Consequences of Social and Institutional Setups for Occurrence Reporting in Air Traffic Organizations

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Abstract. Deficient safety occurrence reporting by air traffic controllers is an important issue in many air traffic organizations. To understand the reasons for not reporting, practitioners formulated a number of hypotheses, which are difficult to verify manually. To perform automated, formally-based verification of the hypotheses an agent-based modeling and simulation approach is proposed in this paper. This approach allows modeling both institutional (prescriptive) aspects of the formal organization and social behavior of organizational actors. To our knowledge, agent-based organization modeling has not been attempted in air traffic previously. Using such an approach four hypotheses related to consequences of controller team composition in particular organizational contexts were examined.

Keywords: Agent-based simulation, organization modeling, formal analysis, air traffic.

1 Introduction

One of the safety problems, which air navigation service providers (ANSP) face, is that many safety occurrences happened during air and ground operations are not reported by air traffic controllers. An example of a ground occurrence is 'taxiing aircraft initiates to cross due to misunderstanding in communication'. Knowledge about occurrences is particularly useful for timely identification of safety problems.

To understand the reasons for such a behavior of controllers a number of hypotheses have been formulated by professionals in air traffic control that concern particular controller types. In [6] the following types of controllers that prevail in controller teams are distinguished: (1) *rule-dependent*: controllers who show strict adherence to formal regulations; (2) *peer-dependent*: controllers whose behaviour depends strongly on the behaviour and opinions of their peers. Following the discussions from [6,1] and based on the interviews with safety professionals from an existing ANSP, the following four hypotheses related to occurrence reporting and to the considered types of controllers have been identified:

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Hypothesis 1: Reprimands provided to controllers for safety occurrences, in which they were involved, serve the purpose of improvement of the reporting quality.
Hypothesis 2: The rule-dependent controllers demonstrate more uniform reporting behavior over time than the peer-dependent controllers of the same team.
Hypothesis 3: Teams with majority of peer-dependent members report poorly in the absence of reprimands in ANSPs with low actual commitment to safety.
Hypothesis 4: To neutralize negative effects of peer influence on reporting, a mixed composition of teams with comparable numbers of controllers of both types is useful.

Hypotheses over safety occurrence reporting were attempted to be verified using conventional analysis techniques in air traffic control, which are based predominantly on fault/event trees used for sequential cause-effect reasoning for accident causation [2]. However, such trees do not capture complex, non-linear dependencies and dynamics inherent in ANSPs. Agent-based modeling has been proposed as a means to assess safety risks of and identify safety issues in air traffic operations in a complex ANSP [8,12,13]. However, existing agent-based approaches known to us model air traffic systems without considering the organizational layer, often with a simplified representation of agents (i.e., without or with a very simple internal (or cognitive) structure), cf. [12,13]. Disregarding significant knowledge about formal and informal organization structures of an ANSP may lead to mediocre analysis results, when actual causes of issues remain unidentified. Furthermore, a large number of existing agent-based approaches aim at efficient air traffic management (planning, scheduling), which is not the type of research questions pursued in this research.

To incorporate organizational aspects in agent-based safety analysis of an ANSP, an approach is proposed in this paper that allows modeling both institutional (prescriptive) aspects of an ANSP and proactive social behavior of organizational agents. To define the prescriptive aspects the general organization modeling framework from [10] was used, which has formal foundations precisely defined based on the order-sorted predicate logic. In this framework formal organizations are considered from three interrelated perspectives: the performance-oriented, the process-oriented, and the organization-oriented. The behavior of organizational agents was modeled from external and internal perspectives. From the external perspective interaction of an agent with other agents and with the environment by observation, communication and performing actions was modeled. From the internal perspective the behavior of an agent was modeled by direct causal relations between internal (or cognitive) agents states, based on which an externally observable behavioral pattern is generated. In particular, the internal dynamics of a decision making process of a controller agent whether to report an observed occurrence is considered in the paper.

The developed model of the formal organization extended with a specification of the agents was used to perform simulation of safety occurrence reporting in an ANSP. The four hypotheses formulated above were tested on the obtained simulation results. Previously an approach for validation of models using the framework from [10] has been developed [11]. Using this validation approach, models developed for verifying hypotheses can be validated.

The paper is organized as follows. In Section 2 the developed model for formal reporting is given. A specification of the organizational agents is described in Section 3. The simulation setup and the hypotheses verification results are described in Section 4. One of the steps of statistical validation of the model sensitivity analysis -is considered in Section 5. Finally, Section 6 concludes the paper.

2 Modeling Formal Reporting in an ANSP

For modeling the formal reporting in an ANSP the modeling framework and methodology from [10] was used, which comprises a sequence of organization design steps. To design the model, data obtained from a real ANSP were used. For a more detailed description with formal details see [15].

