Agent-Based Modeling of Safety Culture in Air Traffic Management

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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 modelling. 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. An approach to validate the developed model is discussed briefly.

1. Introduction

Since the Chernobyl accident, the concept 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 contribute to reporting culture; (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 focussed on characterization of safety culture and on assessment of safety culture of various organizations, including Air Navigation Service Providers (ANSP's) (cf. [4]). However, the links of safety culture with organizational structures and processes are yet not well understood and this affects the determination of ways to improve safety culture. As a way forward, the research results described in this paper aim to enhance safety analysis of organizational processes in air traffic by development of formal approaches for modelling, 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 ANSP's. Although safety occurrence reporting is obligatory in the most ANSPs, still the amount of not reported occurrences is estimated as significant (around 50%) even in ANSPs, which are highly committed to safety. The developed agent-based organizational model is aimed to describe the emergence of safety culture vulnerabilities in relation to safety occurrence reporting in ANSPs' organizational context.

As a basis for development and validation, our research efforts were coordinated with safety culture research pursued at Eurocontrol Experimental Centre. In an effort to measure and understand safety culture at European ANSP's, 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 questionnaires have proven to be statistically robust.

The structure of the paper is as follows. Section 2 describes the identification of safety culture issues of two ANSP's, as a basis for model development. Section 3 considers the model development steps. Some results of agent-based simulations are presented in Section 4. Section 5 concludes the paper.

2. Identification of Safety Culture Issues

To identify safety culture aspects relevant for the occurrence reporting, SCMT results of two ANSP's (ANSP-1, ANSP-2) and safety culture data from the literature have been analysed, and interviews have been conducted with experts at Eurocontrol Head Quarters and at a third ANSP (ANSP-3). As result of this analysis, a categorised set of safety culture issues that impact safety occurrence reporting has been determined (examples are given in Table 1).

Table 1: Examples of 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
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
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
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

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 modelling aspects have been identified. Among these aspects are the ones related to the formal organization (i.e., formally specified structures and processes), as well as to autonomous behaviour of organizational individuals (e.g., informal interaction). Then, based on the three criteria - importance for modelling, availability of data, maturity level of modelling techniques - the selection of the most relevant modelling aspects has been performed for further inclusion in the model, which will be further discussed in the next section.

3. Agent-Based Model For Occurrence Reporting

To model safety occurrence reporting in an ANSP the organization modelling and analysis framework has been used [10]. In contrast to many existing enterprise modeling frameworks (CIMOSA [3], ARIS [9]), 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. Furthermore, this framework includes all the identified modeling aspects related to the formal organization of an ANSP. Also, as it will be shown below, it allows an easy extension by inclusion the required aspects of autonomous behaviour of organizational individuals of an ANSP.

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 the agents that are to perform the roles. It formulates agents' types, their capabilities, their behaviour, and the principles of allocating agents to roles. On the one hand, the behaviour of agents is regulated by the formal organization. On the other hand, the dynamics and stochastic aspects of interacting agents contribute to the performance variability in an organization.

The development of the organizational model along these views is done in a number of steps based on the interviews, the organizational documentation and literature from the domain and social science. All numerous formal technical details of the developed model are provided in Appendix on Internet: http://www.few.vu.nl/~sharp/app.pdf

Specification of the formal organization

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 fulfil them. Each role can be composed by several other roles, until the necessary detailed level of aggregation is achieved. In the model roles are identified at three aggregation levels. Examples of roles are Safety Investigation Unit, Safety manager, Controller,

Supervisor, and Safety Recommendations and Concerns Group.

Step 2. The specification of the interactions between the roles. All interaction relations between roles are represented by interaction and interlevel links at the same and different aggregation levels, respectively. The interaction relations between the subroles of Air Navigation Service Provider role considered at aggregation level 2 are provided in Figure 1 below.

