NLR-TP-2011-030

NLR Air Transport Safety Institute

Research & Consultancy

Executive summary

AGENT-BASED ORGANIZATIONAL MODELLING FOR ANALYSIS OF SAFETY CULTURE AT AN AIR NAVIGATION SERVICE PROVIDER

Problem area
Assessment of safety culture is done predominantly by questionnaire-based studies, which tend to reveal attitudes on immaterial characteristics (values, beliefs, norms). There is a need for a better understanding of the implications of the material aspects of an organization (structures, processes, etc.) for safety culture and their interactions with the immaterial characteristics.

Description of work
This paper presents a new agent-based organizational modelling approach for integrated and systematic evaluation of material and immaterial characteristics of socio-technical organizations in safety culture analysis. It uniquely considers both the formal organization and the value- and belief-driven behaviour of individuals in the organization.

Results and conclusions
Results are presented of a model for safety occurrence reporting at an air navigation service provider. Model predictions consistent with questionnaire-based results are achieved. A sensitivity analysis provides insight in organizational factors that strongly influence safety culture indicators. The modelling approach can be used in combination with attitude-focused safety culture research, towards an integrated evaluation of material and immaterial characteristics of socio-technical organizations. By using this approach an organization is able to gain a deeper understanding of causes of diverse problems and inefficiencies both in the formal organization and in the behaviour of organizational agents, and to systematically identify and evaluate improvement options.

Applicability
Analysis of safety culture.

Report no.
NLR-TP-2011-030

Author(s)
S.H. Stroeve
A. Sharpanskykh
B. Kirwan

Report classification
UNCLASSIFIED

Date
February 2011

Knowledge area(s)
Safety & Security

Descriptor(s)
Safety culture
Organizational modelling
Multi-agent system
Air traffic control

This report is based on an article published in Reliability Engineering and System Safety, Vol. 96 (2011), pp. 515-533, by Elsevier Ltd.

NLR Air Transport Safety Institute

Research & Consultancy

UNCLASSIFIED

NLR Air Transport Safety Institute

Anthony Fokkerweg 2, 1059 CM Amsterdam,
P.O. Box 90502, 1006 BM Amsterdam, The Netherlands
Telephone +31 20 511 35 00, Fax +31 20 511 32 10, Web site: http://www.nlr-atsi.nl

NLR-TP-2011-030

AGENT-BASED ORGANIZATIONAL MODELLING FOR ANALYSIS OF SAFETY CULTURE AT AN AIR NAVIGATION SERVICE PROVIDER

S.H. Stroeve
A. Sharpanskykh[1]
B. Kirwan[2]

[1] Vrije Universiteit Amsterdam
[2] EUROCONTROL

This report is based on an article published in Reliability Engineering and System Safety, Vol. 96 (2011), pp. 515-533, by Elsevier Ltd.

Customer	National Aerospace Laboratory NLR
Contract number	- - - -
Owner	NLR and partners
Division	Air Transport
Distribution	Unlimited
Classification of title	Unclassified
	February 2011

Approved by:

Author	Reviewer	Managing department
22-2-2011	22-2-11	22-2-11

Summary

Assessment of safety culture is done predominantly by questionnaire-based studies, which tend to reveal attitudes on immaterial characteristics (values, beliefs, norms). There is a need for a better understanding of the implications of the material aspects of an organization (structures, processes, etc.) for safety culture and their interactions with the immaterial characteristics. This paper presents a new agent-based organizational modelling approach for integrated and systematic evaluation of material and immaterial characteristics of socio-technical organizations in safety culture analysis. It uniquely considers both the formal organization and the value- and belief-driven behaviour of individuals in the organization. Results are presented of a model for safety occurrence reporting at an air navigation service provider. Model predictions consistent with questionnaire-based results are achieved. A sensitivity analysis provides insight in organizational factors that strongly influence safety culture indicators. The modelling approach can be used in combination with attitude-focused safety culture research, towards an integrated evaluation of material and immaterial characteristics of socio-technical organizations. By using this approach an organization is able to gain a deeper understanding of causes of diverse problems and inefficiencies both in the formal organization and in the behaviour of organizational agents, and to systematically identify and evaluate improvement options.

Contents

1 Introduction

Organizational and safety culture are broadly recognized as important for the safety of operations in various fields [1][2][3][4][5][6], including Air Traffic Management (ATM). The main aspects of organizational culture are reflected in a definition by Uttal [7]: 'Shared values (what is important) and beliefs (how things work) that interact with a company's people, organizational structures and control systems to produce behavioural norms (the way we do things around here).' Safety culture aims to keep the collective mind of an organization, through its entirety of individual minds, continually focused on safety [6]. It has been defined in a variety ways [3]; in this paper, we use the term safety culture as those aspects of organizational culture that may have an effect on safety, which is in line with Hopkins' primary focus on organizational culture and subsequent analysis of its impact on safety [4]. We also follow Hopkins' argumentation to not distinguish between organizational/safety culture versus climate, and we will thus use the term culture also in relation to its overt manifestations. Characteristics that are typically linked to safety culture include learning culture, reporting culture, just culture, flexibility, communication, safety-related behaviour, attitudes towards safety, working situation, risk perception, teaming, trust, responsibility, commitment and involvement [1][5][6].

As is well reflected in Utal's definition of organizational culture [7], the values and beliefs (commonly) held in an organization interact with its structures and processes, and jointly they influence the behaviour of people in the organization. Insofar as these people are working at the sharp end (e.g. airline pilots, air traffic controllers, physicians) and thus in direct control of potentially hazardous operations, their behaviour has a direct effect on the level of safety achieved by the organization. In particular, their performance, their interactions with other operators and technical systems, and their ways to respond to varying contextual and environmental demands contribute to the resilience of the operation and the development of safety-relevant situations [8][9]. It is well realized [1][8][10] that the safety achieved in an organization also depends on the constraints, resources, incentives and demands set, and values and commitments portrayed by people working at the blunt end (e.g. managers, regulators, system developers), who determine the working conditions of and the requirements set upon the people at the sharp end, and who contribute to the organizational culture as a whole and to the safety culture in particular.

Study of the safety culture in an organization can in general be pursued in a variety of ways, including questionnaires, checklists, audits, interviews, workshops, ethnographic research and accident inquiries [4][5][6][11][12]. In practice, the predominant method is the use of questionnaires that address several safety culture characteristics by asking people's opinions about related values and work issues on a preference scale. Such questionnaire-based safety culture research has been characterized as attitude research by Guldenmund [13], where an attitude is defined as a psychological tendency that is expressed by evaluating a particular entity with some degree of favour or disfavour. In an evaluation of questionnaire-based safety culture studies, Guldenmund argues that the dominant factors found in the aggregated data sets of such studies can be ascribed to primarily affective evaluations of the workforce about its management and the perceived influence of management on working conditions rather than of the working conditions themselves. Furthermore, he shows that the correlation between thus obtained safety culture factors and safety performance indicators is typically quite low [13]. As a way forward, he advocates further integration of value aspects in audit tools for organizational processes and structures. The need for socio-technical integration in safety culture research of material characteristics of the organization (e.g. organizational structures and processes) and immaterial characteristics of the organization (e.g. values, beliefs and norms) is also stressed by Grote and Künzler [14][15]. A good understanding of the relations between these material and immaterial characteristics is important for the identification of suitable and robust policies to improve and maintain sufficient levels of safety culture in an organization.

