Agent-based modelling for analysis of resilience in ATM

Sybert H. Stroeve[1], Tibor Bosse[2], Henk A.P. Blom[1,3], Alexei Sharpanskykh[2,3], and Mariken H.C. Everdij[1]

[1]National Aerospace Laboratory NLR, Air Transport Safety Institute, Amsterdam, The Netherlands

[2]Vrije Universiteit Amsterdam, Agent Systems Research Group, Amsterdam, The Netherlands

[3]TU Delft, Faculty of Aerospace Engineering, Delft, The Netherlands

E-mail: stroeve@nlr.nl, tbosse@few.vu.nl, blom@nlr.nl, o.a.sharpanskykh@tudelft.nl, everdij@nlr.nl

***Abstract* — The ability of the sociotechnical ATM system to adjust its functioning to changes and disturbances, and thereby sustain required operations is a key asset, in which human operators play crucial roles. Previously, we have shown that agent-based modelling can effectively support analysis of the safety implications of the behaviour of interacting human operators and technical systems in their effort to deal with disturbances in ATM. In this paper we provide an overview of a library of model constructs for agent-based modelling in ATM and we show the integration of these model constructs. We show that the library of model constructs can effectively model a large set of hazards in ATM and we discuss ways towards effective use of these models for the analysis of safety-focused resilience.**

Keywords – resilience; safety; air traffic management; agent-based modelling; human factors; hazards.

I. INTRODUCTION

In recent years the concept of resilience has gained considerable interest in the air traffic management (ATM) domain. As described by Folke [1], the origins of the resilience perspective stem from ecology in studies on the dynamics and interactions of prey and predator populations [2]. In the early 1990s the resilience perspective for the analysis of ecosystems revived and was also extended to social-ecological systems. In the literature overview of [1], resilience is defined as the capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedback. The introduction of the resilience perspective in ATM has been supported by safety-focused research of Hollnagel and co-workers and their introduction of the resilience engineering research field [3-7]. In the context of ATM, resilience has been defined as the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions [8]. This definition is well in line with the one in [1].

Resilience is important for the sociotechnical ATM system, where large numbers of interacting human operators and technical systems, functioning in different organizations at a variety of locations, must control air traffic safely and efficiently in the context of uncertainty and disturbances (e.g. delays, weather, system malfunctioning). Although procedures and regulations tend to specify working processes in ATM to a considerable extent, the flexibility and system oversight by human operators are essential for efficient and safe operations in normal and rare conditions [9]. The recognition of the positive contributions of human operators for maintaining safety in complex sociotechnical systems has been a main driver of the resilience engineering research field and it explains the focus on the relation between human factors and safety herein [3, 4]. Resilience engineering stresses the inevitability of performance variability of human operators to adjust to the demands and conditions in the working context. As such, resilience engineering emphasises much more the variety of potential ways of human operators to deal with nominal and non-nominal conditions in their effort to support safety, rather than adhering to human error based thinking, such as applied in traditional human reliability assessment and event sequence based accident models.

As a basis for analysis of performance variability, Pariès [10] pointed out that to understand the properties of a complex system, we lay relationships between micro and macro levels, such that macro-level properties emerge from assembling micro-level properties. Here the term ‘emerge’ means that the macro-level properties cannot be inferred from isolated micro-level properties, but that macro-level properties are of a different quality and are the resultant of interacting micro-level properties. The views of Hollnagel [11] and Pariès [10] imply that for managing safety in complex sociotechnical systems, we need analysis approaches that account for the variability in their multi-agent performance and the emergence of safety occurrences from this variability.

Recent developments for the analysis of safety and resilience of sociotechnical systems include the Functional Resonance Analysis Method (FRAM) [5, 11] and the Systems-Theoretic Accident Model and Processes (STAMP) approach [12, 13]. FRAM uses diagrams that reflect functions in an operation, interactions between the functions, and performance variability of the functions. These diagrams are evaluated in a qualitative manner. Application of FRAM to prospective safety analysis appears to be limited, since a method for systematic evaluation of a large variety of hazards in possible

This work is 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.

combinations is yet lacking. The current prospective analysis approach in STAMP is STPA (System-Theoretic Process Analysis) [13]. STPA aims to identify improvements of controls over various hazards in a given operation by a qualitative approach.

