PDF hosted at the Radboud Repository of the Radboud University Nijmegen

Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013)

Modelling of potential hazards in agent-based safety risk analysis

Henk A.P. Blom[1,2], Sybert H. Stroeve[1], Tibor Bosse[3]
[1]National Aerospace Laboratory NLR, Air Transport Safety Institute, Amsterdam, The Netherlands
[2]TU Delft, Faculty of Aerospace Engineering, Delft, The Netherlands
[3]Vrije Universiteit Amsterdam, Agent Systems Research Group, Amsterdam, The Netherlands
E-mail: blom@nlr.nl, stroeve@nlr.nl, tbosse@few.vu.nl

***Abstract* — One of the key steps in safety risk assessment of an Air Traffic Management (ATM) operation is to identify as many potential hazards as is possible. All these potential hazards have to be analysed upon their possible contribution to safety risk of the operation considered. In an agent-based safety risk assessment of ATM operations there are two approaches towards the assessment of the safety risk impacts of hazards. The direct way is to incorporate the hazard in the agent-based model, and to assess this agent-based model on safety risk by conducting Monte Carlo simulations. The alternative is to avoid the modelling of a potential hazard in the agent-based model, and instead assess the impact of the hazard on safety risk through sensitivity analysis and bias and uncertainty assessment. Because agent-based modelling and simulation of hazards might reveal emergent behaviour that remains invisible through sensitivity analysis, there is a need to understand how to model various hazard types in an agent-based model. In order to comply with this need, this paper identifies 38 model constructs that are able to capture more than 97% of the potential ATM related hazards in an agent-based model. The paper also shows that four of the five main model constructs are related to four widely used modelling domains in aviation, i.e. system reliability, human performance simulation, human reliability analysis, and aircraft trajectory simulation. However, the model construct that captures the highest percentage of hazards (41%) is related to the more recent domain of multi-agent systems modelling.**

Keywords- Agent-based modelling; Safety; Human performance; Hazards; Multi-agent dynamic risk modelling

I. INTRODUCTION

Air Traffic Management (ATM) is a complex socio-technical system with various interacting human operators and technical systems, which aims to safely and efficiently control air traffic under various conditions. Motivated by the need to model the dynamics, the stochastics and the interactions of safety-critical multi-agent systems in advanced ATM concepts of operations, NLR has developed the TOPAZ (Traffic Organization and Perturbation AnalyZer) safety risk assessment methodology, e.g. [1, 2].

The quantitative part of the TOPAZ methodology develops an agent-based model of the operation considered, and subsequently uses this model in rare event Monte Carlo (MC) simulation and bias and uncertainty analysis. Preceding to this quantitative part, the TOPAZ methodology comprises a qualitative part which identifies the ATM Concept of Operations (ConOps) to be considered and identifies potential hazards of this ConOps. All identified hazards should be taken into account during the quantitative risk assessment part.

The TOPAZ methodology supports two quantitative approaches in taking a hazard into account. The first approach is to assure that the hazard is captured in the agent-based model that is used for the MC simulations. The second approach is to assess the safety risk impact of the hazard during the bias and uncertainty assessment. The advantage of the former approach is that potential emergent behaviour of a hazard is assessed through MC simulations. The disadvantage is that it tends to make the multi-agent model more complex. Because of this trade-off, for a specific TOPAZ application it is common practice to decide for each hazard how to cover it: either through the agent-based model and simulation, or through the bias and uncertainty assessment.

For the majority of the hazards identified during the qualitative phase within TOPAZ it is known how to model them in an agent-based setting. However there are hazards for which it is not yet known how to capture them in an agent-based model. For this latter category of hazards the only choice available is to assess them through bias and uncertainty assessment. The aim of this paper is to significantly enlarge the set of hazards for which it is known how to model them in an agent-based setting. The expected value of accomplishing this is two-fold:

- It completes an agent-based modelling perspective on the large variety of hazards occurring in ATM.
- It lifts the restriction that certain hazards can only be evaluated through bias and uncertainty assessment.

The paper is organized as follows. Section II provides an explanation of the handling of hazards within the TOPAZ safety risk assessment methodology. Section III presents an overview of a large database of hazards identified during various ATM safety risk analysis studies. Section IV identifies a series of model constructs that allow incorporating almost all hazards from this database in an agent-based model. Section V provides an analysis of the relative importance of the various model constructs to model hazards in an agent-based setting. Finally, Section VI draws conclusions.

II. MULTI AGENT DYNAMIC RISK MODELLING (MA-DRM)

The quantitative modelling and analysis approach in use within TOPAZ integrates the following five computational modelling techniques:

- Agent-based Modelling (ABM);
- Human performance modelling;
- Powerful Petri Net modelling syntax;
- Rare event Monte Carlo (MC) simulation;
- Sensitivity and Bias and uncertainty analysis.

The integrated use of these complementary techniques is also referred to as Multi Agent Dynamic Risk Modelling (MA-DRM). The motivation for integrating each of these complementary techniques is shortly described next.

From a complexity science perspective, ABM forms a logical choice for the evaluation of advanced ATM designs. To conceptualise processes in the world, and in particular open socio-technical systems such as the ATM system, often an agent-oriented perspective is a useful conceptual tool. An ABM approach allows the researcher to consider the world's dynamics to be composed from dynamics based on separate but interacting processes, e.g. [3, 4]. By having distinguished a number of agents and their interaction, the overall process can be analysed as emerging from the individual agent processes and their interactions. This provides a highly modular and transparent way of structuring a model, thus supporting analysis, both conceptually and computationally. From a hazard modelling perspective this means that for each hazard it is identified which agents are involved, and how each agent involvement can be captured in the corresponding agent model.