Step 1. The identification of the organizational roles. A role is a (sub-)set of functionalities of an organization, which are abstracted from specific agents who fulfill them. Each role can be composed by several other roles, until the necessary detailed level of aggregation is achieved. The environment is modeled as a special role. In this study roles are identified at three aggregation levels, among them (see Fig. 1 and 2): ANSP (level 1), Tower Control Unit (level 2), Controller (level 3), Controller Supervisor (level 3), Safety Investigation Unit (level 2), Safety Investigator (level 3). Furthermore, role instances may be specified, which besides the inherited characteristics and behavior of the role may possess additional characteristics. For example, two instances of Controller role were defined for each sector of the airport with the characteristics and behavior of Controller role.

Step 2. The specification of the interactions between the roles. Relations between roles are represented by interaction and interlevel links. An interaction link is an information channel between two roles at the same aggregation level. An interlevel link connects a composite role with one of its subroles to enable information transfer between aggregation levels. For the considered example some of the identified interaction relations are given in Fig. 1 and 2. To formalize interactions, for each role an interaction ontology is introduced. An ontology is a signature or a vocabulary that comprises sets of sorts (or types), sorted constants, functions and predicates. In particular, to specify communications, interaction ontologies of roles include the predicate:

$$communicated\_from\_to : ROLE \times ROLE \times MSG\_TYPE \times CONTENT$$

Here the first argument denotes the role-source of information, the second the role-recipient of information, the third argument denoted the types of the communication (which may be one of the following $observe, inform, request, decision,$ $readback$) and the fourth the content of the communication. The sort $ROLE$

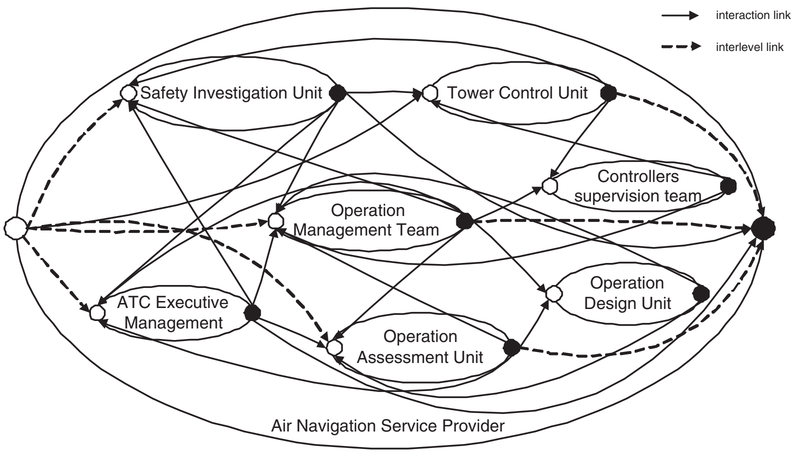

Fig. 1. Interaction relations in ANSP role considered at the aggregation level 2

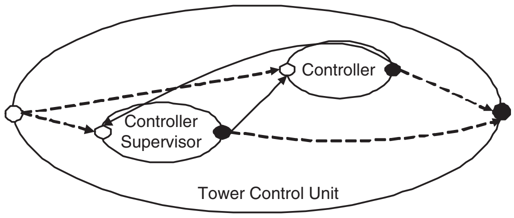

Fig. 2. Interaction relations in Tower Control Unit role considered at the aggregation level 3

is a composite sort that comprises all subsorts of the roles of particular types (e.g., $CONTROLLER$). The sort $CONTENT$ is also the composite sort that comprises all names of terms that are used as the communication content. Such terms are constructed from sorted constants, variables and functions in the standard predicate logic way. For example, communication by role $controller1$ to role $controller\_supervisor$ about $occurrence1$ is formalized as $communicated\_from\_to(controller1, controller\_supervisor, inform, occurrence1)$.

Note that an agent who eventually will be allocated to a role will take over all interaction relations defined for this role. Moreover, an agent may be involved in other (informal) interaction relations with other agents defined in a specification of the agents behaviour (considered in Section 3).

Step 3. The identification of the requirements for the roles. The requirements on knowledge, skills and personal traits of the agent implementing a role at the lowest aggregation level are identified.

*Step 4. The identification of the organizational performance indicators and goals. A performance indicator (PI)*is a quantitative or qualitative indicator that reflects the state/progress of the company or individual. Goals are objectives that describe a desired state or development and are defined as expressions over PIs. PI evaluated in this paper is the reporting quality (ratio reported/observed occurrences) and the corresponding goal is G1 'It is required to maintain reporting quality > 0.75'. A goal can be refined into subgoals forming a hierarchy. Goals are related to roles: e.g., G1 is attributed to ANSPs Tower Control Unit role.

