# Agent-Based Modelling of Hazards in ATM

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*Abstract*—**This paper studies agent-based modelling of hazards in Air Traffic Management (ATM). The study adopts a previously established large database of hazards in current and future ATM as point of departure, and explores to what extent agent-based model constructs are able to model these hazards. The agent-based modelling study is organized in three phases. During the first phase existing agent-based model constructs of the TOPAZ safety risk assessment methodology are compared against the hazards in the database. During the second phase the same is done for existing agent-based model constructs developed by VU Amsterdam. During the third phase, novel model constructs are being developed specifically to model hazards that are not modelled well by the model constructs from the first two phases. The focus of this paper is on describing the model constructs of the third phase. All model constructs from the three phases together are also analysed with respect to the extent to which they model all hazards in the database. The results indicate that the total set of model constructs is capable to model 92% of the hazards well, 6% of the hazards partly and only 2% of the hazards not.**

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

## I.    INTRODUCTION

Air Traffic Management (ATM) is a complex socio-technical system in which a large variety of human and technical agents interact with each other [24]. Thanks to these interactions, the agents jointly cope in an intelligent manner with the various disturbances that may be caused by the environment. Resilience Engineering [25, 26] is the scientific discipline that studies the design of such intelligent socio-technical systems. Resilience indicates that operations and organisations are able to resist a wide variety of demands within their domains and thus should be able to recover from any condition in their domains that may disturb the stability of the operation or organisation. Hence, resilience engineering aims to address a wide range of nominal and non-nominal conditions. Resilience engineering has some common grounds with hazard assessment. Nevertheless, there also are two significant differences:

1.    Resilience engineering emphasises much more the potential ways human agents in the joint cognitive system can respond in a flexible way to the various hazards, rather than assessing safety risks of these hazards.

2.    Focus of traditional hazard assessment (e.g., [14])) is on hazards that can be evaluated using linear causation mechanisms (e.g. fault/event trees); the consequence of which is that many human related hazards tend to fall out of sight.

The flexibility of human responses is especially important to respond well when the air traffic situation evolves into a condition for which the procedures are no longer unambiguous. From a resilience engineering perspective this means that we should find out what these kind of non-nominal conditions are and how humans anticipate upon their potential evolution from a nominal condition into a non-nominal condition.

For a complex socio-technical system as ATM is, resilience engineering is at an early stage of development. During recent years novel psychological model constructs have been studied in capturing human cognition and its interaction with other joint cognitive system entities [25, 26]. A limitation of this approach is a lack of a systematic approach to modelling and simulation of all possible interactions in a complex socio-technical system.

To support a more systematic analysis, the MAREA (Mathematical Approach towards Resilience Engineering in ATM) project aims to develop a mathematical modelling and analysis approach for resilience engineering in ATM. In the literature of modelling and analysis of complex socio-technical systems, agent-based modelling and simulation has emerged as a remarkably powerful approach. For this reason the study of agent-based modelling of hazards in ATM is one of the main MAREA research streams.

As a basis for this agent-based hazard modelling research, a database of hazards in ATM was developed [40, 41]. This development used large numbers of hazards, primarily gathered by hazard brainstorms in ATM safety assessments. The resulting database consists of 525 unique and generalized hazards, dealing with a wide spectrum of issues related to technical systems, human operators, organization of ATM, environmental conditions and others. The model development in MAREA is based upon half of these hazards, the other half is set aside for validation at a next MAREA stage.

The agent-based modelling of hazards is organized in three phases. During the first phase, existing agent-based model constructs of the Traffic Organization and Perturbation

AnalyZer (TOPAZ) safety risk assessment methodology [2,3] are compared against the hazards in the database. This has been reported in [40,41]. During the second phase the same is done for existing agent-based model constructs developed by VU Amsterdam. This has been reported in [5,6]. During the third phase, novel model constructs are being developed specifically to model hazards for which the model constructs from the first two phases fall short. This has been reported in [7].

The aim of this paper is to explain the agent-based model constructs of all three phases. In doing so, the focus of this paper is on describing the model constructs of the third phase. All model constructs from the three phases together are also analysed with respect to the extent to which they model all hazards in the database.

This paper is structured as follows. Section II provides a brief summary of all of the agent-based model constructs that have been analysed during the first two phases [6, 41]. It also explains how well the various hazards in the database are modelled. Section III presents the novel model constructs that have been developed (at a conceptual level) during the third phase. Section IV presents an analysis of the extent to which the final set of model constructs is capable of modelling the hazards from the database. Section V concludes the paper with a discussion.

## II. EXISTING MODEL CONSTRUCTS

### A. Multi-Agent Dynamic Risk Modelling Model Constructs

In the first phase of the hazard modelling study [41], 13 agent-based model constructs have been analysed that are typically used within the Multi Agent Dynamic Risk Modelling approach of the TOPAZ safety risk assessment methodology. These 13 model constructs are briefly summarised in Table I (see [41] for details).

