Can We Predict Safety Culture?

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ABSTRACT
Safety culture is broadly recognized as important for Air Traffic Management and various studies have addressed its characterization and assessment. Nevertheless, relations between safety culture and formal and informal organizational structures and processes are yet not well understood. We aim to improve the understanding of these relations by agent-based organizational modeling and thus provide a way for structured improvement of safety culture. This paper presents the key elements, results and validation of an agent-based organizational model for a particular Air Navigation Service Provider.

Categories and Subject Descriptors
I.6.4 [**Simulation and Modeling**]: Model Validation and Analysis

General Terms
Design, Human Factors, Verification.

Keywords
Safety culture, agent-based organizational modeling, social simulation, model analysis, model validation.

1. INTRODUCTION
Organizational and safety culture are broadly recognized as important for operational safety in various fields, including air traffic management, power plant control and health care. For example, as indicated in [7], investigations into many NASA mission failures pointed to cultural problems and the need for cultural and organizational improvements. Currently, as a prelude to systemic changes in air traffic management via new programmes SESAR in Europe and NextGen in the USA more and more Air Navigation Service Providers (ANSPs) go through safety culture measurement and improvement processes.

The main aspects of organizational culture are reflected in a definition by Uttal [17]: 'Shared values (what is important) and beliefs (how things work) that interact with a company's people, organizational structures and control systems to produce behavioral norms (the way we do things around here).' There exists a variety of definitions of safety culture. The term *safety culture* is used in this paper as those aspects of organizational culture that may have an effect on safety, in line with reasoning of Hopkins [6].

Various studies focused on characterization of safety culture and on assessment of safety culture of various organizations, including ANSPs (cf. [2]). 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. Traditional approaches to safety analysis [5] focus on failure events and human errors and put events into chains or trees, which are used for sequential cause-effect reasoning for accident causation. However, such trees do not account for complex, non-linear dependencies and dynamics inherent in ANSPs and, therefore, cannot be used for safety culture analysis. A more promising approach for modeling and analysis of safety culture using system dynamics was proposed in [7]. This approach abstracts from single events and actors and takes an aggregate view on the organizational dynamics. Consequently, in safety culture models aggregated values are assigned to individual variables such as 'fear of reporting', 'employee participation', 'perceived risk'. By taking an aggregated view a danger exists that important effects of individual differences on local interaction and global organizational dynamics may be overlooked. An agent-based approach for modeling and analysis of safety culture proposed in this paper addresses both this issue and an existing gap between safety culture and organizational structures and processes. It provides a formal 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. This paper demonstrates the application of the approach to an air navigation service provider, including structured modeling, analysis and identification of improvement strategies for the organizational safety culture. The development of the organizational model has been focused on safety occurrence reporting at a real ANSP (called ANSP3 throughout the paper) using an existing formal organization modeling framework [11] and data provided by ANSP3. Air traffic controllers in an ANSP are obliged to report safety occurrences observed during air and ground operations. An example of a ground occurrence is 'taxiing aircraft initiates to cross due to misunderstanding in communication'. Knowledge about safety occurrences is particularly useful for timely identification of safety problems in ANSPs. In practice, however, safety occurrences are not always reported, which may create a serious bottleneck in the organizational safety. It is recognized that there is a strong reciprocal relation between the organizational safety culture and the reporting behavior of air traffic controllers [2]. In the model proposed this relation is elaborated formally, in detail.

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As a basis for the validation, results of a safety culture survey questionnaire for ANSP3 and of the related workshops administered by the EUROCONTROL organization were used.

Thus, the main new contributions of the paper are:

(1) Identification of explicit, formal relations between safety culture indicators and the organizational model.
(2) Analysis methods for structured identification of safety culture issues and safety culture improvement options.
(3) Validation of the obtained model results.

The paper is organized as follows. Section 2 presents the most prominent parts of the developed organizational model and demonstrates how safety culture indicators can be related to the model. The developed method for safety culture analysis is presented in Section 3. Model validation is considered in Section 4. Finally, Section 5 concludes the paper.