The development of multi-agent models for safety analysis in ATM has been supported by the TOPAZ (Traffic Organization and Perturbation AnalyZer) methodology [14-16]. A key method herein is multi-agent dynamic risk modelling (MA-DRM), which uses agent-based stochastic dynamic models of air transport scenarios and rare event Monte Carlo simulations to analyse the probability of emergent safety occurrences. MA-DRM uses a variety of model constructs to model the performance variability and interactions of the agents in the sociotechnical system.

A prime objective of the SESAR WP-E project MAREA (Mathematical Approach towards Resilience Engineering in ATM) is to extend the library of model constructs in MA-DRM, such that these models can represent a larger number of hazards and disturbances in ATM. This paper provides an overview of the main results of the research towards this end. Details on the research steps have been published in earlier conference papers [17-20] and in MAREA reports.

This paper is organized as follows. Section 2 introduces the concept of agent-based model constructs, it presents the developed library of agent-based model constructs, and it gives an overview of the integration of these model constructs. Section 3 describes the extent to which the model constructs can model a large set of hazards in ATM and it highlights the most important model constructs. Section 4 discusses the use of the models for the analysis of safety and resilience in ATM, and it compares the agent-based modelling approach with traditional probabilistic risk assessment (PRA) approaches, as well as with the FRAM and STPA approaches.

II. AGENT-BASED MODELLING OF THE ATM SOCIOTECHNICAL SYSTEM

A. *Model constructs for agents in ATM*

An agent-oriented perspective is useful to conceptualise processes in complex sociotechnical systems, such as ATM. Agent-based modelling considers a sociotechnical system to be composed of several agents and the overall system behaviour emerges from the individual agent processes and their interactions (Figure 1). This provides a highly modular and transparent way of structuring a model, thus supporting systematic analysis, both conceptually and computationally. Agents in a sociotechnical system contain boundaries separating internal states and processes from states and processes external to the agent (in other agents / environment). Relations between an agent's internal and external states or processes are represented strictly via the inputs and outputs of the agent considered. This makes it easier to specify models of complex systems that consist of many interacting entities, thereby facilitating effective study of the emergent behaviour of such systems.

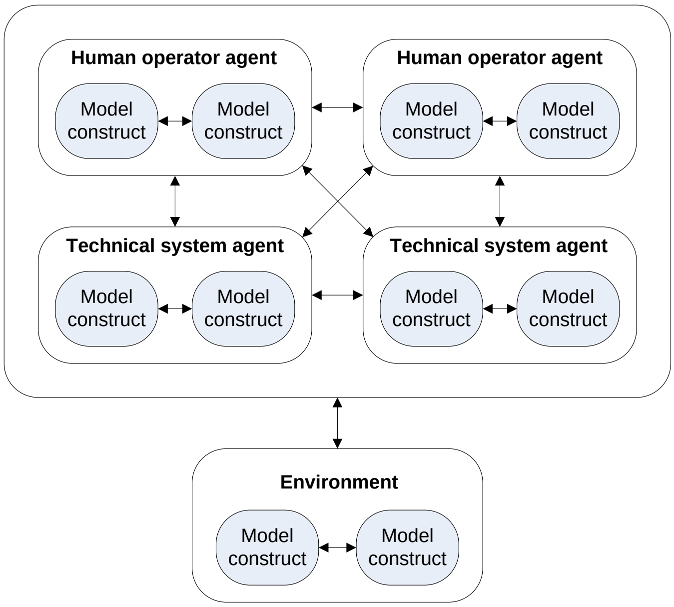

Figure 1. Generic overview of a multi-agent system consisting of human operators and technical systems in an environment. For each agent a number of model constructs is used to represent relevant aspects.

Agents in ATM operations (e.g. pilots, controllers, technical systems) can express a large variety of behavioural patterns and these are influenced by specific processes and characteristics of the agent considered. Especially for human agents there is a wide range of cognitive and affective aspects that influence their behaviour. Such agent-related aspects can be represented by model constructs for each agent (Figure 1). To represent a broad spectrum of such aspects, a library of model constructs has been identified by a systematic approach in three phases [21-23]. A concise overview of the identified model constructs is provided in Tables I-III. Table I contains the original set of TOPAZ MA-DRM constructs, Table II contains agent-based model constructs developed in studies by VU University Amsterdam, and Table III contains additionally identified model constructs.

TABLE I. SUMMARY OF TOPAZ MA-DRM MODEL CONSTRUCTS [21].