Step 5. The specification of the resources. In this step organisational resource types and resources are identified, and characteristics for them are provided, such as: name, category: discrete or continuous, measurement unit, expiration duration: the time interval during which a resource type can be used; location; sharing: some processes may share resources. Examples of resource types are: airport's diagram, aircraft, incident classification database, clearance to cross a runway, an incident investigation report.

Step 6. The identification of the tasks and workflows. A task represents a function performed in an organization and is characterized by name, maximal and minimal duration. Each task should contribute to the satisfaction of one or more organizational goals. For example, task 'Create a notification report' contributes to goal G1 defined at step 4. Tasks use, produce and consume resources: e.g., task 'Investigation of an occurrence' uses a notification report and produces a final occurrence assessment report. *Workflows* describe temporal ordering of tasks in particular scenarios. Fig.3 describes formal occurrence reporting initiated by a controller. For each task from the workflow responsibility relations on roles were defined. In the following the workflow is considered briefly.

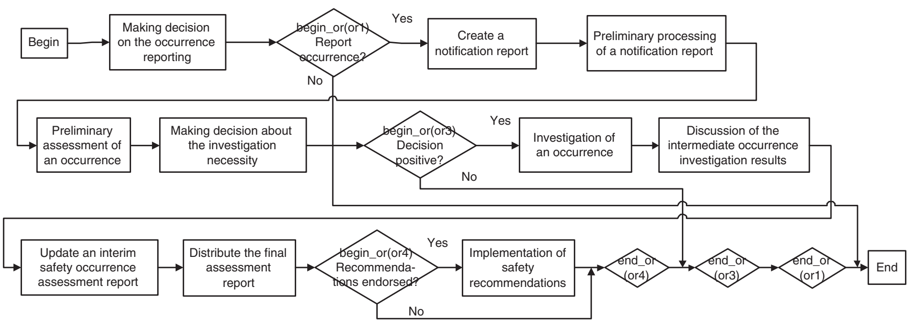

Fig. 3. The workflow for the formal occurrence reporting

After a controller decides to report an observed occurrence, s/he creates a notification report, which is provided to the Safety Investigation Unit (SIU). Different aspects of responsibility relations are distinguished: e.g., Controller role is responsible for execution of and decision making with respect to task Create a notification report, Controller Supervisor is responsible for monitoring and consulting for this task. Depending on the occurrence severity and the collected information about similar occurrences, SIU makes the decision whether

Table 1. Organizational reprimand policies used in simulation

Low severity	$repr(1, A) = 1$
Average severity	$repr(1, A) = 1; repr(1, B) = 0.5$
High severity	$repr(1, A) = 1; repr(1, B) = 0.5;$ $repr(2, C) = 0.2; repr(4, other) = 0.1$

to initiate a detailed investigation. During the investigation accumulated organizational knowledge about safety related issues is used. As the investigation result, a final occurrence assessment report is produced, which is provided to the controller-reporter as a feedback. Furthermore, often final reports contain recommendations for safety improvement, which are required to be implemented by ANSP (e.g., provision of training, improvement of procedures).

Step 7. The identification of domain-specific constraints. Constraints restrain the allocation and behavior of agents. In particular, a prerequisite for the allocation of an agent to a role is the existence of a mapping between the capabilities and traits of the agent and the role requirements. Furthermore, the ANSPs reprimand policies related to reporting were formalized as constraints using function repr that maps the number of occurrences of some type to a reprimand value [0, 1]. Table 1 lists three reprimand policies with the increasing severity of personal consequences used in simulation.

3 Modeling of Agents

First general agent modeling aspects are presented in Section 3.1, then a decision making model of an agent is considered in Section 3.2.

3.1 Modeling Internal States and Interaction

Agent models are formally grounded in order-sorted predicate logic with finite sorts. More specifically, the static properties of a model are expressed using the traditional sorted first-order predicate logic, whereas dynamic aspects are specified using the Temporal Trace Language (TTL) [10], a variant of the order-sorted predicate logic. In TTL, the dynamics of a system are represented by a temporally ordered sequence of states. Each state is characterized by a unique time point and a set of state properties that hold, specified using the predicate $at : STATE\_PROPERTY \times TIME$. Dynamic properties are defined in TTL as transition relations between state properties. For example, the property that for all time points if an agent ag believes that action a is rewarded with r, then ag will eventually perform a, is formalized in TTL as:

$$\forall t : TIME \ [\ at(internal(ag, belief(reward\_for\_action(r, a))), t) \\ \rightarrow \exists t1 \ \&\ t1 > t \ \&\ at(output(ag, performed\_action(a)), t1)\ ]$$

The behavior of an agent can be considered from external and internal perspectives. From the external perspective the behavior can be specified by temporal correlations between agents input and output states, corresponding to interaction with other agents and with the environment. An agent perceives information by observation and generates output in the form of communication or actions.