2. ORGANIZATIONAL MODEL

In this section the agent-based organizational model developed for ANSP3 is presented. Modeling requirements are discussed briefly in Section 2.1. A part of the developed model that describes the formal safety occurrence reporting is considered in Section 2.2. Another part that describes characteristics and behavior of agents is considered in Section 2.3. The model is based on a number of psychological and sociological theories. It contains 22 input variables and 175 parameters, which were estimated based on the documentation provided by ANSP3, interviews with ANSP3 employees and a part of the safety culture survey questionnaire results for ANSP3 not used for analysis and validation. Furthermore, in this section it is demonstrated how some of the identified safety culture indicators can be related explicitly to the model. Due to high model complexity, only a partial, largely informal description of the model is provided. For a complete formal, specification we refer to [13, 15].

2.1 Modeling requirements

To identify safety culture aspects relevant for the safety occurrence reporting, safety culture survey results of two ANSPs (different from ANSP3) and safety culture data from the literature were analyzed and interviews were conducted with experts at EUROCONTROL Head Quarters and at ANSP3. As result of this analysis, a categorized set of safety culture issues that impact safety occurrence reporting was determined. An example of a safety culture issue: ‘feedback from incidents comes too late or not at all’. For each safety culture issue from the set, a number of relevant modeling aspects have been identified. The selection of the modeling aspects to be included in the organization model was performed based on the three criteria: importance for modeling of safety occurrence reporting, availability of data, maturity level of modeling techniques. More details on identification of safety culture issues and modeling aspects are given in [12].

Furthermore, based on the identified set of safety culture issues, eight safety culture indicators used to characterize and evaluate safety culture, were identified. These indicators were used in our study for the evaluation of the quality of the ANSPs safety culture in relation to occurrence reporting. All of these indicators, except for I5.2, are averaged over the whole population of controllers; whereas I5.2 is averaged over the controllers of a team.

I1: Average reporting quality of controllers. It refers to the ratio of reported to observed occurrences.
I2: Average quality of the processed notification reports. It refers to the correctness and completeness of information about the reported occurrences.
I3: Average quality of the final safety occurrence assessment reports. It refers to the completeness of the occurrence report with respect to the causes of the occurrence.
I4: Average quality of the monthly safety overview reports received by controllers. It refers to the completeness of the report with respect to the safety trends.
I5.1: Average commitment to safety of controllers.
I5.2: Average commitment to safety of a team as perceived by controllers.
I6: Average commitment to safety of a supervisor as perceived by controllers.
I7: Average commitment to safety of management as perceived by controllers.

The range of each indicator is [0, 1].

2.2 Modeling the formal reporting

For modeling the formal reporting in ANSP3 the organization modeling framework from [11] was used, which comprises a sequence of organization design steps, some of which are considered below. This framework includes all the modeling aspects related to the formal organization of ANSP3, which were required to be included in the model.

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).

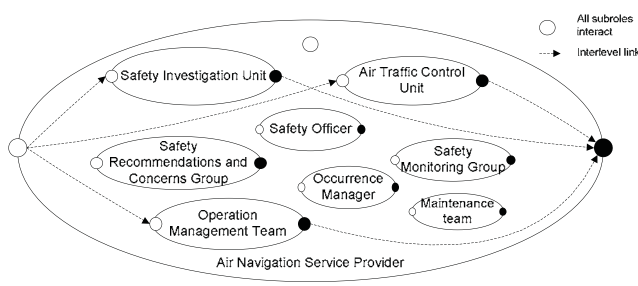

Figure 1. Interaction relations between the subroles of Air Navigation Service Provider role at aggregation level 2

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. The interaction relations between the subroles of Air Navigation Service Provider role are shown in Figure 1. Interaction between roles is enabled by interfaces (i.e., input and output states) formalized using interaction (input and output) ontologies.

The identification of the tasks, resources and workflows.
A task represents a function performed in an organization and is characterized by name, maximal and minimal duration. Tasks use, produce and consume resources: e.g., the 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 2 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 Investigation Unit (SIU). Different aspects of responsibility relations are distinguished: e.g., the Controller role is responsible for execution of and decision making with respect to task 'Create a notification report', the Controller Supervisor is responsible for monitoring and consulting for this task. Depending on the occurrence severity and the collected information about similar occurrences, the Safety Investigator role in SIU 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 the ANSP.