Within a TOPAZ application, human agents as well as technical agents are captured in an ABM by using the wide sense agent type definition of [5]: "An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors." This also means that human operators and technical systems can be modelled through clearly distinguishable (groups of) agents. For the modelling of technical systems, the model details typically can be extracted from technical specifications of the specific systems involved. For a human agent an agent-based model will be developed by integrating various human performance sub-models, e.g. [6, 7]. In addition to this, shared and distributed Situation Awareness (SA) across various agents is modelled using an extension of the situation awareness (SA) model of Endsley [8] to a multi-agent SA (MASA) propagation model [9, 10].

This MASA model makes explicit that in a multi-agent system, SA propagates from one agent to another agent. This is comparable to the game of 'Chinese whisper', where the first person whispers a sentence in the ear of the next person, who whispers what he understood to the next person, etc. Just as in Chinese whisper, where mishearing may sneak in without noticing by the participants, errors may sneak in the SA's of agents in a multi agent system without noticing by the agents.

Because an ATM operation involves many human and technical agents, and each of these agents performs dedicated tasks and functionalities, the resulting ABM tends to be large. In order to manage the systematic development of a mathematical model of such operation, use is made of the powerful Petri Net (PN) syntactical framework developed by [11-14]. The syntax of this powerful PN framework does not pose limitations on the model semantics. An additional challenge is that ATM safety analysis requires covering many magnitude orders in time scales. This can only be accomplished through making use of dedicated rare event MC simulation techniques, e.g. [15, 16].

Finally there is a sensitivity and bias and uncertainty analysis technique [17] which allows assessing the impact of potential differences between the true operation and the agent-based model on the risk level assessed. The types of differences that can be taken into account are: errors in parameter values, hazards not modelled, model structure differences from reality and potential differences in ConOps interpretation by the modellers and how it was meant to be by the ConOps design team.

The above described MA-DRM approach has been applied for safety risk assessment of various ATM operations, such as: Simultaneous landing on converging runways [18], Active runway crossing operations [19] and airborne self-separation [20, 21]. For the active runway crossing operation also a systematic comparison of the MA-DRM approach against a classical event sequence based approach has been made [22, 23]. This revealed many advantages of the former, including considerable differences in the risk results obtained. The only disadvantage is that the former requires significant computational modelling and rare event simulation background.

III. HAZARDS IN ATM OPERATIONS

In the process of analysing the safety of air transport operations, a prime means in gathering potential hazards is by brainstorm sessions with pilots, controllers and other experts. These hazard brainstorm sessions aim to push the boundary between functionally imaginable and functionally unimaginable hazards [24]. Consequently, considerable parts of these hazard brainstorm sessions address human behaviour, including various conditions and technical systems that influence human behaviour and interactions between humans. Since 1995, the hazards identified in a broad range of ATM safety risk assessments have been collected at NLR in an ATM Hazard Database. This collection of hazards contains now more than 4000 hazards, though includes equal or similar hazards and hazards that refer to a study-specific context, e.g. airport layout or route structure.

In [25] all hazards in the ATM Hazard Database have been analyzed in order to select the unique hazards and to formulate them in a generalized way (i.e. without referring to study-specific details). This resulted into a total number of 525 generalized hazards. Subsequently these 525 generalized hazards have been structured in 13 specific clusters as shown in

Table I. Each hazard is included in one cluster only, also when the hazard might have been included in multiple clusters.

It can be observed in Table I that the hazards cover a wide spectrum of issues in ATM, dealing with technical systems, human operators and the organization of ATM.

TABLE I. NUMBER OF HAZARDS PER CLUSTER AND HAZARD EXAMPLES

Hazard cluster	**Number**	**Examples of hazards**
Aircraft systems	27	• Aircraft cannot perform requested manoeuvre, since it is over its performance limits • False alert of an airborne system
Navigation systems	16	• Wrong waypoints in database, e.g. due to update of flight management system software, errors in database, outdated database
Surveillance systems	27	• Transponder sends wrong call-sign • Track drop
Speech-based communication	37	• Failure in frequency changes between subsequent air traffic controllers • Standard R/T not adhered to
Datalink-based communication	20	• Controller does not send a data-link message and forgets to give a clearance by voice
Pilot performance	124	• Over-reliance on system data • Pilot does not know the complexity of the traffic situation • Alert causes attention tunnelling • Change in ATC procedures leads to confusion by pilots • Pilot mixes up different types of ATC clearances • Pilot is fatigued and sleepy • Pilot validates without actually checking
Controller performance	110	• Risk of a conflict is underestimated • Controller wrongly evaluates traffic situation after an alert • Change of ATC procedures affects fluency of controller's performance • Controller has a wrong awareness about the intent of aircraft • Controllers getting used to new systems, such that it becomes hard to do without
ATC systems	25	• Flight plans of ATC system and FMS differ
ATC coordination	24	• ATC centres have different versions of aircraft trajectory plans • Controller is overloaded with coordination tasks
Weather	27	• Weather forecast wrong • Strong variation in view (e.g. due to snowfall or fog patches)
Traffic relations	33	• Resolution of conflict leads to other conflict(s) • Differences in performance of different aircraft types, e.g. at a merging point
Infrastructure & environment	24	• Animals on the runway • Approach lights are not visible
Other	31	• Contingency procedures have not been tested • Insufficient capacity of an ATC centre due to strike or illness

IV. IDENTIFICATION OF AGENT-BASED MODEL CONSTRUCTS

A schematic overview of an open multi-agent model is shown in Figure 1. This figure, although kept simple for presentation purposes, is in principle representative for any system that can be conceptualised as a multi-agent system (i.e., a system involving *n* agents that interact with each other and with external processes). The model is called open because it includes interaction of the system with external processes such as the weather. Note that the notion of agent can refer to any autonomous system that acts in its environment in order to achieve its goals [26]. Human beings (e.g. pilots or air traffic controllers) as well as an 'autonomous' technical systems (e.g., intelligent computer systems like autopilots) may be conceptualised as agents. Hence, ATM operations fit well within a multi-agent system framework.