From the internal perspective the behavior is characterized by a specification of direct causal relations between internal states of the agent, based on which an externally observable behavioral pattern is generated. Such types of specification are called causal networks. In the following different types of internal states of agents are considered that form such causal networks, used further in decision making.

It is assumed that agents create time-labeled internal representations (beliefs) about their input and output states, which may persist over time:

$$\forall ag : AGENT\ \forall p : STATE\_PROPERTY\ \forall t : TIME\ at(input(ag, p), t)$$
$$\rightarrow at(internal(ag, belief(p, t), t + 1))$$

Information about observed safety occurrences is stored by agents as beliefs: e.g., $belief(observed\_occurrence\_with(ot : OCCURRENCE\_TYPE, ag : AGENT)), t : TIME)$. Besides beliefs about single states, an agent forms beliefs about dependencies between its own states, observed states of the environment, and observed states of other agents (such as expectancies and instrumentalities from the following section):

$belief(occurs\_after(p1 : STATE\_PROPERTY, p2 : STATE\_PROPERTY, t1 : TIME, t2 : TIME), t : TIME)$, which expresses that state property $p2$ holds t' ($t1 < t' < t2$) time points after $p1$ holds.

In social science behavior of individuals is considered as goal-driven. It is also recognized that individual goals are based on needs. Different types of needs are distinguished: (1) *extrinsic needs* (n1) associated with biological comfort and material rewards; (2) *social interaction needs* that refer to the desire for social approval and affiliation; in particular own group approval (n2) and management approval (n3); (3) *intrinsic needs* that concern the desires for self-development and self-actualization; in particular contribution to organizational safety-related goals (n4) and self-esteem, self-confidence and self-actualization needs (n5). Different needs have different priorities and minimal acceptable satisfaction levels for individuals in different cultures. To distinguish different types of controllers investigated in this paper, the cultural classification framework by Hofstede [4] was used. The following indexes from the framework were considered: *individualism*(IDV) is the degree to which individuals are integrated into groups; *power distance index* (PDI) is the extent to which the less powerful members of an organization accept and expect that power is distributed unequally; and *uncertainty avoidance index* (UAI) deals with individuals tolerance for uncertainty and ambiguity. The indexes for individuals from the Western European culture adapted from [4] were changed to reflect the features of peer-dependent (low IDV) and rule-dependent (high UAI) agents (see Table 2).

The knowledge of an agent w.r.t. the ATC task is dependent on the adequacy of the mental models for this task, which depends on the sufficiency and timeliness

Table 2. The ranges for the uniformly distributed individual cultural characteristics and minimal acceptable satisfaction values of needs used in simulation

Agent type	IDV	PDI	UAI	$min(n1)$	$min(n2)$	$min(n3)$	$min(n4)$	$min(n5)$
peer-dependent	[0.3, 0.5]	[0.3, 0.5]	[0.4, 0.6]	1	0.8	0.5	0.7	0.9
rule-dependent	[0.7, 0.9]	[0.3, 0.5]	[0.7, 0.9]	1	0.5	0.7	0.7	0.9

of training provided to the controller and the adequacy of knowledge about safety-related issues. Such knowledge is contained in reports resulted from safety-related activities: final occurrence assessment reports resulted from occurrence investigations and monthly safety overview reports. Many factors influence the quality of such reports, for specific details we refer to [15]. Thus, the maturity level of a controller agent ($e5$) is calculated as:

$$e5 = w22 \cdot e19 + w23 \cdot e20 + w24 \cdot e21 + w25 \cdot e10 + w26 \cdot e42 + w27 \cdot e43,$$

here $e19 \in [0, 1]$ is the agent's self-confidence w.r.t. the ATC task (depends on the number of occurrences with the controller); $e20 \in [0, 1]$ is the agent's commitment to perform the ATC task; $e21 \in [0, 1]$ is the agents development level of skills for the ATC task; $e10 \in [0, 1]$ is the indicator for sufficiency and timeliness of training for changes; $e42 \in [0, 1]$ is the average quality of the final occurrence assessment reports received by the agent; $e43 \in [0, 1]$ is the average quality of the received monthly safety overview reports, $w22 - w27$ are the weights (sum up to 1).

The agent's commitment to safety is also influenced by the perceived commitment to safety of other team members and by how much the priority of safety in enforced and supported by management. An agent evaluates the managements commitment to safety by considering factors that reflect the managements effort in contribution to safety (investment in personnel and technical systems, training, safety arrangements).

In such a way, the commitment value is calculated based on a feedback loop: the agent's commitment influences the team commitment, but also the commitment of the team members and of the management influence the agents commitment:

$$e6 = w1 \cdot e1 + w2 \cdot e2 + w3 \cdot e3 + w4 \cdot e5,$$

here $e1 \in [0, 1]$ is the priority of safety-related goals in the role description, $e2 \in [0, 1]$ is the perception of the commitment to safety of management, $e3 \in [0, 1]$ is the perception of the average commitment to safety of the team, $e5 \in [0, 1]$ is the controller's maturity level w.r.t. the task; $w1 - w4$ are the weights (1 in total). For rule-dependent agents $w1 > w3$ and $w2 > w3$ and for peer-dependent agents $w3 > w2$ and $w3 > w1$.