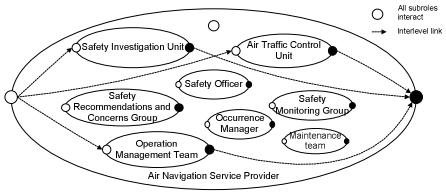

Figure 1: Interaction relations between the subroles of Air Navigation Service Provider role at aggregation level 2

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

Step 4. The identification of the organizational performance indicators and goals. Goals are objectives that describe a desired state or development of the company, unit or individual. Performance indicators are quantitative or qualitative indicators that reflect the state with respect to a goal. A goal can be refined into subgoals forming a hierarchy. For example, goal G18 'It is required to maintain timeliness and a high quality of occurrence investigation' is based on two PIs 'timeliness of occurrence investigation' and 'quality of occurrence investigation'.

Step 5. The specification of the resources. Organizational resources such as tools, supplies, components and digital artefacts are defined.

Step 6. The identification of the tasks and relations between the tasks, the resources and the goals. A task represents a function performed in the organization. Tasks use, consume and produce resources. For example, task T4.4 'Investigation of an occurrence' is related to resources as follows: it uses a notification report and produces a final occurrence assessment report. Each task is related to the satisfaction of one or more goals.

Step 7. The specification of the authority relations

The following types of authority relations are distinguished: superior-subordinate relations on roles with respect to tasks, responsibility relations, control for resources, authorization relations. For example, Safety Investigator role is responsible for execution of and making technological decisions with respect to task T4.4, role Safety Manager is responsible for monitoring, consulting and making managerial decisions related to T4.4.

Step 8. The specification of the workflows. Workflows describe temporal ordering of processes of an organization in particular scenarios. Figure 2 describes the execution of the formal occurrence reporting initiated by a controller.

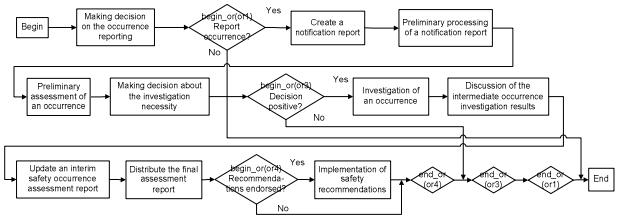

Figure 2: The workflow for formal occurrence reporting.

Specification of agents

To model internal dynamics of agents, an approach based on causal networks has been used (cf. [10]). In this approach the agent behaviour is specified by direct causal relations between cognitive states of the agent, leading to the generation of externally observable behavioural patterns. Furthermore, with each agent's state a degree of evidence is associated, and to each causal relation a weight is assigned.

Step 9. Identification of types and characteristics (skills, psychological and cognitive characteristics) of agents. In the model the following agent types have been introduced: controller, supervisor, safety officer), safety investigator, safety manager and occurrence manager. The number of agent instances range from one (e.g. occurrence manager) to 48 (controller).

A number of studies have identified an important role of the national culture of an agent, which influences the agent's priority of needs, values, attitudes and behaviour. In particular, Hofstede [5] distinguishes the following dimensions of a national culture: power distance index, individualism, masculinity, and uncertainty avoidance index. These dimensions were incorporated in the model, e.g., in decision making.

Step 10. Identification of goals and needs of agents.

It is recognized that high level goals of individuals are largely dependent on their needs. In the model the following needs of the agent controllers are considered: (1) *extrinsic needs*, which are associated with biological comfort and material rewards; (2) *social interaction needs*, which refer to the desire for social approval and affiliation from both own group and the management; (3) intrinsic needs, which concern the

desires for self-actualization. The identified goals and needs play an important role in the decision making model described in step 15.

Step 11. Identification of commitments, obligations and responsibilities of agents. An agent has a high organizational commitment when it accepts the organizational goals and is willing to exert effort on behalf of the organization [7]. In this step commitment to safety of a controller agent is modelled through the prism of its own needs. More specifically, the commitment to safety is determined: (1) through extrinsic needs – by safety reprimands and rewards; (2) through management approval needs – by the priority of the organizational safety goals and the agent's perception of the management commitment to safety; (2) through own group approval needs - by the perception of the group's commitment to safety; (3) through intrinsic needs - by the perceived own influence degree on safety and the possibility of self-actualization.