Each agent model can integrate several agent-based model constructs. The identification of agent-based model constructs is based on the list of hazards presented in Section III. About half of the hazards of this list were selected randomly for the model construct identification phase. The other half was set aside for a later validation phase.

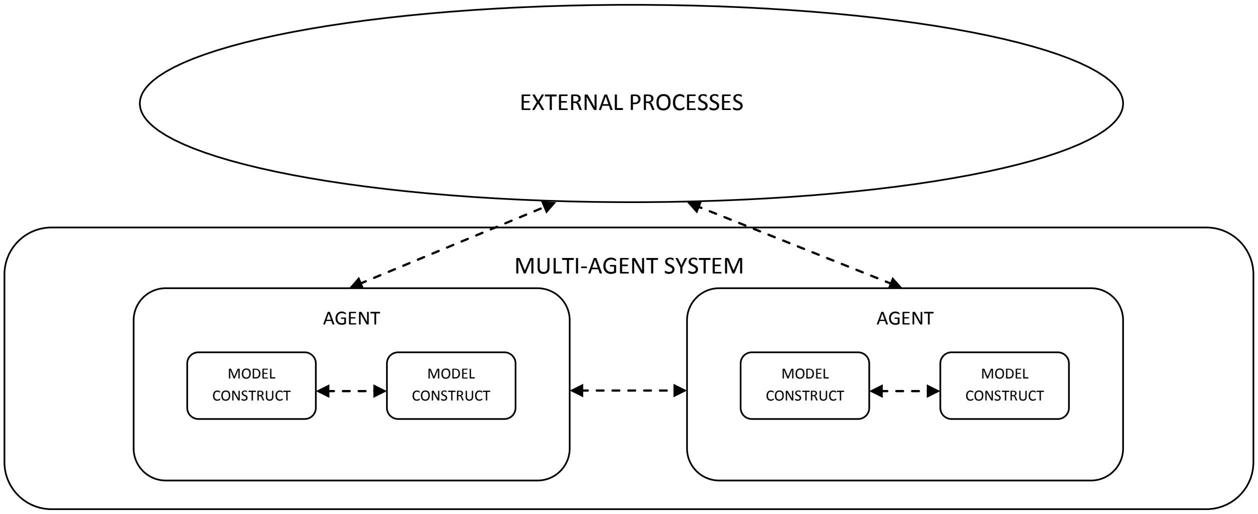

Figure 1. Schematic overview of an open hierarchical multi-agent model.

For each hazard in the model construct identification set, it was analysed which model construct or combination of model constructs could represent it. This was done by performing ‘mental simulation’, i.e. qualitative reasoning by a team of analysts about the way that the models can reflect a hazard. The result of this analysis is that a hazard can be well covered, partly covered or not covered by the model constructs. As part of the analysis argumentation was provided about the mechanism by which the models can cover a hazard, and the aspects that are yet missing. A detailed overview of the results of the analysis is presented in ([27], Appendix B).

The ‘mental simulation’ based analysis of the hazard modelling capabilities of model constructs was done in three phases. First, the model constructs that have been applied in TOPAZ safety studies were identified and analysed [28], [29]. Table II presents an overview of the 13 TOPAZ based model constructs. ‘Mental simulation’ with these 13 model constructs showed that 58% of the hazards could be modelled well, 11% could be partially modelled and 30% could not be modelled by these 13 model constructs.

During the second phase, 11 complementary model constructs have been identified through searching human performance sub-models that have been applied by the Agent Systems research group at VU University Amsterdam [30]; these are shown in Table III. After this extension, 80% of the hazards could be well modelled, 7% could be partially modelled, and 14% could not be modelled.

During the third phase, 14 novel model constructs were identified for the hazards that had not yet been fully modelled by the TOPAZ and VU model constructs [31]; these 14 model constructs are presented in Table IV.

With the total set of 38 (=13+11+14) model constructs, ‘mental simulation’ based analysis showed that 92% of the hazards could be well modelled, 6% could be partially modelled, and less than 3% could not be modelled.