3.2 Modeling Decision Making of a Controller Agent

Reporting quality analyzed in this paper is determined based on the decisions of controllers agents whether to report observed occurrences. To model decision making of agents a refined version of the expectancy theory by Vroom [7] has been used. Some advantages of the expectancy theory are: (a) it can be formalized; (b) it allows incorporating the organizational context; (c) it has received good empirical support. According to this theory, when a human evaluates alternative possibilities to act, s/he explicitly or implicitly makes estimations for the following factors: *valence*, *expectancy* and *instrumentality*. In Fig. 4 and 5 the decision making models for reporting and not reporting an occurrence are shown.

Expectancy refers to the individual's belief about the likelihood that a particular act will be followed by a particular outcome (called a first-level outcome). For example, E12 refers to the agent's belief of how likely that reporting of an occurrence will be followed by an administrative reprimand. *Instrumentality* is a belief concerning the likelihood of a first level outcome resulting into a particular second level outcome; its value varies between -1 and +1. Instrumentality takes negative values when a second-level outcome does not follow a first-level outcome. A second level outcome represents a desired (or avoided) by an agent state of affairs that is reflected in the agent's needs. For example, I32 refers to the belief about the likelihood that own group appreciation of the action results in own group approval. In the proposed approach the original expectancy model is refined by considering specific types of individual needs, described in section 3.1 *Valence* refers to the strength of the individual's desire for an outcome or state of affairs. Values of expectancies, instrumentalities and valences change over time, in particular due to individual and organizational learning.

In the Vrooms model the force on an individual to perform an act is defined as:

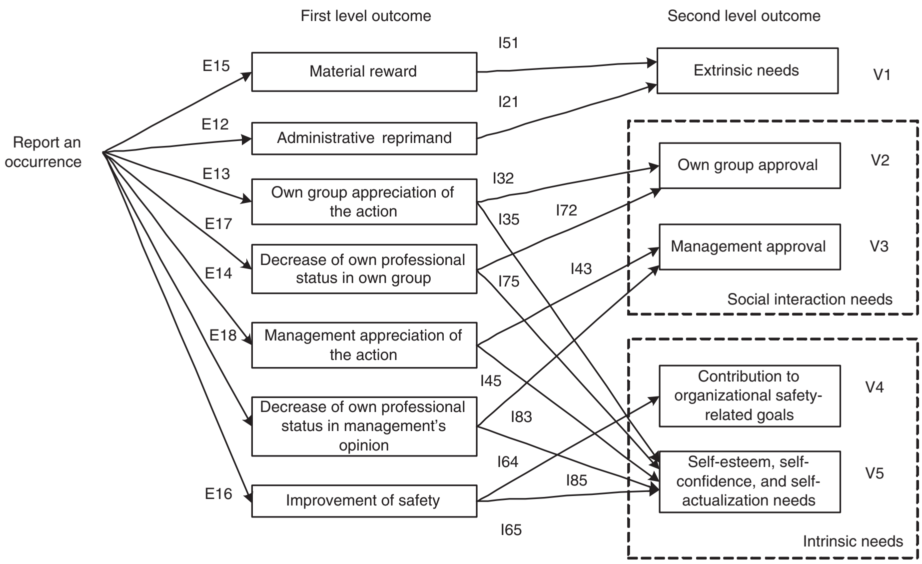

Fig. 4. Decision making model for reporting an occurrence. Here E's are expectancies, I's are instrumentalities and V's are valences.