Step 12. Identification of attitudes and beliefs of agents. Agents create time-labelled internal representations (beliefs) about their observations, actions and communications. Agents may create beliefs about observed single states (e.g., a notification report is created, an occurrence is reported) and about dependencies between observed states (e.g., the belief of a controller agent about the dependency between providing of a notification report on an occurrence to the supervisor and receiving a final assessment report on the occurrence (i.e., feedback) from a safety investigator agent).

Step 13. Identification of relations between agents and informal structures of agents. To model informal interaction relations of controllers the social contagion theory of Burt [1] has been used. According to this theory, the intensity of informal communication between the agents is influenced positively by the following factors: (1) similarity of the communication patterns of the roles of the agents; (2) equality of the statuses of the roles of the agents in the organization; (3) physical possibilities to communicate; (4) degree of acquaintance of the agents with each other. A team of controllers has intensive informal communication. In the model informal interaction relations enhance the knowledge of controllers about safety-related issues and occurrences.

Step 14. Identification of shared beliefs, attitudes, norms and values of (groups of) agents. Teams with intensive informal communication tend to have essential control over attitudes and actions of their members. In the model, a controller agent forms the beliefs about the team's averaged attitude to reporting by observing occurrence reporting of other agents from the team. The perception of a controller agent of the team's commitment to safety involves commitment to safety of the supervisor, and commitment to safety of the team members. The supervisor is responsible for realizing goals and strategies of the management in the team. Thus, the commitment to safety of the supervisor depends on the commitment of the management, as well as, on the supervisor's level of development of the managerial skills.

Step 15. Identification of performance variability in formal and informal flows of control

To model performance variability of the organizational processes, a number of quality parameters have been identified, among which quality (i.e., correctness and completeness) of a processed notification report, quality of a monthly safety overview report and quality of a final safety occurrence assessment report.

Provision of feedback on notification reports based on final safety occurrence assessment reports, and of generalized monthly safety overview reports is an important aspect of organizational learning. Whereas monthly safety overview reports are often provided in written (printed) form, a feedback on a safety occurrence may be provided both orally and in written form. In the model, provision of the feedback is modelled as a stochastic process. Furthermore, decision making of an agent controller whether to report an occurrence is modelled as a complex process that involves reasoning about own needs, capabilities and experiences, about the surrounding formal organization and (informal) social structures and processes. To formalize the decision making process the expectancy theory of Vroom has been used [7]. According to this theory, when an individual evaluates alternative possibilities to act, s/he makes estimations for the following factors: *expectancy (E's)*, *instrumentality (I's)*, and *valence (V's)* (see Figure 3).

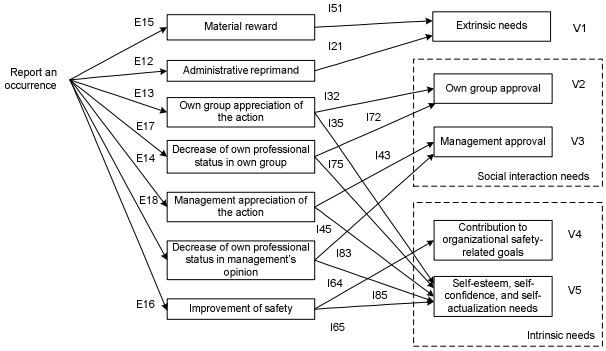

Figure 3: Decision making model for reporting act

Expectancy refers to the individual's belief about the likelihood that a particular act will be followed by a

particular outcome. For example, E12 is the expectancy that the act 'report an occurrence' will result in 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. A second level outcome represents a desired (or avoided) by an agent state of affairs that is reflected in the agent's goals and needs. For example, I21 is the instrumentality that administrative reprimand will result into the satisfaction of the extrinsic needs. Valence refers to the strength of the individual's desire for an outcome or state of affairs. For example, V3 is the valence of the controller's management approval needs.

In the Vroom's model the motivational force F_i of an agent to perform an action i is defined by:

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

As the result of decision making an alternative with the highest force value is chosen for execution.