Code	Name	Brief description
C1	Human information processing	Sensory processing of signals external to the human, perception, response selection (decision making), response execution, the effect of the human response on the environment and the feedback on the human.
C2	Multi-agent situation awareness	Situation awareness (SA) addresses perception of elements in the environment, their interpretation and the projection of the future status. The multi-agent SA model construct describes the SA of each agent in a system (human, technical system) as time-dependent information of other agents, including identity, continuous state variables, mode variables and intent variables.
C3	Task identification	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. 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 that need 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 considers that the execution of a task by a human operator may include large deviations from normal and intended practice and that such deviations may be expressed as 'errors'. The human error modelling construct 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 task specific error probability may be influenced by other model constructs, such as the cognitive 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. These modes have particular durations or modes changes occur instantaneously.
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 system. For a human operator it specifies the variability in task aspects (e.g. duration, start time, accuracy) in contextual conditions, i.e. given the state of other human performance model constructs, such as situation awareness, cognitive control mode and other human modes.
C13	Contextual condition	Describes the context of the operation, such as weather, route structure, environmental conditions and airport infrastructure.

TABLE II. SUMMARY OF VU MODEL CONSTRUCTS [22].

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*) 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 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 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 to an occurrence reporting cycle exists in the context of an existing air navigation service provider.
MC6	Situation awareness with complex beliefs	An extended situation awareness model, addressing sophisticated inference algorithms based on mental models, as well as 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	A model for 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, so that the 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 an external state of the environment that has been created by an agent and helps this agent in its mental processing (e.g., flight process strips).

TABLE III. SUMMARY OF COMPLEMENTARY MODEL CONSTRUCTS [23].

Code	**Name**	**Brief description**
NM2	Approach	Captures the factors that influence pilot task demand during final approach, based on task demand load and mental load.
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	Confusion/ Surprise – Complex Procedures	Describes the generation of surprise based on: 1) expectation disconfirmation, 2) importance of the observed event, 3) valence, 4) difficulty of explaining / fitting it in an existing schema, and 5) novelty. In this particular case the model is applied to complex procedures.
NM15	Confusion/ Surprise –	Describes the generation of surprise based on: 1) expectation disconfirmation, 2) importance of the

	Changed Procedures	observed event, 3) valence, 4) difficulty of explaining / fitting it in an existing schema, and 5) novelty. 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 (collecting more information about the world state) and exploitation (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 determines the dynamics of weather conditions that obstruct safe and efficient flight, such as reduced visibility (due to fog), convective weather, and wind shear.
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 extent 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 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.

B. Integration of model constructs

It is manifest from Tables I-III that the model constructs describe a considerable range of aspects that may be encountered in ATM scenarios. For the integration of these model constructs in an agent-based model, we need to account for the interconnectivity between the model constructs.

Figure 2 provides an overview of the interconnections between the model constructs of a human agent. The rounded rectangles represent model constructs, and the arrows denote information flow between model constructs. In case multiple model constructs address a similar topic, they have been clustered using a larger rounded rectangle. As indicated in Figure 2, a human agent interacts with its environment and some model constructs have been split in sub-constructs that are partly internal and external to the human agent considered, e.g., Safety culture-awareness (MC5a) and Safety culture-interaction (MC5b).

In Figure 2 the clusters sensing-sensemaking-deciding-actuating roughly resemble a standard sense-reason-act process, as is often used to represent human information processes within agent-based systems. In addition, this information processing flow interacts with the clusters task planning and functional state. Next, we discuss the prime features of these clusters.

Sensing addresses a number of processes related to human perception. The input of this cluster consists of stimuli from the environment, and its output consists of sensory representations of these observations. The cluster includes model constructs for processes that direct the human's focus of attention to particular aspects of the environment (both in an object-oriented and a goal-oriented manner), as well as the impact of information presentation thereon. Also, it includes the process by which physical properties of the world are converted into sensory representations ('extended mind perception').

Sensemaking involves the process by which a human generates beliefs about the state of the environment (i.e., developing situation awareness) and combines them in order to build up more complex beliefs. Hence, its input consists of sensory representations (transferred from the sensing cluster), and its output consists of beliefs. A specific instance of the entities about which situation awareness can be created is the safety culture of an organisation. Also, situation awareness creation has some interaction with the human's state of trust (in the sense that humans are more likely to generate beliefs about information from sources that they trust). In case several generated beliefs are not consistent with each other, confusion and/or surprise is generated.

Deciding addresses a goal-directed process by which incoming beliefs about the world are processed in order to derive appropriate plans and actions to be performed as output. The main model construct involved in this cluster is 'decision making', but it also contains a more specific model construct that addresses the process of deciding when to look for additional information.