TABLE I. OVERVIEW OF TOPAZ MODEL CONSTRUCTS

Code	Name	Description
C1	Human information processing (HIP)	HIP considers processing of information from the environment to maintain Situation Awareness (SA) and based on this to take actions that may influence the environment during tasks that the human operator uses for the fulfilment of his/her work [32]. The details of a HIP submodel is based on a task analysis, and takes into account the multiple human resources [32]. This way subtasks and resources are modelled according to time-critical task/resources combinations [6],[33].
C2	Multi-agent situation awareness (MASA)	Situation awareness (SA) addresses perception of elements in the environment, their interpretation and the projection of the future status [8]. MASA has been developed to systematically capture potential differences between SAs of different agents [9],[10]. To accomplish this, MASA addresses the SA of all agents (both human and technical) in a multi-agent model, including the relations between the SA’s of the individual agents. In an air traffic environment the MASA submodel captures the SA of each agent as time-dependent information about the SA of all other agents, including identity, continuous state variables, mode variables and intent variables
C3	Task identification	Based on the premise that a human operator has a number of tasks, this model construct determines the ways that the operator identifies the tasks that need to be performed at a particular time instance.
C4	Task scheduling	Determines which tasks may be performed concurrently as well as a priority among the tasks that cannot be performed concurrently.
C5	Task execution	Describes the performance of a human operator with regard to the execution of a specific task. The performance characteristics depend on the task considered.
C6	Cognitive control mode	This model construct considers that humans can function in a number of cognitive control modes, such as Strategic, Tactical, Opportunistic and Scrambled [34]. The cognitive control mode may depend on human performance aspects such as the range of tasks to be done and the situation awareness of the human.
C7	Task load	Describes the number of tasks to be performed, as considered in the task scheduling process. The task load influences the cognitive control mode of the human operator. At a more detailed level, the task load may also describe the resources required by tasks at the level of visual, auditory, cognitive and motor performance.
C8	Human error	This model construct covers slips, lapses, mode errors and knowledge and rule-based mistakes that may occur during the human information processing steps [35],[32]. It does not represent in detail the mechanisms that may have given rise to the error, but it considers the behaviour resulting from these mechanisms at a probabilistic level for a specific task. The error probability is task specific and is influenced by other model constructs, such as the cognitive control mode. For instance, the probability of an error is higher in the Opportunistic control mode than in the Tactical control mode.
C9	Decision making	A model construct for the decision making process of human operators in safety relevant situations. It describes the decision making on the basis of the situation awareness and decision rules by a human agent.
C10	System mode	Describes the behaviour of a technical system by different modes. These modes are discrete states for the functioning of technical systems, such as failure conditions, system settings, etc. Mode switching may happen stochastically or as a result of an outside input to the technical system.
C11	Dynamic variability	Describes the variability of states of agents due to dynamic processes. For instance, it can describe the movements of an aircraft according to differential equations relating states such as position, velocity, acceleration and thrust.
C12	Stochastic variability	Describes the stochastic variability in the performance of human operators and technical systems. For a human operator it specifies the variability in task aspects (e.g. duration, start time, accuracy) under the given conditions.
C13	Contextual condition	Captures the context of the operation, such as weather, route structure, environmental conditions and airport infrastructure. It has similarity with the model construct System mode (C10). However, the construct System mode is restricted to technical systems.

TABLE II. OVERVIEW OF VU MODEL CONSTRUCTS.

Code	Name	Brief description
MC1	Object-oriented attention	Describes the development of a human's state of attention over time, as a function of the person's gaze direction, the locations of the objects in the environment, and their characteristics (such as their brightness and size).
MC2	(Experience-based) decision making	Describes a person's decision making process, based on either the expected outcomes or the experienced emotional response (called *somatic marker* [36]) of an option.
MC3	Operator functional state	Determines a person's *functional state* as a dynamical state, which is a function of task properties and personal characteristics. The model [37] is based on two different theories: (1) the *cognitive energetic framework*, which states that effort regulation is based on human recourses and determines human performance in dynamic conditions, and (2) the idea that when performing sports, a person's generated power can continue on a *critical power* level without becoming more exhausted.
MC4	Information presentation	This model construct consists of two interacting dynamical models, one to determine the human's functional state (see MC3) and one to determine the effects of the chosen type and form of information presentation.
MC5	Safety culture	A model construct for various aspects of safety culture, including organisational, cultural and individual aspects. An application of the model to an occurrence reporting cycle is available in the context of an existing air navigation service provider [38].
MC6	Situation awareness (with complex beliefs)	An extension of the model of Endsley [8], which includes the perception of cues, the comprehension and integration of information, and the projection of information for future events. In particular, some sophisticated AI-based inference algorithms based on mental models are incorporated, as well as the notion of aggregated complex beliefs.
MC7	Trust	Describes trust as a dynamical, numerical variable which is influenced based on experiences in combination with several individual characteristics.
MC8	Formal organisation	Can be used to model formal organisations from three interrelated perspectives (views): the process-oriented view, the performance-oriented view, and the organisation-oriented view. A formal organisation is imposed on organisational agents, described in the agent-oriented view.
MC9	Learning	Addresses learning in the context of decision making. By neurological learning processes, the decision making mechanism is adapted to experiences, sush that decision choices made are reasonable or in some way rational, given the environment reflected in these past experiences.
MC10	Goal-oriented attention	Describes how an 'ambient' agent (either human of artificial) can analyse another agent's state of attention, and to act according to the outcomes of such an analysis and its own goals.
MC11	Extended mind	Represents the philosophical notion of an *extended mind* [39], i.e., an 'external state of the environment that has been created by an agent and helps this agent in its mental processing'. It can be used to explain the similarities and differences between reasoning based on internal mental states (e.g., beliefs) and reasoning based on external mental states (e.g., flight process strips).

TABLE III. OVERVIEW OF NOVEL MODEL CONSTRUCTS.

