An Agent-based Approach to Modeling and Analysis of Safety Culture in Air Traffic

Alexei Sharpanskykh
Artificial Intelligence Department
Vrije Universiteit Amsterdam
Amsterdam, the Netherlands
sharp@few.vu.nl

Sybert Stroeve
Air Transport Safety Institute
National Aerospace Laboratory NLR
Amsterdam, the Netherlands
stroeve@nlr.nl

***Abstract*— Safety culture is currently recognized as important in many domains and various studies have addressed its characterization and assessment. However, relations between safety culture and formal and informal organizational structures and processes are yet not well understood. This impedes structured improvement of safety culture. We aim to improve the understanding of these relations by agent-based organization modeling and analysis. This paper presents an organization model for safety occurrence reporting at an air navigation service provider in relation to its safety culture. Furthermore, the paper discusses the results of agent-based simulation studies performed based on the developed model.**

Keywords-safety culture, organization modeling, agent-based simulation

I. Introduction

Since the Chernobyl accident, the relevance of safety culture has become increasingly recognized in many industries (e.g., nuclear, air traffic management, chemical). Many studies showed that safety culture is a key predictor of safety performance of an organization [2]. Currently, many definitions of safety culture exist [6]. Most of them encompass five components: (1) informed culture that collates data from accidents and incidents and combines them with information from proactive measures (e.g., safety audits); (2) reporting culture in which employees feel free to report safety-related occurrences; (3) just culture characterized by an atmosphere of trust; (4) flexible culture that successfully manages safety during organizational changes; (5) learning culture needed to draw conclusions from the information collected along with the will to implement necessary changes.

Various studies focused on characterization of safety culture and on assessment of safety culture of various organizations, including Air Navigation Service Providers (ANSP's) (cf. [3]). Such studies typically use statistical analysis of safety culture surveys, which are based on questionnaires addressing a variety of safety culture issues and which are distributed among the personnel of the organization under study. Although such surveys can provide a broad overview of the opinions of employees about safety culture issues, the relation of safety culture with organizational structures and processes can not be well inferred from such survey results. This limitation affects the determination of ways to improve safety culture. As a way forward, the aim of this study is to enhance safety analysis of organizational processes in air traffic by development of formal approaches for modeling, simulation and analysis of organizational relationships and processes. These models may provide a proper basis for understanding the causal relations between organizational processes that influence safety culture, such that robust and flexible policies may be identified to improve and maintain a sufficient level of safety culture in an organization.

The development of the model has been focused on safety occurrence reporting and its relation with safety culture at ANSPs. The reporting of safety-related occurrences is obligatory in Air Traffic Management (ATM) and it is an important constituent of the Safety Management System (SMS) of ANSP's. The model aims to describe the emergence of safety culture vulnerabilities in relation to safety occurrence reporting in ANSPs' organizational context. To develop the model the organization modeling and analysis framework of [11] has been used. In contrast to many existing organization modeling frameworks (cf. ARIS [10]; [7]), this framework has a precisely defined formal basis: to express structural relations sorted predicate logic-based languages are used, whereas the Temporal Trace Language (TTL) is used for specifying dynamic aspects of organizations. In this framework organizations are considered from four interrelated views: The organization-oriented view describes organizational roles, interaction and formal authority relations on roles. The performance-oriented view describes the organizational goals and performance indicators and relations between them. The process-oriented view describes organizational tasks and processes, static and dynamic relations between them (e.g., decomposition, ordering and synchronization), and the resources used and produced. The agent-oriented view creates the link between the role-based formal organization and agents that are to perform the roles.

As a basis for the model development and validation, our research efforts are coordinated with safety culture research pursued at Eurocontrol Experimental Centre. In an effort to measure and understand safety culture at European ANSPs, Eurocontrol has been developing a Safety Culture Measurement Tool (SCMT) that uses safety culture questionnaires with statements about potential enablers and disablers of safety culture.