Actuating involves the execution of the plans generated by deciding. The effectuation of 'extended mind states' can be considered a specific instance of this. The output of this cluster is transferred to the environment to process the effect of these actions. The (modified) state of the environment is input for the sensing cluster, which closes the loop between human and environment.

Task planning addresses identification and scheduling of tasks. It sets goals for the human information processing, thereby placing a focus on particular aspects of the processes of sensing, sensemaking, deciding, and actuating.

Functional state is a cluster of model constructs, which includes operator functional state, task load, cognitive control mode, and emotional state. These model constructs have effect on the amount of resources that can be spent for the sense-reason-act processes. As such they can describe biased or erroneous sensing, sensemaking, decision making or actuating in case of high task load, stress, or emotions.

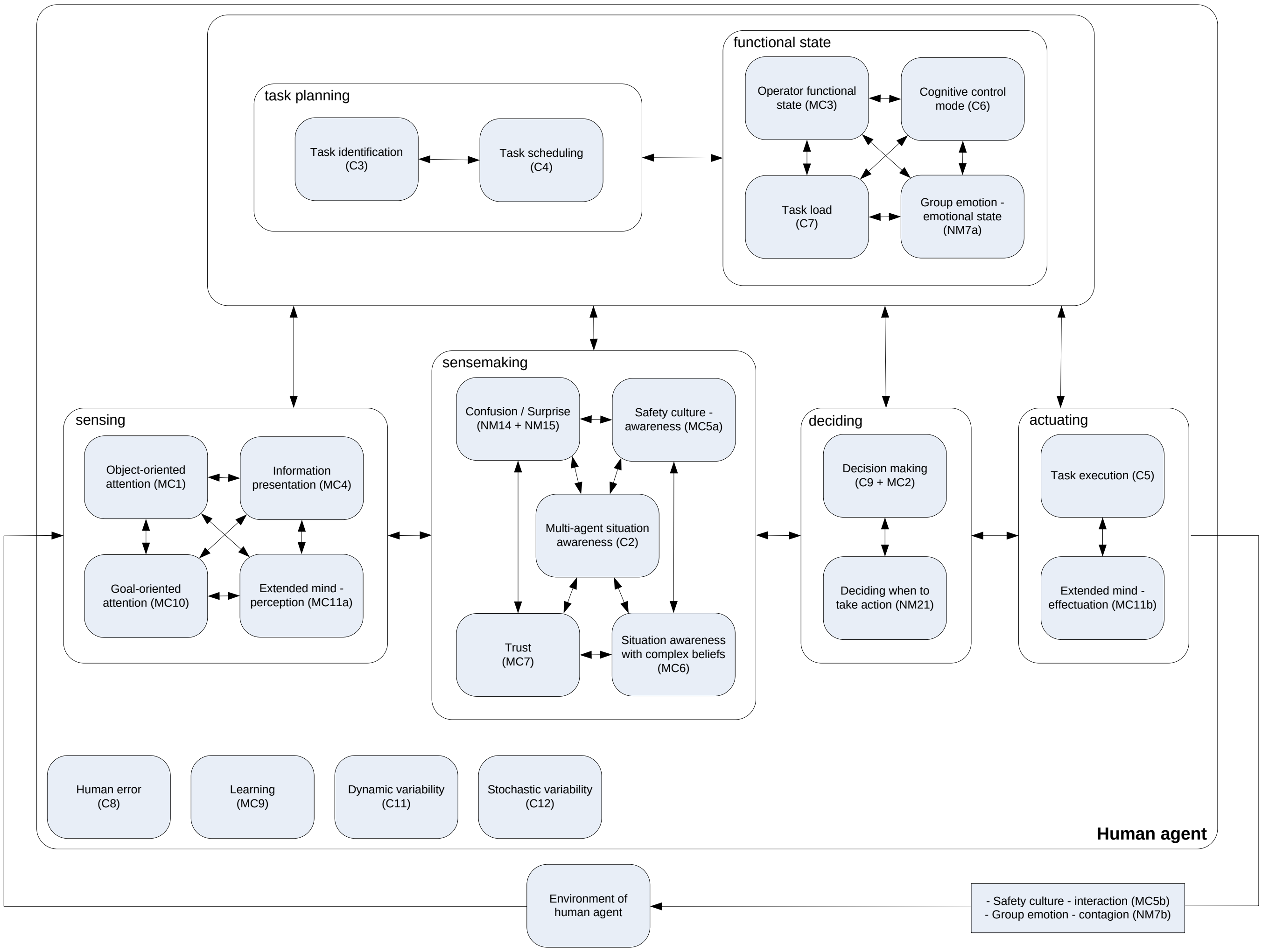

Figure 2. Overview of the integration of model constructs related to a human agent.