For the 13 model constructs in Table I, a systematic analysis has been performed to assess how well the hazards in the database are modelled or not. This analysis indicates that 58% of the hazards in the ATM hazard database are modelled well, 11% are partly modelled, and 30% of the hazards are not modelled [41]. It should be noticed that within the TOPAZ methodology, the impact of unmodelled hazards on safety risk is evaluated using sensitivity analysis and bias and uncertainty analysis [15].

### B. VU Model Constructs

In the second phase of the hazard modelling study [6], 11 agent-based model constructs have been identified that follow the modelling and analysis approach used by the Agent Systems research group at VU University Amsterdam. These 11 agent-based model constructs have an emphasis on human factors, and are briefly summarised in Table II (see [6] for details).

For the 11 additional agent-based model constructs in Table II a systematic analysis has been performed to assess how well the modelling of the hazards in the database has been

improved. Based on this second analysis, the percentage of hazards that has been found to be well modelled increased from 58% to 80%, the percentage of hazards partly modelled decreased from 11% to 7%, and the percentage of hazards not modelled decreased from 30% to 14%. This improvement was mainly due to the modelling of additional human performance-related hazards. In particular, the coverage of hazards related to pilot performance increased from 50% to 85% and the coverage rate for controller performance shows an increase from 42% to 87%. The analysis also pointed out that the majority of the hazards that were still not modelled are in the 'weather' and 'other' clusters.

TABLE I.        SUMMARY OF TOPAZ MODEL CONSTRUCTS.

| Code | Name | Brief description |
|---|---|---|
| C1 | Human information processing | Includes 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 [44]. |
| C2 | Multi-agent situation awareness | Situation awareness (SA) addresses perception of elements in the environment, their interpretation and the projection of the future status [13]. 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 | 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 is a modelling construct for human performance, cf. [23]. It 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 error probability is thus task specific and it 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 the 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, etc., in a 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. It has similarity with the model construct System mode (C10). However, the construct System mode is restricted to technical systems. |

TABLE II. SUMMARY OF VU MODEL CONSTRUCTS.

| Code | Name | Brief description |
|---|---|---|
| MC1 | Bottom-up 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* [11]) 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* [22], 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 [21]. |
| 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. |
| MC6 | Complex Beliefs in Situation awareness | An extension of the model of Endsley [13], 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 / adaptivity | 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 the philosophical notion of an *extended mind* [10], 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. NOVEL MODEL CONSTRUCTS.

| Code | Novel Model Construct |
|---|---|
| A | Unstabilised Approach |
| B | Handling Inconsistent Information by a Technical System |
| C | Sub-optimal Emotional Atmosphere |
| D | Complex or Unclear Procedures Leading to Confusion |
| E | Changes in Procedures Leading to Problems |
| F | Human Does Not Know When to Take Action |
| G | Problems with Access Rights to an Information System |
| H | Merging or Splitting ATC Sectors |
| I | Reduced Visibility |
| J | Weather Forecast Wrong |
| K | Strong Turbulence |
| L | Icing |
| M | Influence of Many Agents on Flight Planning |
| N | Uncontrolled Aircraft |

## III. NOVEL MODEL CONSTRUCTS

During the third phase, novel model constructs have been developed which have the potential to model a significant part of the remaining 20% of the hazards. This has been done in an iterative way. The kind of activities used in each iteration are:

i) identifying common elements in the remaining hazards, ii) trying to develop novel model constructs using literature and authors insight, iii) verifying how this reduces the percentage of remaining hazards. Rather than describing these iterations, in this section we describe the novel model constructs proposed, and in the next section we show how these novel model constructs improve the percentage of modelled hazards.

Table III provides a listing of the developed novel model constructs, which are presented at a conceptual level in subsections A through N.

### A. Unstabilised Approach

The modelling of unstabilised approach has been studied in depth within the context of a PhD Thesis by Heiligers [19]. The model developed captures the factors that influence pilot task demand during approach. In particular, a distinction is made between 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). Task Demand Load is defined as a function of the following four factors: 1) the approach trajectory and its altitude and velocity constraints, 2) the wind speed and wind direction, 3) the aircraft type, and 4) the aircraft mass.

For the transformation of pilot Task Demand Load to pilot mental load the model of [20] is proposed. This model takes factors such as fatigue, skill and training into account. As a result, whereas for a given approach the Task Demand Load is the same, the mental load may vary over pilots, and may even very between different occasions for the same pilot.

### B. Handling Inconsistent Information by a Technical System

When a technical system has to deal with inconsistent information (e.g. when an aircraft picks up different beacons with the same frequency), then the system typically handles this along one the following four types of responses: 1) to process the input information correctly (e.g., only present the correct beacon to the pilot), 2) to process the input information incorrectly (e.g., only present the incorrect beacon to the pilot), 3) to leave the input information unchanged, and have the user solve the inconsistency (e.g., present both beacons to the pilot), and 4) to generate an error message.