The research described in this paper aims to develop new methods for improving the understanding of the relations between material and immaterial characteristics in socio-technical organizations. To this end we initiated research towards the development of organizational models for analysis of safety culture. These models should be able to describe organizational structures and processes, socio-technical integration, the integration with immaterial characteristics and they should facilitate simulations and analysis. A secondary reason for this organizational model development is that by future coupling of organizational models with accident risk models more explicit descriptions and a better understanding of the relation between safety culture and accident risk may be achieved.

The organizational modelling research was done in coordination with safety culture survey-based research at EUROCONTROL and was focused on a particular case of safety culture issues in relation to the organization of safety occurrence reporting at a West-European air navigation service provider (ANSP). The steps, modelling details and results of this study are described in a series of reports, which can be accessed in Ref. [16]. A companion paper [17] focuses on the technical details of the organizational model and the performed simulations. Current paper focuses on the principles of the modelling, its use in safety culture analysis, the model results obtained and the coordination and comparison with the safety culture survey approach. Section 2 provides a review on organizational modelling. Section 3 highlights the key features of the development of the organizational model. Section 4 presents the simulation results of the model and their comparison with safety culture survey results. Section 5 presents a discussion of the methods and results.

2 Review of related literature

As an onset to the identification of a suitable organizational modelling framework we reviewed related literature [18]. This section provides a synopsis of this review that helps explaining the choices made. Section 2.1 provides an overview of organization theory, Section 2.2 describes organizational modelling methods and Section 2.3 describes methods on organizational modelling for safety analysis.

2.1 Organization theory

Organization theory studies structures and dynamics of human organizations. Its research methods stem from a broad range of disciplines such as economics, psychology, sociology, political science, anthropology and system theory; related practical disciplines include human resources and industrial and organizational psychology. Depending on the perspective, various definitions for an organization have been formulated in organization theory:

- An organization is a planned, coordinated and purposeful action of human beings to construct or compile a common tangible or intangible product [19];
- An organization is a social arrangement which pursues collective goals, which controls its own performance, and which has a boundary separating it from its environment [20];
- An organization is a structure that comprises sets of interrelated roles, which are intentionally organized to ensure a desired (or required) pattern of activities [21];
- An organization is a system that represents an organized collection of parts that are highly integrated in order to accomplish an overall goal [22].

The definitions in [19][20][21] are formulated from the positions of sociology, the definition in Ref. [22] is given from the perspectives of system theory.

Organizations are investigated at different aggregation levels: micro, meso and macro levels. The micro level considers the behaviour of individuals and groups in an organization and it includes aspects such as perception of an individual in the organizational context [20], work motivation and satisfaction [23], the influence of personal and/or organizational values on the motivation and work-related behaviour of an individual [24][25], group formation [26], group norms and regulations [20], social influence and conformity [27], leadership [24], individual conflicts in organizations [28], and power and influence in groups [24]. The meso level considers structures and dynamics at the level of the whole organization and it includes aspects such as organization structure and behaviour [29][30][31], organization authority and power structures [20][30][32], organization normative systems [20], intergroup conflict within an organization [28], organization reward system [23][33], technology in organizations [20][31] and organizational change [34]. The macro level focuses on the interactions between the organization and its environment and it includes aspects as inter-organizational formations (e.g. mergers, consolidations, joint ventures) [20] , governmental impact on organizations [31], organizations and politics [35], interactions between organizations and the society [20], organizations and markets [36] and virtual organizations [37].

2.2 Organizational modelling

The first formal computational organization modelling approaches have been developed in the areas of the system dynamics theory [38] and operation research [39]. Organizational models specified in system dynamics (SD) are based on sets of coupled differential equations with exogenous variables, e.g. stock and flow diagrams that describe the dynamics of a labour market from a global perspective. Operation research proposes mathematical methods for identifying best possible solutions to problems related to coordination and execution of the operations within an organization [39], e.g. an optimization of a production line in an organization.

Both system dynamics and operation research modelling approaches abstract from single events, entities and actors of organizations and take an aggregate view on the organizational dynamics. Such methods can be useful for the analysis of the organizational dynamics at macro levels, such as market fluctuations, or general trends of the organizational development. They do not support the investigation of the behaviour of organizational individuals and (the dynamics of) relations between them at detailed levels. As a high complexity of social dynamics may result from diverse local interactions among organizational actors, the examination of an organization at more detailed levels may help identifying causes of organizational malfunctioning and inefficiencies.

Agent-based modelling approaches take into account such local perspectives of possibly large numbers of separate components and their specific behaviours and interactions in a system. The concept of an agent may be used to model both human beings as well as hardware and software components of socio-technical systems [40][41]. Most agent definitions agree that an agent is an entity that is able to perceive its environment and to act upon this environment. Multi-agent systems are frequently used in computational organization theory [42], which uses computational and mathematical techniques for the investigation of human organizations. Multi-agent organizational models typically describe organizations at various aggregation levels, such as the whole organization + its environment, group levels and individual levels. Various methodologies for modelling and design of multi-agent systems have been developed, including GAIA [43], AGR [44], SODA [45] , MOISE [46] and TROPOS [47]. Models used in computational organization theory often focus on a limited number of organizational aspects that are directly related to the considered research problem. For instance, organization-oriented models of multi-agent systems were used to support processes at organizations, such as structuring of organizational goals [48][49], modelling organizational interactions [50] and task coordination [51].

In an effort to provide a generic and broad-scope framework that enables analysis and prediction of organizational behaviour by considering concepts and their relations across different perspectives and at various aggregation levels, a multi-view hybrid organizational modelling framework was developed [52]. This modelling framework considers the following four interrelated views to describe both institutional aspects of the formal organization, as well as the social behaviour of organizational actors (agents):

- The *organization-oriented view* describes a functional decomposition of an organization by a composite structure of roles at various aggregation levels. These roles are abstracted from particular agents that may fulfil them, e.g. business unit, department, manager or operator. The organization-oriented view describes interactions between roles and specifies the authority relations in an organization: superior-subordinate relations on roles with respect to tasks, responsibility relations, authorization relations and control for resources;
- The *performance-oriented view* describes the goals of the organizational roles in a goal structure of generic and specific goals. It uses performance indicators as measures of goal achievement for organizational roles;
- The *process-oriented view* describes tasks and processes in the organization. It specifies static and dynamic relations between processes, e.g. decomposition, ordering and synchronization, and the resources used and produced;
- The *agent-oriented view* describes the link between the role-based formal organizational model 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 performance and interactions of agents are regulated by the formal organization, on the other hand the dynamics and stochastic aspects of interacting agents contribute to performance variability in an organization.

It follows from a comparison with a number of multi-agent modelling methods [18] that this multi-view hybrid organizational modelling framework considers the widest repertoire of relevant aspects for multi-agent modelling of organizations.

2.3 Organizational modelling for safety analysis

For systematic reasoning about the risk of operations at the sharp end, there exists an extensive tradition of modelling the effects of errors and failures by techniques such as fault trees, event trees and Bayesian belief networks. Safety models of the blunt end are more seldom and below we discuss STAMP and SoTeRiA as interesting recent developments below. Given the focus on agent-based modelling in this research we also discuss the agent-based approach followed in TOPAZ accident risk modelling.