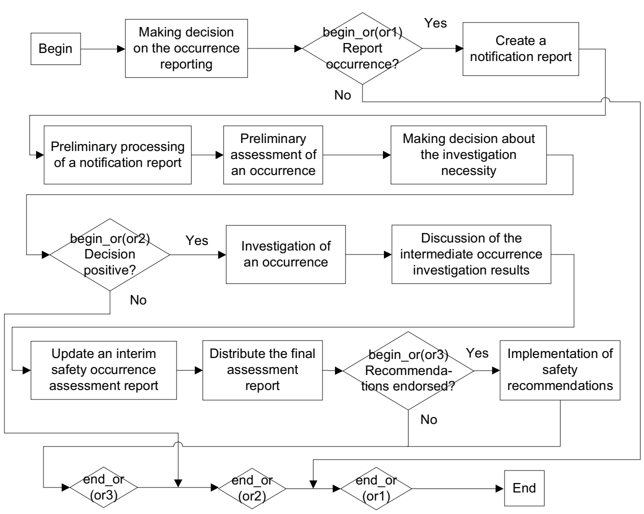

Figure 2. The workflow for the occurrence reporting

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 ANSP3's reprimand policy for reporting was formalized as constraints using a function repr that maps the number of occurrences of some type to a reprimand value [0, 1]: repr(1, A) = 1; repr(1, B) = 0.5.

2.3 Modeling agents

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) [1]. The behavior of an agent is considered from external and internal perspectives. From the external perspective the behavior is 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.

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 specifications are called causal networks. In the following, different types of internal states of agents are considered that form such causal networks. Furthermore, it is demonstrated how these states are related to safety culture indicators.

It is assumed that agents create time-labeled internal representations (*beliefs*) about their input and output states, which may persist over time. Information about observed safety occurrences is stored by agents as beliefs. 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 of agents in the decision making model provided below):

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* 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 and management approval; (3) *intrinsic needs* that concern the desires for self-development and self-actualization; in particular contribution to organizational safety-related goals and self-esteem and self-actualization needs. Different needs have different priorities for individuals in different cultures. The cultural characteristics of the controller agents in the model of ANSP3 were defined based on the cultural classification framework by Hofstede [4] for the Western European culture. The following indexes from the framework were used: *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 that power is distributed unequally; and *uncertainty avoidance index* (UAI) deals with individual's tolerance for uncertainty and ambiguity.

An internal state that determines the value of the safety culture indicator I5.1 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 w.r.t, its tasks. In the theory of situational leadership [3] 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.

The maturity value changes over time as a result of gaining new knowledge and skills, and changing self-confidence of a controller. In an ANSP that is committed to safety, the maturity of a controller grows until some high value is reached and then fluctuates slightly around this value (see [2, 3]).

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 (safety culture indicators I2, I3 and I4), for specific details we refer to [13, 15].

Thus, the maturity level of a controller agent a specified by the evidence variable $e5_{a,t}$ (here and further in the paper subscript a indicates an agent, t indicates a time point) is calculated as:

$$e5_{a,t} = w22 \cdot e19_{a,t-1} + w23 \cdot e20_{a,t} + w24 \cdot e21_{a,t} + w25 \cdot e10_{a,t} + w26 \cdot e42_{a,t-1} + w27 \cdot e43_{a,t-1},$$

here $e19_{a,t-1}$ is the agent's self-confidence w.r.t. the ATC task at time point t-1 (depends on the number of occurrences with the controller); $e20_{a,t}$ is the agent's commitment to perform the ATC task; $e21_{a,t}$ is the agent's development level of skills for the ATC task; $e10_{a,t}$ is the indicator for sufficiency and timeliness of training for changes; $e42_{a,t-1}$ is the average quality of the final occurrence assessment reports received by the agent up to the time point t-1; $e43_{a,t-1}$ is the average quality of the received monthly safety overview reports up to the time point t-1, w22-w27 are the weights (sum up to 1). All e-variables vary in the range [0, 1].