Finally, Figure 2 contains a number of model constructs (i.e., human error, learning, dynamic variability and stochastic variability) that potentially play a role in any of the other model constructs. For instance, errors can be made in practically all sub-processes involved. To prevent a complex, fully connected drawing, these model constructs have been drawn in isolation.

As shown in Figure 1, a particular human agent may interact with other human agents and technical systems within a specific environment of the multi-agent system. The model constructs listed in Tables I-III that are not within the human agent model as depicted in Figure 2, reside in the 'Environment of human agent'. These include the following types of model constructs:

- Organisation related model constructs, describing structural and functional aspects of the organisation in which the human agent acts, e.g. an airline, airport, or department.
- Weather related model constructs, describing bad weather phenomena, effects of bad weather like turbulence and icing, and weather forecasting.
- Technical system related model constructs, describing generic system modes as well as specific aspects of technical systems, such as system access rights, handling of inconsistent information and uncontrolled aircraft.

Details of the integration of model constructs in the environment of a human agent can be found in [24].

III. MODELLING OF HAZARDS IN ATM

A. *Database of hazards in ATM*

In the process of assuring the safety of air transport operations, the assessment of the risk implications of hazards in the operation considered plays a central role. Here a 'hazard' means any condition, event, or circumstance which could induce an accident [25]. For the assessment of the risk of a particular operational concept, a systematic evaluation has to be performed addressing the wide variety of conditions, events and circumstances that may be encountered by relevant entities and their interactions in the operation, most notably the human operators, technical systems and environmental conditions.

A prime means in gathering hazards for safety assessments is brainstorm sessions with pilots, controllers and other experts. These hazard brainstorm sessions aim to push the boundary between functionally imaginable and functionally unimaginable hazards [26]. Consequently, considerable parts of these hazard brainstorm sessions address human behaviour, conditions and interactions between humans and technical systems. As part of safety risk analyses conducted since 1995 for many proposed ATM changes, NLR has identified a broad range of related hazards. These hazards have been collected in a Hazard Database, which contains now over 4000 hazards.

As explained in Section 1, resilience of the sociotechnical ATM system means its ability to adjust in response to changes and disturbances, and the role of human operators is important for resilience in ATM. Given the broad view on hazard identification and the systematic inclusion of human-related performance herein, we have set forth to use the hazards collected in the NLR ATM Hazard Database as a broad source of disturbances for the study of safety-related resilience in ATM.

The NLR ATM Hazard Database has been analysed in order to select the unique hazards and to formulate them in a generalized way (i.e. without referring to study-specific details) [21]. This resulted into a total number of 525 generalized hazards. Examples of such hazards are ‘False alert of an airborne system’, ‘Pilot mixes up different types of ATC clearances’, or ‘Controllers getting used to new systems, such that it becomes hard to do without’. The full list of hazards is provided in [21].

B. *Mental simulation of hazards*

For each of the 525 generalized hazards it has been determined whether it can be modelled by the identified model constructs. To this end, modelling experts performed mental simulations to assess whether (sets of) model constructs could represent a hazard. By mental simulation we mean that the analyst would imagine that the model constructs in question were actually executed, as a way towards deriving the relations between the events and conditions considered in the hazard. In case that the events and conditions evolving in the mental simulation would fit the description of the hazard, the model constructs were considered relevant for the coverage of the hazard. For each hazard this resulted in a set of model constructs that were considered relevant for that hazard. If this set was empty, the hazard was considered ‘not modelled’. If the set was non-empty and the combination of model constructs would lead to a mental simulation that included all relevant aspects of the hazard, the hazard was considered ‘modelled’. If the set was non-empty and the combination of model constructs would lead to a mental simulation that included some of the relevant aspects of the hazard, the hazard was considered ‘partly modelled’.

To illustrate this process we next provide some examples of this hazard modelling analysis.