Code	Name	Brief description
NM2	Approach	Captures the factors that influence pilot task demand during final approach, based on Task Demand Load (i.e., the objective difficulty of the task performed by the pilot that is flying an approach) and mental load (i.e., the workload as experienced by the pilot performing the task).
NM3	Handling inconsistent information	Probabilistic model for a technical system that, upon receiving inconsistent information as input, generates one of the following four types of response: 1) processing the input information correctly, 2) processing the input information incorrectly, 3) leaving the input information unchanged, and have the user solve the inconsistency, and 4) generating an error message.
NM7	Group emotion	Describes the dynamics of the spread of emotion over a group of individuals, based on personal characteristics of the individuals and relations between individuals.
NM14	Surprise (A)	Describes the generation of surprise based on: 1) expectation disconfirmation, 2) importance of the observed event, 3) valence (i.e., whether the observed event is seen as positive or negative), 4) difficulty of explaining / fitting it in an existing schema, and 5) novelty (contrast with earlier experiences). In this particular case the model is applied to complex procedures.
NM15	Surprise (B)	Describes the generation of surprise based on: 1) expectation disconfirmation, 2) importance of the observed event, 3) valence (i.e., whether the observed event is seen as positive or negative), 4) difficulty of explaining / fitting it in an existing schema, and 5) novelty (contrast with earlier experiences). In this particular case the model is applied to changes in procedures.
NM21	Deciding when to take action	Model that enables an agent to make a deliberation between exploration (i.e., collecting more information about the world state before making an action) and exploitation (i.e., exploiting its current knowledge to choose an action to perform).
NM31	Access rights	Probabilistic model that, based on a request of an actor to have access to the system, determines whether this access in indeed granted or not.
NM32	Merging or splitting ATC sectors	Model that describes the process of merging and splitting ATC sectors as a form of organisational change. Changes in the decomposition of ATC sectors are represented by dynamic re-allocation of agents to roles, triggered by the amount of work load.
NM33	Bad weather	Probabilistic model that represents visibility via multiple discrete modes (e.g., for good visibility, reduced visibility and no visibility), between which switches take place based on statistics of the specific airport considered.
NM34	Weather forecast wrong	Probabilistic model that determines errors in weather forecast, among others, in terms of deviations from predicted wind velocity and direction.
NM35	Turbulence	Probabilistic model that switches between turbulence intensity categories based on specific sources like Convective Induced Turbulence, Clear Air Turbulence, and Mountain Wave Turbulence.
NM36	Icing	Upon receiving input in terms of weather information and de-icing or anti-icing methods, this model determines the extend of ice formation on an aircraft.

NM38	Influence of many agents on flight planning	Represents the influence of many agents on flight planning within organisations, using the generic organisation modelling framework from [40], which includes notions like roles, power relations between roles, and principles of allocation of roles to agents.
NM40	Uncontrolled aircraft	Switches between two discrete modes (controlled and loss of control), depending on the following factors: 1) Significant Systems or Systems Control Failure, 2) Structural Failure and/or Loss of Power, 3) Crew Incapacitation, 4) Flight Management or Control Error, 5) Environmental Factors, 6) Aircraft Load, and 7) Malicious Interference.

TABLE IV. HAZARD MODELLING RESULTS: USE OF THE AGENT-BASED MODEL CONSTRUCTS AND LEVELS OF HAZARDS MODELLING.

Model construct		**Number of hazards**	
C1	Human information processing	38	14.3%
C2	Multi-agent situation awareness	110	41.4%
C3	Task identification	11	4.1%
C4	Task scheduling	15	5.6%
C5	Task execution	21	7.9%
C6	Cognitive control mode	11	4.1%
C7	Task load	5	1.9%
C8	Human error	48	18.0%
C9	Decision making	13	4.9%
C10	System mode	53	19.9%
C11	Dynamic variability	23	8.6%
C12	Stochastic variability	8	3.0%
C13	Contextual condition	17	6.4%
MC1	Object-oriented attention	8	3.0%
MC2	(Experience-based) decision making	11	4.1%
MC3	Operator functional state	22	8.3%
MC4	Information presentation	6	2.3%
MC5	Safety culture	7	2.6%
MC6	Situation awareness with complex beliefs	17	6.4%
MC7	Trust	18	6.8%
MC8	Formal organisation	9	3.4%
MC9	Learning	7	2.6%
MC10	Goal-oriented attention	2	0.8%
MC11	Extended mind	5	1.9%
NM2	Approach	1	0.4%
NM3	Handling inconsistent information	1	0.4%
NM7	Group emotion	1	0.4%
NM14	Surprise (A)	9	3.4%
NM15	Surprise (B)	8	3.0%
NM21	Deciding when to take action	1	0.4%
NM31	Access rights	2	0.8%
NM32	Merging or splitting ATC sectors	1	0.4%
NM33	Bad weather	9	3.4%
NM34	Weather forecast wrong	1	0.4%
NM35	Turbulence	1	0.4%
NM36	Icing	1	0.4%
NM38	Influence of many agents on flight planning	1	0.4%
NM40	Uncontrolled aircraft	1	0.4%
-	Not modelled	6	2.3%

V. HAZARD MODELLING RESULTS

The identification of model constructs in Section IV was based on a 'mental simulation' based analysis of their ability to model hazards in ATM. Table V presents an overview of the number and percentages of hazards covered for each of the 38 model constructs.

It follows from Table V that of the total set of 38 model constructs, there are 10 model constructs that are used for modelling one specific hazard in the set considered. The other 28 model constructs are used for modelling multiple hazards, i.e. ranging from 2 till 110 hazards. The highest number/percentage of hazards (110 / 41.4%) applies for the multi-agent situation awareness construct C2. In addition to C2, also various other model constructs from the TOPAZ base have been applied most frequently[1].

The results in Table V show that the five highest ranking model constructs are:

Rank 1 (41.4%): C2 'Multi-agent situation awareness'

Rank 2 (19.9%): C10 'System mode',

Rank 3 (18.0%): C8 'Human error',

Rank 4 (14.3%): C1: 'Human Information Processing',

Rank 5 (8.6%): C11: 'Dynamic Variability'

The model constructs that rank 2nd through 5th are based on model developments within four widely studied domains, i.e. system reliability analysis, human reliability analysis, human performance simulation, and aircraft trajectory simulation,. In contrast with this, the by far highest ranking model construct C2 'Multi-agent situation awareness' belongs to the novel domain of multi-agent systems. These relations are further explained next.