The agent's commitment to safety is also influenced by the perceived commitment to safety of other team members (determines indicator I5.2) and the management (determines indicator I7). 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). The perception of agent a of the average commitment to safety of its team G ($e3_{a,G,t}$) is based on the perception of commitment to safety of the team supervisor s (determines indicator I6) and of other team members and is calculated as:

$$e3_{a,G,t} = w16 \cdot (w14 \cdot e14_{s,G,t} + w15 \cdot e2_{a,t-1}) + w17 \cdot \Sigma_{i \in T}\ e6_{i,G,t-1} / |T|,$$

here $T = \{ag \mid \exists ag{:}AGENT\ is\_in\_team(ag, G)\ AND\ a \neq ag\ AND\ ag \neq s\}$; $e14_{s,G,t}$ is the level of development of the managerial skills of the team supervisor; $e2_{a,t-1}$ is the perception of the commitment to safety of management at time point t-1; w14-w17 are weights.

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:

$$e6_{a,G,t} = w1 \cdot e1_{a,t} + w2 \cdot e2_{a,t-1} + w3 \cdot e3_{a,G,t-1} + w4 \cdot e5_{a,t-1},$$

here $e1_{a,t}$ is the priority of safety-related goals in the role description, $e2_{a,t-1}$ is the perception of the commitment to safety of management, $e3_{a,G,t-1}$ is the perception of the average commitment to safety of the team, $e5_{a,t-1}$ is the controller's maturity level w.r.t. the task; w1-w4 are the weights.

The value of the safety culture indicator I1 'Average reporting quality' (i.e., the ratio of reported to observed occurrences) depends on the decisions of controller agents to actually report observed occurrences. To model decision making of agents a refined version of the expectancy theory by Vroom [8] has been used. 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 Figure 3 the decision making models for reporting an occurrence is 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).

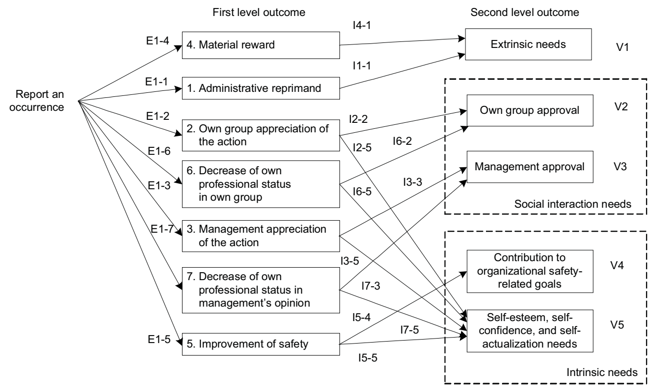

Figure 3. Decision making model for reporting

For example, E1-1 in Figure 3 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, I2-2 in Figure 3 refers to the belief about the likelihood that own group appreciation of the action results in own group approval. 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. In the Vroom's model the force on an individual to perform an act is defined as:

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

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

The factors E1-4, E1-1, I4-1 and I1-1 are defined based on the ANSP3's formal reprimand/reward policies (Section 2.2). In particular, E1-1 = 1 for an observed occurrence if a reprimand is provided according to the policy; E1-1 = 0 otherwise. The values of E1-2 and I2-2 depend largely on the average commitment of the team of controllers to safety, and E1-7 and I3-3 depend on the management commitment to safety.

I2-5 and I6-5 are based on the agent's individualism index IDV, which indicates the degree of importance of team's opinions for the agent. I3-5 and I7-5 are based on the agent's power distance index PDI. Furthermore, also the values of the valences in Figure 3) of a controller agent depend on its Western European cultural indexes: $V1 = 1$; $V2 = 1\text{-}IDV$; $V3 = 0.7 \cdot PDI + 0.3 \cdot UAI$; $V4 = 0.3+0.7 \cdot UAI$.

Expectancies and instrumentalities vary due to individual and organizational learning. In particular, the expectancies E1-4 and E1-1 change depending on the received (observed) reprimands and rewards for occurrences reported by the agent (or by another agent from the team). E1-2 is adjusted by the agent based on the observed team's averaged attitude to reporting of different types of occurrences (social learning). E1-6 is 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 controller agents during breaks (social learning).