2.3.1 STAMP

Recognizing the limitations of traditional sequential accident models, Leveson developed the Systems-Theoretic Accident Modeling and Processes (STAMP) methodology [53], which uses system and control theory to describe socio-technical organizations. Here, an accident is not understood in terms of a series of events, but rather as the result of a lack of constraints imposed on the system design and on operations. STAMP uses system dynamics (SD) to describe interactions and dynamics between organizational processes and their effect on safety. The variables in such models typically are at an aggregated organizational level, rather than at the level of individuals in the organization. For example, in a model for safety culture at NASA, sub-models such as Launch Rate, System Safety Resource Allocation, Perceived Success by Management, and System Safety Status were used [54]. The dynamics are mostly continuous time-based with some triggering events; they are based on coupled ordinary differential equations with exogenous inputs, which may express event occurrences. STAMP models may describe relations between a large number of organizational variables, e.g. Perceived Concern for Performance, Perceived Concern for Safety, Level of Risk, and Fraction of Corrective Action to Fix Systemic Problems [54]. STAMP does not provide probability estimates of incidents or accidents. A STAMP model is evaluated via simulation runs showing dynamic traces of relevant variables. By varying model settings, the effects of conditions and decisions on dynamic traces for variables of interest can be evaluated.

2.3.2 SoTeRiA

As a basis for the development of the Socio-Technical Risk Analysis (SoTeRiA) framework [55] presented a wide list of principles of organizational risk analysis stemming from diverse disciplines, such as risk analysis, industrial/organizational psychology, organizational theory and human reliability. Mohaghegh et al. [56] propose a hybrid technique that uses three types of modelling techniques to specify a SoTeRiA model: (1) stock and flow diagrams from system dynamics (SD) to describe the deterministic dynamics of interrelated organizational factors; (2) Bayesian Belief Networks to represent probabilistic relations between organizational factors; (3) Event Sequence Diagrams (ESDs) and Fault Trees (FTs) to describe relations between conditions, failures and errors in risk scenarios, leading to probability estimates of hazardous events. The application of this hybrid technique is illustrated [56] by an example of aircraft maintenance and the effects of its quality on aircraft airworthiness and accident risk. This application includes SD models such as management safety commitment, financial pressure, training management, hiring management, technicians' commitment and technicians' error probabilities. BBNs are used to represent internal auditing factors, regulatory auditing factors and aircraft airworthiness. FTs and ESDs are used to represent the effect of maintenance-induced engine failure on flight safety risk levels. The results of this example provided in [56] indicate related variations in management commitment, technician commitment, management financial distress, technician error probability and aircraft accident risk. All in all, the illustrated variations in the accident risk levels are very small (less than 0.4%).

2.3.3 TOPAZ

Traffic Organization and Perturbation AnalyZer (TOPAZ) is an air traffic risk assessment methodology, which uses agent-based Dynamic Risk Modelling (DRM) by Dynamically Coloured Petri Nets (DCPNs) and Monte Carlo simulation-based collision risk assessment as key techniques on which we focus our discussion here [57][58]. The development of TOPAZ models has been focused on the organization at the sharp end, i.e. pilots and controllers supported by technical systems in the context of specific traffic scenarios. The variables in these models are at the level of individual systems and operators, rather than at aggregated levels. The agents in the model represent systems or generic operators performing particular roles (e.g. runway controller, pilot flying). The dynamics are continuous time-based with internal stochastic triggering events, which are based on stochastic differential equations with jump processes. Monte Carlo simulations including speed-up techniques provide probability estimates of adverse safety events, typically in the order of about 1E-10 to 1E-7. Sensitivity analysis is used to assess the effect of operational aspects on the level of safety risk. These risk sensitivities are used to assess bias and uncertainty levels in the safety risk. Examples of applications include collision risk analyses of parallel en-route lanes [59], of active runway crossing operations [58] and of airborne separation assurance system-based (free flight) concepts [60].

2.3.4 Comparison

STAMP and SoTeRiA are similar in their application of SD organizational models. Such models abstract from single events, entities and actors of organizations and overall they take an aggregate view on the organizational dynamics. On the one hand, using such aggregate views may be simpler as it restricts the model complexity by focusing on presumed key aspects in the organization. On the other hand, it may be difficult to map actual organizational structures and processes to abstract aggregated model variables. By doing so, the link to the behaviour of organizational individuals and their interactions is lost, so that the level of analysis is reduced. Moreover, a high complexity of social dynamics of interacting organizational actors may result in unexpected emergent effects in the organization, which cannot be observed based on the aggregate view adhered to in SD models.

In addition to STAMP, SoTeRiA provides a link to risk assessment via BNNs, ESDs and FTs. These techniques provide static mappings of risk levels, based on assumed probabilistic relations between events and conditions. Overall, risk levels in SoTeRiA may fluctuate as a result of the SD-based fluctuations in organizational variables. A drawback of the static risk mappings via BNNs, ESDs and FTs is that they may be limited to accurately describe the risk of complex socio-technical operations with concurrently interacting operators and systems [58][61][62].

Key differences of TOPAZ with STAMP and SoTeRiA are its scope, which has been restricted to operations rather than whole organizations, its use of agent-based models, which directly describe the performance of people and systems in the operation rather than aggregated variables, and its use of MC simulations and speed-up techniques to obtain low probabilities of adverse events.

3 Development of an organizational model

3.1 Choice of the modelling framework

Following the literature review (Section 2, [18]) we selected a modelling framework that fits our research aims. As put forth in the review, the recently developed safety-focused organizational modelling methods STAMP and SoTeRiA heavily rely on system dynamics (SD) models, which tend to abstract from single events, entities and actors and to take an aggregate view on the organizational dynamics. Since safety culture is about shared beliefs, values and norms, and as such can be seen as a concept at an aggregated level, its representation and the analysis of its relation with organizational processes by SD models seems to be a feasible approach. Nevertheless, it is clear that the basis of organizational and safety culture is formed by the beliefs, values and norms of individuals in the organization. It is their beliefs, values and norms that may be influenced by organizational processes, goals, policies, management and interactions, taking into account generic psychological and sociological characteristics and the specific context and experiences of the individuals. In other words, the integration of material and immaterial characteristics of an organization is grounded at the level of its individuals. As argued in the review, taking aggregated views at the start of the analysis may lead to neglecting organizational (e.g. safety culture) issues due to the complexity of interacting individuals in the organizational context. Agent-based organizational modelling uses the individual as starting point for its modelling and therefore well supports our analysis aims.

In addition to the aim to integrate material and immaterial characteristics in the analysis of safety culture, the organizational modelling should set a basis for the analysis of the relations of safety culture and accident risk. In the review we showed that agent-based dynamic risk modelling (DRM), such as used in TOPAZ, is able to describe the variability in the dynamic performance of operators, systems and environmental conditions of complex safety-relevant scenarios, and that Monte Carlo simulations reveal the risk effects emerging from these variably performing and interacting agents. As future coupling of the organizational modelling and DRM is supported by using common modelling structures, this provides a second argument for using agent-based organizational modelling.

Based on above reasoning we set forth to use an agent-based organizational modelling framework in this research. It was found in the review that the multi-view hybrid organizational modelling framework of [52] is a generic and broad-scope framework that enables analysis and prediction of organizational behaviour by considering concepts and their relations across different perspectives and at various aggregation levels. As it was found to consider the widest repertoire of relevant aspects for multi-agent organizational modelling, this modelling framework was selected for this study.