- The hazard ‘Radar is not working’ can be modelled by model construct C10 ‘System mode’, representing this failure mode by a particular probability and stochastic duration.
- The hazard ‘Pilot reports wrong position’ can be modelled by the model construct C2 ‘Multi-agent situation awareness’, representing a wrong aircraft position in the situation awareness of a pilot, which causes a wrong report. Alternatively, it can be modelled by the model construct C8 ‘Human error’, representing an error in the communication.
- The hazard ‘Pilots do not react to controller call due to high workload’ can be modelled by a combination of the model constructs C3 ‘Task identification’, C4 ‘Task scheduling’, and C6 ‘Cognitive control mode’. A high workload may lead to an opportunistic control mode (C6). In the opportunistic control mode, the task for responding to an incoming call (as identified by C3) may be given a low priority in the process of task scheduling (C4), such that the pilots do not react to the call.
- The hazard ‘Pilot performance is affected due to alcohol, drugs or medication’ can be partly modelled by MC3 ‘Operator functional state’ for the effect of alcohol/drugs/medication and by MC5 ‘Safety culture’ for the decision making to use these substances. For both aspects more detailed knowledge would be required to better describe the hazard.
- The hazard ‘Sabotage’ cannot be modelled by the set of model constructs.

This hazard modelling analysis has been done in two phases and the total set of hazards was randomly split in two similarly sized sets, called Hazard Set I and Hazard Set II. In a model identification and development phase, mental simulation was used for Hazard Set I as a way to extend the set of model constructs for multi-agent dynamic risk modelling [21-23], leading to the extension by the model constructs in Tables II and III of Section 2. In a model validation phase, mental simulation was used for Hazard Set II [27].

TABLE IV. MENTAL SIMULATION RESULTS FOR THE TWO HAZARD SETS.

Mental simulation result	**Hazard Set I**				**Hazard Set II**	
	Initial model set		Final model set		Final model set	
Well modelled	155	58.3%	244	91.7%	237	91.5%
Partly modelled	30	11.3%	16	6.0%	20	7.7%
Not modelled	81	30.5%	6	2.3%	2	0.8%
Total	266	100%	266	100%	259	100%

The results for the extent that hazards can be modelled by the model constructs are listed in Table IV. The results for Hazard Set I show that the number of hazards that can be modelled by the final set of model constructs (Tables I, II and III combined) has been improved considerably in comparison with the initial set of model constructs (only Table I). In particular, the percentage of hazards that could be well or partly modelled increased from 70% to 98%. The results for Hazard Set II show that similar results have been obtained in the validation phase for the final model set. This similarity indicates that the final library of model constructs has not been biased towards the particular hazards in Set I as used in the model identification and development phase. Overall, the results for the two sets show that 92% of the hazards can be well modelled, about 6-8% can be partly modelled, and about 1-2% cannot be modelled by the final set of model constructs [23, 27].

C. Frequency of the use of the model constructs

There exists a considerable variety in the extent to which the different model constructs have been applied in the hazard modelling analysis. Table V provides an overview of the frequency of the use of the different model constructs for the total set of 525 hazards; detailed results for Hazard Sets I and II are presented in [27]. The results in Table V indicate the importance of the model constructs for agent-based modelling of hazards in MA-DRM. It follows that model construct C2 'Multi-agent situation awareness' is a key model for understanding and analysing hazards in the ATM sociotechnical system. In particular, many hazards can be understood as differences between situation awareness of different agents (humans and technical systems) and the propagation of such differences may have considerable safety consequences. Numbers 2 and 3 in Table V represent modes of technical systems and error modes of human operators. These model constructs have some similarity with failure mode analysis and human reliability analysis in traditional safety analyses, but the way that the effect of such modes are evaluated in MA-DRM is quite different from the classical approaches [16, 28]. Of the 25 newly identified model constructs, the highest applicability has been found for MC6 'Situation awareness with complex beliefs', which represents formation of complex beliefs on the basis of observations and mental models, for MC3 'Operator functional state', which relates task demands, effort, exhaustion and personal characteristics of human operators, and for MC2 'Experienced-based decision making', which describes a person's decision making process, based on either the expected outcomes or the experienced emotional response of an option.

TABLE V. FREQUENCY OF USE OF MODEL CONSTRUCTS FOR THE REPRESENTATION OF ALL HAZARDS BY MENTAL SIMULATION [27].