3. ANALYSIS

First, this section discusses simulation results obtained based on the developed model (Section 3.1). These results reflect the estimated quality of the organizational safety culture. Next, a sensitivity analysis approach to identify main sources of deficiencies in the safety culture is proposed in Section 3.2. Moreover, it is demonstrated how results of such analysis can be used for structured identification of safety culture improvement options.

3.1 Simulation

Based on the developed model 3000 simulation trials were performed in the Matlab environment, where each trial represents three years of operations. The values for the input variables and parameters of the model used in the simulation trials are provided in [15]. The obtained values of the safety culture indicators and their variances are provided in Table 1 (columns 2 and 3).

Table 1. Simulation results for the safety culture indicators

SCI	Value	Variance	Low	Medium	High
I1	0.74	5e-3	[0, 0.55]	(0.55, 0.76]	(0.76, 1]
I2	0.54	4e-4	[0, 0.27]	(0.27, 0.45]	(0.45, 1]
I3	0.2	7e-3	[0, 0.14]	(0.14, 0.32]	(0.32, 1]
I4	0.58	6e-5	[0, 0.44]	(0.44, 0.66]	(0.66, 1]
I5.1	0.56	2e-3	[0, 0.43]	(0.43, 0.63]	(0.63, 1]
I5.2	0.55	1e-3	[0, 0.43]	(0.43, 0.63]	(0.63, 1]
I6	0.6	8e-4	[0, 0.48]	(0.48, 0.7]	(0.7, 1]
I7	0.61	4e-5	[0, 0.45]	(0.45, 0.63]	(0.63, 1]

For qualitative estimation of the obtained results, three classes for classification of the values of the safety culture indicators were introduced: Low, Medium and High. To determine the boundaries of the classes, a range of results for the safety culture indicators was obtained by performing numerous Monte Carlo simulations for variations in the values of the model parameters. In particular, all input variables were varied over their full range, except the national culture variables which were associated with the Western European culture. Figure 4 provides examples of histograms for the Monte Carlo simulations results for two safety culture indicators (1000 simulation trials each).

It follows from an analysis of survey questionnaire results of a particular ANSP2 (different from ANSP3) that for this ANSP the Low boundary cuts the first 30% of the safety culture indicator values, the following 55% of the values belong to the class Medium and the remaining 15% belongs to the class High. Following such a percentage distribution, on the basis of the Monte Carlo simulation results, the class ranges for each safety culture indicator were determined (see Table 1, columns 4-6).

Thus, most of the safety culture indicator values for ANSP3 in column 2 of Table 1 are classified as Medium, which indicates that some deficiencies exist in the organizational safety culture. To identify possible organizational sources of these deficiencies, sensitivity analysis was performed, which is considered in the following section.

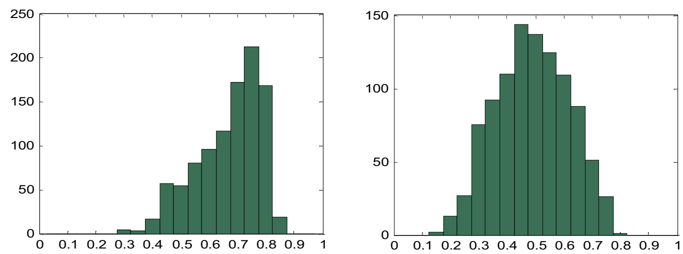

Figure 4. Examples of distributions of safety culture indicators (Monte Carlo simulation results)

3.2 Sensitivity analysis

Sensitivity analysis can be used to identify the most influential organizational factors for each safety culture indicator. Values of these factors determine to a large extent the safety culture indicator value. Thus, the cause of a deficiency in the value of an indicator can be attributed to the corresponding organizational factors. The sensitivity analysis method used in this study is Monte Carlo filtering [10]. The aim of Monte Carlo filtering is to identify the model parameters of which the variation according to associated credibility intervals lead to significant differences in attained model output classes. It consists of two steps, which are presented next.