The structure of the paper is as follows. Section II describes identification of safety culture issues of two ANSPs, as a basis for model development. Section III considers modeling formal reporting in an ANSP. In Section IV modeling of agents is described. Some results of agent-based simulations are presented in Section V. Section VI concludes the paper.

II. IDENTIFICATION OF SAFETY CULTURE ISSUES

To identify safety culture aspects relevant for the occurrence reporting, SCMT results of two ANSPs and safety culture data from the literature were analyzed and interviews were conducted with experts at Eurocontrol Head Quarters and at a third ANSP (ANSP-3). As result of this analysis, a categorized set of safety culture issues that impact safety occurrence reporting were determined (examples are given in Table I).

The categorization has been performed along four aggregation levels: (1) the level of an individual in the organization (e.g. a controller, a manager); (2) the level of a team (e.g. a team of air traffic controllers); (3) the level of an organization (i.e. intra-organizational structures); (4) the level of inter-organizational interaction (i.e. influences from other organizations). For each issue in the identified set, required organization modeling aspects have been identified.

TABLE I. EXAMPLES OF THE IDENTIFIED SAFETY CULTURE ISSUES

Group 1: Individual aspects
Occurrence reporting may lead to ‘naming and blaming’ and therefore it may not be in the personal interest of an actor
The confidentiality of reporting is not trusted
Actors are not motivated to report their safety concerns because of the lack of feedback and interest experienced in the organisation.
Group 2: Team aspects
Willingness of actors to cooperate with an actor may decrease after s/he has been involved in a (serious) incident
Problems are not raised as actors do not want to be seen as trouble-makers
Supervisors may not effectively reinforce safety culture
Group 3: Intra-organizational aspects
Importance of safety-related goals may be threatened by performance-related goals
Feedback / lessons learned from incidents comes too late or not at all
Information about changes in procedures and in the system is not provided on time to (some) actors that require this information
Group 4: Inter-organizational aspects
The Ministry of Justice may decide to investigate (severe) occurrences and to prosecute involved organisations or human operators. In investigation and prosecution, occurrence reports may be used
Lack of open communication between ANSP and Regulator.

Among these aspects are the ones related to the formal organization (i.e., formally specified structures and processes), as well as to autonomous behavior of organizational individuals (e.g., informal interaction) (see Figure 1). Then, based on the three criteria - importance for modeling of safety occurrence reporting, availability of data, maturity level of modeling techniques - the selection of the most relevant modeling aspects has been performed for further inclusion in the model. The model will be discussed in the next section. For more details about the identification of safety culture issues we refer to [12].

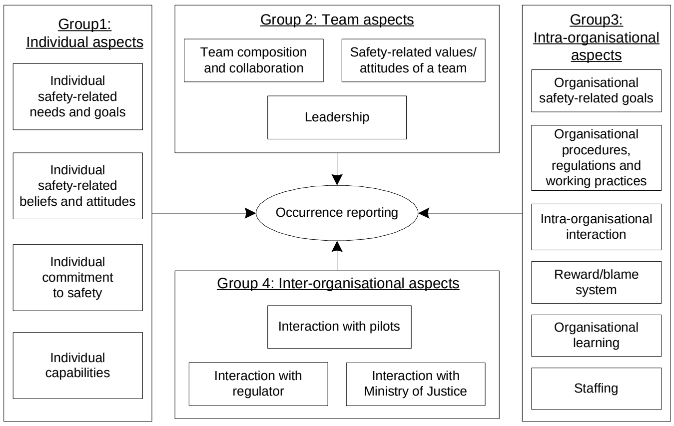

Figure 1. The groups of aspects that influence safety occurrence reporting

III. MODELING FORMAL REPORTING IN AN ANSP

For modeling the formal reporting in an ANSP the modeling framework and methodology from [11] was used, which comprises a sequence of organization design steps. This framework includes all the identified modeling aspects related to the formal organization of an ANSP. Also, as it will be shown in Section IV, it allows an easy extension by inclusion the required aspects of autonomous behavior of organizational individuals of an ANSP. To design the model, data obtained from a real ANSP were used. For a more detailed description of the design steps with formal details see [13].