Rank	**Model construct**		**Total**	
			No.	**Perc.**
1	C2	Multi-agent situation awareness	219	41.7%
2	C10	System mode	118	22.5%
3	C8	Human error	117	22.3%
4	C1	Human information processing	95	18.1%
5	C5	Task execution	57	10.9%
6	C11	Dynamic variability	53	10.1%
7	MC6	Situation awareness with complex beliefs	50	9.5%
8	MC3	Operator functional state	49	9.3%
9	C12	Stochastic variability	48	9.1%
10	C13	Contextual condition	48	9.1%
11	MC2	Experience-based decision making	40	7.6%
12	MC8	Formal organisation	37	7.0%
13	C4	Task scheduling	31	5.9%
14	MC7	Trust	31	5.9%
15	NM14	Confusion / Surprise (A)	28	5.3%
16	C9	Decision making	27	5.1%
17	C3	Task identification	25	4.8%
18	C6	Cognitive control mode	24	4.6%
19	C7	Task load	23	4.4%
20	NM33	Bad weather	18	3.4%
21	MC1	Object-oriented attention	16	3.0%
22	MC9	Learning / adaptivity	15	2.9%
23	MC5	Safety culture	10	1.9%
24	NM15	Confusion / Surprise (B)	10	1.9%
25	MC4	Information presentation	9	1.7%
26	MC11	Extended mind	8	1.5%
27	NM7	Group emotion	5	1.0%
28	NM21	Deciding when to take action	5	1.0%
29	NM34	Weather forecast wrong	4	0.8%
30	NM31	Access rights	3	0.6%
31	MC10	Goal-oriented attention	2	0.4%
32	NM2	Approach	2	0.4%
33	NM35	Turbulence	2	0.4%
34	NM36	Icing	2	0.4%
35	NM38	Influence of many agents on flight planning	2	0.4%
36	NM3	Handling Inconsistent Information	1	0.2%
37	NM32	Merging or splitting ATC sectors	1	0.2%
38	NM40	Uncontrolled aircraft	1	0.2%

IV. DISCUSSION

In the MAREA project we identified a set of 25 model constructs, which complement an existing set of 13 model constructs in multi-agent dynamic risk modelling (MA-DRM). The additional model constructs include a variety of human, environmental and organization related model constructs, e.g. Operator functional state, Trust, Situation awareness with complex beliefs, Bad weather, and Formal organisation. This additional set of model constructs entails a larger variety in psychological and organisational factors, which supports the analysis of resilience in complex sociotechnical systems. By including such additional model constructs in the agent-based models of MA-DRM based safety assessments, a larger set of hazards can be represented in a direct manner. This implies that the emergent effects of the interactions between the model constructs used in the agent-based model can be directly reflected in the Monte Carlo simulation results.

Agent-based modelling and simulation has considerable advantages over traditional probabilistic risk assessment (PRA) and human reliability assessment (HRA) approaches [16, 28]. In particular, the broad set of model constructs identified in MAREA supports direct representation of a wide variety of hazards in the ATM sociotechnical system by agent-based modelling, which can at best be represented indirectly by error/failure probabilities and error producing condition factors in traditional PRA/HRA. Due to the detailed agent-based modelling in MA-DRM, the behaviour of the interacting agents changes in response to encountered hazards/disturbances. Analysis of the implications of such changed behaviour in the agent-based model thus provides insight in the level of resilience of the ATM sociotechnical system.

The agent-based modelling approach of MAREA forms a large contrast with the prospective FRAM [5] and STPA [13] approaches. Firstly, FRAM and STPA are qualitative approaches leading to qualitative results, whereas the MAREA approach uses agent-based mathematical models and accelerated Monte Carlo simulations, leading to quantitative risk results. Secondly, for the MAREA approach it has been shown that it can model a large number of hazards in ATM, whereas FRAM lacks methods to effectively model large sets of hazards, and the STPA approach is focused primarily on hazards from a control design perspective.

A follow-up question is how the MAREA improved view of agent-based hazard modelling can be exploited toward a further improvement of agent-based safety risk assessment. Because a straightforward inclusion of all 25 complementary model constructs in the MA-DRM approach would lead to a further extension of the agent-based model of the ATM operation considered, a minimal modelling approach has been proposed in [28]. This minimal modelling approach aims to capture the interaction based behaviour effects of the model constructs, though by using a simpler Monte Carlo simulation model. The key to this development is that of those model constructs that have similar interaction based behaviour effects, the main one is included in the MC simulation, while the effects of the remaining model constructs are taken into account through bias and uncertainty assessment [29].

In conclusion, the MAREA project has demonstrated that a mathematical approach towards resilience engineering provides novel methods for prospective analysis of safety implications of resilience in ATM, which are complementary to already on-going resilience engineering developments. In the light of the shown practical feasibility of MA-DRM for safety assessment of air transport operations, we expect that the MAREA enhanced set of agent-based model constructs can further support the analysis of safety-relevant relations in the ATM sociotechnical system. In this way, resilience in ATM can be supported, thereby improving the ability of the ATM sociotechnical system to adjust to disturbances/hazards and sustaining safe operations. In future research we plan to apply the enhanced model set in detailed assessments of resilience in ATM.

