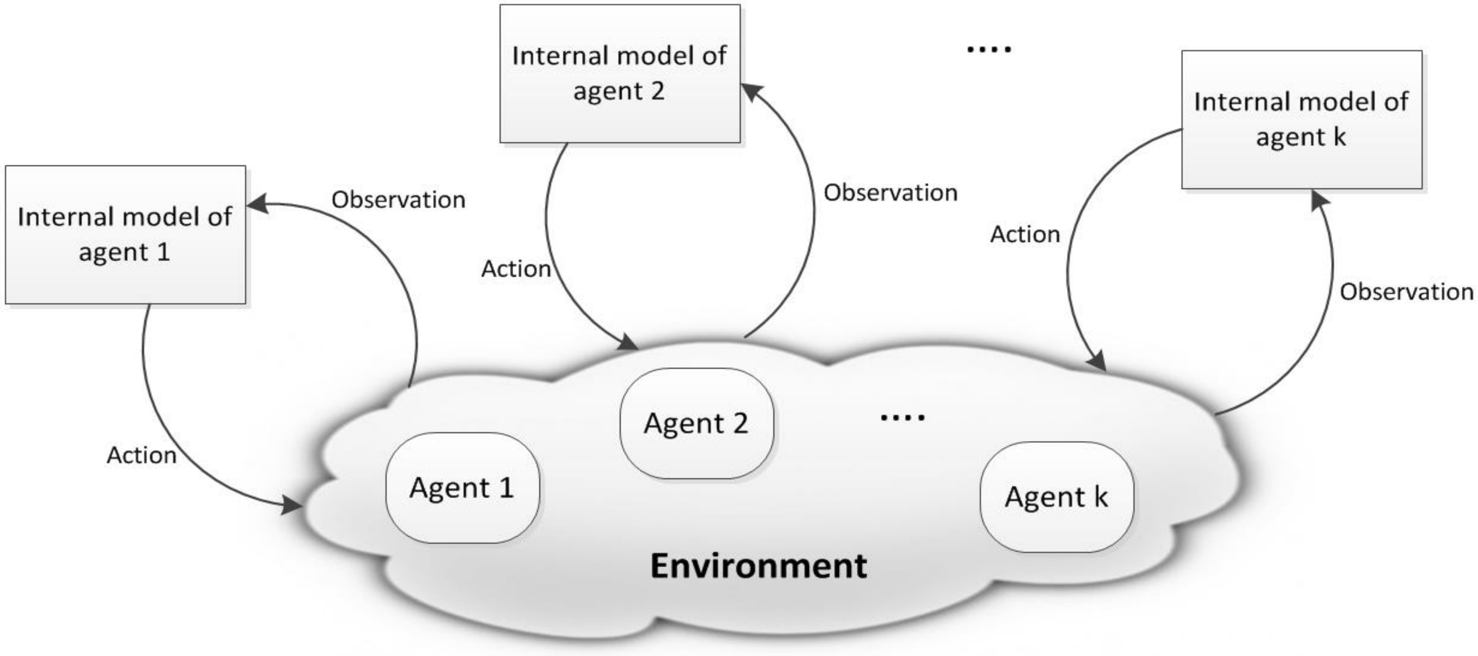
- <u>Agent-based Modelling and Simulation</u>
- Agent-based Safety Risk Analysis
- Multi Agent Situation Awareness
- Active Runway Crossing
- Sensitivity Analysis and Uncertainty Quantification
- Comparison with Event Sequence based approach

Agent Based Modelling and Simulation

Agents are autonomous entities that are able to perceive their environment and act upon this environment. Agents may be humans, systems, organizations, or another other entity that pursues a certain goal.



Interacting Agents applications in:

- Ecology
- Political science
- Social science
- Economics
- Evolutionary biology
- Biomedical science
- Computer science

Use of agent sub-models in capturing hazards (non-nominal events) [1]

Top 5 sub-models	% of hazards
1. Multi Agent Situation Awareness differences [2]	41.4 %
2. Technical System Modes (Configurations, Failures)	19.9 %
3. Basic Human Errors (Slips, Lapses, Mistakes)	18.0 %
4. Human Information Processing	14.3 %
5. Dynamic Variability (e.g. aerodynamics)	8.6 %

[1] Blom et al. (2013) [2] Stroeve et al. (2003)

Top-5 Model constructs/types: use in aviation studies (1/2)

Rank 1 (41.4%): Multi-Agent SA (MA-SA):

- Multi Agent extension of Endsley’s (1995) SA model
- Allows to capture SA differences between agents

Rank 2 (19.9%): System mode:

- RAMS: Reliability, Availability, Maintainability and Safety of technical systems

Rank 3 (18.0%): Basic Human error

- Slips, Lapses and Mistakes only (Reason, 1990)

Top-5 Model constructs/types: use in aviation studies (2/2)

Rank 4 (14.3%): C1 - Human Information Processing

- Human performance simulation, e.g. MIDAS, Air-MIDAS, PUMA, ACT-R, IMPRINT/ACT-R, D-OMAR

Rank 5 (8.6%): C11 - Dynamic Variability

- Simulation of aircraft dynamical behaviour:
    - Aircraft performance models
    - Human-In-The-Loop simulations
    - Fast Time simulations

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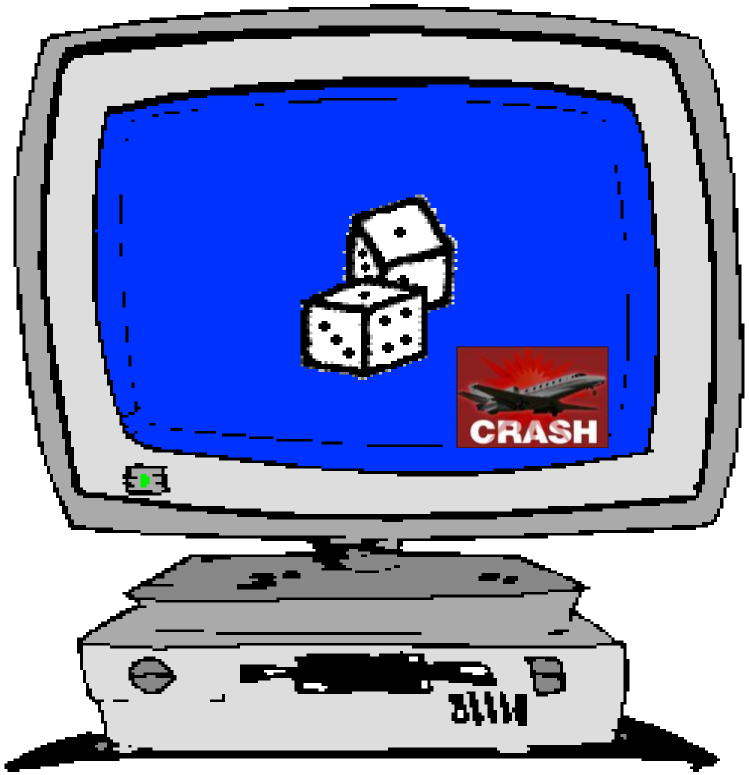
Monte Carlo simulation of an Agent Based Model (ABM)