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: ANSP (level 1), Air Traffic Control Unit (level 2), Controller (level 3), Controller Supervisor (level 3), Safety Monitoring Group (level 2), Safety Investigator (level 3), Crew (level 2). Role instances may possess additional characteristics besides the inherited characteristics and behavior. For example, two instances of Controller role were defined for each air traffic control sector with the characteristics and behavior of Controller role.

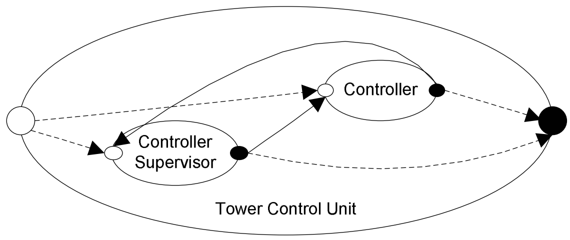

Figure 2. Interaction relations between the subroles of Tower Control Unit role at aggregation level 3

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 (for example, see Figure 2). An interlevel link connects a composite role with one of its subroles to enable information transfer between aggregation levels. For example, in Figure 3 only Safety Investigation Unit, Air Traffic Control Unit and Operation Management Team roles can receive/output information from/to roles outside of ANSP role via interlevel links.

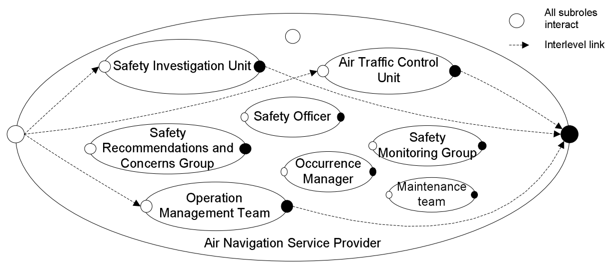

Figure 3. Interaction relations between the subroles of Air Navigation Service Provider role at aggregation level 2

Interaction between roles is enabled by interfaces (i.e., input and output states) formalized using interaction (input and output) ontologies. For specifying communications the interface ontologies for all roles include the following predicate:

communicated_from_to: ROLE x ROLE x MSG_TYPE x CONTENT

Here the first argument denoted 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 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.

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 ANSP's Air Traffic Control Unit role.

Step 5. The specification of the resources. In this step organizational 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 tasks may share resources. Note that information is also modeled as a resource type. Examples of resource types of the ATO 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. Figure 4 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. After a controller decides to report an observed occurrence, s/he creates a notification report, which is provided to the Safety Recommendation and Concern Group (SRCG). 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, SRCG