3.2 The modelling case and related safety culture issues

The modelling case focused on in this paper is safety culture in relation to safety occurrence reporting at a particular West-European air navigation service provider (ANSP-3). Various sources of information were used as a basis for the model development in this case:

- Parts of the documentation of the safety management system (SMS) at ANSP-3 gave information on the formal arrangements of safety occurrence assessment and safety monitoring at the ANSP;
- Interviews with an incident investigator and a safety manager at ANSP-3 provided insight in the implementation of the safety occurrence assessment procedures and related informal aspects;
- An interview with a safety occurrence assessment expert at EUROCONTROL Head Quarters provided information about general safety occurrence processing procedures and related informal aspects, regulations and consequences;
- EUROCONTROL safety culture survey results of two other ANSPs (ANSP-1, ANSP-2) provided us insight in the ranges of the survey results and the safety culture issues at those ANSPs;
- General literature provided insight in safety culture issues at ANSPs [2][5][63] as well as general psychological and sociological aspects relevant for the agent-based model (e.g. [19][64]).

Next, we highlight identified aspects of safety occurrence reporting at ANSPs as well as related safety culture issues.

In Europe, regulations [65][66] require ANSPs to report safety occurrences and they describe a large variety of occurrences that must be reported. Examples of safety occurrences are separation minima infringement, runway incursion, aircraft deviation from air traffic control (ATC) clearance or inability to provide air traffic management (ATM) services. Air traffic controllers typically work in teams under the supervision of a supervisor. When having observed a safety occurrence, a controller should describe it in a report. The draft report is reviewed and maybe corrected by the supervisor and it is provided to the Safety Investigation Unit of the ANSP. The ANSP reports safety occurrences to the National Supervisory Authority (NSA) and the NSAs report to EUROCONTROL at a European scale. The Safety Investigation Unit of an ANSP analyses the reported occurrence, possibly supported by automatically logged information, and tries to find contributory factors. At ANSP-3, individual occurrences and possible trends are discussed monthly by an experts group (incident investigator, safety manager, controllers, procedural, system and human factor experts). The resulting recommendations are published in a company-wide accessible database. Conclusions on individual occurrences may be told by the incident investigator to the controller(s) concerned. We were informed that at some European ANSPs there exists a punitive culture, where controllers may receive verbal and/or financial punishment when they are involved in an occurrence; this is not the case at ANSP-3. In general a consequence of a more severe occurrence may be that during its analysis, the licence of the involved controller(s) is temporarily retracted. If it follows from the analysis that the controller made an important mistake, the controller(s) may be assigned a dedicated training to regain the licence. Externally invoked consequences of (typically severe) safety occurrences may be prosecution by a Public Prosecution Department or media attention; their impact on the well-being of the people involved may be high.

The safety culture issues identified in the references indicated can be categorized along the following four aggregation levels:
1. The level of an individual (e.g. a controller, a supervisor, a manager);
2. The level of a team (e.g. a team of air traffic controllers);
3. The level of intra-organizational structures (e.g. a department);
4. The level of inter-organizational interaction (i.e. influences from other organizations).

Examples of safety culture issues for these four aggregation levels are shown in Table 1.

Table 1: Examples of identified safety culture issues; a full list is in [67].

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 find it difficult to keep up with numerous changes in procedures/the system.
Group 2: Team aspects
Willingness of actors to cooperate may decrease when the other actor has been involved in an 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.
Formal procedures do not always sufficiently describe the required work processes and sometimes need to be worked around.
It takes too long to create an occurrence report.
Minor safety occurrences are not defined precisely.
Feedback / lessons learned from incidents come too late or not at all.
Controllers do not receive acknowledgement for reporting.
The organisation does not use feedback from occurrences to improve the way of working / technical systems.
Insufficient number of safety experts and support staff for tasks such as processing of occurrence reports.
Group 4: Inter-organizational aspects
Information about occurrences in other ANSPs is not provided by the ANS.
Regulator may put too many irrelevant requirements and norms on ANSPs that are hard to fulfil and that decrease the freedom of ANSPs significantly.
The Public Prosecution Department may decide to investigate occurrences and decide to prosecute involved organizations or humans; here occurrence reports may be used.

Based on the safety occurrence processes and related safety culture issues, we identified groups of aspects that are relevant for safety occurrence reporting at the four aggregation levels. Figure 1 shows a high-level categorization of these aspects, which may refer to more detailed levels, e.g. the category 'Individual safety-related beliefs and attitudes' includes sub-categories such as 'Trust in the confidentiality of reporting', ' Trust in the effectiveness of reporting' and 'Perception of the commitment to safety of management'. We identified potential modelling methods and data for these aspects and we decided on the key aspects to be included in the organizational model [67]. As a part of this choice, we decided to restrict the scope of the model to aggregation levels 1, 2 and 3 of an ANSP; thus leaving out inter-organizational aspects such as interactions with airlines and NSA at this stage.

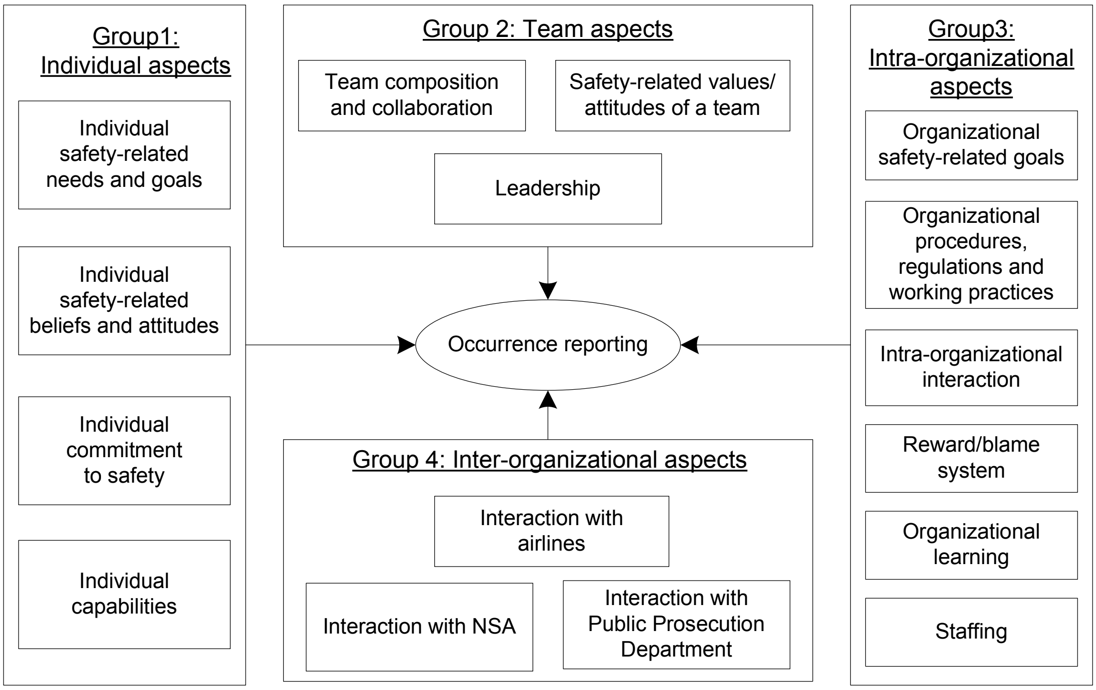

Figure 1: Identified groups of aspects that influence safety occurrence reporting

3.3 Modelling of the formal organization

The multi-view hybrid organizational modelling framework considers four interrelated views to describe the institutional aspects of the formal organization as well as the social behaviour of the organizational actors. Sorted predicate logic restricted to finite sorts has been chosen as a formal basis for the definition of dedicated modelling languages for each of these views [52]. Temporal relations in the specifications of the views are specified by the Temporal Trace Language (TTL), which is a variant of reified order-sorted temporal predicate logic. In TTL the organizational dynamics are represented by a trace, i.e. a temporally ordered sequence of states. Each state is characterized by a unique time point and a set of state properties that hold (i.e., are true). The state properties are specified using the dedicated language(s) of the view(s). The temporal properties are defined in TTL as transition relations between the 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 units perform a, is formalized in TTL as:

$$\forall t{:}TIME\ [\ at(internal(ag,\ belief(reward\_for\_action(r,\ a))),\ t) \rightarrow at(output(ag,\ performed\_action(a)),\ t+30)\ ]$$

Both specifications in the dedicated languages of the views and in TTL are suitable for performing computations. In particular, in [68] it is shown that any TTL formula can be automatically translated into executable format that can be implemented in most commonly used programming languages.