- Conduct N simulation runs with ABM
- Per run: use independent random numbers
- Count number C of runs with a crash

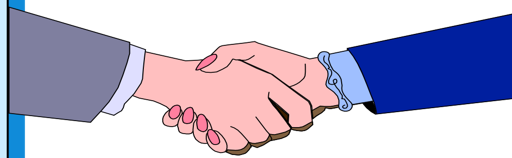
- Estimated crash risk = C/N per ABM run
- Analyse simulated trajectories of each crash

- Advantage over classical risk assessment:
  - Safety relevant event sequences follow from Monte Carlo simulation
  - No need to identify early on which event sequences are safety relevant

- Challenge: Straightforward Monte Carlo simulation takes extremely much time

Integrating ABM and Mathematical tools

Agent Based Modelling and Simulation



Mathematical Tools

↓

Agent Based Safety Risk Analysis

Mathematical Tools

Stochastically & Dynamically Coloured Petri Nets

Fokker-Planck-Kolmogorov evolution

Probabilistic Reachability Analysis

Conditional Monte Carlo Simulation

Particle Swarm Intelligence

Importance Sampling

Sensitivity/Elasticity Analysis

Uncertainty Quantification

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Situation Awareness (SA)

- Situation Awareness (SA) is a dynamic state of knowledge, which discerns three levels (Endsley, 1995)
  - perception of elements in the environment
  - comprehension of their meaning
  - projection of their future status
- Situation assessment
  - Process of achieving, acquiring and maintaining SA
- Shared situation assessment
  - Team processes (communication, coordination, etc.) impacting SA of team members, and leading to Shared SA

SA vector in ATM

$$\sigma = SA = \begin{pmatrix} \text{Identity} \\ \text{State} \\ \text{Mode} \\ \text{Intent} \end{pmatrix}$$

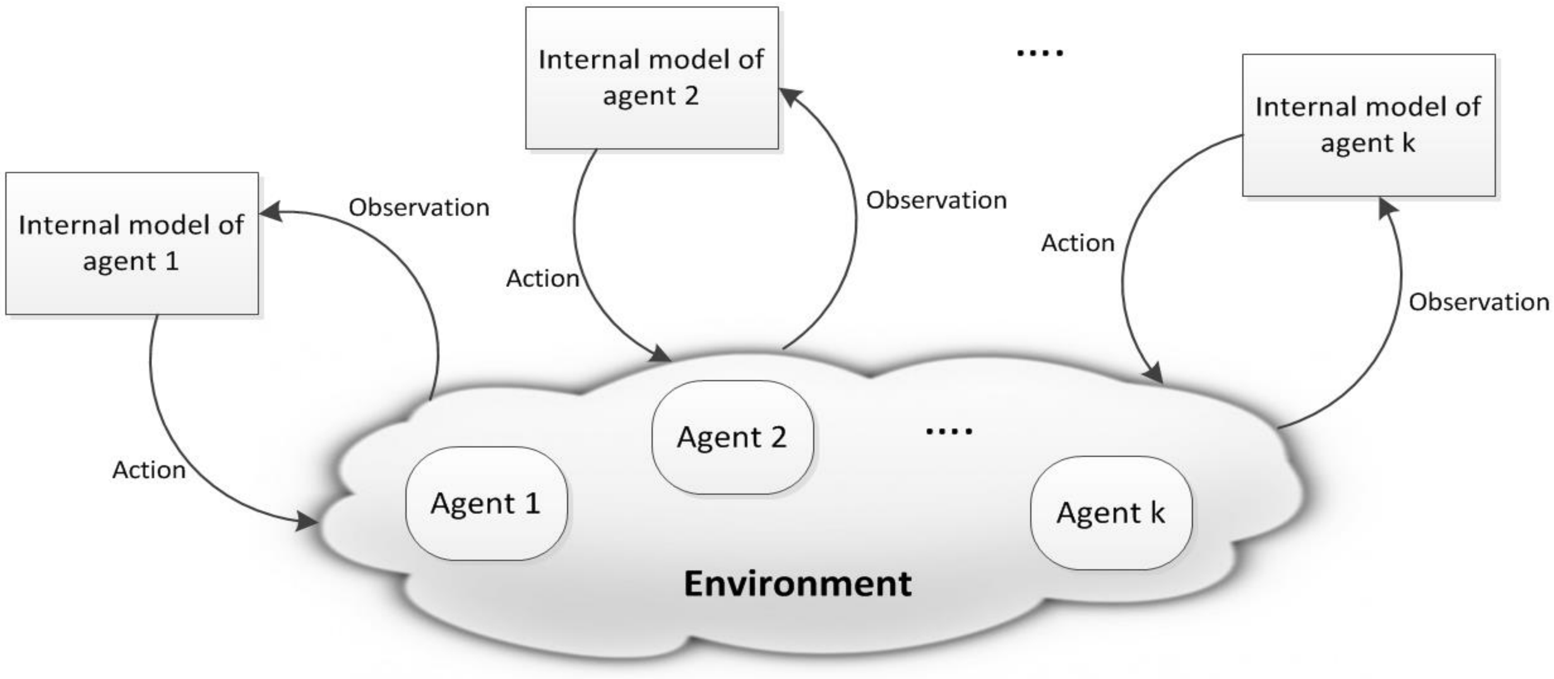
	Examples
Identity	Call-sign Active stopbar ID Alert type
State	Aircraft position Aircraft speed Aerodrome geometry data
Mode	Alert status Stopbar status Flight mode
Intent	Taxiing route Take-off time Crossing time

Dynamics of SA updating

$$\sigma_{t+\Delta} = f^{SA}(\sigma_t, u_t, \varepsilon_t)$$

Duration	Trigger time	Input	Stochastics
Examples			
Alert interpretation	Alert active	Alert	Alert misinterpretation
Clearance interpretation by pilot	Clearance issued by controller	Clearance	Misinterpretation of clearance
Visual observation of traffic situation	Internal trigger	Visual cue	Observation error
ADS-B data processing	Surveillance data update moment	ADS-B data	Data corruption

Wide sense Agents to capture Multi Agent Situation Awareness differences



An Agent is an autonomous entity that is able to perceive its environment through sensors and to act upon that environment through effectors. A Wide sense agent is any entity that at least acts upon its own state. The set of wide-sense agents includes all agents.