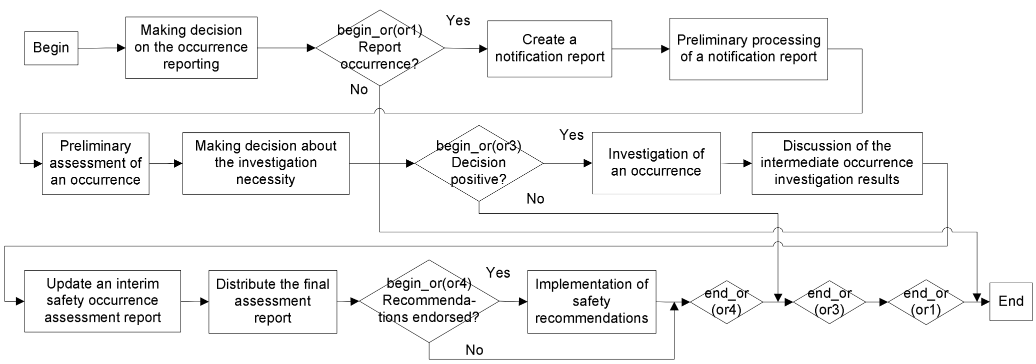

Figure 4. The workflow for the formal occurrence reporting

makes the decision whether 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 provides feedback to the controller-reporter. 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 ANSP's reprimand policies related to reporting were formalized as constraints using a function repr that maps the number of occurrences of some type to a reprimand value [0, 1]. Table II lists three reprimand policies with the increasing levels of personal consequences used in simulation. For example, if a controller was involved in 1 occurrence of type B and 2 occurrences of type C during an evaluation period in an ANSP in which the reprimand policy with high personal consequences is applied, then the controller will receive the reprimand value 0.7.

TABLE II. ORGANIZATIONAL REPRIMAND POLICIES USED IN SIMULATION

Low personal consequences	repr(1, A) = 1
Medium personal consequences	repr(1, A) = 1; repr(1, B) = 0.5
High personal consequences	repr(1, A) = 1; repr(1, B) = 0.5; repr(2, C) = 0.2; repr(4, other) = 0.1

IV. MODELING OF AGENTS

The specification of a formal organization forms a part of an overall organizational specification. Another part describes characteristics and behavior of agents. Thus, an overall organizational specification combines prescriptive aspects of a formal organization with the specification of the autonomous behavior of agents. Using such specifications, investigations of different scenarios of organizational behavior can be performed by simulation. In this section first general agent modeling aspects are presented in Section IV.A, then a decision making model of an agent is considered in Section IV.B.

A. 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) [11], 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 x 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 after 30 time points perform a, is formalized in TTL as:

∀t:TIME [at(internal(ag, belief(reward_for_action(r, a))), t) → at(output(ag, performed_action(a)), t+30)]

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 agent's input and output states, corresponding to interaction with other agents and with the environment. Agents perceive information by observation and generate output in the form of communication or actions. Since agents are allocated to organizational roles, communication among them is specified using the interaction ontologies of roles. Furthermore, an agent observes the behavior of other agents and of the environment. Passive and active observations are distinguished. In contrast to a passive observation, an active observation is always concerned with the agent's initiative. An active observation of a state property p by an agent is formalized using the function to_be_observed(p: STATE_PROPERTY). Observation results are provided to the agent's input using the function observation_result(p: STATE_PROPERTY, sign: BOOL), which indicates whether p holds in the environment or for another agent. Actions of an agent generated at its output are specified by performed(act:ACTION).

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:

∀ag:AGENT ∀p:STATE_PROPERTY ∀t:TIME at(input(ag, p), t)→ 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 the considered case each controller agent creates the belief about the dependency between providing of a notification report on an occurrence of some type to his/her supervisor and receiving a final assessment report on the occurrence (i.e., feedback) from a safety investigator agent. Moreover, often final assessment reports include recommendations for organizational and environmental improvement, which when implemented may be observed by the controller-reporter. These dependencies are formalized as:

belief(occurs_after(output(ag_controller,
communicated_from_to(ag_controller, ag_supervisor, inform,

