Agent-based Modelling and Simulation (ABMS) in SESAR WP-E research projects MAREA and EMERGIA

Dedicated to innovation in aerospace

Henk Blom
NLR and TUDelft

Pre-SID 2016 Workshop, Delft, 7th November 2016

ABMS in MAREA and EMERGIA

Part 1: Type of problem

- Role of emergent behaviour in ATM design
- Agent-based modelling (ABM) and simulation (ABMS)
- Type of problem addressed in EMERGIA
- ABMS development steps
- Scenarios considered

Part 2: Techniques

Part 3: Results

What is the role of Emergent Behaviour in ATM design?

In complexity science a property or behaviour of a system is called emergent if it is not a property or behaviour of the constituting elements of the system, though results from the interactions between its constituting elements.

→ Emergent behaviour may be Negative or Positive
→ Typically Negative as long as it is not identified

In the Open Socio-technical air transportation system the interactions are between human operators, technical systems, procedures (at airlines, airports and air traffic centres) and external conditions (e.g. weather, travel demand).

→ Data based identification of emergent behaviour works for current ATM
→ For future ATM design: Simulation based identification of emergent behaviours

Agent Based Modelling (ABM) and Simulation (ABMS)

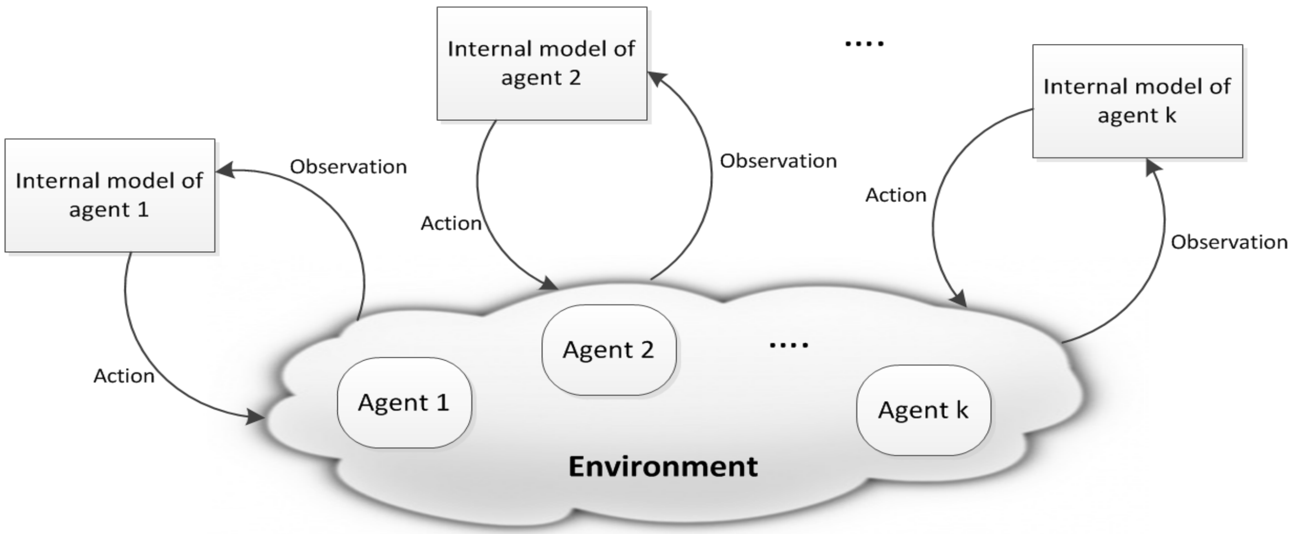
Emergent behaviour can be identified through ABMS.

Agents are entities that are able to perceive their environment and act upon this.

Environment of an agent consist of other agents and of non-agent entities.

A **proactive agent** pursues own goals, a **reactive agent** not.