Multi-Agent SA in ATM

$$\sigma_{t,k}^{j} = \textbf{SA of agent } \boldsymbol{k} \textbf{ at time } \boldsymbol{t} \textbf{ about agent } \boldsymbol{j} = \begin{pmatrix} \text{Identity}_{t,k}^{j} \\ \text{State}_{t,k}^{j} \\ \text{Mode}_{t,k}^{j} \\ \text{Intent}_{t,k}^{j} \end{pmatrix}$$

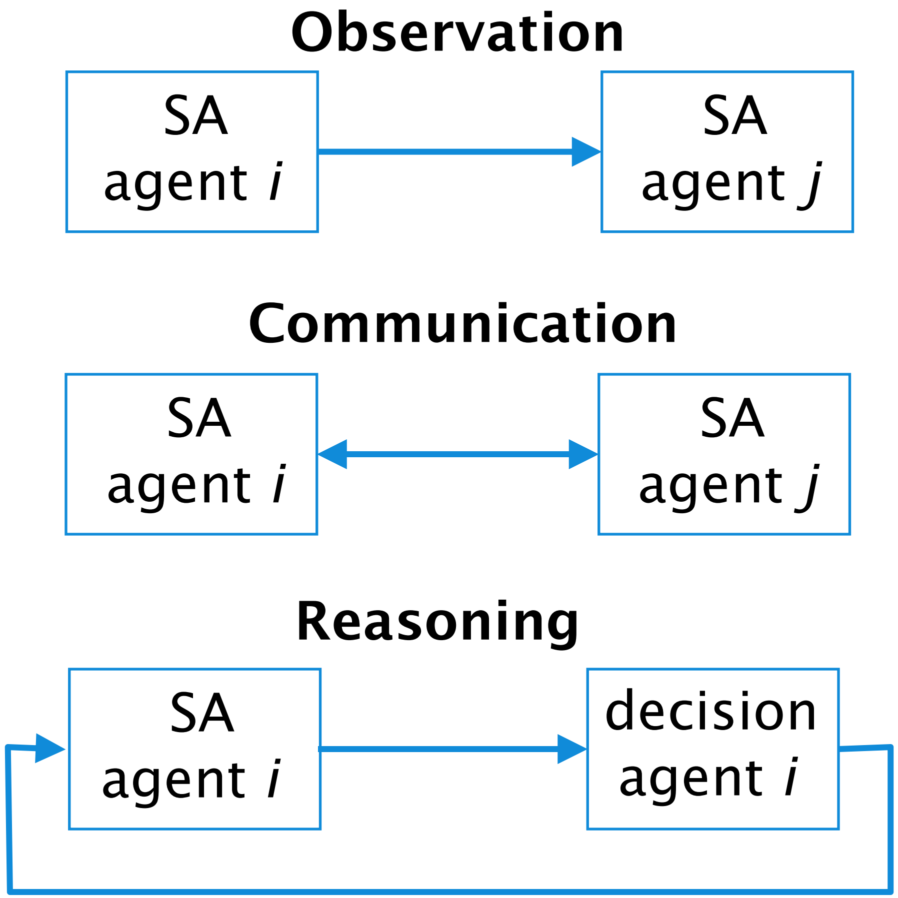
Example of Multi-Agent SA in ATM

Agent *k* = ATCo
Agent *j* = Aircraft-*i*

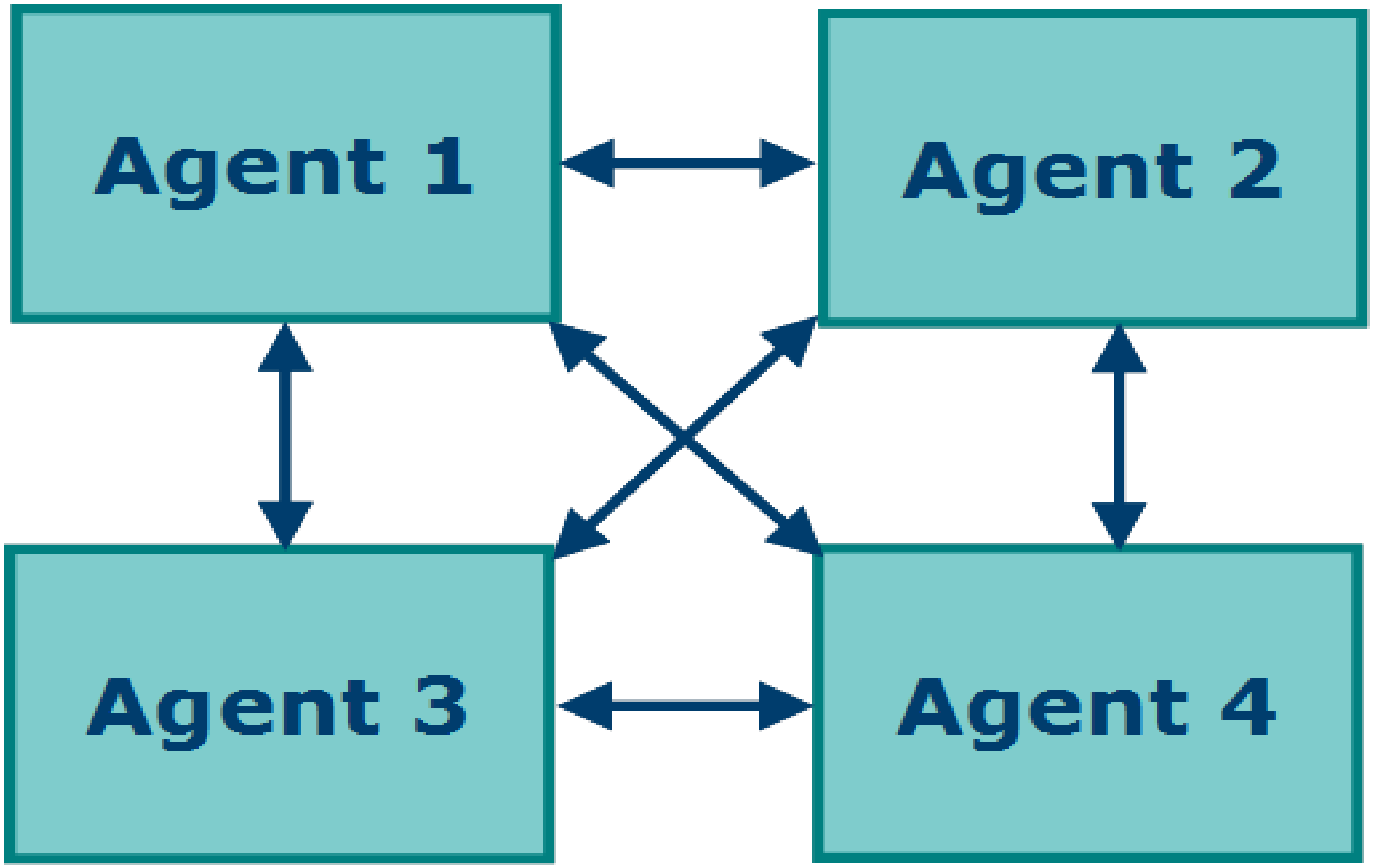
Substitution yields:

$$\sigma_{t,k}^{j} = \text{SA of ATCo at time } t \text{ about Aircraft-}i = \begin{pmatrix} \text{Identity}_{t,ATCo}^{Aircraft-i} \\ \text{State}_{t,ATCo}^{Aircraft-i} \\ \text{Mode}_{t,ATCo}^{Aircraft-i} \\ \text{Intent}_{t,ATCo}^{Aircraft-i} \end{pmatrix}$$