DISCLAIMER

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

REFERENCES

[1] Folke C. Resilience: The emergence of a perspective for social–ecological systems analyses. Global Environmental Change. 2006;16:253-67.

[2] Holling CS. Resilience and stability of ecological systems. Annual Review Ecological Systems. 1973;4:1-23.

[3] Hollnagel E, Woods DD, Leveson N. Resilience engineering: Concepts and precepts. Aldershot, England: Ashgate; 2006.

[4] Hollnagel E, Nemeth CP, Dekker S. Resilience Engineering Perspectives, Volume 1: Remaining sensitive to the possibility of failure. Aldershot, England: Ashgate; 2008.

[5] Hollnagel E. FRAM: The Functional Resonance Analysis Method; Modelling complex socio-technical systems. Farnham, England: Ashgate; 2012.

[6] Woltjer R. Functional modeling of constraint management in aviation safety and command and control. Linköping University; PhD thesis, No. 1249; 2009.

[7] Macchi L, Hollnagel E, Leonhard J. Resilience engineering approach to safety assessment: An application of FRAM for the MSAW system. Mines ParisTech; hal-00572933, version 1; 2011.

[8] Eurocontrol. A white paper on Resilience Engineering for ATM. Eurocontrol; 2009.

[9] Eurocontrol / FAA AP15 Safety. Human performance in air traffic management safety: A white paper. Eurocontrol; 2010.

[10] Paries J. Complexity, emergence, resilience. In: Hollnagel E, Woods DD, Leveson N, editors. Resilience Engineering: Concepts and Precepts. Aldershot, England: Ashgate; 2006.

[11] Hollnagel E. Barriers and accident prevention. Aldershot, England: Ashgate; 2004.

[12] Leveson N. A new accident model for engineering safer systems. Safety Science. 2004;42:237-70.

[13] Leveson NG. Engineering a safer world: Applying systems thinking to safety. Cambridge (MA), USA: MIT Press; 2011.

[14] 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.

[15] 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: Proceedings of the Fourteenth Safety-citical Systems Symposium, Bristol, UK, 7-9 February 2006: Springer; 2006.

[16] 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;109:133-49.

[17] Stroeve SH, Everdij MHC, Blom HAP. Studying hazards for resilience modelling in ATM. First SESAR Innovation Days, Toulouse, France, 2011.

[18] Bosse T, Sharpanskykh A, Treur J, Blom HAP, Stroeve SH. Modelling of human performance-related hazards in ATM. Proceedings Third International Air Transport and Operations Symposium, Delft, The Netherlands, 2012.

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

[20] Blom HAP, Stroeve SH, Bosse T. Modelling of potential hazards in agent-based safety risk analysis. Tenth USA/Europe Air Traffic Management Research and Development Seminar, Chicago, USA, 2013.

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

[22] Bosse T, Sharpanskykh A, Treur J, Blom HAP, Stroeve SH. Library of existing VU model constructs. SESAR Joint Undertaking; E.02.10-MAREA-D2.1; 2012.

[23] Bosse T, Sharpanskykh A, Treur J, Blom HAP, Stroeve SH. New model constructs for hazard coverage. SESAR Joint Undertaking; E.02.10-MAREA-D2.2; 2012.

[24] Bosse T, Treur J, Stroeve SH, Blom HAP, Sharpanskykh A. Formal specification of model constructs. Brussels, Belgium: SESAR Joint Undertaking; E.02.10-MAREA-D2.4; 2013.

[25] European Commission. Commission implementing regulation (EU) No 1035/2011 of 17 October 2011 laying down common requirements for the provision of air navigation services and amending Regulations (EC) No 482/2008 and (EU) No 691/2010. 2011.

[26] De Jong HH. Guidelines for the identification of hazards: How to make unimaginable hazards imaginable. Amsterdam, The Netherlands: National Aerospace laboratory NLR; NLR-CR-2004-094; 2004.

[27] Bosse T, Treur J, Mogles NM, Stroeve SH, Blom HAP, Sharpanskykh A. Model constructs validation. SESAR Joint Undertaking; E.02.10-MAREA-D3.1; 2013.

[28] Blom HAP, Everdij MHC, Stroeve SH, Mogles NM. Assessment of MAREA approaches in safety analysis and design. SESAR Joint Undertaking; E.02.10-MAREA-D5.2; 2013.

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