Step 1: MC simulations

For the complete set of model parameters, lower and upper bounds of credibility intervals of their values were determined based on our knowledge of the ANSP3 organization and on our knowledge about the uncertainty in modeled aspects. Next, 8000 Monte Carlo simulation trials were performed where in each simulation the parameters were chosen uniformly within their credibility interval bounds [15]. 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 a High safety culture indicator (as defined in Table 1), and $x_i|\underline{B}$, containing all x_i values that produced a Low or Medium safety culture indicator.

Step 2: Smirnov test

A Smirnov two sample test was performed for each input factor independently. The applied test statistics are

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

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 was 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, the classification High / Medium / Low for the importance of each factor was used. If $\alpha \leq 0.01$, then the importance of the corresponding factor x_i is High; if $0.01 < \alpha \leq 0.1$, then the importance of the corresponding factor is Medium, and if $\alpha > 0.1$, then the importance of the corresponding factor is Low.

In Table 2 some examples of the importance of input variables are given for some safety culture indicators, according to above methodology.

Table 2. Importance of some input variables (High / Medium / Low) for some ANSP3's safety culture indicators

Var	I1	I2	I3	I4	I5.1	I7
e1: Priority of safety-related goals in a role description	M	M	L	M	H	H
e4: Influence of a controller on safety activities	H	L	L	L	H	H
e7: Sufficiency of the amount of safety investigators	M	L	H	H	H	H
e10: Sufficiency and timeliness of training for changes	L	L	L	L	H	H
e12: Developed and implemented SMS	M	M	L	L	H	H

A *total safety culture sensitivity index* is defined by firstly setting a value 0 for Low sensitivity, a value 0.5 for Medium sensitivity and a value 1 for High sensitivity, and subsequently summing those values over all safety culture indicators that need to be improved for a particular variable. For example, the total safety culture sensitivity index for e1 is 5.5 (calculated using Table 2). Input variables with the total safety culture sensitivity indexes greater than or equal to 4 are considered to be major organizational factors with the greatest influence upon the safety culture indicators that require improvement.

For all other types of parameters in the model, the same sensitivity analysis was performed. Overall, the importance of the other parameters for the total set of safety culture indicators is more modest than the importance of the input variables. Only for one weight, which describes the relation between the commitment of a supervisor to safety and the perception of the commitment to safety in a team, a total safety culture index of 4 is achieved. All other parameters are less important.

Thus, based on the sensitivity analysis of the model for ANSP3, eight Major Organizational Factors (MOFs) with the greatest influence on the organizational safety culture were identified:

MOF1: Sufficiency of the number of controllers
MOF2: Level of development of managerial skills of supervisors
MOF3: Sufficiency of the number of safety investigators
MOF4: Priority of safety-related goals in the role description
MOF5: Availability of reliable and ergonomic technical systems for controllers
MOF6: Influence of a controller on safety activities
MOF7: Developed and implemented Safety Management System
MOF8: Sufficiency and timeliness of training for changes

The sensitivity analysis results for ANSP3 obtained by performing 8000 simulations are completely reproducible.

Since MOFs exert a significant effect on the organizational safety culture, they can serve as a good basis for identification of organizational improvement options. Based on the MOFs identified for ANSP3, five organizational improvement options (OIOs) were identified. Two of them are provided below:

OIO1*: More involvement of controllers in safety assessment for development of new systems and procedures (based on MOF4, 5, 6):*

(a) Controllers should be more involved in safety assessments for development of new systems and procedures.
(b) These safety assessments should have a sufficiently broad scope such that the variability in the working context of the controllers is addressed in a way that is well recognized and understood by the controllers involved in the assessment.
(c) The assessment should explicitly address the consideration of capacity versus safety in nominal and non-nominal conditions.

OIO-2: *Improve workload of controllers by developing explicit rules for balancing safety and capacity in nominal and non-nominal conditions (based on MOF1, 4):*

(a) The workload of controllers should be improved by explicit guidelines that support the supervisors and the controllers in balancing safety and capacity.
(b) These guidelines should be determined in a safety assessment as indicated in OIO1 with involvement of controllers.
(c) A result of these guidelines may be that the number of controllers should increase.