Multi-Agent SA Update types



Multi Agent SA propagation



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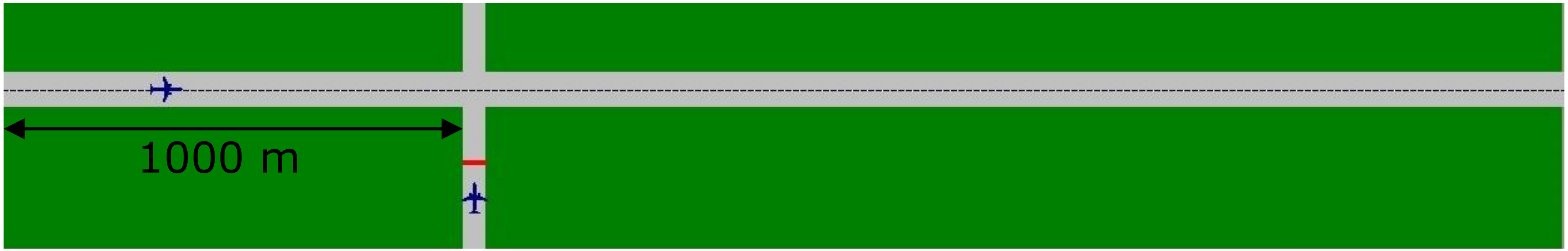
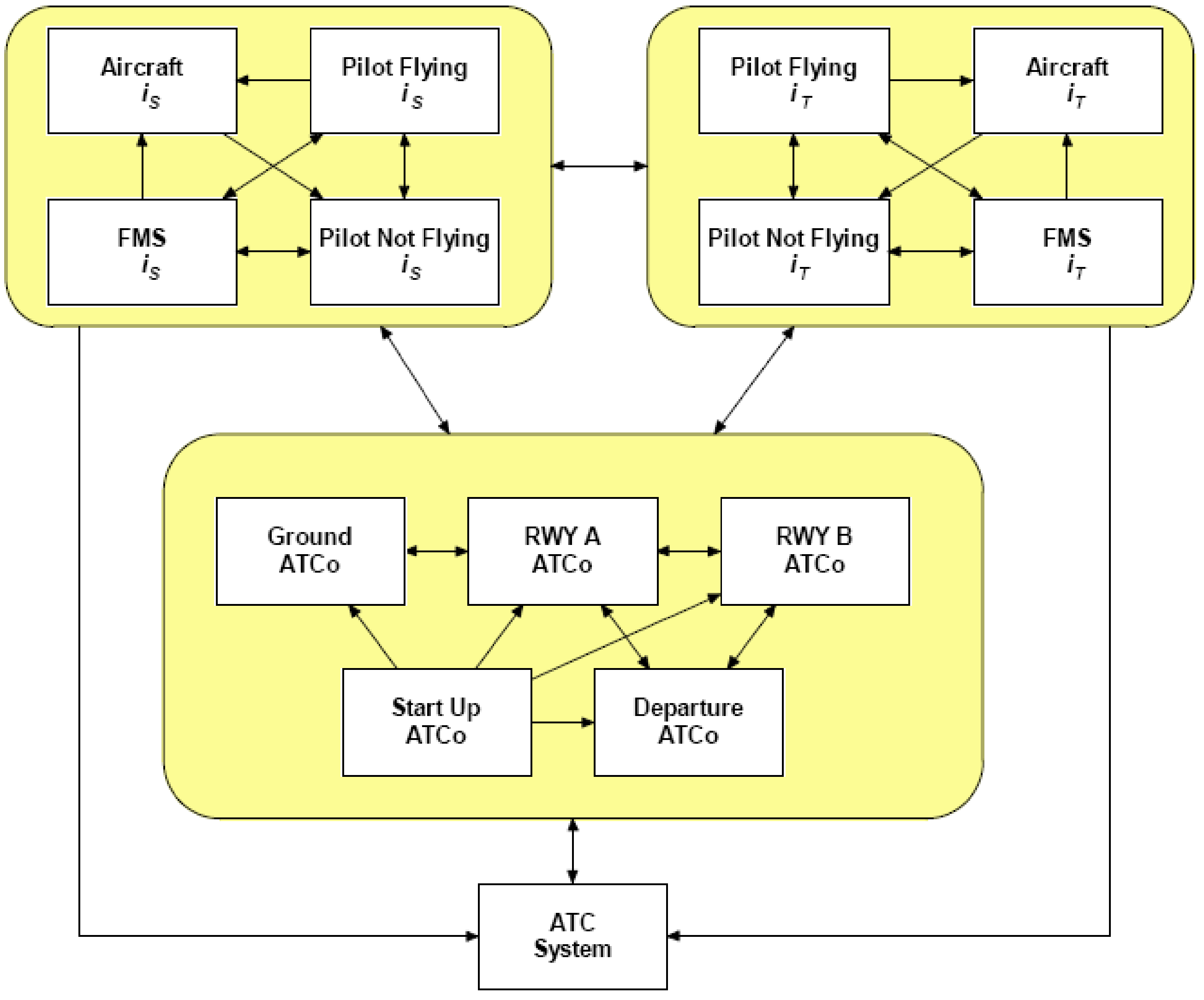
Active runway crossing