Below a concise high-level description of the three views specifying the formal organization is provided: organization-oriented view, performance-oriented view and process-oriented view. For more details on the formal specification we refer to the companion paper [17] or to the related reports [69][70].

The *organization-oriented view* describes a functional decomposition of an organization by a composite structure of the roles at various aggregation levels. These roles are abstracted from particular agents that may fulfil them. In the case study, the ANSP is at the highest aggregation level, it includes at a second aggregation level composite roles such as maintenance unit, safety investigation unit, safety monitoring unit and air traffic control unit, and it has at a third aggregation level roles such as safety investigator, safety manager, air traffic controller and supervisor. As an example, Figure 2 shows the interactions between the roles in an ANSP at the second aggregation level. For each role, requirements on the level of knowledge, skills and personal traits are defined. The organization-oriented view also describes interactions between roles and specifies the authority relations in an organization: superior-subordinate relations on roles with respect to tasks, responsibility relations, authorization relations and control for resources.

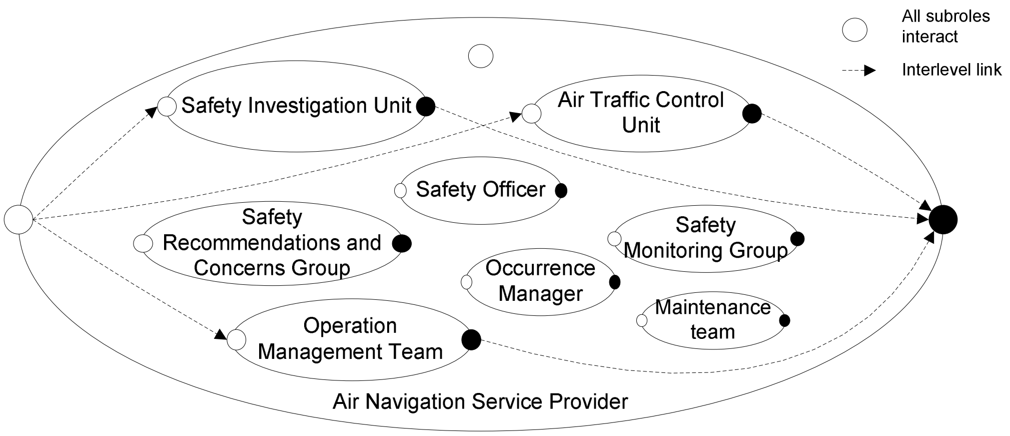

Figure 2: Example of interactions between roles in an ANSP

The *performance-oriented view* describes the goals that are aimed for by the roles in the organization and it uses performance indicators to reflect the state or progress of a role with respect to a goal. The definition of goals includes their level of priority, time horizon, ownership, perspective, hardness and negotiability. Goals can be refined into more specific goals and thus form goal structures. For instance, a goal to maintain high quality of incident investigation may be made more specific by sub-goals requiring a high proficiency level for incident investigators, detailed incident notification reports and timely investigation of incidents.

The *process-oriented view* describes the formal tasks, their relations and the resources used and produced in an organization. In the modelling framework, tasks may range from generic to specific and this is specified by a task decomposition. For each task, minimum and maximum timelines are indicated and it is specified what resources a task uses and produces. Workflows are defined that describe sequences of tasks in particular scenarios. In relation with the performance-oriented view it is specified to what goals a task contributes. In relation with the organization-oriented view it is specified which roles are authorized and/or responsible for the task.

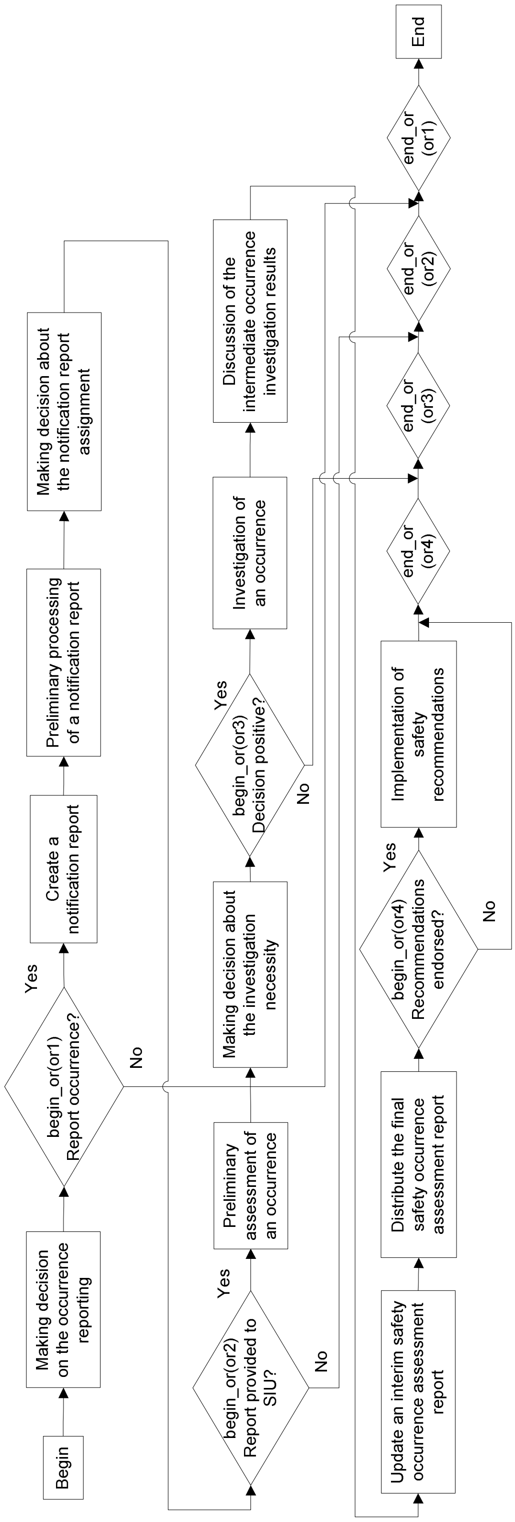

Figure 3: Workflow example: occurrence reporting

Safety occurrence reporting is a key process in the organizational model and the workflow for its tasks is shown in Figure 3 as an example. The workflow describes the actions for the reporting of occurrences and the processing of reported occurrences, starting with deciding by a controller to report an occurrence, up to assessment of occurrences and implementation of policies to prevent similar occurrences. In relation with the organization-oriented view, the responsibilities of the roles for the tasks in the workflow are defined, e.g., the controller is responsible for execution of and decision making with respect to the task 'Create a notification report', the supervisor is responsible for monitoring and consulting for this task. Note that the responsibilities of roles are not indicated in the graphical representation of the workflow, but rather defined as a part of the formal specification.