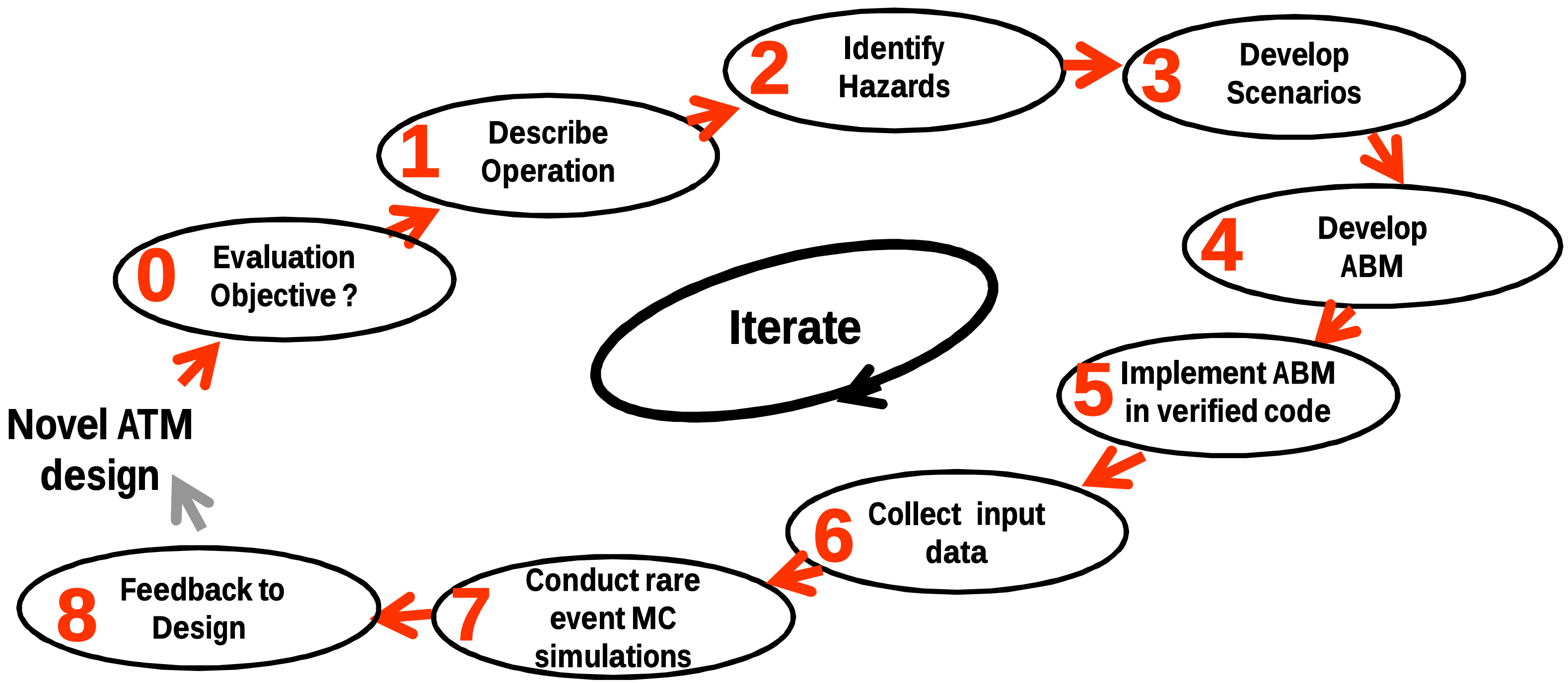
Autonomy: There is no central memory and no overall simulation program that determines what an agent uses from other agents, and neither what an agent does.



ABMS applications in:

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

ABMS of an ATM design on KPA's incl. safety



Step 4: Compositional development of an ABM

ConOps decomposition sub-steps:

Step 4.1: Identify the relevant agents

Step 4.2: Identify the relevant entities per agent

ABM composition sub-steps:

Step 4.3: Specify entity models per agent

Step 4.4: Interconnect entity models within each agent

Step 4.5: Interconnect entity models between agents

Step 4.6: Iterate

WP-E project EMERGIA

EC-FP6 project **iFly** conducted ABMS of an advanced pure airborne self-separation concept of operations (A3 ConOps).

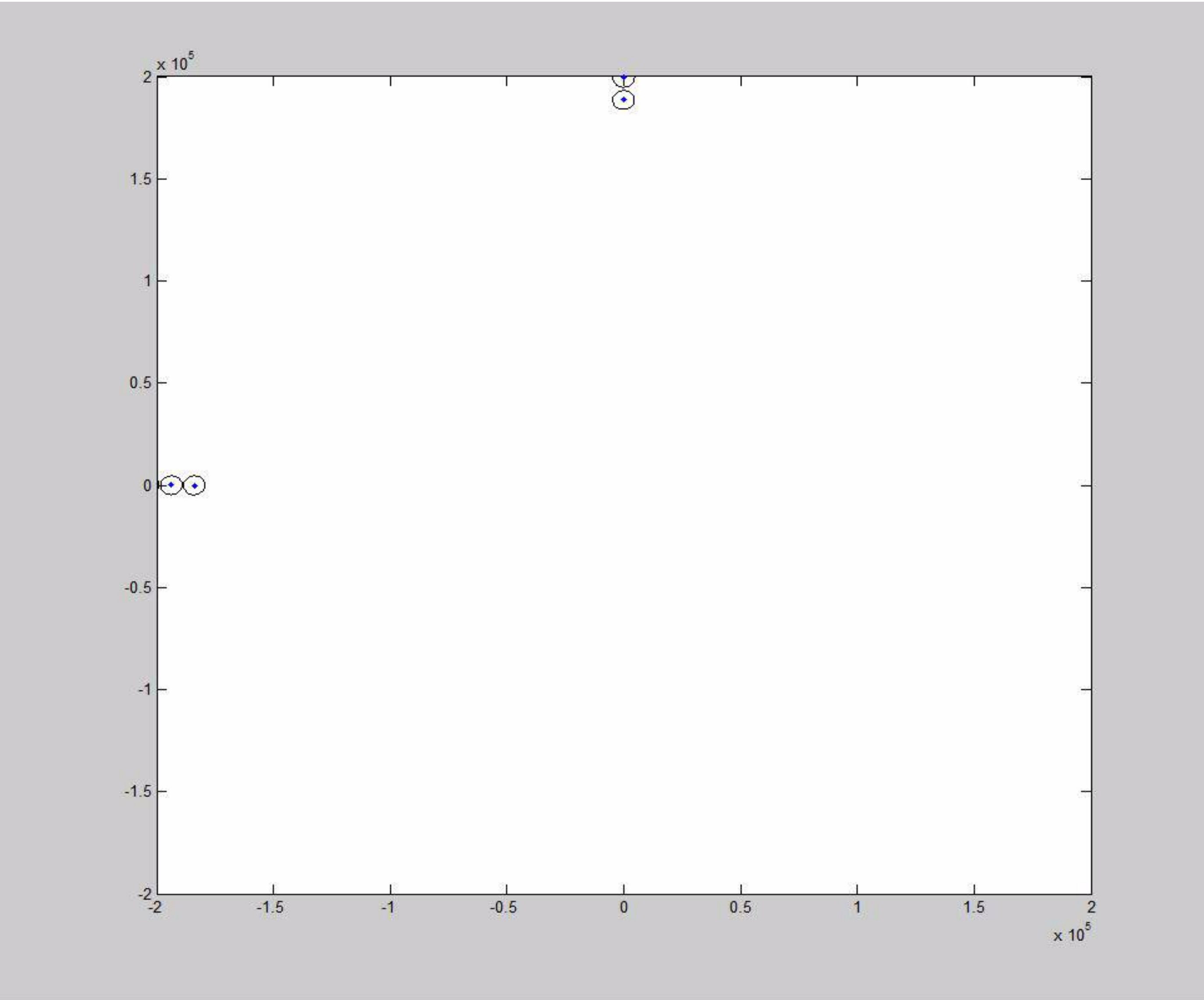
iFly showed remarkably positive emergent behaviours/properties of A3 ConOps:

1. Tactical layer is very effective in the tactical resolution of uncertainties that are not (timely) resolved by 4D trajectory plans (Trajectory Based Operation).
2. Centerlines of 4D trajectory plans may be at minimum separation values: no need for any buffers.
3. No phase transition happens at traffic demands multiple times higher than 3x high 2010 en-route in busy sector.

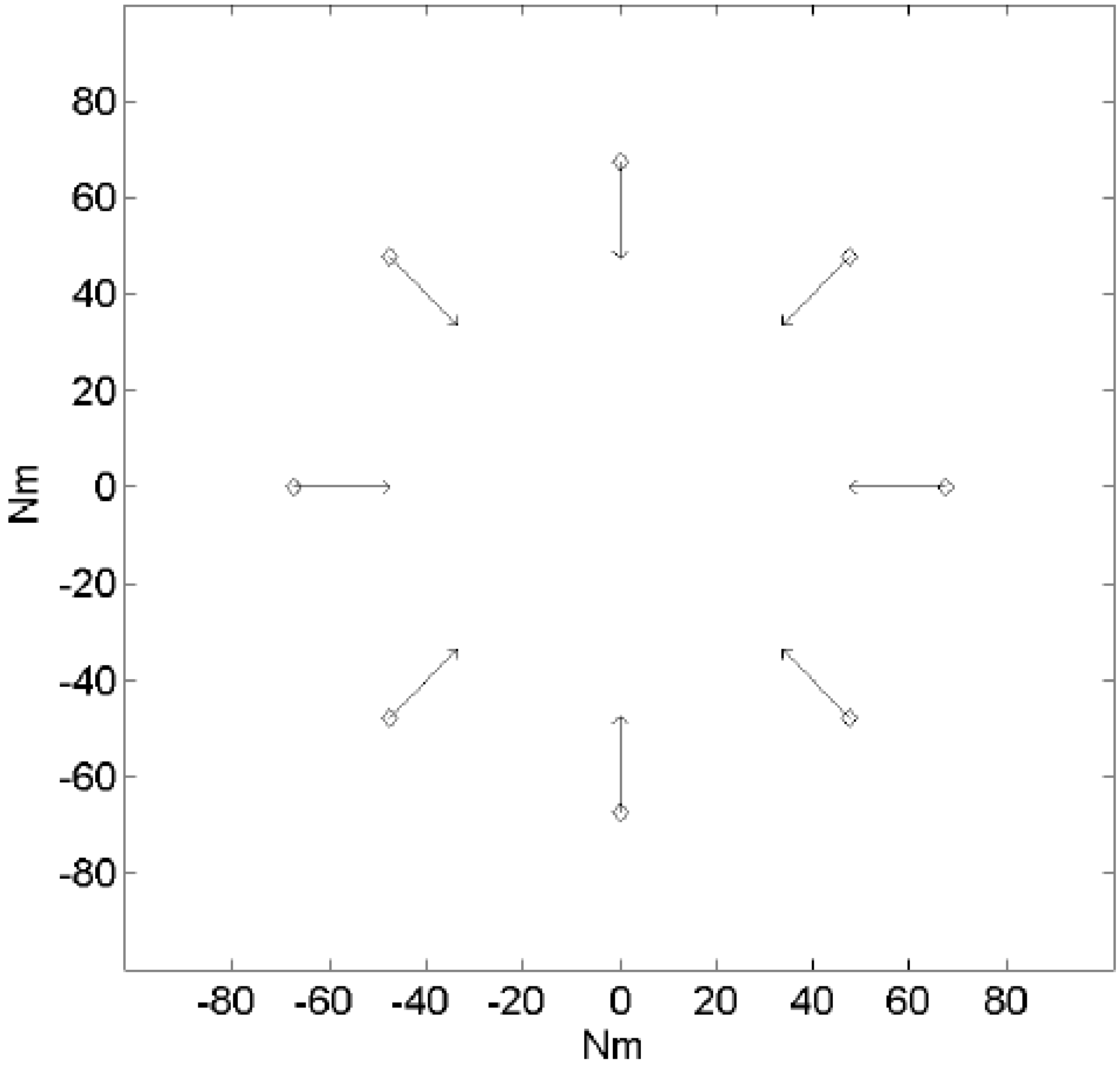
EMERGIA project addresses the research question:

- Can a ground-based version of the A3 ConOps produce similarly positive emergent behaviours/properties ?