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                                        notification_report_for_B)),
  output(ag_investigator,communicated_from_to(ag_investigator,
     ag_controller,  inform, final_assessment_report_for_B))), 24h,
1440h)
belief(occurs_after(output(ag_investigator,
    communicated_from_to(ag_investigator, ag_controller, inform,
    final_assessment_report_for_B)),
  output(env,
observation_result(recommendations_implemented_for_B))),
      360h,8640h))
```

An agent may have beliefs about faulty dependencies and/or make incorrect estimation of likelihoods (e.g., some controllers may believe that reporting of insignificant occurrences is punishable, whereas in reality it is not).

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 [5] 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 individual's tolerance for uncertainty and ambiguity. The cultural indexes for controllers from the Western and Eastern European cultures adapted from [5] used in simulation are given in Tables III and IV.

TABLE III. THE RANGES OF THE UNIFORMLY DISTRIBUTED CULTURAL INDEXES FOR CONTROLLERS FROM THE WESTERN AND EASTERN EUROPEAN CULTURES USED IN SIMULATION

Agent type	IDV	PDI	UAI
Eastern culture	[0.2, 0.4]	[0.8, 1]	[0.8, 1]
Western culture	[0.7, 0.9]	[0.3, 0.5]	[0.4, 0.6]

TABLE IV. MINIMAL ACCEPTABLE SATISFACTION VALUES OF NEEDS OF CONTROLLERS FROM THE WESTERN AND EASTERN EUROPEAN CULTURES USED IN SIMULATION

Agent type	min_ accept (n1)	min_ accept (n2)	min_ accept (n3)	min_ accept (n4)	min_ accept (n5)
Eastern culture	1	0.8	1	0.7	0.6
Western culture	1	0.6	0.5	0.7	0.9

Another internal state highly relevant for decision making is the agent's *commitment to safety*. In the following a causal network that forms this state is discussed. Commitment to safety is determined largely by the agent's maturity degree the agent's tasks [4]. In the theory of situational leadership [4] the agent's maturity w.r.t. to a task is defined as an aggregate of the agent's experience, willingness and ability to take responsibility for the task. The agent's willingness to perform a task is determined by the agent's confidence and commitment, which are necessary for the ATC task execution. The ability of an agent to perform a task is determined by its knowledge and skills. Thus, the agent's maturity is a complex notion, which value is calculated based on other variables of the model. Furthermore, the maturity value changes over time as a result of gaining new knowledge and skills, and changing self-confidence of a controller. In an efficient, committed to safety ANSP the maturity of a controller grows until some high value is reached and then fluctuates slightly around this value.

In the model, the adequacy of the mental models for the air traffic control (ATC) tasks depends on the sufficiency and timeliness of training provided to the controller and the adequacy of knowledge about safety-related issues. Such knowledge is contained in reports that 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 [13]. 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 agent's 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 the management. An agent evaluates the management's commitment to safety by considering factors that reflect the management's 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 agent's 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).

B. *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 [8] 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 [8]. 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 Figures 4 and 5 the decision making models for reporting and not reporting an occurrence and is shown.

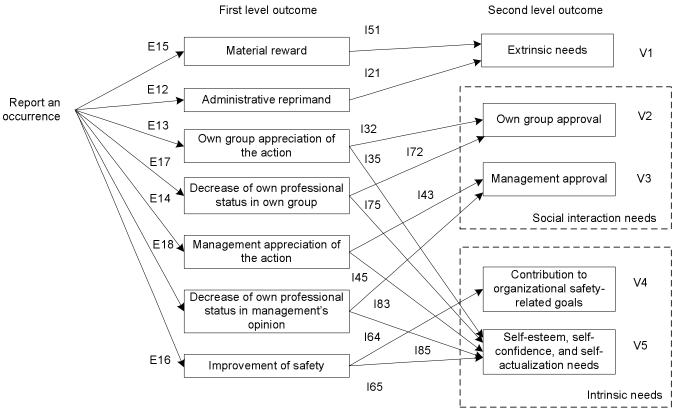

Figure 4. Decision making model for reporting an occurrence.

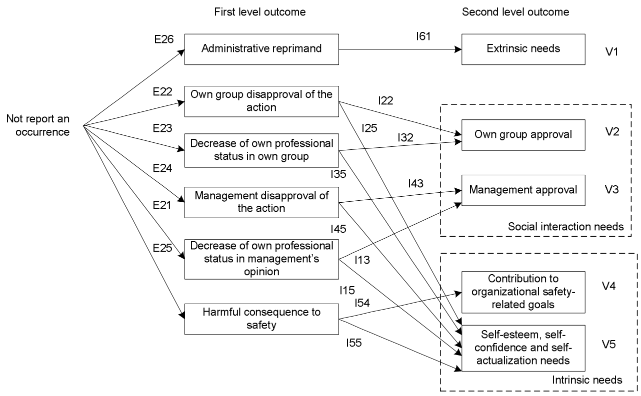

Figure 5. Decision making model for not reporting an occurrence.

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 in Figure 4 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) state of affairs that is reflected in the agent's needs. For example, I32 in Figure 4 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 IV.A. Valence refers to the strength of the individual's desire for an outcome or state of affairs; it is also an indication of the priority of needs. Values of expectancies, instrumentalities and valences change over time, in particular due to individual and organizational learning.

In the Vroom's model the force on an individual to perform an act is defined as:

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

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 (Figure 4). The precise, elaborated details of the mathematical model can be found in [13].

The factors E15, E12, I51 and I21 are defined based on the ANSP's formal reprimand/reward policies (see Table II). 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 IV.A).

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. 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 Figure 4) of a controller agent depend on its indexes:

$v1_b = 1 \quad v2_b = 1\text{-IDV} \quad v3_b = 0.7 \cdot PDI + 0.3 \cdot UAI \quad v4_b = 0.3 + 0.7 \cdot UAI$

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:

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

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

V. SIMULATION RESULTS

The developed model was used for analysis of the behavior of controllers agents related to safety occurrence reporting in different types of organizations in the Eastern and Western European cultures. The organizational types have been specified by a set of organizational aspects related to formal commitment to safety, investment in personnel, quality of technical systems, formal support for confidentiality of reporting, quality of management of safety activities, personal consequences of occurrences etc. Some of the organizational types used in the simulation are summarized in Table V. The simulated organizations were populated with 48 controllers agents distributed over 6 air traffic control sectors, working in 4 homogeneous shifts, 12 hours per day during three years (12 controllers per shift; 2 per sector). 1000 simulations for each organization type have been performed.

To identify safety culture vulnerabilities in relation to safety occurrence reporting in the simulated ANSPs, a set of safety culture indicators was introduced. This set is based on the most prominent safety culture issues related to occurrence reporting discussed in Section II. The values of these indicators obtained by simulation for each ANSP type from Table V in the Eastern and Western European cultural contexts are provided in Tables VI and VII. The value of each indicator belongs to the range [0, 1].

TABLE V. ANSP TYPES (SETTINGS) USED IN SIMULATION

#	Description
1	Organization is formally highly committed to safety, but its actual investment in safety and the quality of safety arrangements are lower. It enforces the high severity reprimand policy and controls closely its implementation.
2	Formally committed organization which puts substantial investments in safety. It enforces the high severity reprimand policy and controls closely its implementation.
3	The same as the setting 3, except that the reprimand policy is of low severity.
4	Organization has low commitment to safety and makes low investment in safety. It enforces the high severity reprimand policy and controls closely its implementation.
5	The same as the setting 5, except that the reprimand policy is of low severity.

TABLE VI. THE SIMULATION RESULTS (MEANS) FOR THE SAFETY CULTURE INDICATORS OF AN EASTERN EUROPEAN ANSP

SC Indicators / Setting # (ANSP type)	1	2	3	4	5
Reporting quality (ratio reported/observed safety occurrences)	0.67	0.77	0.86	0.45	0.37
Average quality of the produced notification reports	0.44	0.67	0.73	0.24	0.20
Average quality of the received final safety occurrence assessment reports	0.19	0.51	0.5	0.07	0.07
Average quality of the received monthly safety overview reports	0.48	0.86	0.86	0.33	0.33
Average commitment to safety	0.60	0.7	0.74	0.37	0.37
Average perceived commitment to safety of the management	0.54	0.74	0.79	0.25	0.25

TABLE VII. THE SIMULATION RESULTS (MEANS) FOR THE SAFETY CULTURE INDICATORS OF A WESTERN EUROPEAN ANSP

SC Indicators / Setting # (ANSP type)	1	2	3	4	5
Reporting quality (ratio reported/observed safety occurrences)	0.77	0.77	0.9	0.43	0.20
Average quality of the produced notification reports	0.5	0.67	0.77	0.23	0.11
Average quality of the received final safety occurrence assessment reports	0.18	0.5	0.5	0.07	0.07
Average quality of the received monthly safety overview reports	0.48	0.86	0.86	0.33	0.32
Average commitment to safety	0.5	0.61	0.68	0.37	0.36
Average perceived commitment to safety of the management	0.55	0.74	0.77	0.25	0.25