The model proposed is that upon receiving inconsistent information as input, a technical system follows one of these four types of responses with a certain probability. The probabilities assigned to each of them depend on the domain-specific aspects of the technical system at hand. For instance, for the case of an aircraft that picks up different beacons with similar frequencies, available information about the particular technical system involved could be used (see, e.g., [9] for notes on non-directional beacons and associated automatic direction finding). The probabilities might also depend on context information such as the number of conflicting inputs, the level of inconsistency of the inputs, the weather, and so on.

## C. Sub-optimal Emotional Atmosphere

If the emotional atmosphere within a team is not optimal, team performance can be degraded [4]. The development of a sub-optimal atmosphere (e.g., either too 'jolly' or too sad) usually is based on an emotion contagion process. Emotion contagion processes in groups can take place in a non-biased or biased form. In a non-biased form the emotion levels usually converge to a level which is some weighted average of the original emotion levels of the members. In a biased form emotion contagion spirals can occur that lead to converging emotion levels that may even be higher (upward bias) or lower (downward bias) than the original levels of all members. An example of a computational model for such biased emotion contagion processes can be found in [4]. This model distinguishes a number of aspects that play a role in the contagion spirals, varying from aspects related to the sender, the channel between sender and receiver and the receiver of the transferred emotion. Accordingly, the model distinguishes three parts in the process of transfer of emotion: a sender $S$, a receiver $R$, and the channel from $S$ to $R$.

In addition, a number of related parameters are distinguished, namely 1) the current level of the sender's emotion, 2) the current level of the receiver's emotion, 3) the extent to which the sender expresses the emotion, 4) the openness or sensitivity of the receiver for the emotion, and 5) the strength of the channel from sender to receiver.

Finally, for the receiver a bias factor is introduced, representing its tendency to adapt emotions upward or downward. This factor may in turn depend on other factors, in particular on how occupied each of the group members is with the individual task load. If this task load is experienced as very low (for example when the work is very monotonous) this may easily lead to boredom (e.g., [39]). Boredom may result in an upward bias for emotion contagion and possibly in jolly, 'mischievous' behaviour. In contrast, a task load experienced as very high may result in a downward bias for emotion contagion. Given this, this type of hazard may be covered by two model constructs, one for biased emotion contagion (e.g., [4]), and one for experienced work load. For the latter, model construct MC3 for functional state (see Table II) can be used.

## D. Complex or Unclear Procedures Leading to Confusion

When the procedures that a human needs to follow are ambiguous or ill-defined, this may cause confusion. Examples are "Unclear and ambiguous standard operating procedures for cockpit crew" or "Lack of well-defined low visibility procedures".

In order to develop a model construct that is able to represent the mechanisms that lead to confusion in these cases, we propose to take inspiration from computational models of surprise. According to [12], surprise is an adaptive, evolutionary-based reaction to unexpected events with emotional and cognitive aspects that has effects on human behaviour; among others, on facial expressions and on the interruption of ongoing action.

One of the more influential models that explain the mechanisms behind how surprise intensity is generated in human is the *expectancy-disconfirmation* model [38]. According to the expectancy-disconfirmation theory, the main contributing factor to surprise is expectancy disconfirmation. In this view, people create expectations on how events in the world unfold. If they subsequently encounter an event that does not fall within their expectations, they will be surprised. This leads to an attribution process, a form of causal reasoning which leads to an attribution of the situation to certain causes in order to make sense of the situation. The duration of this causal attribution process depends on not only the surprise intensity but also other factors such as importance of the surprising event. Inspired by the expectancy-disconfirmation theory, in [33] a computational model for surprise is put forward. In addition to expectancy disconfirmation, this model takes a number of other relevant factors into account, which results in the following list of concepts that influence the intensity of surprise: 1) expectation disconfirmation, 2) importance of 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).

The surprise model by [33] would be particularly useful to simulate the process that leads to a state of surprise or confusion. In order to represent the effects of the confusion on the human's behaviour, also some earlier models about human functioning would be needed. In particular, these would be model construct MC1 (to represent an incorrect attention focus), MC6 (to represent the negative impact on situation awareness), and MC7 (to represent the impact on trust; see Table II), as well as models for default reasoning.

## E. Changes in Procedures Leading to Problems

Changes in Procedures may lead to confusion, errors or lack of operational fluency by humans involved. This type of problem is related to the previous one, with the exception that the confusion is now due to *changes* in procedures, rather than ambiguity in the procedures themselves. Examples are "Change in ATC procedures leads to confusion by pilots", "Differences in procedures in Europe / USA lead to confusion", "Change of ATC procedures affects fluency of controller's performance", or "Difference in missed approach procedures Europe / USA".

Similar as in Section III.D, the proposed model uses the surprise model [33]. More specifically, two situations can be distinguished, namely 1) changes in procedures over time and 2) differences in procedures in different countries. Both of these situations can be modelled by using the expectancy-disconfirmation mechanism of the surprise model. The former can be modelled by combining an expectation of an old procedure with an observation of a new procedure, whereas the latter can be modelled by combining an expectation of a procedure in one country with an observation of a procedure in another country.