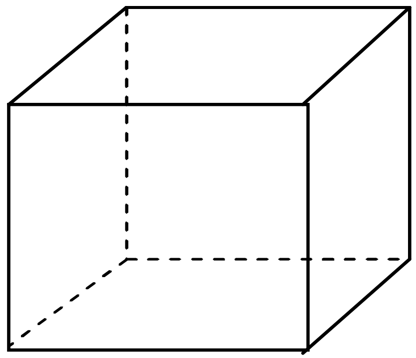
Two crossing traffic flows



8 a/c encounter scenario



Random Traffic Scenario



- Periodic Boundary Condition (PBC)
- Eight a/c per packed box/ no climbing or descending a/c
- Vary container size in order to simulate:
  - 3x as dense as high density area in 2005

ABMS in MAREA and EMERGIA

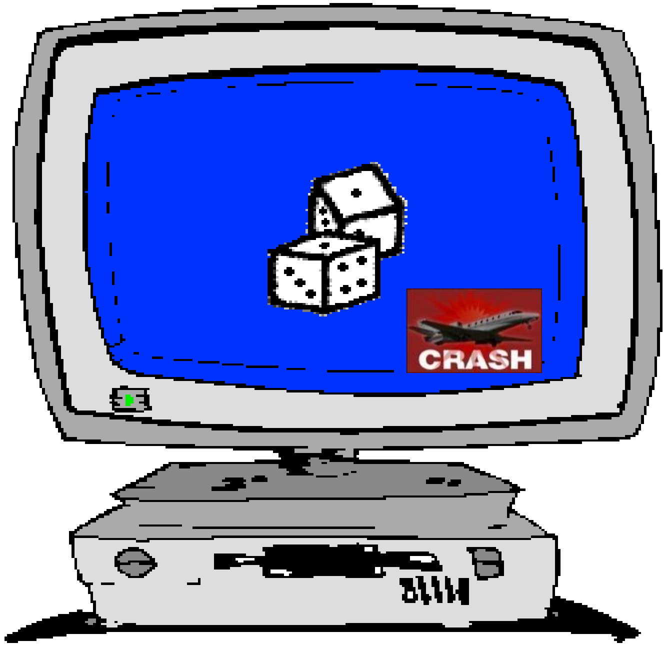
Part 1: Type of problem

Part 2: Techniques

- Uncertainty and rare event simulation in an ABM
- Development framework/platform/tools used
- Agent-based hazards modelled in MAREA
- Agents modelled in EMERGIA
- Systematic variation of parameter values in EMERGIA
- EMERGIA input and output data

Part 3: Results

Uncertainty and rare event simulation in an ABM



Monte Carlo (MC) simulation

- Conduct N simulation runs with ABM
- Per run: use independent random numbers
- Count number C of runs with a specific event
- Estimated event risk = C/N per ABM run

- Emergent behaviour:
  - Backtracking of interactions and behaviour in these C runs

- Challenges:
  - Acceleration of MC simulation to reduce CPU time
  - Managing large CPU memory needs
  - Managing backtracking in big data output

ABMS development framework: TOPAZ
-Traffic Organization and Perturbation AnalyZer-

Modelling framework:

- Syntax: ***SDCPN*** (Stochastically and Dynamically Coloured Petri Net)
- Semantics: Based on literature and long term research collaboration with safety experts, cognitive psychologists, and ABMS experts.
- Computer language: C++, Java, Delphi, ..

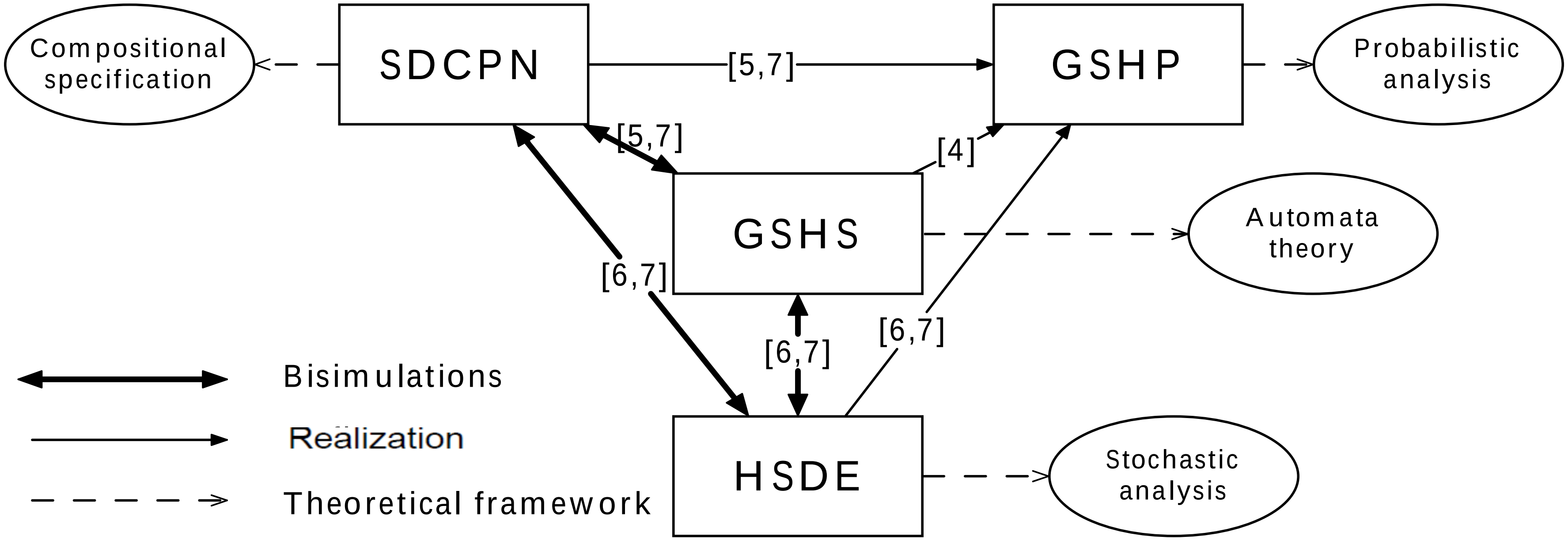
Data Base:

- Previously developed SDCPN models of various agents
- Library of agent-based hazard sub-models by ***MAREA***
- Parameter value knowledge (statistics and expert based methods)

Verification & Validation techniques:

- ABM and ABMS systematic verification protocols
- Face value validation of ABMS results by ATM (design) experts
- Systematic assessment of differences between ABM and reality
  - Sensitivity/elasticity analysis
  - Uncertainty quantification

Mathematical power of SDCPN modelling syntax

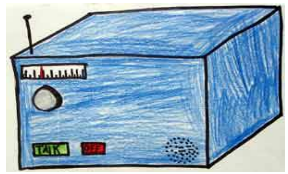


[4]: [Bujorianu & Lygeros, 2006]
[5]: [Everdij & Blom, 2006]
[6]: [Everdij & Blom, 2010]
[7]: [Everdij, 2010]

WP-E project MAREA
Agent-based modelling of hazards in aviation


- Hazard = “Anything that may influence the operation”
  - Events / conditions / performance aspects
  - Humans / systems / environment
  - Interactions






TOPAZ Hazard Database

- 4000+ hazards
- Source: 15+ years conducting hazard identification and safety assessment projects in aviation

Agent-based modelling of aviation hazards

MAREA identified 38 agent-based hazard models (Stroeve et al., 2012)

- 13 from TOPAZ applications (NLR)
- 11 from LEADSTO applications (VU)
- 14 newly identified by MAREA

These 38 can model 98% of aviation hazards (Stroeve et al., 2013)

Integration of these agent-based hazard models (Bosse et al., 2013)

Technique used: Mental simulation of agent-based hazard model

Top 5 of agent based hazard models

Rank	% of hazards
1. Multi Agent Situation Awareness differences	41%
2. System Modes (Configurations, Failures)	20%
3. Basic Human Errors (Slips, Lapses, Mistakes)	18%
4. Human Information Processing (human simulation models)	14%
5. Dynamic Variability (aircraft dynamics simulation)	9%

- Models ranking 2 through 5 are familiar
- Highest ranking model is a multi agent extension of Endley's (1995) Situation Awareness model
- Several other valuable models, such as e.g. Uncertainty, Surprise, Learning, Access Rights, Group Emotion.

Agents in EMERGIA's iA3G model

For each aircraft i, with i = 1,..,N:

- Aircraft-i
- a/c-i's Guidance, Navigation and Control (GNC)
- Pilot-Flying-i
- Pilot-Not-Flying-i

For the ATC system:

- ATC ground system
- MTCR-IIS within ATC ground system
- STCR-IIS within ATC ground system
- Air Traffic Controller (ATCo)
- Global Communication, Navigation & Surveillance systems

Total number of agents: 4N+5
Total number of entities: 46N+17

EMERGIA specifics: input and output data

Input data through an electronic spreadsheet:

- iA3G model parameter values
- Scenario type and duration
- Wind input simulation model
- Number of CPU cores to be used
- Number of MC simulation runs to be conducted per CPU core
- Selection of data storage mode: normal, or backtracking support mode

Output data:

- Normal mode: miss distance, time and aircraft involved, for each MC run
- Backtracking support mode: full ABM state history, for most risky MC runs (1GB)

Visualization:

- In normal mode: pre-defined graphs and miss distance figures
- In backtracking support mode: case-selected visualization of aircraft encounter evolution in combination with agent actions.

EMERGIA specifics: agents and parameter values

Novel agents:

- MTCR-IIS within ATC ground system
- STCR-IIS within ATC ground system

ABM parameters:

- Total: 164
- Varied within EMERGIA: 43

Strategy in Parameter value variation:

1. Adopt parameter values from A3 model and known ATC system values
2. Evaluate performance of novel model on 8 a/c encounters
3. Thighten parameter values until novel model performs similar to A3 model
4. For each thightened novel model value find out how much it can be relaxed
5. Test if the combination of relaxed novel model values performs as A3 model
6. If OK, then this defines the set of novel baseline model parameter values
7. Sensitivity analysis is done relative to novel baseline model parameter values

ABMS in MAREA and EMERGIA

Part 1: Type of problem

Part 2: Techniques

<u>Part 3: Results</u>

- KPA's measured
- Milestones in EMERGIA project
- Graphical presentation of MC simulation results
- Backtracking of output data from MC simulation results
- iA3G vs. A3
- Findings in terms of emergent behaviour/properties

KPA's measured within EMERGIA

- Capacity: Factor more traffic than in a busy en-route sector in 2005
- Human Task load: Activity frequencies of Pilots and ATCo's
- Safety: Event frequency as a function of decreasing miss distance
- Efficiency: % extra flight length
- Parameter value requirements

EMERGIA key ABMS milestones

2013: ABMS of a ground-based version (A3G) of A3 ConOps

2014: Rare event simulation shows weak A3G performance

- 22 documented rare event simulation figures (~ 1 million runs each)