Number 1: C2, 'Multi-agent SA'. As has been explained in Section II, this model construct has been developed in the domain of agent-based modelling and simulation of ATM operations [9, 10]. The development of this model construct was motivated by the recognition of the many hazards involving differences in between SA of different agents (human-human as well as human-technical system), and that such differences tend to propagate further through the multi-agent system.

Number 2, C10 'System mode' represents a broad range of technical system modes (e.g., failure modes). This kind of model construct corresponds very well with the way how reliability, availability and maintainability of technical systems is modelled in event sequence based analysis.

Number 3, C8 'Human error' represents the basic errors that can be made by a human [35]. These basic errors consist of *slips* in speech, memory or physical actions that arises from the unconscious mind, memory *lapses* and *mode errors* that are due to weak recollection of recent events or data, and knowledge and rule based *mistakes* that may be made by a human. Model construct C6 "Cognitive Control Mode" (4.1%) may have significant impact on C8. It should be

---

[1] The hazard scores for the 25 novel model constructs are influenced by the incremental process that has been followed in the analysis of the hazards. First all hazards were analysed by the TOPAZ-based model constructs, then the remaining hazards were coupled to the novel model constructs.

noticed that C6 and C8 form a small subset only of the large range of human factors considered within the domain of Human Reliability Analysis (HRA), e.g. [41]. For example, in a classical event sequence based safety risk analysis, HRA is used to handle hazards related to model construct C3, but also to handle hazards related to model constructs C1 and C2.

Number 4, C1: 'Human Information Processing', is a model construct that is commonly used in human performance simulation [6]. A significant role is played by the manner how a human operator manages competing task demands. This is captured through model constructs[2]: C3: Task identification (4.1%), C4: Task scheduling (5.6%), C5: 'Task execution' (7.9%; rank 7), C7: 'Task load' (1.9%), and C9: 'Decision making' (4.9%).

Number 5, C11: 'Dynamic Variability' is a model construct that allows using differential equations, for example to model aircraft evolution behaviour. Hence this is a model construct that is commonly used in a large set of real-time and fast-time simulators in aviation. Within TOPAZ the model construct C12 'stochastic variability' typically allows to also model random influences, such as wind variations.

For the 25 newly identified model constructs, the highest applicability has been found for MC3 'Operator functional state' (8.3%; rank 6), which relates task demands, effort, exhaustion and personal characteristics of human operators; MC7 'Trust' (6.8%; rank 8), which represents trust of human operators in technical systems or other human operators; and MC6 'Situation awareness with complex beliefs' (6.4%; rank 9), which represents formation of complex beliefs on the basis of observations and mental models.

VI. CONCLUSIONS

As demonstrated in various TOPAZ applications and evaluations [18-22], multi-agent dynamic risk modelling (MA-DRM) is a powerful approach in safety risk assessment of changes in ATM operations. In particular, this agent-based modelling approach provides the capability to represent the performance and interactions of agents in the ATM socio-technical system, and to derive accident risk as an emergent property by Monte Carlo simulations.

Through a series of studies [29-31], 38 specific model constructs have been identified that allow to model (partially) well over 97% of the large set of hazards considered. Of these 38 model constructs, 13 are commonly in use within the TOPAZ safety risk assessment methodology, and 25 are novel. The 13 TOPAZ based model constructs appear to be able in modelling about 70% of the hazards (partially) well. Together with the 25 novel model constructs this percentage increases to over 97%. In other words, the percentage of hazards for which it is not fully known how to model them in an agent-based approach has been reduced from 30% to less than 3%. For MA-DRM applications this means that the percentage of hazards for which the risk impact could only be assessed through bias and uncertainty assessment has been reduced from 30% to less than 3%.

The results obtained in this paper also show that the top five ranking hazard model constructs are all coming from the TOPAZ base. The highest ranking model construct C2 'Multi-agent situation awareness' belongs to the novel domain of multi-agent systems. The model constructs that rank 2nd through 5th are based on developments within four widely studied modelling domains in aviation:

- System reliability analysis,
- Human reliability analysis (HRA)
- Human performance simulation,
- Aircraft trajectory simulation.

It also was noticed that in an agent-based modelling and simulation approach, HRA has to capture a much smaller subset of hazards then it has to do in a classical event sequence based safety risk analysis. For example, in a classical event sequence based approach, hazards related to the model constructs C1 (Human Information Processing) and C2 (Multi-agent Situation Awareness) have also to be covered by HRA, whereas in an agent based approach these are covered through models from the human performance simulation and multi-agent modelling and simulation domains.

In follow-up research it will be studied how the 25 newly identified model constructs can be integrated with the 13 existing TOPAZ based model constructs. A complementary question that will be studied is which of the 38 model constructs should be incorporated in an agent-based model and which should better be covered through bias and uncertainty analysis. As it has been explained in the introduction, the advantage of the former approach is that potential emergent behaviour of a hazard is assessed through MC simulations. A disadvantage is that it tends to make the multi-agent model more complex. Because of this trade-off, for each hazard there should be some optimal way in capturing its impact on the safety risk. For a specific application, such optimum can then for example be reached by an iterative development of a Multi-Agent Dynamic Risk Model (MA-DRM).

Complementary follow-up research is to use the agent-based model constructs of hazards in the continuation of our study [28] of a mathematical approach towards resilience engineering.

ACKNOWLEDGEMENT

The research presented in this paper was done in the project Mathematical Approach towards Resilience Engineering in ATM (MAREA), which is a part of the SESAR WP-E programme on long-term and innovative research in ATM. It is co-financed by Eurocontrol on behalf of the SESAR Joint Undertaking.

---

[2] In [29] these complementary model constructs are assumed to make implicit part of the the model construct C1.

DISCLAIMER

The paper does not purport to represent views or policies of VU, NLR, Eurocontrol or SESAR-JU. The views expressed are those of the authors.