## F. Human Does Not Know When to Take Action

When a human does not know when to act, then our proposed human model determines this time point by using decision making models addressing exploitation and exploration of information by an agent can be used. One of such models is described in [28]. In this model the agent learns to predict the dynamics of the environment. If the environment is predicted to be unstable, the agent collects more information before performing an action (exploration). Otherwise the agent exploits its knowledge and chooses an action to perform (exploitation). Another exploration/exploitation model [42] is based on a reinforcement learning mechanism. In this model the agent gains the exploration/exploitation experience by statistical learning based on rewards from the past. If the agent does not have the possibility to gain experience by exploration (e.g., due to time constraints, lack of training) and/or lacks previous experience with similar decisions, it will have a high degree of uncertainty about when to act.

## G. Problems with Access Rights to an Information System

There are two (opposite) kinds of problems with access rights to Information Systems: 1) actors have access to information in a specific system while they should not, and 2) actors do not have access to information in a specific system while they should.

The question whether or not the appropriate actors have access to information in such a system is related to the area of computer security. According to [34], computer security in the aviation industry can be compromised by hardware and software malpractice, human error, and faulty operating environments. Threats that exploit computer vulnerabilities can stem from sabotage, espionage, industrial competition, terrorist attack, mechanical malfunction, and human error.

An initial model construct is a 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. The model construct should be such that in the vast majority of cases, access is granted to authorised actors and is denied to unauthorised actors. However, in exceptional cases, the model should decide that access is denied to authorised actors and is granted to unauthorised actors. The specific percentage of cases in which this will happen can be extracted from statistics reported in literature such as [43]. In addition, a more complex model construct could also represent the causes of access right problems as mentioned above, such as sabotage, mechanical malfunction, and so on.

## H. Merging or Splitting ATC Sectors

Regarding a model for merging and splitting ATC sectors, for this purpose the Organisational Change model from [27] can be used. This thesis presents a formal, agent-based approach for analysis and simulation of organisational change. This approach takes the Agent-Group-Role (AGR) model by [16] as a basis, and extends this with formal behavioural specifications. The idea of the AGR model is that organisations can be described in terms of *agents* (active communicating entities), *roles* (abstract representations of functions within a group) and *groups* (atomic sets of roles). Furthermore, the approach distinguishes different types of organisational change, namely *centralised*, *decentralised* and *mixed* change.

Using this approach, the process of merging and splitting ATC sectors can be described as a form of organisational change. In particular, two types of change are relevant: merging multiple ATC sectors into a single one, and splitting a single ATC sector into multiple sectors. Following the AGR approach, the different sectors can be modelled as groups, and the changes in their decomposition by dynamic re-allocation of agents to roles. The triggers for these two transitions mainly involve the amount of work load: in case of overload, sectors are split, and in case of underload (e.g. at night), sectors are merged.

## I. Reduced Visibility

Visibility is typically modelled through capturing the distance at which an object or light can be clearly discerned. Around airports, applicable procedures largely depend on this distance. For this, the ICAO A-SMGCS manual [29] discerns different visibility conditions, which are related to the capability of pilots and controllers to discern the traffic. Hence, an effective dynamical model for visibility in aviation has multiple discrete modes: e.g., one for good visibility, one for reduced visibility and one for no visibility. Coupled to the reduced visibility mode only there is a random variable for the visibility distance, which is distributed according to a probability density that applies for the specific airport considered. The rates of switching between the three visibility modes also represent the visibility switching statistics of the specific airport considered.

## J. Weather Forecast Wrong

A good paper addressing weather forecasting accuracy is [31]. Subsequently [30] provides models for capacity estimation of weather impacted airspace. A second order stochastic random field model of wind velocity forecasting error has been developed in [18]; this can for example be used to perform Monte Carlo simulations of deviations from predicted wind velocity (and direction).

## K. Strong Turbulence

A good reference for turbulence is [32], which is used as the source for the explanation given below. Turbulence that affects aircraft may be created by various forcing mechanisms, and the resulting turbulence is typically classified according to its source. At cruising altitude there are three common sources of turbulence: 1) *Convective Induced Turbulence* (CIT), the sources of which are convective clouds (both in-cloud and near-cloud), 2) *Clear Air Turbulence* (CAT), the sources of which are enhanced wind shears and reduced stabilities in the vicinity of jet streams, the tropopause and upper-level fronts, and 3) *Mountain Wave Turbulence* (MWT), the source of which is the breaking of gravity waves above mountainous terrain.

Typically three turbulence intensity categories are considered: Light turbulence usually does not affect ride comfort and safety. Moderate-or-Greater (MoG) and Severe-or-Greater (SoG) turbulence categories dictate the likelihood of aircraft deviations. For high altitude sectors, MoG turbulence encounters are about equally divided between clear-air and in-cloud occurrences, although many in-cloud reports are actually in stratiform clouds associated with mid-latitude winter storms.