Values of expectancies, instrumentalities and valences change over time due to individual and organizational learning. In particular, the agent's expectancies E15, E12 and E26 change depending on the received (observed) reprimands and rewards for occurrences reported by the agent (or by another agent from the team). E13 and E22 are adjusted by the agent based on the observed team's averaged attitude to reporting of different types of occurrences. E16 and E25 are adjusted based on the feedbacks from the safety investigator agent on the previously reported occurrences and the observed implementation of safety recommendations for previous reports, and safety information informally provided by other controllers during breaks.

Step 16. Allocation principles of agents to roles. For simulation 4 airport sectors were modelled. The agent controllers work in 4 shifts, 12 hours per day (12 controllers per shift; 2 per sector). Stable teams of controllers and teams with a variable composition are considered. Each shift (or team) is managed by a supervisor agent (1 supervisor for 2 shifts).

Step 17. The identification of the generic and domain-specific constraints. Generic constraints ensure internal consistency of an organizational specification. Domain specific constraints restrain behaviour of individuals in a particular organization.

Step 18. Specification of the environmental dynamics

The simulation time is 3 years. The frequencies of different types of occurrences used in the simulation are based on safety occurrence statistics of ANSP-3.

4. Simulation Results

The developed model has been used for analysis of the behavior of controllers agents related to 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 2.

Table 2:Some of the organization types used in simulation

#	Description
1	Organization formally makes an appearance of a highly committed to safety, however its actual commitment is lower. It performs average control over activities of controllers and reprimands for occurrences.
2	Formally committed organization which puts substantial investments in safety. It performs close control over activities of controllers and reprimands for occurrences.
3	Formally committed organization, which puts substantial investments in safety. However, the quality of management of safety activities is low. No reprimands are provided for occurrences, except for the class A (severe occurences).
4	Organization has low commitment to safety and makes low investment in safety. It performs close control over activities of controllers and reprimands for occurrences.

To evaluate the results of simulations a set of safety culture indicators has been introduced based on the most prominent safety culture issues related to occurrence reporting discussed in Section 2. Some of these indicators are given in Table 3.

Table 3: Some of the safety culture indicators.

Index	Safety Culture Indicator
S1.1	Reporting quality (ratio reported/observed occurrences)
S2.1	Average quality (completeness and correctness) of the processed notification reports produced by controllers
S3.1	Average quality (completeness and correctness) of the final safety occurrence assessment reports received by the controllers
S5.1	Average commitment to safety of the controller agents
S5.2	Average perceived commitment to safety of a team of controllers
S7	Perceived commitment to safety of management

It follows from the simulation results that the formal reward/reprimand system of an ANSP has a noticeable

impact on reporting. In particular, 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 (S1.1) in both cultures. On the contrary, in organizations with little commitment to and investments in safety, 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 (S2.1 (e.g., by holding back relevant details) in the case of high personal consequences of occurrences. The lowest quality of notification reports occurs in simulations of an Eastern European ANSP with a low commitment to and investment in safety.

The controller's commitment to safety (S.5.1) 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. The commitment of controllers in the Eastern European ANSP is influenced by the ANSP's reward/reprimand system and by the quality of identification of occurrences, whereas a similar dependence has not been identified for the Western European ANSP.

The simulations show that varying shift composition has almost no effect on the values of safety culture indicators in ANSP's that are committed to safety. Only in Eastern European organizations with low investment in safety and personnel, a positive effect of the varying shift composition on reporting is visible.

5. Conclusions

James Reason once said that 'safety culture has the definitional precision of a cloud' [8]. 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 behaviour of agents in it. Such modelling 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.

The developed model is based on the psychological and sociological theories that were validated (cf. social contagion theory [1]; expectancy theory [7]; the framework on national cultures [5]). To validate the proposed model a validation approach has been used, which comprises the following steps:

(1) Sensitivity analysis to identify major factors that influence the safety culture indicators and obtaining additional information for these factors, which may be used to adjust 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 is left out due to the space limitations and will be considered elsewhere.

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