3.4 Modelling of the agents in the organization

An agent is an entity that is able to perceive and act upon its environment. The behaviour of an agent can be considered from external and internal perspectives. From the external perspective, the behaviour can be specified by dynamic relations between agent's input and output states, according to the interaction with other agents and with the environment in a multi-agent organization. In order to illustrate a multi-agent organization in our case study, Figure 4 shows interactions between selected agents in safety occurrence reporting. Consider that controller agent 1 observes a separation minimum infringement in the environment, discusses it with controller agents 2 and 3, and decides to report it. Controller agent 1 provides a draft report to supervisor agent 1 and next the report is provided to the incident investigator agent. After a particular time, the incident investigator may provide feedback on the particular incident to supervisor agent 1, and the safety manager agent may provide generic feedback to supervisor agents 1 and 2. The supervisor agents communicate about this specific and generic feedback to the controller agents in their teams and thereby influence their behaviour. Note that the interactions and performance of the agents in this example reflect their roles and tasks as described in the formal organizational modelling views. In addition, the agent-oriented view describes the informal interactions and agents' behaviour, based on the agents' internal perspectives.

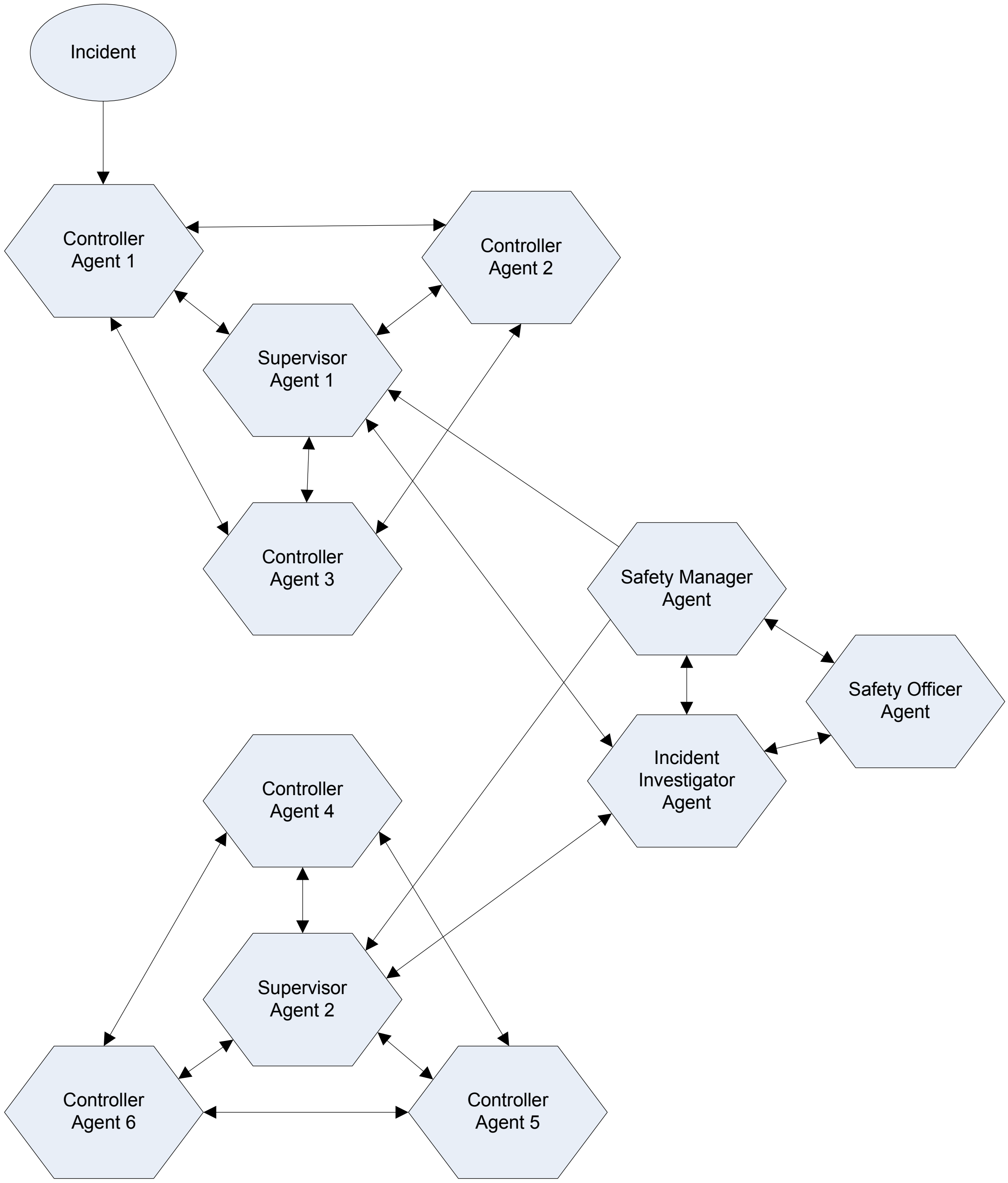

Figure 4: Example of interactions between selected agents in a multi-agent organization

From the internal perspective the behaviour of an agent is characterized by causal relations between internal states of the agent, based on which externally observable behavioural patterns are generated (Figure 5). An agent perceives information by observation or communication and generates output in the form of communication or actions. The internal states of an agent include information attitudes (e.g. belief, knowledge) and pro-attitudes (e.g. desire, intention, obligation, commitment) [71].

Agents are considered as goal-driven, where pro-attitudes are based on needs. The externally observable behaviour based on the internal states is determined by the decision making process. The way in which these aspects of agent are represented in this study is discussed next.

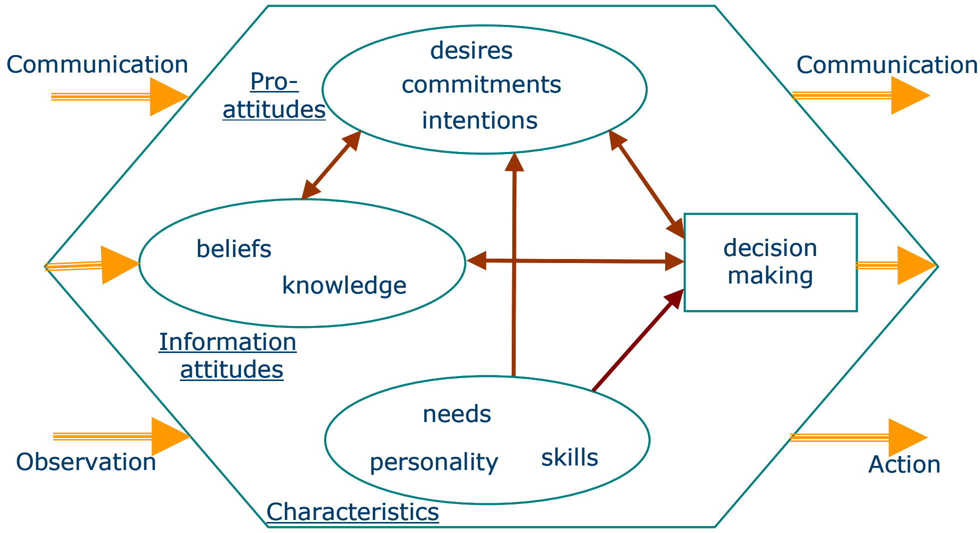

Figure 5: Internal perspective of an agent

3.4.1 AGENT'S INFORMATION ATTITUDES AND PRO-ATTITUDES

Agents create dynamic internal representations about their input and output states, such as observed events, messages of other agents and occurrence reports. These may consider single states as well as more complex beliefs about dependencies between its own states and observed states of the environment and other agents. Temporal relations between state properties are represented by TTL. In the developed model, relations between agent's internal states are often represented by causal networks [72], which describe weighted mappings between 'evidence variables' with values in the range from 0 to 1. As an example,
Figure 6 shows the causal network for the commitment to safety of a controller. It represents that a controller agent's commitment to safety is influenced by the perceived commitment to safety of team members and the management, by the priority of safety-related goals in the role description, by the influence of the controller on safety activities and by the maturity level of the controller [64][73]. The rounded boxes in
Figure 6 refer to evidence variables that are considered as input of the organizational model and the rectangular boxes refer to evidence variables that depend on other evidence variables in the model. For instance, an agent evaluates the management's commitment to safety by considering factors that reflect the management's effort in contributing to safety, such as investment in personnel and technical systems,

training and safety arrangements. As another example, the maturity level of a controller depends on aspects as the self-confidence, the commitment to perform the ATC task, the level of skill and training of the agent and the quality of feedback on occurrence reporting received by the agent. By interconnection of causal networks complex dynamic relationships can be represented, including feedback loops.