Cho et al. [8] explains that when these turbulence conditions may obstruct safe flight, then flight plans will be adapted in line with the applicable procedures of airlines, air traffic sectors and airports involved.

*L. Icing*

In aviation, icing conditions are those atmospheric conditions that can lead to the formation of water ice on the surfaces of an aircraft, or within the engine as carburettor icing. Inlet icing is another engine-related danger, often occurring in jet aircraft; see [17]. Icing conditions exist when the air contains droplets of supercooled liquid water; icing conditions depend on the droplet size, the liquid water content and the air temperature. These parameters affect the extent and speed of ice formation on an aircraft. Civil aviation regulations contain a definition of icing conditions that some aircraft are certified to fly into. Supercooled Large Droplet (SLD) conditions are those that exceed that specification and represent a particular hazard to aircraft.

In addition to the weather-related icing conditions, models related to icing of the wings include the effect on flight characteristics and de-icing / anti-icing methods. The effect of icing of the wing is that the wing ordinarily stalls at a lower angle of attack, and thus a higher airspeed is required. Even small amounts of ice have an effect, and if the ice is rough, it can be a large effect. Thus an increase in approach speed is advisable if ice remains on the wings. How much of an increase depends on both the aircraft type and amount of ice. Stall characteristics of an aircraft with ice contaminated wings are degraded, and serious roll control problems are not unusual. The ice accretion may be asymmetric between the two wings and the outer part of a wing typically collects more ice.

To protect against icing there exist several de-icing methods (removal of ice) and anti-icing methods (prevention of ice accumulation). Such methods include ice removal by mechanical means, de-icing fluids or heating prior to takeoff, or the use of route engine bleed air, electrical heating or a weeping wing system which dispenses anti-icing fluid during flight.

*M. Influence of Many Agents on Flight Planning*

The proposed modelling approach is to incorporate all relevant agents in one organisational model. One of the relevant organisation types that remains to be modelled for this is an Airline Operational Centre (AOC). A good description of AOC's is given in [35]. This description can be formalised using the generic organisation modelling framework from Sharpanskykh [36]. The organisation-oriented view from the framework provides means to specify roles (such as aircraft routers, crew schedulers, dispatchers), interaction and power relations between roles, and principles of allocation of roles to agents. The process-oriented view from the framework allows describing organisational processes and flows of processes. The obtained model can be parameterised using data from [35], in particular for specifying the dynamics of the environment and defining properties of processes.

*N. Uncontrolled Aircraft*

The proposed model for an uncontrolled aircraft switches between two discrete modes: *controlled* and *loss of control*.

Loss of control usually occurs because the aircraft enters a flight regime which is outside its normal envelope, usually, but not always at a high rate, thereby introducing an element of surprise for the flight crew involved. For the switching from the controlled mode to the loss of control mode a transition rate applies which depends of various conditions of aircraft evolution related agents, such as the aircraft itself, the flight crew, aircraft systems and the environment. The specific functionality of these transition rates remains to be developed. Literature provides high level descriptions of the main causes of switching to an in-flight loss of control. Skybrary [37] identifies seven categories of in-flight loss of control: 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.

In order to realize a switching back from the loss of control mode to the controlled mode, the aircraft flight evolution has to be brought back within its performance envelope. Hence it is of utmost importance that pilots are able to recover from loss of control events. The pilot's ability to accomplish this depends on the nature of the upset causing loss of control, the height at which loss of control starts, and the experience and ability of the pilots [37]. Hence the proposed model is that recovery from loss of control takes a random delay. The probability density of this random delay depends of various conditions that applied at the moment of switching to loss of control mode.

IV. IMPROVED MODELLING OF HAZARDS

This section analyses to what extent the total set of model constructs presented in Section II and III can be used to model the hazards included in the hazard database discussed in [41].

For each hazard 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 is 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 ([7],

Appendix B). Based on this analysis, Table IV provides an overview of the numbers of hazards that are modelled by one or several model constructs per hazard cluster (as defined in [41]). The numbers between round brackets indicate the modelling based on the TOPAZ model constructs only. The numbers between square brackets indicate the modelling when also considering the VU model constructs.

As can be seen in Table IV, including the novel model constructs identified in Section III has again led to an increased coverage of hazards. In particular, 92% of the generalised hazards are now well modelled by the considered combination of model constructs (which was 58% based on the TOPAZ model constructs only, and 80% based on the TOPAZ model constructs and VU model constructs). Moreover, 6% of the hazards are partly modelled, and only 2% is not modelled. Four of the six unmodelled hazards are in the "other" cluster and they involve topics like 'security' or 'UAVs', which were considered out of scope of the MAREA project.