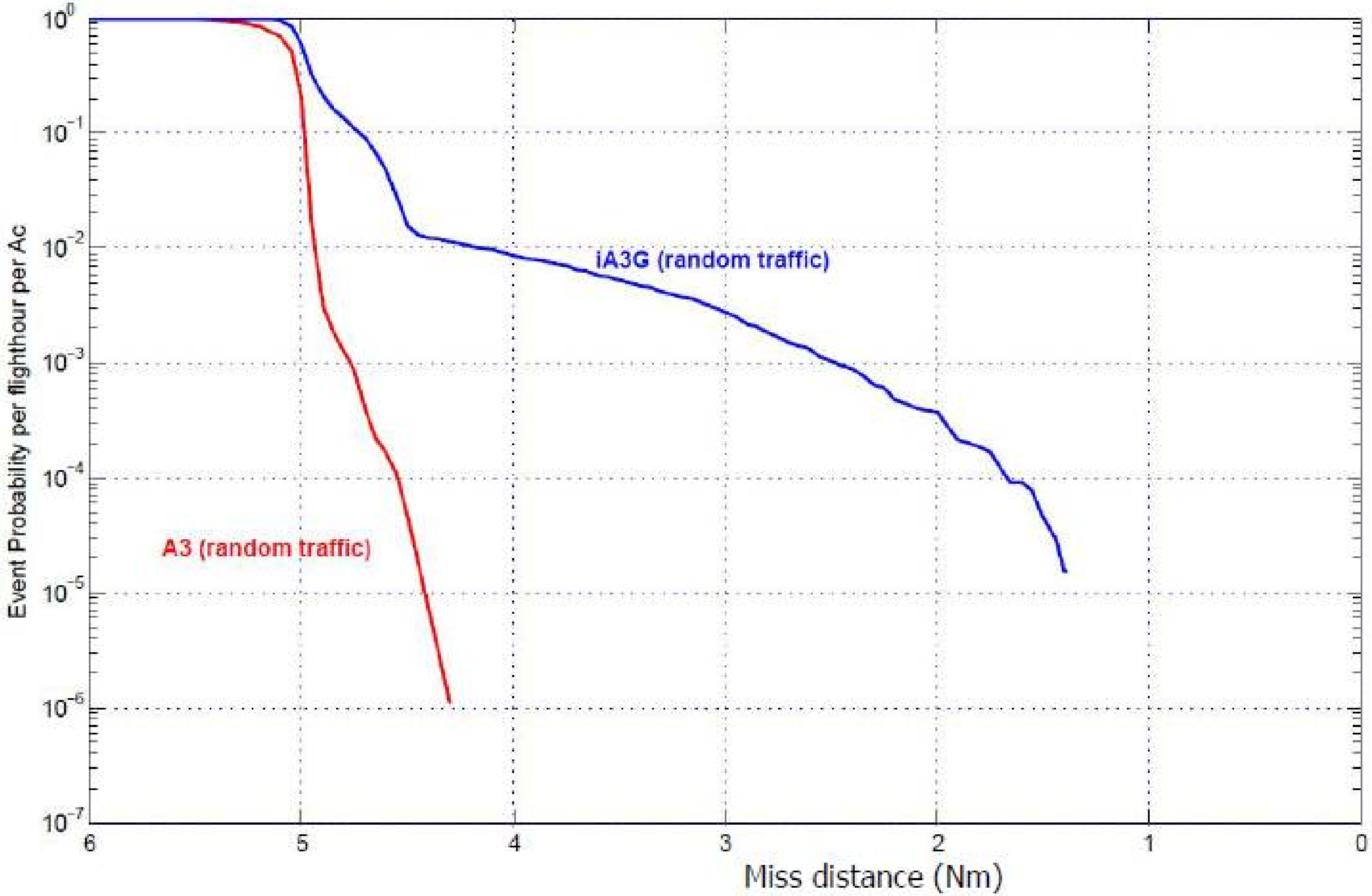
2015a: Design team uses feedback to improve A3G (iA3G)