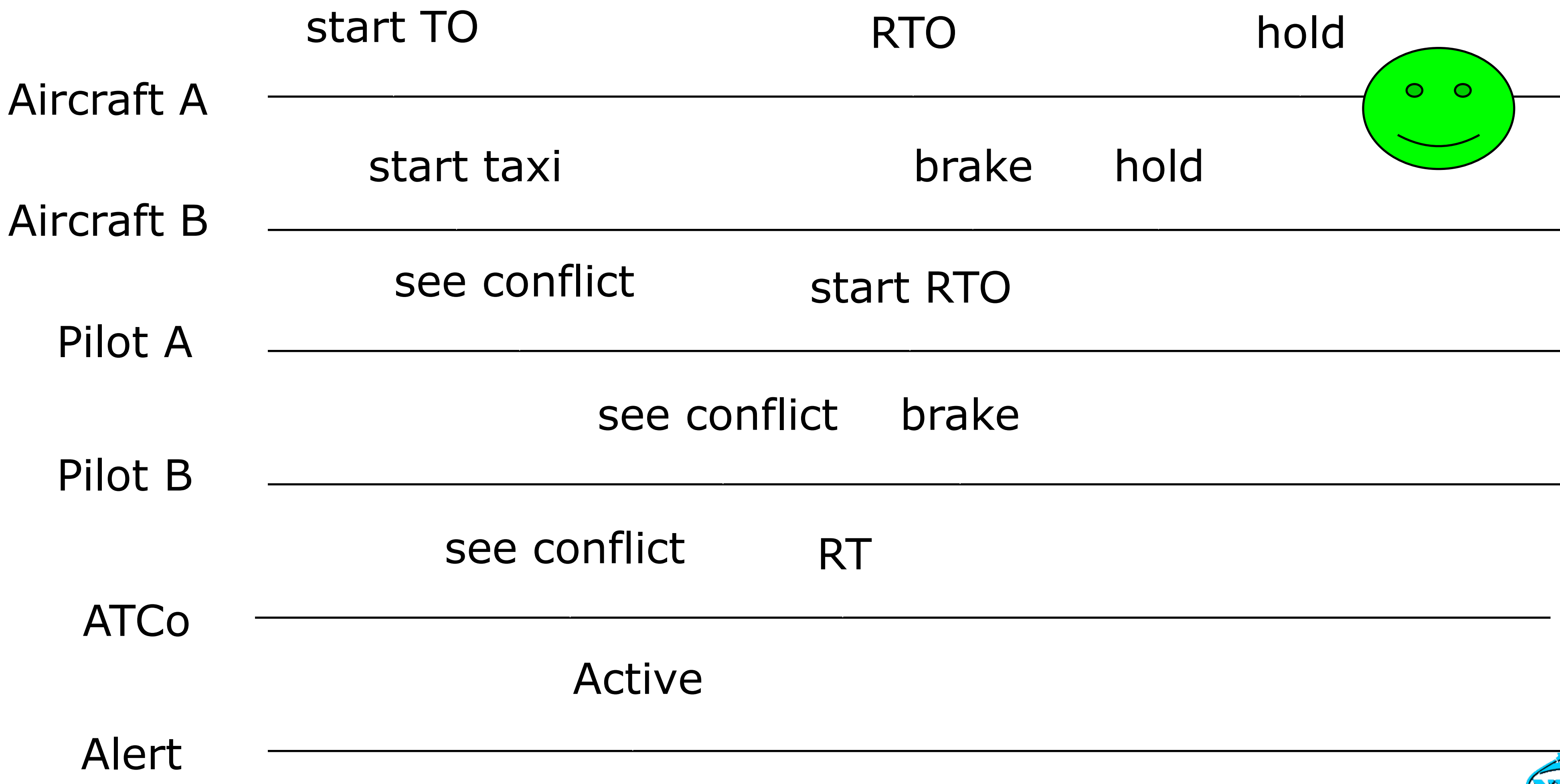


- **Human operators**
  - Pilots aircraft taking-off
  - Pilots aircraft taxiing
  - Runway controller
  - Ground controller
- **Visibility conditions**
  - Visibility condition 1
    - Unrestricted range
  - Visibility condition 2
    - Range of 400 – 1500 m
- **Technical systems**
  - VHF R/T communication
  - Ground radar
  - Active stopbar
  - ATC alert system
    - Ground radar data
    - Alerts runway controller
  - Cockpit alert system
    - GPS ownship data
    - ADS-B linked othership data
    - Alerts pilots

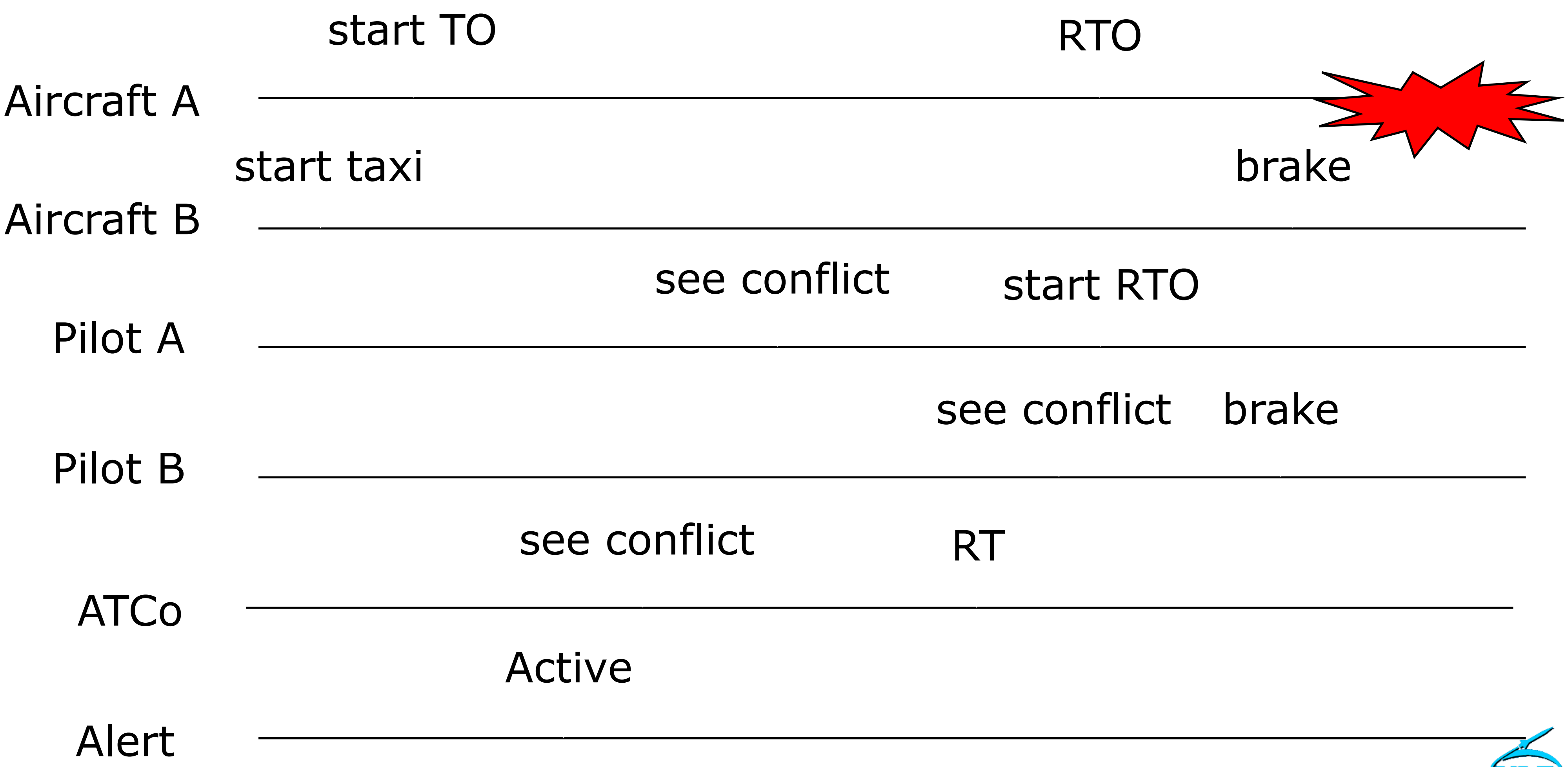
Multiple Agent Model View



Conflict scenario timeline example 1



Conflict scenario timeline example 2



Risk decomposition and conditional Monte Carlo simulation

e.g., SA PF taxiing a/c "Proceed taxiway" and ATC alert not working

$$\text{Total Risk} = \sum_{\text{event}} \text{Risk(event)}$$

$$= \sum_{\text{event}} \text{Probability(event)} \times \text{Conditional Risk(event)}$$