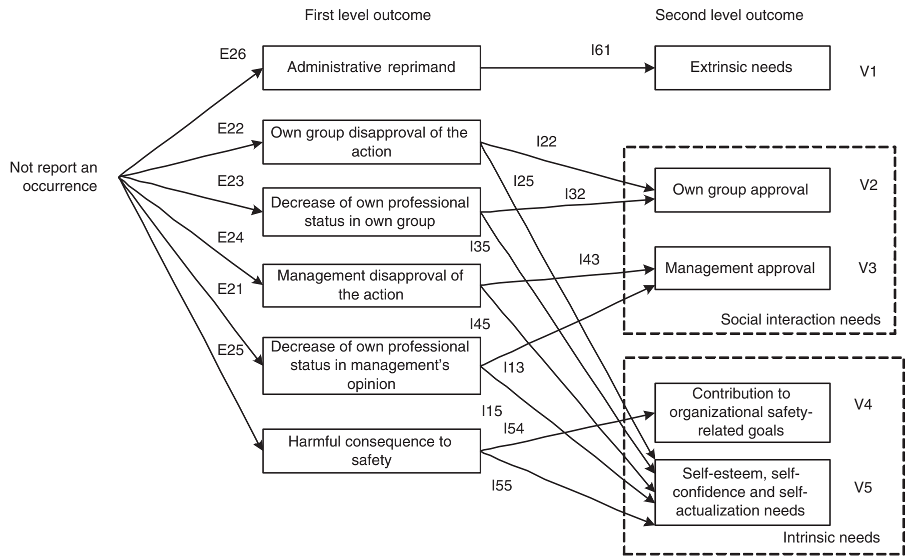

Fig. 5. Decision making model for not reporting an occurrence. Here E's are expectancies, I's are instrumentalities and V's are valences.

$$F_i = \sum_{j=1}^{n} E_{ij} \cdot \sum_{k=1}^{m} V_{ik} \cdot I_{jk}$$

Here E_{ij} is the strength of the expectancy that act i will be followed by outcome j; V_{ik} is the valence of the second level outcome k; I_{jk} is perceived instrumentality of outcome j for the attainment of outcome k.

The agent's decision making consists in the evaluation of the forces for two alternatives: to report and to not report. The agent chooses to perform the alternative with a greater force. In the following the basis for calculation of the variables of the decision making model for reporting is discussed. The precise, elaborated details of the mathematical model can be found in [15].

The factors $E15$, $E12$, $I51$ and $I21$ are defined based on the ANSP's formal reprimand/reward policies (see Table 1). In particular, $E12 = 1$ for an observed occurrence, which completes a set of occurrences, for which a reprimand is defined; $E12 = 0$ for all other observed occurrences. The values of $E13$ and $I32$ depend largely on the average commitment of the team of controllers to safety, and $E18$ and $I43$ depend on the management commitment to safety (considered in section 3.1).

With each set of occurrences, in which a controller agent was involved during an evaluation period (e.g., a month), the measure of severity is associated, calculated as the sum of the severities of the occurrences from the set. The factors $E17$, $E18$, $I72$, $I43$ depend mostly on the severity of the set of occurrences of the controller known to his/her team and known to the management. $E16$ is based on the agent's beliefs about the dependencies between previous reporting of similar occurrences and improvement of safety that followed.

$I35$ and $I75$ are based on the agent's IDV index, which indicates the degree of importance of team's opinions for the agent (e.g., high for peer-dependent agents, low for rule-dependent agents). $I45$ and $I85$ are based on the agent's PDI index. Furthermore, also the values of the basis valences (the degrees of importance of particular needs taken alone, see Fig.2) of a controller agent depend on its indexes:

$$v1_b = 1 \; v2_b = 1 - IDV \; v3_b = 0.7 \cdot PDI + 0.3 \cdot UAI \; v4_b = 0.3 + 0.7 \cdot UAI$$

The values of valences change over time depending on the degree of satisfaction of the agent's needs: the more a need is satisfied, the less its valence:

$$v(need) = \begin{cases} v_b \cdot \frac{min\_accept(need)}{sat(need)}, & sat(need) \geq min\_accept(need) \\ v_b + v_b \cdot \frac{min\_accept(need) - sat(need)}{min_accept(need)} & sat(need) < min\_accept(need) \end{cases}$$

here $sat(need)$ is the current satisfaction value of a need.

4 Simulation Results

To test the hypotheses formulated previously 6 types of ANSPs have been considered (see Table 3). The informal descriptions of the ANSPs were formalized using the modeling framework from Section 2. The simulated organizations were populated with 48 controller agents distributed over 6 airport sectors, working in 4 shifts, 12 hours per day (12 controllers per shift; 2 per sector). The simulation has been done in the Matlab environment.

Many evidences exist (cf [1]) that due to a strict selection procedure and similarity of training, controllers have highly developed ATC skills which was also specified in the simulation model. Three types of controller teams were considered for each ANSP type: (a) with majority of peer-dependent members (75%); (b) with equal numbers of peer- and rule-dependent members; (c) with majority

Table 3. ANSP types used in simulation

Organizational aspect	Settings 1/2	Settings 3/4	Settings 5/6
Formal commitment to safety	high	high	low
Investment in personnel average	high	low	
Quality of technical systems	average	high	low
Formal support for confidentiality of reporting	average	high	low
Quality of management of safety activities	low	high	low
Personal consequences of occurrences	high/low	high/low	high/low
Influence of a controller on organizational safety arrangements	low	high	low
Quality of identification of occurrences	high/average	high/average	high/average

Table 4. The average reporting quality obtained from the simulations for each ANSP setting

Setting #	1	2	3	4	5	6
more rule-dependent	0.78	0.7	0.78	0.86	0.43	0.35
more peer-dependent	0.74	0.48	0.77	0.87	0.34	0.22
equal number	0.78	0.64	0.78	0.88	0.4	0.27