2015b: ABMS of iA3G shows good nominal performance

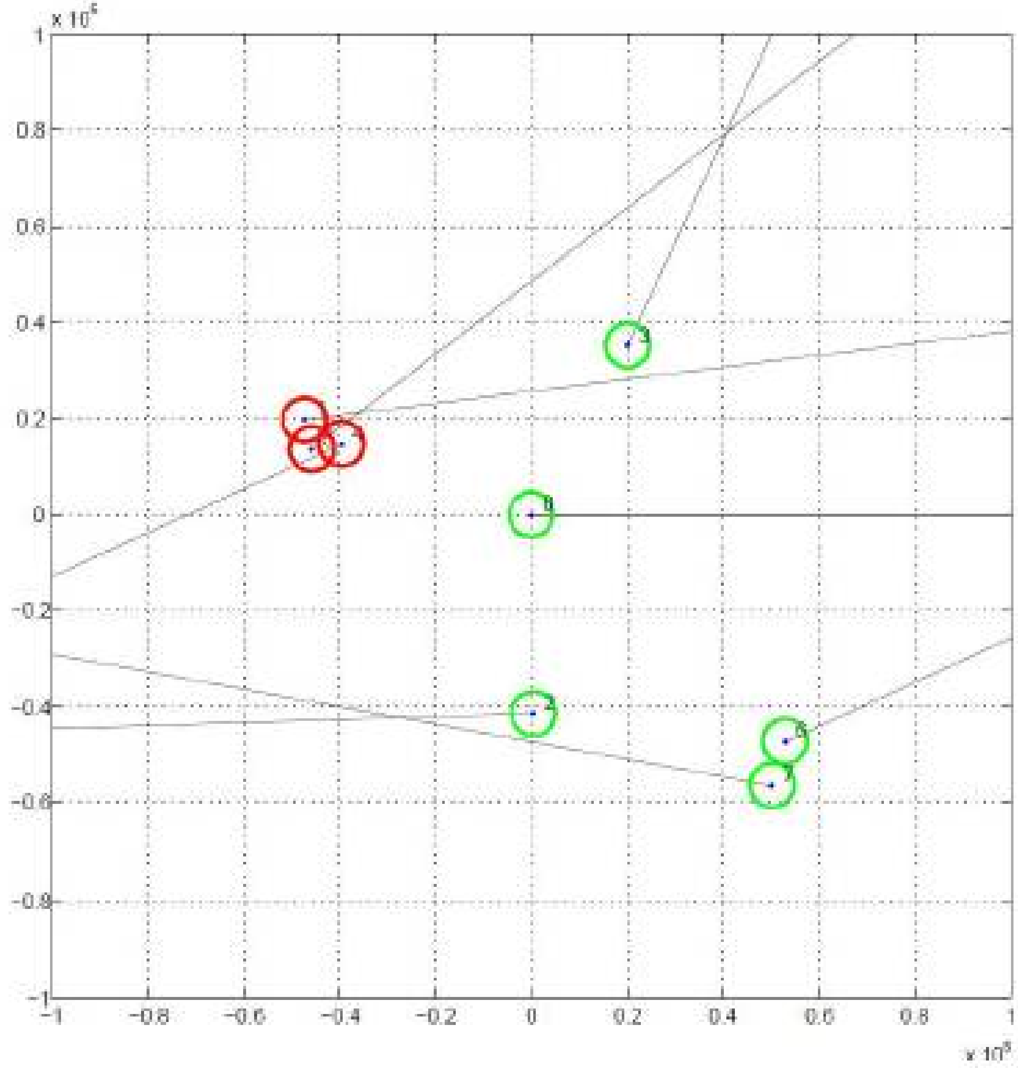
2016: Rare event simulation shows promising iA3G performance, but below A3's

- 32 documented rare event simulation figures (~ 1 million runs each)