TABLE IV. OVERVIEW OF COVERAGE OF HAZARDS PER CLUSTER. THE RESULTS OBTAINED IN [41] AND [6] ARE SHOWN BETWEEN ROUND AND SQUARE BRACKETS, RESPECTIVELY.

| Hazard cluster | Total number of hazards | Hazard coverage | | | | | |
|---|---|---|---|---|---|---|---|
| | | Well covered | | Partly covered | | Not covered | |
| Aircraft systems | 14 | 14 [13] (11) | 100% [93%] (79%) | 0 [0] (2) | 0% [0%] (14%) | 0 [1] (1) | 0% [7%] (7%) |
| Navigation systems | 8 | 8 [7] (7) | 100% [88%] (88%) | 0 [0] (0) | 0% [0%] (0%) | 0 [1] (1) | 0% [13%] (13%) |
| Surveillance systems | 14 | 14 [14] (14) | 100% [100%] (100%) | 0 [0] (0) | 0% [0%] (0%) | 0 [0] (0) | 0% [0%] (0%) |
| Speech-based communication | 19 | 17 [16] (13) | 89% [84%] (68%) | 1 [0] (2) | 5% [0%] (11%) | 1 [3] (4) | 5% [16%] (21%) |
| Datalink-based communication | 10 | 10 [10] (9) | 100% [100%] (90%) | 0 [0] (0) | 0% [0%] (0%) | 0 [0] (1) | 0% [0%] (10%) |
| Pilot performance | 62 | 58 [53] (31) | 94% [85%] (50%) | 4 [7] (13) | 6% [11%] (21%) | 0 [2] (18) | 0% [3%] (29%) |
| Controller performance | 55 | 52 [48] (23) | 95% [87%] (42%) | 3 [4] (7) | 5% [7%] (13%) | 0 [3] (25) | 0% [5%] (45%) |
| ATC systems | 13 | 12 [10] (7) | 92% [77%] (54%) | 1 [1] (2) | 8% [8%] (15%) | 0 [2] (4) | 0% [15%] (31%) |
| ATC coordination | 12 | 11 [9] (8) | 92% [75%] (67%) | 1 [0] (0) | 8% [0%] (0%) | 0 [3] (4) | 0% [25%] (33%) |
| Weather | 14 | 12 [2] (2) | 86% [14%] (14%) | 2 [4] (4) | 14% [29%] (29%) | 0 [8] (8) | 0% [57%] (57%) |
| Traffic | 17 | 15 [13] (13) | 88% [76%] (76%) | 1 [1] (0) | 6% [6%] (0%) | 1 [3] (4) | 6% [18%] (24%) |
| Infrastructure & environment | 12 | 12 [11] (11) | 100% [92%] (92%) | 0 [0] (0) | 0% [0%] (0%) | 0 [1] (1) | 0% [8%] (8%) |
| Other | 16 | 9 [6] (6) | 56% [38%] (38%) | 3 [1] (0) | 19% [6%] (0%) | 4 [9] (10) | 25% [56%] (63%) |
| **Total** | **266** | **244 [212] (155)** | **92% [80%] (58%)** | **16 [18] (30)** | **6% [7%] (11%)** | **6 [36] (81)** | **2% [14%] (30%)** |

## V. DISCUSSION

Within the agent-based modelling stream of the MAREA project, a set of 38 agent-based model constructs have been identified towards agent-based modelling of hazards in ATM. Of these 38 model constructs, of 13 are TOPAZ model constructs [41]), 11 are VU model constructs [6], and 14 are novel model constructs, which have been developed in [7], and presented in Section III. By an informal comparison the total set of 38 agent-based model constructs has been found capable in modelling a large number of hazards of the hazards in the large database [40]. In particular, 92% of the hazards are now well modelled by the considered combination of model constructs (which was 80% based on the TOPAZ and VU model constructs combined). This gain is mainly due to the development of model constructs for human confusion and for weather hazards. Moreover, 6% of the hazards are now partly modelled, and only 2% are not modelled. These 2% come down to 6 specific hazards, 4 of which are in the cluster 'other' hazards.

The analysis discussed in this paper is the third intermediate result in the agent-based hazard modelling stream of the MAREA project. In follow-up research on agent-based hazard modelling, the applicability of the 38 agent-based model constructs will be explored in more detail. To this end, agent-based model constructs need to be tailored to the ATM domain, formalised and integrated in an agent-based overall model. For example, when applying the model construct for handling of inconsistent information by a technical system, choices need to be made regarding the exact inputs and outputs that will be modelled. Such choices will generally depend on domain-specific aspects of the system under consideration.

Integration of the different model constructs in an agent-based overall model will make it possible to explore the effects of the interactions between the individual model constructs in Monte Carlo simulations of the overall agent-based model. We expect that this will lead to modelling of safety-relevant scenarios that cannot be captured by individual model constructs alone. For example, bad weather in itself may not lead to a safety-relevant scenario, but in combination with an incorrect focus of the pilot's attention (as modelled via the 'goal-oriented attention' model construct) it could. These types of safety-relevant scenarios can emerge when the separate model constructs are connected together, and the global behaviour of the integrated system is studied (e.g., by simulation) [1].