Table 5. The variances of reporting quality obtained from the simulations for each ANSP setting

Setting #	1	2	3	4	5	6
more rule-dependent	5e-3	2e-3	5e-3	5e-3	3e-3	7e-3
more peer-dependent	4e-3	3e-3	7e-3	3e-3	3e-3	2e-3
equal number	6e-3	3e-3	6e-3	8e-3	3e-3	4e-3

of rule-dependent members (75%). Different types of occurrences happened randomly in the environment with the frequencies provided by a real ANSP. 1000 simulations of each type have been performed. The obtained average reporting quality is given in Tables 4 and 5. As follows from the obtained results, the hypothesis 1 which states that reprimands serve the purpose of improvement of reporting quality was confirmed for settings 1 (in comparison with 2) and 5 (in comparison with 6). However, in setting 3 quite an opposite effect was observed: reprimands and close control in the ANSPs committed to safety cause a notable decrease in the reporting quality (in comparison with 4).

To verify the hypothesis 2 that rule-dependent controllers demonstrate more uniform reporting behavior over time than peer-dependent controllers, the mean and standard deviation values of the reporting force for the teams of types (a) and (c) were calculated. The obtained results show that the difference between the standard deviation values of the forces for the teams of types (a) and (c) for all settings was 7% (of the team's (a) value) at most. This finding may be explained by a high coherence of the teams of type (a), in which the attitude towards reporting (i.e., reporting force) stabilizes quickly due to intensive observation/interaction of/between the team members. In the teams of type (c) the homogeneous reporting behavior is achieved by rule adherence of most of the team members. Thus, although the standard deviation was less for the team of type (c) in all settings, the hypothesis 2 is supported weakly.

The hypothesis 3, which states that in ANSPs with low actual commitment to safety in the absence of reprimands, teams of type (a) may not report often, has been confirmed strongly by the simulation results. As can be seen from Table 4 the reporting quality dropped from 0.74 in the setting 1 to 0.48 in the setting 2 and from 0.34 in the setting 5 to 0.22 in the setting 6.

The hypothesis 4 that to neutralize negative effects of peer influence, mixing composition of teams may be proposed is also supported by the simulation results. From Table 4 it can be seen that the reporting quality of the teams of type

(b) is never worse and for some settings is much better than of the teams of type (a). Furthermore, as can be seen from Table 4 such an increase in reporting depends non-linearly on the number of rule-dependent agents; this is a joint effect of the organizational context and the non-linear behavior of the agents situated in this context.

5 Sensitivity Analysis

The validity of the results of automated checking of hypotheses depends on the validity of the model used. One of the tools used commonly for statistical validation of simulation models is sensitivity analysis [5,9,14]. By sensitivity analysis one can identify the most important factors of a model that influence particular outputs of the model. Then, the validity of the significance of the identified factors for the models outputs may be checked by performing face validation with domain experts and/or based on available domain knowledge.

The simulation model considered in this paper has one measured output the average occurrence reporting quality in the ANSP. Using sensitivity analysis the degree of influence of the input factors of the model given in Table 6 on the average occurrence reporting quality in the ANSP was investigated. To this end two sensitivity analysis techniques were used: Monte-Carlo filtering [14] and factor fixing [9].

Table 6. The input factors of the ANSP model

Factor	Description
e1	Priority of safety-related goals in the role description
e4	Influence of a controller on safety activities
e7	Sufficiency of the amount of safety investigators
e8	Sufficiency of the amount of controllers
e9	Availability of up-to-date technical systems for controllers
e10	Sufficiency and timeliness of training for changes
e11	Regularity of safety meetings
e12	Developed and implemented SMS
e14	Level of development of managerial skills of the controller supervisor
e19	Initial value of the self-confidence of a controller
e20	Commitment to perform ATC task
e21	Development level of skills for ATC task
e25	Sufficiency of the number of maintenance personal
e26	Quality of formal procedures for system checks and repairs
e35	Intensity of informal interactions in the team of controllers
e36	Quality of the formal safety occurrence assessment procedure
e40	Quality of the communication channel between controllers and safety investigators
e44	Average commitment of the agents involved in the safety analysis
e71	Formal support for confidentiality of reporting

Monte-Carlo filtering is often applied if a definition for 'good' or 'acceptable' model outcome can be given, e.g., through a set of constraints. In the considered model, the acceptable reporting quality is considered to be > 0.8. The aim of the Monte Carlo filtering is to perform multiple model evaluations with the input factors randomly chosen from suitable ranges and then split the output values into two subsets: those considered as 'acceptable' and those considered as 'unacceptable', depending on whether they lead to acceptable or unacceptable outputs. All factors in Table 6 have range (0, 1]. The Smirnov test is applied to each input factor to test whether the distributions of the 'acceptable' and 'unacceptable' values can be regarded as significantly different [9]. The higher the Smirnov test value for an input factor, the higher its influence on the model output, and hence the higher the sensitivity of output due to changes in the input. In detail, the Monte Carlo filtering method is implemented by the following two steps.