Statistical data and

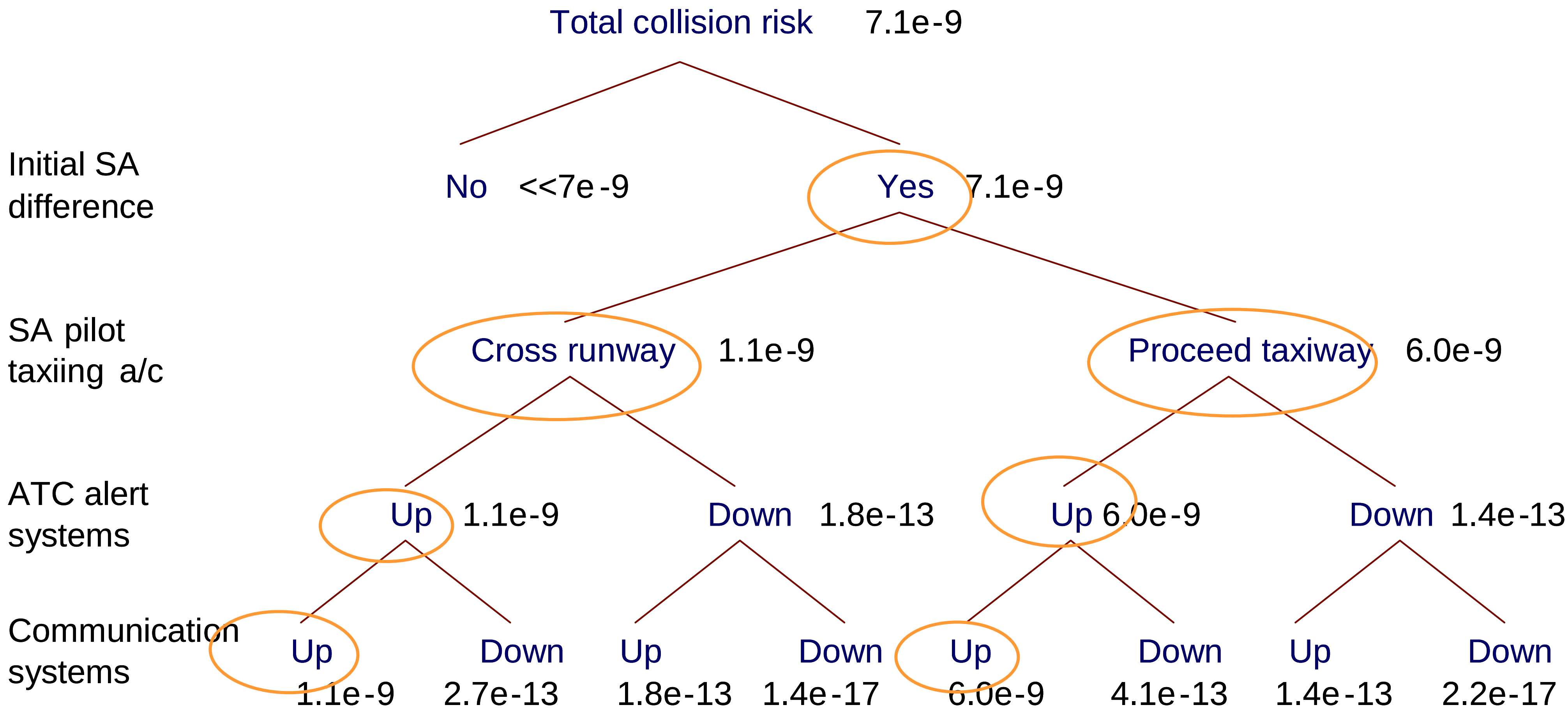
semi-Markov chain analysis

Conditional Monte Carlo simulation

Risk assessment results for runway crossing at 1000m from take-off starting point; values are point estimates per take-off

Condition: SA by PF of Taxiing aircraft	Probability of event Condition	Event conditional collision probability	Collision probability
Cross runway	$2.3\ 10^{-4}$	$4.8\ 10^{-6}$	$1.1\ 10^{-9}$
Proceed taxiway	$3.5\ 10^{-5}$	$1.7\ 10^{-4}$	$6.0\ 10^{-9}$
Total	**$2.7\ 10^{-4}$**	**$2.6\ 10^{-5}$**	**$7.1\ 10^{-9}$**