It follows from the simulation results that the formal reward/reprimand system of an ANSP has a noticeable impact on reporting. In particular, the results for setting 3 versus setting 2 show that the introduction of reprimands and of a close control over activities of controllers in the ANSP's that are committed to safety, causes a notable decrease in the reporting quality in both cultures. On the contrary, it follows from a comparison of the results of setting 4 versus setting 5 that in organizations with little commitment to and investments in safety there is a significant increase in reporting quality as results of reprimands and a close control over controller agents. In such organizations these measures thus could be considered as instruments to make controller agents report (forcedly).

In both national cultures the controller agents tend to decrease the quality of produced notification reports (e.g., by holding back relevant details) in the case of high personal consequences of occurrences (settings 1, 2, 4). The lowest quality of notification reports occurs in simulations of an Eastern European ANSP with a low commitment to and investment in safety.

The quality of the received monthly safety overview reports depends in both cultures mostly on the investment in personnel and on the quality of management of safety activities. Also, a positive correlation between the reporting quality and the quality of the received monthly safety overview reports can be observed in the simulation results.

The controller's commitment to safety in both cultures is influenced greatly by the perceived actual organizational commitment to safety. The average controller's commitment to safety in the Western European culture is influenced notably by the perceived controller's influence on organizational safety arrangements (for example, in setting 3). The commitment of controllers in the Eastern European ANSP is influenced by the ANSPs reward/reprimand system and by the quality of identification of occurrences, whereas a similar dependence has not been identified for the Western European ANSP.

VI. Conclusions

James Reason once said that 'Few phrases occur more frequently in discussions about hazardous technologies than *safety culture*. Few things are so sought after and yet so little understood.' [9]. Although currently a considerable amount of work has been done to characterize safety culture via survey studies, the causal relations with organizational processes and their effect on risk are in general still vague. This paper proposes an approach to systematically develop models that account for a large variety of organizational aspects, thus providing a different and structured view on safety culture from the perspective of the formal organization in relation with the variable behavior of agents in it. Such modeling provides the opportunity of the structured development of policies for improvement of safety culture. The development of the model has been done on the basis of data from Eurocontrol's SCMT as well as specific organizational data of ANSP-3. The obtained simulation results provide remarkable insights in potential relations between the quality of occurrence reporting and organizational factors at an ANSP. As was demonstrated by simulation, some of these relations depend on the national culture, which is also supported by existing literature [2, 3, 5].

The developed model is based on the psychological and sociological theories that were validated: social contagion theory [1]; expectancy theory [8]; the framework on national cultures [5]. However, to ensure the correct integration of these theories in one approach and application in the air traffic management domain, a dedicated validation approach has been developed and applied for ANSP-3 [14]. The developed validation approach comprises the following steps:

(1) Sensitivity analysis by Monte-Carlo sampling to identify major factors that influence the safety culture indicators and obtaining additional information for these factors, which may be used to calibrate the model.

(2) Relating the identified safety culture indicators to specific questions in the SCMT questionnaire that has been used for ANSP-3.

(3) Prediction of the results of the SCMT questionnaire for ANSP-3 and determination of the level of validity of the organizational model.

(4) Sensitivity analysis based inventory of safety culture improvement strategies and discussion of these with the SCMT team.

A detailed description of the approach and the obtained results will be considered elsewhere.

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