REFERENCES

[1] Blom HAP, Bakker GJ, Blanker PJG, Daams J, Everdij MHC, Klompstra MB. Accident risk assessment for advanced air traffic management. In: Donohue GL, Zellweger AG, editors. Air Transport Systems Engineering: AIAA; 2001. p. 463-80.

[2] Blom HAP, Stroeve SH, De Jong HH. Safety risk assessment by Monte Carlo simulation of complex safety critical operations. In: Redmill F, Anderson T, editors. Developments in Risk-based Approaches to Safety: Proc. 14th Safety-citical Systems Symposium, Bristol, UK, 7-9 February 2006: Springer; 2006.

[3] Aleksander I. Impossible minds: My neurons, my consciousness. London, UK: Imperial College Press; 1996.

[4] Dobbyn C, Stuart S. The self as an embedded agent. Minds and Machines. 2003, Vol. 13, pp. 187-201.

[5] Russel S, Norvig P. Artificial Intelligence: a Modern Approach: Pearson Education Asia Limited and Tsinghua Univ. Press; 2006.

[6] Foyle DC, Hooey BL (Eds.), Human performance modeling in aviation, Boca Raton, (FL), USA, CRC Press, 2008

[7] Blom HAP, Corker KM, Stroeve SH. On the integration of human performance and collision risk simulation models of runway operation. 6th USA-Europe ATM R&D Seminar, Baltimore, USA, 2005.

[8] Endsley MR. Toward a Theory of Situation Awareness in Dynamic Systems. Human Factors: The Journal of the Human Factors and Ergonomics Society. 1995, Vol. 37, pp. 32-64.

[9] Stroeve SH, Blom HAP, Bakker GJ. Multi-agent situation awareness error evolution in accident risk modelling. 5th USA/Europe Air Traffic Management R&D Seminar, Budapest, Hungary, 2003.

[10] Blom HAP, Stroeve SH. Multi-agent situation awareness error evolution in air traffic. Proc. Probabilistic Safety Assessment and Management: PSAM 7 - ESREL '04, Berlin, Germany, 2004.

[11] Everdij MHC, Blom HAP. Hybrid Petri Nets with diffusion that have into-mappings with generalised stochastic hybrid processes. In: Blom HAP, Lygeros J, editors. Stochastic Hybrid Systems: Theory and Safety Critical Applications. Springer, Berlin, 2006. pp. 31-63.

[12] Everdij MHC, Blom HAP. Piecewise deterministic Markov processes represented by Dynamically Coloured Petri Nets. Stochastics. 2005; Vol. 77, pp. 1-29.

[13] Everdij MHC, Klompstra MB, Blom HAP, Obbink BK. Compositional specification of a multi-agent system by stochastically and dynamically coloured Petri nets. In: Blom HAP, Lygeros J, editors. Stochastic hybrid systems: Theory and safety critical applications: Springer; 2006. pp. 325-350.

[14] Everdij MHC, Blom HAP. Hybrid state Petri nets which have the analysis power of stochastic hybrid systems and the formal verification power of automata. In: Pawlewski P, editor. Petri Nets. Vienna, Austria: I-Tech Education and Publishing; 2010. pp. 227-252.

[15] Blom HAP, Bakker GJ, Everdij MHC, Van der Park MNJ. Collision risk modelling in air traffic. Proc. IFAC European Control Conference 2003, Cambridge, UK, 2003.

[16] Blom HAP, Krystul J, Bakker GJ, Klompstra MB, Klein Obbink B. Free flight collision risk estimation by sequential Monte Carlo simulation. In: Cassandras CG, Lygeros J, editors. Stochastic hybrid systems; recent developments and research trends. Boca Raton, USA: CRC Press; 2007. pp. 249-281.

[17] Everdij MHC, Blom HAP, Stroeve SH. Structured assessment of bias and uncertainty in Monte Carlo simulated accident risk. Proceedings 8th Int. Conf. on Probabilistic Safety Assessment and Management, New Orleans, USA, 2006.

[18] Blom HAP, Klompstra MB, Bakker GJ. Accident risk assessment of simultaneous converging instrument approaches. Air Traffic Control Quarterly. 2003; Vol. 11, pp.123-155.

[19] Stroeve SH, Blom HAP, Bakker GJ. Systemic accident risk assessment in air traffic by Monte Carlo simulation. Safety Science. 2009; Vol. 47, pp. 238-249.

[20] Blom HAP, Klein Obbink B, Bakker GJ. Simulated safety risk of an uncoordinated airborne self separation concept of operation. ATC Quarterly. 2009; Vol. 17, pp. 63-93.

[21] Blom HAP, Bakker GJ. Can airborne self separation safely accommodate very high en-route traffic demand? Proc AIAA ATIO Conf., Indianapolis, Indiana, USA, 2012.

[22] Stroeve SH, Blom HAP, Bakker GJ. Contrasting safety assessment of a runway incursion scenario by event trees and agent-based dynamic risk modelling. Ninth USA/Europe Air Traffic Management R&D Seminar, Berlin, Germany, 2011.

[23] Stroeve SH, Blom HAP, Bakker GJ. Contrasting safety assessments of a runway incursion scenario: Event sequence analysis versus multi-agent dynamic risk modelling. Reliability Engineering & System Safety. 2013; Vol. 109, pp. 133-149.

[24] H.H. de Jong, H.A.P. Blom and S.H. Stroeve, How to identify unimaginable hazards?, Proc. 25th International System Safety Conference (ISSC2007), 13-17 August 2007, Baltimore, USA.