Decomposition of point estimated values



P(event) =2.3e-4
CR(event)=4.8e-6

P(event) =3.5e-5
CR(event)=1.7e-4

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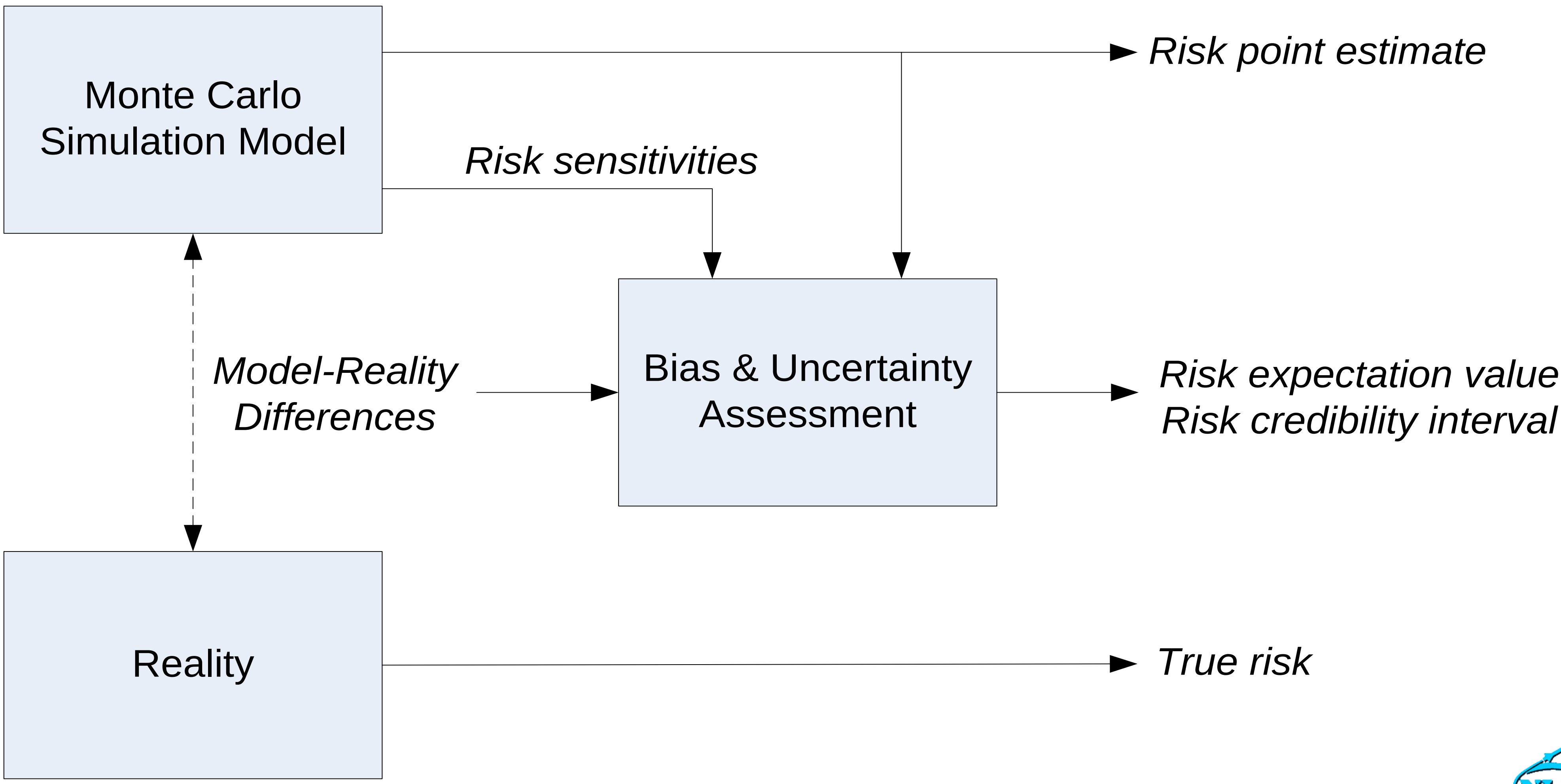
Bias and uncertainty in assessed risk values

- By definition: model ≠ reality
  - Numerical approximations
  - Parameter values
  - Model structure
  - Hazards not covered
  - Operational concept
- Bias and uncertainty assessment
  - Identify differences between model and reality
  - Assess the size of these differences (operational expert interviews)
  - Assess the impact of these differences at the risk level
- Typical output: expected risk and 95% bracket
- For the example considered, bias and uncertainty mainly is in the probability of the event: “proceed taxiway” under “SA difference”

Risk assessment through MC simulation + bias & uncertainty assessment



Results MC simulation + B&U assessment

- **Conditional accident risk: 1.7 E-4 (95% range: 4.1 E-6 – 7.3 E-4)**
- **Examples of significant bias & uncertainty effects**
  - Type of manoeuvre of taking-off aircraft to avoid collision
  - Conflict decision process by pilots of taking-off aircraft
  - Speed of taxiing aircraft
  - Monitoring frequency by pilots of taxiing aircraft
  - Deceleration of taking-off and taxiing aircraft
  - Time before braking is initiated by pilots of taking-off aircraft
- **Examples of small bias & uncertainty effects**
  - Performance of R/T communication systems
  - Performance of surveillance systems
  - Performance of runway incursion alert system
  - Task scheduling of runway controller