A validation of the agent-based model constructs will be pursued by performing 'proof-of-concept simulations', which qualitatively describe ways that hazards can evolve in ATM scenarios. The behaviour of the agent-based models will be evaluated for a second hazard set (as defined in [40]) and by having experts judge the plausibility of the resulting proof-of-concept simulations. Through a complementary study, a comparison will be made between our agent-based hazard modelling and the psychological modelling that has been triggered by [25, 26].

REFERENCES

[1] Bedau, M. (2002). Downward Causation and the Autonomy of Weak Emergence. Principia, vol. 6, issue 1, 2002.

[2] Blom, H.A.P., Bakker, G.J., Blanker, P.J.G., Daams, J., Everdij, M.H.C., and Klompstra, M.B. (2001). Accident risk assessment for advanced air traffic management. In G. L. Donohue & A. G. Zellweger (Eds.), Air Transport Systems Engineering, pp. 463-480, AIAA, 2001.

[3] Blom, H.A.P., Stroeve, S.H., and Jong, H.H. de (2006). Safety risk assessment by Monte Carlo simulation of complex safety critical operations. In F. Redmill & T. Anderson (Eds.), Proc. 14th Safety-critical Systems Symposium, Bristol, U.K.: Springer, 2006.

[4] Bosse, T., Duell, R., Memon, Z.A., Treur, J., and Wal, C.N. van der, (2009). A Multi-Agent Model for Emotion Contagion Spirals Integrated within a Supporting Ambient Agent Model. In: Yang, J.-J.; Yokoo, M.; Ito, T.; Jin, Z.; Scerri, P. (eds.), Proc. of PRIMA'09. Lecture Notes in Artificial Intelligence, vol. 5925. Springer Verlag, 2009, pp. 48–67.

[5] Bosse, T., Sharpanskykh, A., Treur, J., Blom, H.A.P., and Stroeve, S. (2012). Library of Existing VU Model Constructs. Technical report for the SESAR WP-E project MAREA, E.02.10-MAREA-D2.1.

[6] Bosse, T., Sharpanskykh, A., Treur, J., Blom, H.A.P., and Stroeve, S. (2012). Modelling of Human Performance-Related Hazards in ATM. Proc. 3rd Int. Air Transport Operations Symp. (ATOS). IOS Press, 2012.

[7] Bosse, T., Sharpanskykh, A., Treur, J., Blom, H.A.P., and Stroeve, S. (2012). New Model Constructs for Hazard Coverage. Technical report for the SESAR WP-E project MAREA, E.02.10-MAREA-D2.2.

[8] Cho, J.Y.N., Welch, J.D., and Underhill, N.K. (2011). Analytical workload model for estimating en route sector capacity in convective weather, 9th USA/Europe Air Traffic Management R&D Seminar (ATM 2011), Berlin, Germany.

[9] Civil Aviation Safety Authority. (2005). Operational Notes on Non-Directional Beacons and Associated Automatic Direction Finding. Gov. of Australia. http://www.casa.gov.au/pilots/download/NDB.pdf.

[10] Clark, A., and Chalmers, D. (1998). The Extended Mind. In: Analysis, vol. 58, 1998, pp. 7-19.

[11] Damasio, A. (1996). The Somatic Marker Hypothesis and the Possible Functions of the Prefrontal Cortex. Philosophical Transactions of the Royal Society: Biological Sciences, 351, 1413-1420.

[12] Ekman, P. and Friesen, W.V. (1975). Unmasking the face. Englewood Cliffs, NJ: Prentice-Hall.

[13] Endsley, M.R. (1995). Toward a Theory of Situation Awareness in Dynamic Systems. Human Factors: The Journal of the Human Factors and Ergonomics Society, 37(1), 32-64.

[14] Eurocontrol (2004). Air navigation system safety assessment methodology. SAF.ET1.ST03.1000-MAN-01, edition 2.0.

[15] Everdij, M.H.C., Blom, H.A.P., and Stroeve, S.H. (2006). Structured assessment of bias and uncertainty in Monte Carlo simulated accident risk, Proc. 8th Int. Conf. on Probabilistic Safety Assessment and Management (PSAM8), May 2006, New Orleans, USA.

[16] Ferber, J. and Gutknecht, O. (1998). A meta-model for the analysis and design of organisations in multi-agent systems. In: Proceedings of the Third International Conference on Multi-Agent Systems (ICMAS'98), IEEE Computer Society Press, pp. 128-135.

[17] Federal Aviation Regulations (2012). Atmospheric Icing Conditions for Aircraft Certification. FAR, Part 25, Appendix C, 2012.

[18] Glover, W. and Lygeros, J. (2004). A stochastic hybrid model for air traffic control simulation, Eds: Rajeev Alur and George J. Pappas, Proc. 7th Int. Workshop Hybrid System Computation and Control (HSCC 2004), Philadelphia, PA, USA, March 25-27, 2004.

[19] Heiligers, M. (2011). Pilot task demand load during RNAV approaches, PhD Thesis, TU Delft, January 2011.