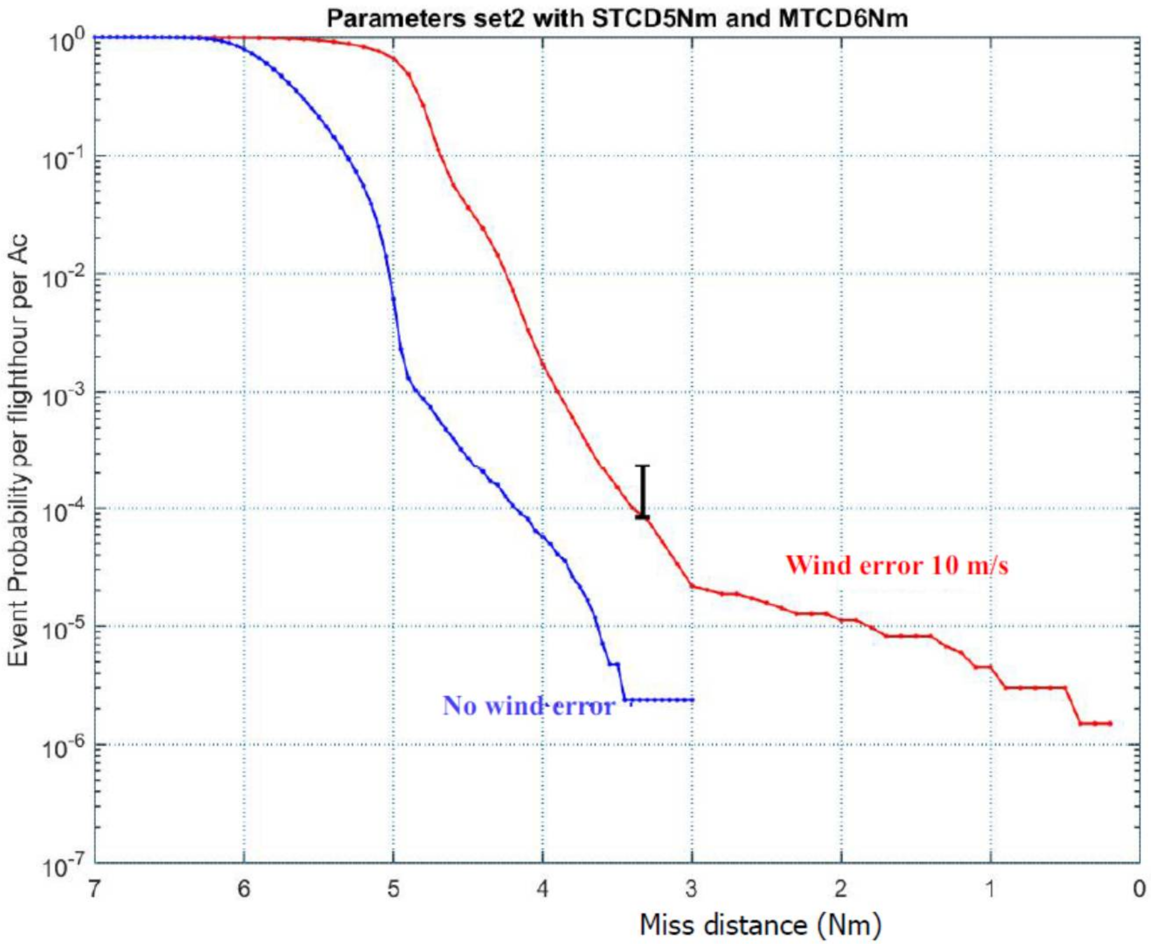
iA3G result that asked for backtracking



iA3G backtracking finding

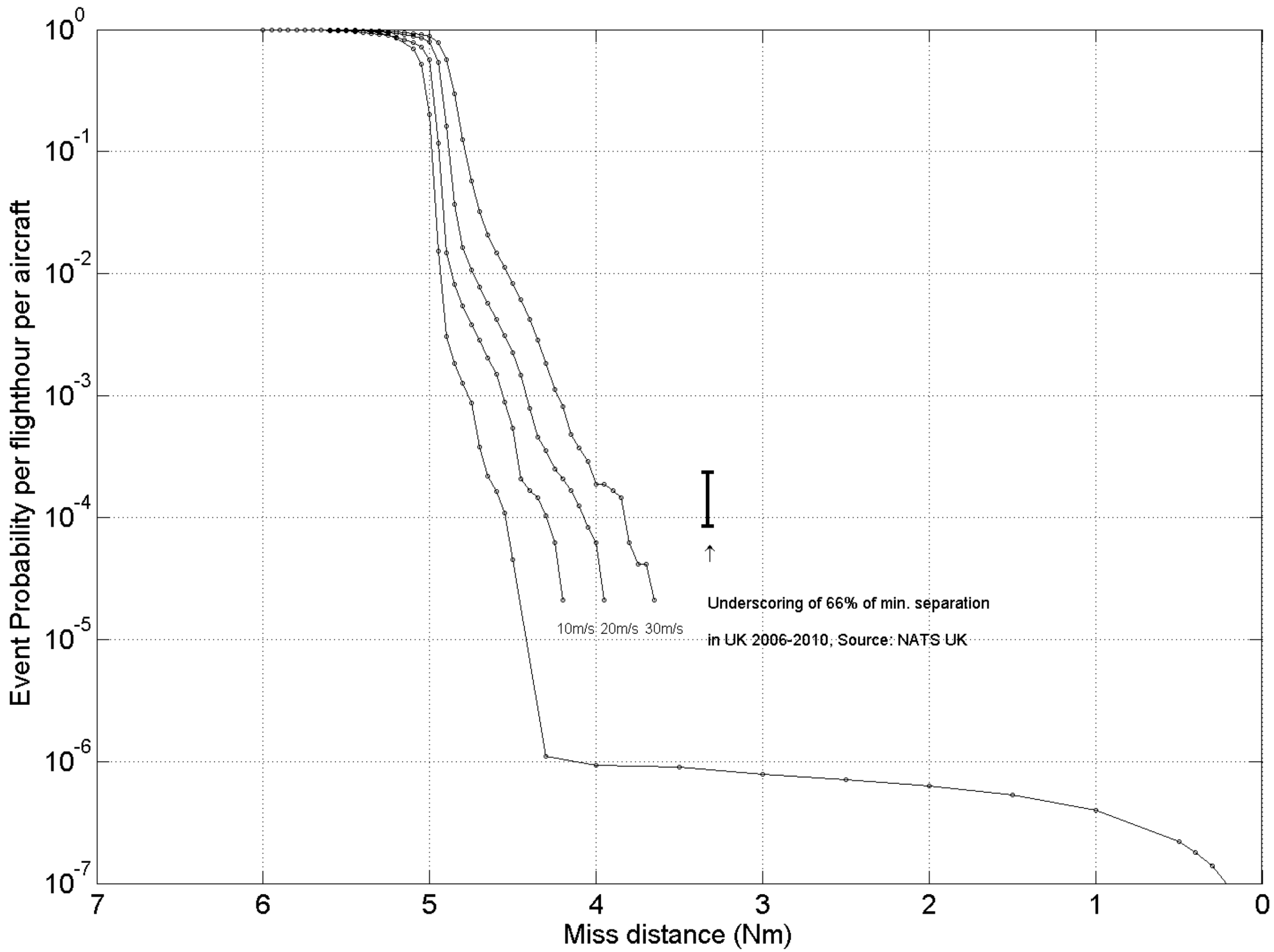


iA3G rare event simulation result



Typo:
Wind error 10 m/s should be Wind error 30 m/s

A3 rare event simulation result



Parameter value requirements

P#	Key model parameter	Baseline
P0	ANP / Separation / Resolution *minima*	1/5/6 Nm
P1	GNSS receiver *failure prob.*	1.0E-7
P2	ADS-B transmitter *failure prob.*	1.0E-8
P3	ATC Ground system *failure prob.*	1.0E-7
P4	ADS-B ground receiver *failure prob.*	1.0E-7
P5	Uplink or ADS-B *frequencies occupied*	1.0E-7
P6	ATCo-T maximum *response time*	1 s
P7	ATCo-P maximum *response time*	30 s
P8	ATC uplink transmitter *sending duration*	1 s
P9	Pilot mean *response time*	5.7 s

EMERGIA main findings

- iA3G Conops has been developed that performs nominally similarly well as A3 ConOps does
- iA3G has less good non-nominal emergent behaviours:
  - Collaboration between layers takes more time
  - iA3G needs resolution spacing **>** minimum separation
  - ATCo taskload puts limit on traffic demand
  - iA3G dependability requirements are higher then A3's
- iA3G ConOps differs significantly from SESAR2020+:
  - Scope: Traffic demand & Equippage
  - TBO layer: Time horizon & MTCR system supporting ATCo-P
  - Tactical layer: Time horizon & STCR system supporting Pilots

Time for Questions

Dedicated to innovation in aerospace

Henk Blom, blom@nlr.nl
ABM Workshop, Pre-SID2016, Delft, 7th November 2016