4. MODEL VALIDATION

As a basis for the validation, results of the safety culture survey questionnaire for ANSP3 and of the related workshops administered by the EUROCONTROL organization were used. The validation study of the model results was performed in two phases (see Figure 5):

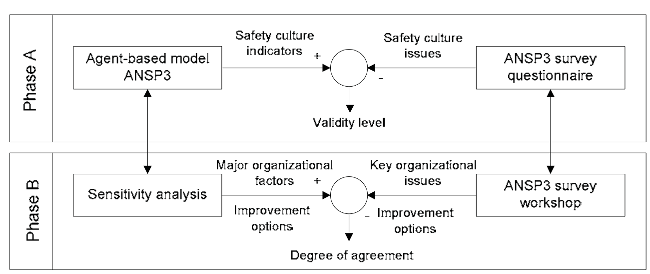

Figure 5. Schematic representation of the two phases of the validation plan.

Phase A: The level of validity of the results was determined by the comparison of the model-based and survey-based safety culture indicators. The results of this phase are presented in Section 4.1.

Phase B: The degree of agreement was determined between major organizational factors affecting safety culture indicators and related improvement options which were inferred from a sensitivity analysis of the organizational model, and key issues and related improvement options stemming from the safety culture survey workshop results. The results of this phase are described in Section 4.2.

4.1 Validation Phase A

As a basis for the validation in this phase, results of the safety culture survey questionnaire at ANSP3 were used. The questionnaire comprises a set of statements about potential enablers and disablers of safety culture in an ANSP. The questionnaire results include mean scores for the level of agreement of employees of ANSP3 to the statements on a scale from 1 ("fully disagree") to 5 ("fully agree"). To enable comparison of the questionnaire results with the obtained model results, relations between the identified safety culture indicators and particular statements from the questionnaire were established prior to the questionnaire results were received. Some examples of such relations are given in Table 3. For the cases where a safety culture indicator was related to multiple statements, a weight was assigned to each statement indicating the degree of its relevance for the estimation of the indicator. The weights for a safety culture indicator sum up to 1. The value of a survey-based safety culture indicator was calculated as a weighted average over the scores for the statements related to the indicator.

Table 3. Examples of relations between safety culture indicators (SCIs) and safety culture survey questions

SCI	Related statements from the questionnaire	Weight
I1	People understand the need to report incidents in order to identify trends and make changes to the system if required	0.5
	If I see an unsafe practice by a colleague I am able to report it in a way that we all learn lessons from it.	0.3
	If I do something unsafe I am aware that I may be asked to explain myself	0.2
I5.2	My colleagues are committed to safety.	0.7
	Everyone at my Unit/Team feels that safety is their personal responsibility.	0.3

Since the questionnaire and model scales are different and the results for neither of them can be expected to be uniformly distributed along the full scales, three classes for the values of the indicators were introduced – Low, Medium and High – along which the model and questionnaire results were classified. In Section 3.1 it was shown how the values of the model-based safety culture indicators had been mapped to these three classes. Similarly, in line with the relative (percentage) contributions of ANSP2, the values on the questionnaire result scale were classified as follows: the range [1, 3.25] was associated with the class Low, (3.25, 4] -with the class Medium and (4, 5] - with the class High.

Using the introduced mapping mechanisms, the model and questionnaire results were classified as shown in Table 4. The comparison of the class labels for the model- and survey-based safety culture indicator values shows that the results are consistent for six out of seven indicators. Only the result for indicator I6 is lower in the survey than in the model. The indicator I2.1 was not relevant for the survey study.

Table 4. The classified values of the safety culture indicators obtained from the model and the survey questionnaire data.

