Modelling of potential hazards in agent-based safety risk analysis

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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>
<thead>
<tr>
<th>Hazard cluster</th>
<th>Number</th>
<th>Examples of hazards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft systems</td>
<td>27</td>
<td>- Aircraft cannot perform requested manoeuvre, since it is over its performance limits</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- False alert of an airborne system</td>
</tr>
<tr>
<td>Navigation systems</td>
<td>16</td>
<td>- Wrong waypoints in database, e.g. due to update of flight management system software, errors in database, outdated database</td>
</tr>
<tr>
<td>Surveillance systems</td>
<td>27</td>
<td>- Transponder sends wrong call-sign</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Track drop</td>
</tr>
<tr>
<td>Speech-based</td>
<td>37</td>
<td>- Failure in frequency changes between subsequent air traffic controllers</td>
</tr>
<tr>
<td>communication</td>
<td></td>
<td>- Standard R/T not adhered to</td>
</tr>
<tr>
<td>Datalink-based</td>
<td>20</td>
<td>- Controller does not send a data-link message and forgets to give a clearance by voice</td>
</tr>
<tr>
<td>communication</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot performance</td>
<td>124</td>
<td>- Over-reliance on system data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Pilot does not know the complexity of the traffic situation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Alert causes attention tunnelling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Change in ATC procedures leads to confusion by pilots</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Pilot mixes up different types of ATC clearances</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Pilot is fatigued and sleepy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Pilot validates without actually checking</td>
</tr>
<tr>
<td>Controller performance</td>
<td>110</td>
<td>- Risk of a conflict is underestimated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Controller wrongly evaluates traffic situation after an alert</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Change of ATC procedures affects fluency of controller’s performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Controller has a wrong awareness about the intent of aircraft</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Controllers getting used to new systems, such that it becomes hard to do without</td>
</tr>
</tbody>
</table>

| Infrastructure          | 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.
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>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Human information processing (HIP)</td>
<td>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].</td>
</tr>
<tr>
<td>C2</td>
<td>Multi-agent situation awareness (MASA)</td>
<td>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.</td>
</tr>
<tr>
<td>C3</td>
<td>Task identification</td>
<td>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.</td>
</tr>
<tr>
<td>C4</td>
<td>Task scheduling</td>
<td>Determines which tasks may be performed concurrently as well as a priority among the tasks that cannot be performed concurrently.</td>
</tr>
<tr>
<td>C5</td>
<td>Task execution</td>
<td>Describes the performance of a human operator with regard to the execution of a specific task. The performance characteristics depend on the task considered.</td>
</tr>
<tr>
<td>C6</td>
<td>Cognitive control mode</td>
<td>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.</td>
</tr>
<tr>
<td>C7</td>
<td>Task load</td>
<td>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.</td>
</tr>
<tr>
<td>C8</td>
<td>Human error</td>
<td>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 it 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.</td>
</tr>
<tr>
<td>C9</td>
<td>Decision making</td>
<td>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.</td>
</tr>
<tr>
<td>C10</td>
<td>System mode</td>
<td>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.</td>
</tr>
<tr>
<td>C11</td>
<td>Dynamic variability</td>
<td>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.</td>
</tr>
<tr>
<td>C12</td>
<td>Stochastic variability</td>
<td>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.</td>
</tr>
<tr>
<td>C13</td>
<td>Contextual condition</td>
<td>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.</td>
</tr>
</tbody>
</table>

**Table I. Overview of TOPAZ Model Constructs**
<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC1</td>
<td>Object-oriented attention</td>
<td>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).</td>
</tr>
<tr>
<td>MC2</td>
<td>(Experience-based) decision making</td>
<td>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.</td>
</tr>
<tr>
<td>MC3</td>
<td>Operator functional state</td>
<td>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 resources 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.</td>
</tr>
<tr>
<td>MC4</td>
<td>Information presentation</td>
<td>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.</td>
</tr>
<tr>
<td>MC5</td>
<td>Safety culture</td>
<td>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].</td>
</tr>
<tr>
<td>MC6</td>
<td>Situation awareness (with complex beliefs)</td>
<td>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.</td>
</tr>
<tr>
<td>MC7</td>
<td>Trust</td>
<td>Describes trust as a dynamical, numerical variable which is influenced based on experiences in combination with several individual characteristics.</td>
</tr>
<tr>
<td>MC8</td>
<td>Formal organisation</td>
<td>Can be used to model formal organisations from three interrelated perspectives (views): 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.</td>
</tr>
<tr>
<td>MC9</td>
<td>Learning</td>
<td>Addresses learning in the context of decision making. By neurological learning processes, the decision making mechanism is adapted to experiences, such that decision choices made are reasonable or in some way rational, given the environment reflected in these past experiences.</td>
</tr>
<tr>
<td>MC10</td>
<td>Goal-oriented attention</td>
<td>Describes how an ‘ambient’ agent (either human or artificial) can analyse another agent’s state of attention, and to act according to the outcomes of such an analysis and its own goals.</td>
</tr>
<tr>
<td>MC11</td>
<td>Extended mind</td>
<td>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).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NM2</td>
<td>Approach</td>
<td>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).</td>
</tr>
<tr>
<td>NM3</td>
<td>Handling inconsistent information</td>
<td>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.</td>
</tr>
<tr>
<td>NM7</td>
<td>Group emotion</td>
<td>Describes the dynamics of the spread of emotion over a group of individuals, based on personal characteristics of the individuals and relations between individuals.</td>
</tr>
<tr>
<td>NM14</td>
<td>Surprise (A)</td>
<td>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.</td>
</tr>
<tr>
<td>NM15</td>
<td>Surprise (B)</td>
<td>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.</td>
</tr>
<tr>
<td>NM21</td>
<td>Deciding when to take action</td>
<td>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).</td>
</tr>
<tr>
<td>NM31</td>
<td>Access rights</td>
<td>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.</td>
</tr>
<tr>
<td>NM32</td>
<td>Merging or splitting ATC sectors</td>
<td>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.</td>
</tr>
<tr>
<td>NM33</td>
<td>Bad weather</td>
<td>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.</td>
</tr>
<tr>
<td>NM34</td>
<td>Weather forecast wrong</td>
<td>Probabilistic model that determines errors in weather forecast, among others, in terms of deviations from predicted wind velocity and direction.</td>
</tr>
<tr>
<td>NM35</td>
<td>Turbulence</td>
<td>Probabilistic model that switches between turbulence intensity categories based on specific sources like Convective Induced Turbulence, Clear Air Turbulence, and Mountain Wave Turbulence.</td>
</tr>
<tr>
<td>NM36</td>
<td>Icing</td>
<td>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.</td>
</tr>
</tbody>
</table>
TABLE IV. HAZARD MODELLING RESULTS: USE OF THE AGENT-BASED MODEL CONSTRUCTS AND LEVELS OF HAZARDS MODELLING.

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

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.

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: 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 complementatory 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.

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