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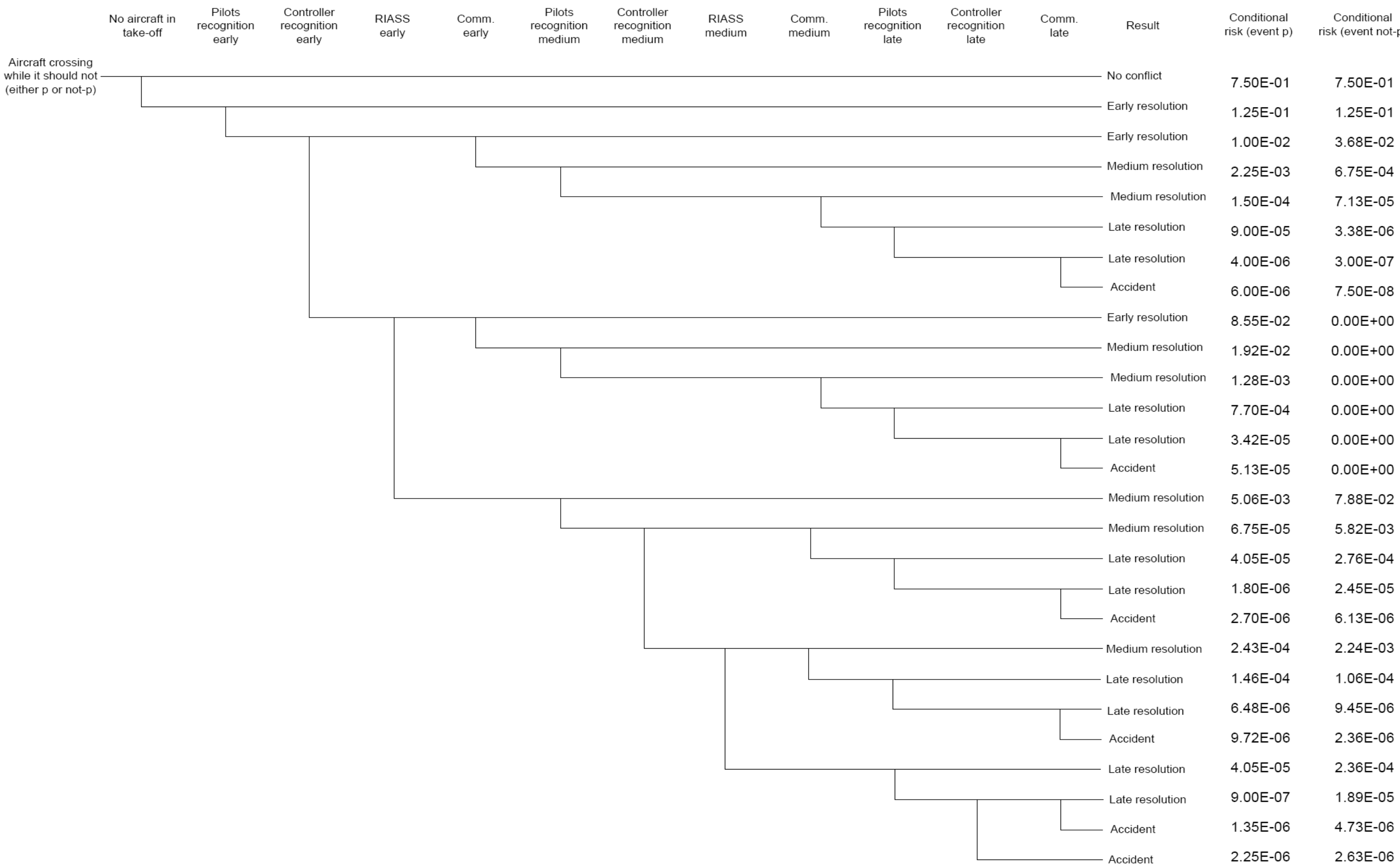
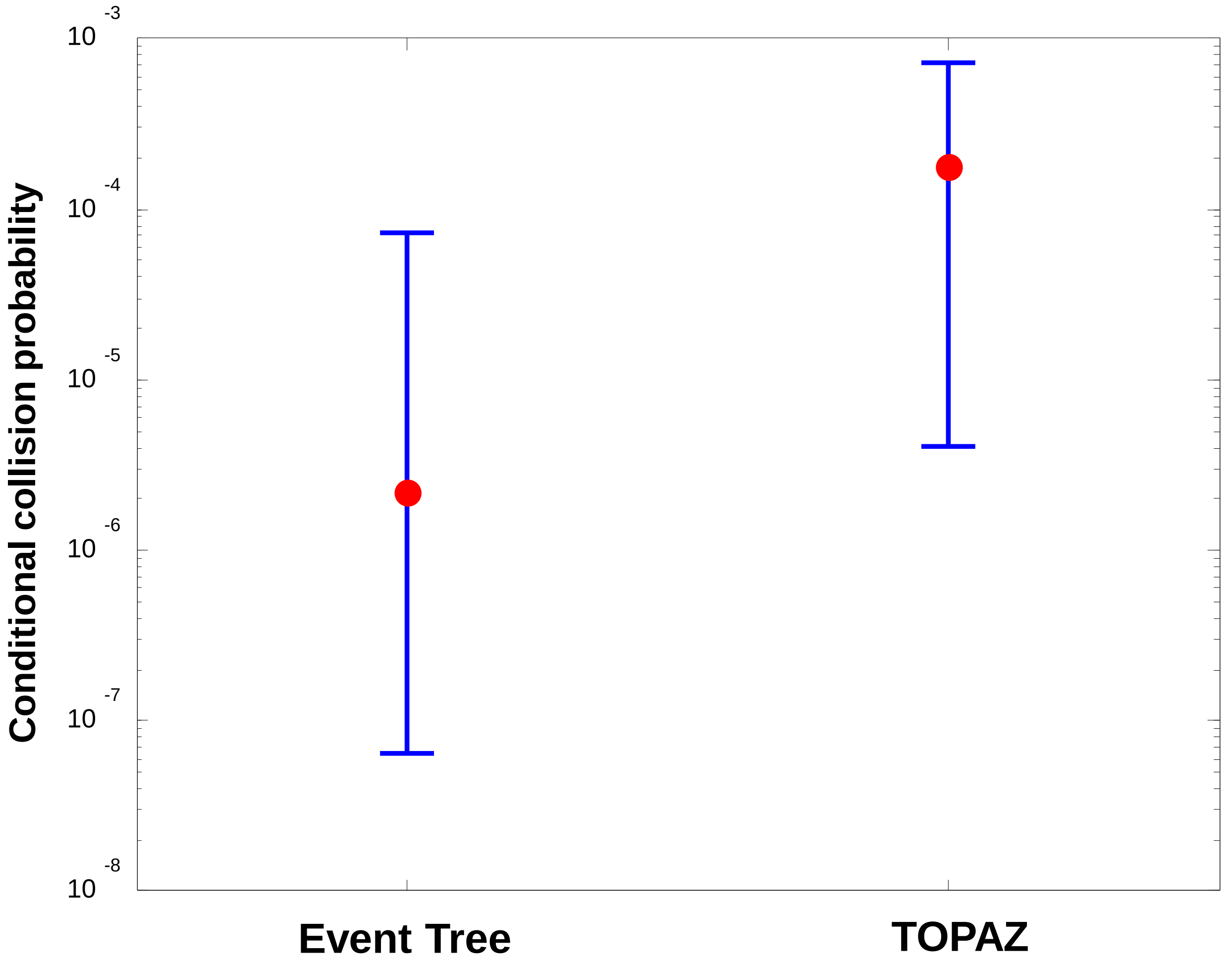
Event tree


No aircraft in take-off
Pilots recognition early
Controller recognition early
RIASS early
Comm. early
Pilots recognition medium
Controller recognition medium
RIASS medium
Comm. medium
Pilots recognition late
Controller recognition late
Comm. late
Result
Conditional risk (event p)
Conditional risk (event not-p
Aircraft crossing while it should not (either p or not-p)
No conflict 7.50E-01 7.50E-01
Early resolution 1.25E-01 1.25E-01
Early resolution 1.00E-02 3.68E-02
Medium resolution 2.25E-03 6.75E-04
Medium resolution 1.50E-04 7.13E-05
Late resolution 9.00E-05 3.38E-06
Late resolution 4.00E-06 3.00E-07
Accident 6.00E-06 7.50E-08
Early resolution 8.55E-02 0.00E+00
Medium resolution 1.92E-02 0.00E+00
Medium resolution 1.28E-03 0.00E+00
Late resolution 7.70E-04 0.00E+00
Late resolution 3.42E-05 0.00E+00
Accident 5.13E-05 0.00E+00
Medium resolution 5.06E-03 7.88E-02
Medium resolution 6.75E-05 5.82E-03
Late resolution 4.05E-05 2.76E-04
Late resolution 1.80E-06 2.45E-05
Accident 2.70E-06 6.13E-06
Medium resolution 2.43E-04 2.24E-03
Late resolution 1.46E-04 1.06E-04
Late resolution 6.48E-06 9.45E-06
Accident 9.72E-06 2.36E-06
Late resolution 4.05E-05 2.36E-04
Late resolution 9.00E-07 1.89E-05
Accident 1.35E-06 4.73E-06
Accident 2.25E-06 2.63E-06

Conditional collision risk results



What are the causes of the differences?

Conditional accident risk results

Method	Conditional accident risk
MC simulation (+ B&U)	1.7 E-4 (4.1 E-6 – 7.3 E-4)
Event tree (+ B&U)	2.2 E-6 (6.5 E-8 – 7.3 E-5)

What are the causes of the differences?

Main differences

- **Event Tree**
  - Risk reducing contributions by PF's and RC are treated as being independent.
  - RIAS for RC significantly reduces the total collision risk; the remaining risk is largely due to late RIAS alerts
- **MC simulation**
  - The risk reducing contributions by PF's and RC are not independent because RC and PF's concurrently work towards solving a safety critical runway incursion.
  - When visibility is good, even nominal RIAS triggered actions by the RC often arrive when PF's already have started proper action

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Questions / Discussion