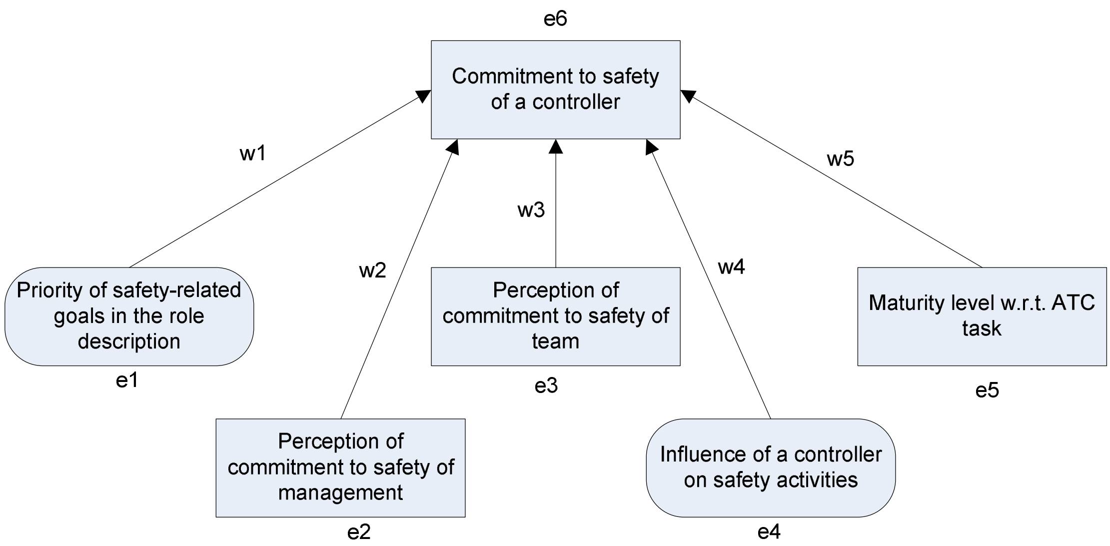

Figure 6: Causal network for 'Commitment to safety of a controller'

3.4.2 Agent's needs

The behaviour of individuals is considered to be goal-driven, where the individual goals are based on needs. Three 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, e.g. own group approval and management approval; (3) intrinsic needs that concern the desires for self-development and self-actualization, e.g. contribution to safety-related goals, self-esteem and self-confidence [74]. Different needs have different priorities and minimal acceptable satisfaction levels for individuals in different cultures. In this study we use three indices of the cultural classification framework of Hofstede [75]: the individualism index reflects the degree to which individuals are not integrated into groups; the power distance index is the extent to which the less powerful members of an organization accept and expect that power is distributed unequally; and the uncertainty avoidance index deals with individual's tolerance for uncertainty and ambiguity. The model uses values for these indices that are suitable for the Western European culture [75]. The model has internal states that represent to what extent the agent's needs are satisfied as result of external events, the behaviour of other agents and decisions made. The level of satisfaction of agent's needs influences the decision making process, as will be explained next.

3.4.3 Agent's decision making process

The decision making model of agents is based on the expectancy theory by Vroom [23][74], which is illustrated in Figure 7. According to Vroom's theory, when a human evaluates alternative possibilities to act, the following factors are explicitly or implicitly taken into account:

- *Expectancy*: the individual's belief about the likelihood that a particular act will be followed by a particular first-level outcome. For example in Figure 7, the expectancy E12 refers to the belief of the likelihood that reporting of an occurrence results in a reprimand;
- *Instrumentality*: the belief concerning the likelihood that a first-level outcome results into a second-level outcome, which may be liked or disliked as reflected by the agent's needs. For example in Figure 7, the instrumentality I32 refers to the belief about the likelihood that own group appreciation of the action results in own group approval;
- *Valence*: the strength of the individual's desire for an outcome or state of affairs. The values of valances depend on the degree of satisfaction of the agent's need: the more a need is satisfied, the less is its valence. An example in Figure 7 is the need and valence V2 for own group approval as part of social interaction needs.

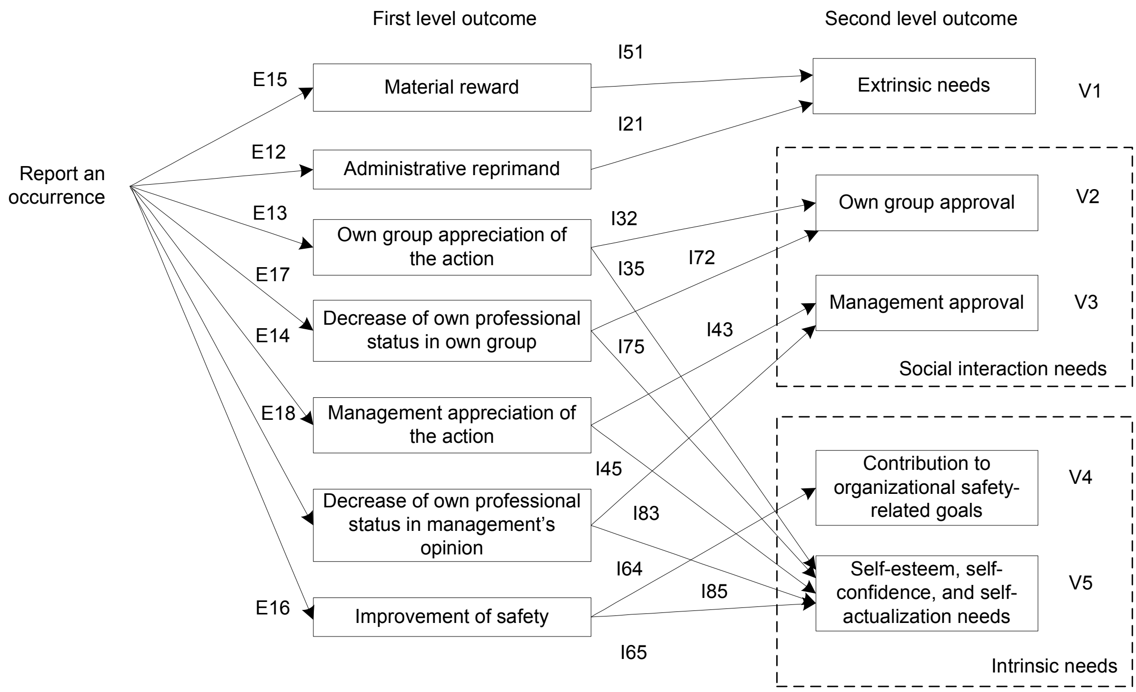

Figure 7: Decision making model for reporting an occurrence (E's are expectancies, I's are instrumentalities and V's are valences)

In the model for the safety occurrence reporting, a controller agent considers the possibilities to report or not to report, depending on their expectancies, instrumentalities and valences. These are dynamic variables that change over time due to individual and organizational learning. In particular, in the model their values depend on the occurrence of safety-relevant events and on related evidence variables. For example, agent's expectancies E12 and E15 change depending on the reprimands and rewards for occurrences reported by the agent or another agent in its shift. As another example, the expectancy E16 that reporting improves safety is adjusted based on the feedback from the safety investigator agent on previously reported occurrences, on the observed implementation of safety recommendations for previous reports, as well as on the safety information provided informally by other controllers during breaks.