Step 1: MC simulations: 1000 Monte Carlo simulations were performed. For each input factor x_i two sets of values were determined: $x_i|B$, containing all values of x_i from the simulations that produced the desired organizational behaviour, and $x_i|B$, containing all x_i values that did not produce the desired behaviour.

Step 2: Smirnov test: The Smirnov two sample test was performed for each input factor independently. The test statistics are defined by

$$d(x_i) = sup_Y||F_B(x_i|B) - F_{\underline{B}}(x_i|\underline{B})||,$$

where F_B and $F_{\underline{B}}$ are marginal cumulative probability distribution functions calculated for the sets $x_i|B$ and $x_i|\underline{B}$, respectively, and where Y is the output.

A low level of $d(x_i)$ supports the null-hypothesis $H_0 : F_B(x_i|B) = F_{\underline{B}}(x_i|\underline{B})$, meaning that the input factor x_i is not important, whereas a high level of $d(x_i)$ implies the rejection of H_0 meaning that x_i is a key factor.

It is determined at what significance level α, the value of $d(x_i)$ implies the rejection of H_0, where α is the probability of rejecting H_0 when it is true. In the sensitivity analysis, we used the classification High / Medium / Low for the importance of each factor:

- If $\alpha \leq 0.01$, then the importance of the corresponding factor x_i is considered High;
- If $0.01 < \alpha \leq 0.1$, then the importance of the corresponding factor is considered Medium;
- If $\alpha > 0.1$, then the importance of the corresponding factor is considered Low.

The Monte Carlo filtering method provides a measure of the sensitivity of the model output with respect to variations in the input factors. A limitation is that it captures only first-order effects and it does not detect interactions among factors. To solve this problem, variance-based global sensitivity analysis techniques can be used. Such techniques are able to capture interaction (correlation) between input factors by decomposing the variance of the output. One of such

Table 7. Importance of input factors classified by categories High and Medium for three types of controller teams

Importance	High	Medium
more rule-dependent	$e1, e4, e7, e8, e9, e10, e12, e14, e71$	$e11, e20, e21$
more peer-dependent	$e1, e4, e7, e8, e9, e10, e12, e14, e35$	$e11, e20, e21$
equal number	$e1, e4, e7, e8, e9, e10, e12, e14$	$e11, e20, e21$

techniques - the factor fixing [9] was used in this study. By this technique one is able to identify input factors recognized as insignificant by the Monte Carlo filtering approach, but which nevertheless should be considered as significant due to their interaction with other input factors.

The results of the sensitivity analysis for the simulation model considered in this paper are given in Table 7.

The factors $e1, e7, e8, e9, e10, e12$ were identified as highly influential for the quality of occurrence reporting by domain experts. The factor $e4$ is particularly important for high-quality reporting in a Western European ANSP, as argued in the literature [1,6]. Although the factor $e14$ was recognized as relevant, the degree of its influence on occurrence reporting was difficult to judge for the experts. A high importance of $e71$ for occurrence reporting in teams with most rule-dependent members can be explained by the rule adherence of the members. The factor $e35$ gains a high importance for teams with most peer-dependent members due to high importance of informal interactions in such teams.

Thus, none of the identified factors of high importance was identified as irrelevant or incorrect by domain experts and in the literature.

6 Conclusions

Many existing ANSPs face the problem that many safety occurrences observed by controllers are not reported. Practitioners in air traffic formulated hypotheses in the attempt to understand the reasons for such behavior. However, most of these hypotheses are difficult to verify manually due to a high complexity and temporal interdependency of institutional and social factors that should be taken into account. To address this issue an approach based on formal agent-based modeling and simulation has been proposed. Four hypotheses related to consequences of team composition in particular organizational contexts were examined. Two of these hypotheses were supported strongly by the simulation results, for one hypothesis only a weak support was found, and one hypothesis was partially supported, for particular types of organizational contexts only.

The validity of the results of automated checking of hypotheses depends on the validity of the model used. In general, to prove that a developed simulation model is valid, a number of validation steps should be performed [5]. In this paper the results of an important statistical validation step - sensitivity analysis are presented. The identified important factors influencing the average quality of occurrence reporting in an ANSP were recognized as highly relevant by domain experts and the literature.

However, sensitivity analysis alone is not sufficient to ensure the validity of a model. Previously, an approach for validation of agent-based organization models in air traffic based on questionnaires was developed [11]. Such an approach can be followed for simulation models similar to the one considered in the paper, when relevant questionnaire data are available.

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15. Appendix, `http://www.few.vu.nl/~sharp/app.pdf`