[25] Stroeve SH, Everdij MHC, Blom HAP. Hazards in ATM: Model constructs, coverage and human responses. SESAR Joint Undertaking; Report E.02.10-MAREA-D1.2; 2011.

[26] Wooldridge M, Jennings NR. Intelligent agents: Theory and practice. The Knowledge Engineering Review. 1995;Vol. 10, pp. 115-152.

[27] Bosse T, Sharpanskykh A, Treur J, Blom HAP, Stroeve SH. New model constructs for hazard coverage. Report for SESAR Joint Undertaking; 2012.

[28] Stroeve SH, Everdij MHC, Blom HAP. Studying hazards for resilience modelling in ATM. Proc. 1st SESAR Innovation Days, Toulouse, France, 2011.

[29] SH Stroeve, HAP Blom, How well are human-related hazards captured by multi-agent dynamic risk modelling? Proceedings 4th Int. Conf. on Applied Human Factors and Ergonomics (AHFE), San Francisco (CA), USA, 21-25 July 2012, pp. 5403-5412.

[30] Bosse T, Sharpanskykh A, Treur J, Blom HAP, Stroeve SH. Modelling of human performance-related hazards in ATM. Proc. 3rd Int. Air Transport and Operations Symposium (ATOS2012), Delft, The Netherlands, 2012.

[31] Bosse T, Sharpanskykh A, Treur J, Blom HAP, Stroeve SH. Agent-based modelling of hazards in ATM. Proc. 2nd SESAR Innovation Days, Braunschweig, Germany, 2012.

[32] Wickens CD, Hollands JG. Engineering psychology and human performance. Upper Saddle River (NJ), USA: Prentice Hall; 2000.

[33] Blom HAP, Daams J, Nijhuis HB. Human cognition modelling in ATM safety assessment. In: Donohue GL, Zellweger AG, editors. Air Transport Systems Engineering. Washington D.C., USA: AIAA; 2001, pp. 481-511.

[34] Hollnagel E. Human reliability analysis, context and control. London, UK: Academic Press; 1993.

[35] Reason J, Human Error, Cambridge University Press, 1990.

[36] Damasio A. The somatic marker hypothesis and the possible functions of the prefrontal cortex. Philosophical Transactions of the Royal Society: Biological Sciences. 1996; Vol. 351, pp. 1413-1420.

[37] Bosse T, Both F, Van Lambalgen R, Treur J. An Agent Model for a Human's Functional State and Performance. Proc. 8th IEEE/WIC/ ACM Int. Conf. on Intelligent Agent Technology, IAT'08, 2008.

[38] Stroeve SH, Sharpanskykh A, Kirwan B. Agent-based organizational modelling for analysis of safety culture at an air navigation service provider. Reliability Engineering & System Safety. 2011; Vol. 96, pp. 515-533.

[39] Clark A, Chalmers D. The extended mind. Analysis. 1998;Vol. 58, pp. 7-19.

[40] Sharpanskykh A. On computer-aided methods for modeling and analysis of organizations, Ph.D. thesis, VU University Amsterdam; 2008.

[41] HSE, Review of human reliability assessment methods, Report RR679, Health and Safety Executive, London, 2009..

AUTHOR BIOGRAPHIES

Henk Blom is Full Professor at Delft University of Technology (chair Air Traffic Management Safety) and Principal Scientist at National Aerospace Laboratory NLR, both in The Netherlands. He received his BSc and MSc degree from Twente University in 1975 and 1978 respectively, and his PhD from Delft University of Technology in 1990. Dr. Blom has over twenty five years experience in exploiting the theory of stochastic modeling and analysis based computational intelligence for safety risk analysis and multi-sensor data fusion with application in air traffic management. He is author of over hundred refereed articles in scientific journals, books and conference proceedings, and of the volume “Stochastic Hybrid Systems, Theory and Safety Critical Systems”, Springer, 2006. He has been organizer and coordinator of several European collaborative research projects, such as ARIBA, HYBRIDGE and iFly. Dr. Blom is Fellow IEEE.

Sybert H. Stroeve was born in Hardenberg, The Netherlands, in 1967. He received a M.Sc. degree in Electrical Engineering from Twente University, The Netherlands, in 1991, and a Ph.D. degree in Mechanical Engineering from Delft University of Technology, The Netherlands, in 1998. The Ph.D. research concerned modelling of neuromuscular control of human arm movements. In 1998, he joined Radboud University Nijmegen, The Netherlands, as a postdoc for research on neural network systems. Since 2000, he has been with National Aerospace Laboratory NLR, The Netherlands. Currently he is Senior Scientist at the Air Transport Safety Institute of NLR. In this position he has conducted research in human performance modelling, organizational modelling and dynamic risk modelling for multi-agent environments. He has applied this research in a range of safety assessment studies for air traffic applications.

Tibor Bosse was born in Abcoude, The Netherlands, in 1978. He received a M.Sc. degree in Computer Science from VU University Amsterdam, The Netherlands, in 2001, and a Ph.D. degree in Artificial Intelligence from the same university in 2005. Since 2006, he works as an Assistant Professor in the Agent Systems Research Group at the Department of Computer Science at VU University Amsterdam. His research focuses on computational (agent-based) modelling and simulation of human-related (social, cognitive, and physiological) processes. The developed models are used both for theoretical purposes (to gain a deeper understanding of the processes themselves) and for practical applications, among others, in the domains of Ambient Intelligence, Serious Gaming, Human-Computer Interaction, and Human Factors Design. His publication list (see http://www.few.vu.nl/~tbosse/papers.html) covers more than 150 papers in the major journals and conferences within Artificial Intelligence, Modelling and Simulation, Cognitive Science, and AI Applications, as well as a number of edited books in those areas.