[20] Hilburn, B. and Jorna, P. (2001). Task demand load versus mental load, Eds: Hancock and Desmond, Stress, workload and fatigue: theory, research and practice, Erlbaum, Hillsdale, NJ, USA, 2001.

[21] Hill, D.W. (1993). The critical power concept. Sports Medicine, vol.16, pp. 237-254.

[22] Hockey, G.R.J. (1997). Compensatory Control in the Regulation of Human Perfomance under Stress and High Workload: a Cognitive-Energetical Framework. Biological Psychology 45, 1997, 73-93.

[23] Hollnagel, E. (1993). Human reliability analysis, context and control. London, UK: Academic Press.

[24] Hollnagel, E., and Woods, D.D. (2005). Joint cognitive systems: Foundations of cognitive systems engineering. CRC Press, Boca Raton (FL), USA.

[25] Hollnagel, E., Nemeth, C.P., and Dekker, S. (2008). Resilience Engineering Perspectives, Volume 1: Remaining sensitive to the possibility of failure. Ashgate, Aldershot, England.

[26] Hollnagel, E., Woods, D.D., and Leveson, N. (2006). Resilience engineering: Concepts and precepts. Ashgate, Aldershot, England.

[27] Hoogendoorn, M. (2007). Modeling of Change in Multi-Agent Organizations, PhD thesis, VU University Amsterdam.

[28] Hoogendoorn, M., Jaffry, S.W., and Treur, J. (2010). Exploration and Exploitation in Adaptive Trust-Based Decision Making in Dynamic Environments. In: Huang, X.J., Ghorbani, A.A., Hacid, M.-S., Yamaguchi, T. (eds.), Proc. of IAT'10. IEEE Computer Society Press, 2010, pp. 256-260.

[29] ICAO (2004). Advanced Surface Movement Guidance and Control Systems (A-SMGCS) Manual. International Civil Aviation Organization, Doc 9830, AN/452, First Edition.

[30] Klein, A. and Cook, L. (2011). Three models for weather impacted airspace capacity estimation and forecast, Proc. 9th USA/Europe Air Traffic Management R&D Seminar (ATM2011), Berlin, Germany.

[31] Klein, A. Kavoussi, S., and Lee, R.S. (2009). Weather forecast accuracy: study of impact on airport capacity and estimation of avoidable costs, Proc. 8th USA/Europe Air Traffic Management R&D Seminar (ATM2009), Napa, CA, 2009.

[32] Krozel, J., Klimenko, V., and Sharman, R. (2011). Analysis of clear-air turbulence avoidance maneuvers, ATC Quarterly, Vol. 19 (2011), pp. 147-168.

[33] Merk, R.-J. (2010). A Computational Model on Surprise and Its Effects on Agent Behaviour in Simulated Environments. In: Y. Demazeau et al. (eds.), Adv. in Practical Applications of Agents and MAS, Advances in Intelligent and Soft Computing, vol. 70, Springer Verlag, pp. 47-57.

[34] Neumann, P.G. (1997). Computer Security in Aviation. In: Proceedings of the International Conference on Aviation Safety and Security in the 21st Century, White House Commission on Safety and Security, 1997.

[35] Pujet, N. and Feron, E. (1998). Modeling an Airline Operations Control Center, Proc. 2nd USA/Europe ATM R&D Seminar, 1-4 December 1998, Orlando, FL, USA.

[36] Sharpanskykh, A. (2008). On Computer-Aided Methods for Modeling and Analysis of Organizations, PhD thesis, VU University Amsterdam.

[37] Skybrary (2012). Loss of control, 16th May 2012.

[38] Stiensmeier-Pelster, J., Martini, A., and Reisenzein, R. (1995). The role of surprise in the attribution process. Cognition and Emotion 9, pp. 5-31.

[39] Straussberger, S. (2007). Monotony in Air Traffic Control. Air Traffic Control Quarterly, vol. 15, pp 183-207.

[40] Stroeve, S.H., Everdij, M.H.C., and Blom, H.A.P. (2011). Hazards in ATM: model constructs, coverage and human responses. Technical report for the SESAR WP-E project MAREA, E.02.10-MAREA-D1.2.

[41] Stroeve, S.H., Everdij, M.H.C., and Blom, H.A.P. (2011). Studying hazards for resilience modelling in ATM - Mathematical approach towards resilience engineering. In D. Schaefer (Ed.), Proceedings of the SESAR Innovation Days 2011. Brussels: Eurocontrol.

[42] Sykulski, A. M. (2011). The exploration-exploitation trade-off in sequential decision making problems, PhD thesis, Uni. of Southampton.

[43] United States Government Accountability Office (GAO) (2005). Information Security: Progress Made, but Federal Aviation Administration Needs to Improve Controls over Air Traffic Control Systems. GAO-05-712, Washington DC, Aug. 26, 2005.

[44] Wickens, C.D. and Hollands, J.G. (2000). Engineering psychology and human performance. Upper Saddle River (NJ), USA: Prentice Hall.