Safety Culture Indicator	Model	Survey
I1: Average reporting quality of controllers	Medium	Medium
I2: Average quality of the processed notification reports	High	-
I3: Average quality of the final safety occurrence assessment reports	Medium	Medium
I4: Average quality of the monthly safety overview reports received by controllers	Medium	Medium
I5.1: Average commitment to safety of controllers	Medium	Medium
I5.2: Average commitment to safety of a team as perceived by controllers	Medium	Medium
I6: Average commitment to safety of a supervisor as perceived by controllers	Medium	Low
I7: Average commitment to safety of management as perceived by controllers	Medium	Medium

4.2 Validation Phase B

As a basis for the validation in this phase, results of the safety culture workshop, which was held by EUROCONTROL personnel at ANSP3, were used. The purpose of this workshop was to perform a deeper investigation of the issues identified by the safety culture questionnaire at ANSP3 by conducting interviews with ANSP3's employees. The model results were obtained without any knowledge about the workshop results. The model and workshop results were compared with the assistance of the workshop organizers by identifying for each Major Organizational Factor from the model (from Section 3.2) the range of related results of the safety culture workshop. In such a way, a conclusion about the agreement between the results of the model and the workshop was reached.

It was concluded that from the eight model-based Major Organizational Factors there is some agreement for two factors (MOF1, 4) and good agreement for the remaining six factors (MOF2, 3, 5, 6, 7, 8). In particular, for MOF1 (Sufficiency of number of controllers) it was expressed in the workshop that with the current reduction in traffic volume there is no shortage in controller resources, however it may be a problem in contingency situations and in the long term. For MOF4, no lack of priority of safety-related goals in the role description of controllers was identified in the workshop, however for some other roles the safety-related goals are not always appropriately understood.

Also, the model-based improvement options (from Section 3.2) were evaluated. Together with the workshop organizers it was concluded that the model-based recommendations are consistent with the recommendations of the survey study. The latter recommendations tend to reflect the larger detail in the organizational context as has emerged in the workshop at ANSP3. In addition to the list of consistent recommendations, the survey study identified a number of recommendations that are not or only partly addressed in the model-based study. Recommendations that were not addressed reflect aspects that are out of the scope of the model, e.g. on-the-job-training or learning processes of the Engineering department. Recommendations that were only partly addressed mostly reflect aspects for which the organizational context is known in more detail via the workshops at ANSP3. Thus, a high level of agreement of the results from the model- and survey-based studies was concluded in this validation phase.

5. CONCLUSIONS

In this paper a new, agent-based approach for structured analysis and improvement of organizational safety culture is proposed. Agent-based modeling and analysis have been used previously to study the efficiency or safety of air traffic scenarios (e.g. [9, 14, 16]), however agent-based modeling at the organizational level to study safety culture is a new subject both in air traffic management and in the area of multi-agent systems.

The main added value of the proposed approach is that it defines explicit formal relations between safety culture indicators and organizational processes and structures, thus enabling identification of important organizational aspects impacting safety culture by sensitivity analysis techniques.

The model results have been validated in two phases. In the validation phase A mostly valid model results for the safety culture indicators have been obtained. In validation phase B the model results obtained based on the sensitivity analysis are mostly consistent with the results of the safety culture survey workshop. Both the model and the workshop used outcomes of the survey questionnaire as input, but the processes for achieving their results were completely different and independent. As such, the consistency in both validation phases is a good indication of the model's validity. The validity of the model results depends greatly on the validity of the estimation of the model inputs. Our experience shows that the formal organizational documentation and interviews provide a limited basis for such estimation. The highest validity level of the estimation was achieved with the use of anonymous survey data from ANSP3, different from the ones used for the model analysis and validation. In general, the developed model has a range of input variables that reflect attitudes and opinions of people in the organization. A safety culture survey questionnaire is a suitable tool to obtain a reliable initialization for these variables.

In comparison with the survey-based results, the model proposed is more limited in scope and the level of details of the organizational context. On the one hand, this is a fundamental modeling issue, in the sense that a model is always an abstraction of reality. On the other hand, the range of organizational aspects that are considered in detail in the model may be enhanced. In the current study, the model development was focused on the occurrence reporting cycle and other processes such as management actions, engineering activities and traffic management actions by controllers were modeled at a high (abstract) level.

Safety culture professionals from EUROCONTROL recognized a high potential of the proposed approach. To gain the best effect, the agent-based organization modelling approach can be used in synergy with the survey-based approach. On the one hand, survey data can be used for a reliable model initialization. On the other hand, insights in relations between safety culture indicators and organizational structures and processes may be used to further enhance safety culture questionnaires and prepare safety culture survey workshops.

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