4 Safety culture results

4.1 Introduction

The developed model was used to predict and analyse the safety culture performance of ANSP-3 and the model results were compared with the results of a EUROCONTROL safety culture survey study of this ANSP. This was done in the following three phases:

- Phase 1: Comparison of model-based and survey-based safety culture indicators, where the input values of the model were completely based on organizational information available prior to the survey questionnaire results;
- Phase 2: Comparison of model-based and survey-based safety culture indicators, where the input values of the model used organizational information in combination with survey questionnaire results;
- Phase 3: Comparison of major organizational factors affecting the safety culture indicators and related organizational improvement options, which were inferred from a sensitivity analysis of the organizational model, with key issues and recommendations stemming from the safety culture survey workshop results.

Next, Section 4.2 highlights the safety culture survey study and Sections 4.3 to 4.5 present the details of the three phases.

4.2 Safety culture survey study

As a prelude to systemic changes in air traffic management (ATM), EUROCONTROL developed a safety culture survey approach for ANSPs, which includes questionnaires and subsequent workshops as main steps [6]. The safety culture questionnaires provide people in the organization the opportunity to reflect anonymously on a range of statements about the attitudes and the way the work is done. The questions address the following topics: commitment, responsibility & risk awareness, involvement, teamwork, learning & reporting and communications & trust. In the workshops the key items found by the questionnaires are discussed to interpret and analyse their background and to find ways to improve them. This safety culture survey approach has now been applied at a large number of ANSPs in Europe.

The questionnaire distributed at ANSP-3 contained 32 statements in a general section common to all respondents, 18 statements directed to operational experts as controllers, supervisors and trainers, 19 statements directed to engineers, technicians and maintainers, and 23 statements directed to the management staff. For each statement the respondents were asked to select a response on a five-point scale: ‘1: strongly disagree’, ‘2: disagree’, ‘3: neither’, ‘4: agree’ and ‘5: strongly agree’. The questionnaire was completed by 222 people of ANSP-3’s personnel; about half of the questionnaires were from air traffic controllers. Descriptive statistics were derived for the responses, including mean and standard deviation of the scores as well as percentages of favourable and unfavourable responses with respect to safety. Examples of the questions and mean scores are provided in Table 3 (Section 4.3) and Table 5 (Section 4.4); the complete questionnaire results are confidential. Following a preliminary analysis of the data, six workshop sessions were organized to interpret and analyse their key findings: one session with managers, one session with human resources and security, and four sessions with operational and engineering staff. The latter four sessions focussed on specific topics. Based on the questionnaire data and subsequent workshops, conclusions were reached on the safety culture status for the various topics and their contributing organizational factors, and recommendations were made for further improvement of the safety culture. Examples of organizational factors identified in the workshops are listed in Table 8 (Section 4.5).

4.3 Phase I

In Phase 1 we compared safety culture indicators stemming from the model with indicators from the questionnaires. Based on the identification of safety culture issues as discussed in Section 3.2, we selected eight model variables as relevant safety culture indicators (see list in Table 2). Per definition these model-based safety culture indicators have values in the range from 0 to 1, but their distributions over this interval are not a priori known. To analyse these distributions we performed Monte Carlo simulations in which all evidence input variables (see list in Table 7) were varied over their full range, except for the national culture variables (e61 - e64), which were associated with Western European culture. Figure 8 provides examples of histograms for the Monte Carlo simulations results for two safety culture indicators. In the Monte Carlo simulation results mostly three areas in the sample populations of the safety culture indicators could be identified: a range of infrequently occurring low values, a range of frequently occurring medium values and a range of infrequently occurring high values. Based on this observed trichotomy, we defined the classes Low/Medium/High for the values of the safety culture indicators. We associated the first 30% of these values with the class Low, the next 55% with the class Medium and the last 15% with the class High. The resulting ranges of the class definitions for the model-based safety culture indicators are shown in Table 2.

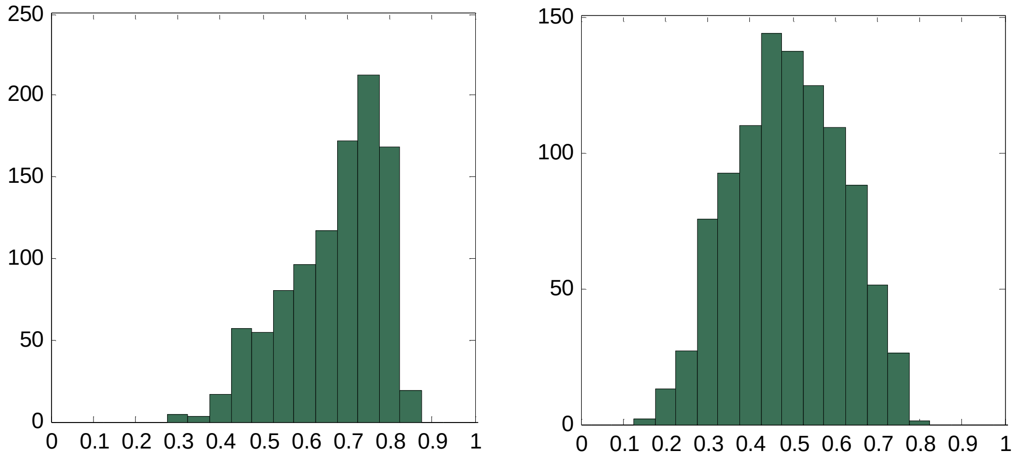

Figure 8: Examples of distributions of safety culture indicators (Monte Carlo simulation results): I1.1 Average reporting quality of controllers (left figure) and I5.1 Average commitment to safety of controllers (right figure).

Table 2: Distribution of model-based safety culture indicators over three classes as obtained by Monte Carlo simulations. N.B. (a,b] signifies all values x with a < x ≤ b.

Safety culture indicator		**Low**	**Medium**	**High**
		0 – 30%	**30 – 85%**	**85 – 100%**
I1.1	Average reporting quality of controllers	[0, 0.55]	(0.55, 0.76]	(0.76, 1]
I2.1	Average quality of the processed notification reports	[0, 0.27]	(0.27, 0.45]	(0.45, 1]
I3.1	Average quality of the final safety occurrence assessment reports	[0, 0.14]	(0.14, 0.32]	(0.32, 1]
I4.1	Average quality of the monthly safety overview reports received by controllers	[0, 0.44]	(0.44, 0.66]	(0.66, 1]
I5.1	Average commitment to safety of controllers	[0, 0.43]	(0.43, 0.63]	(0.63, 1]
I5.2	Average commitment to safety of a team as perceived by controllers	[0, 0.43]	(0.43, 0.63]	(0.63, 1]
I6	Average commitment to safety of a supervisor as perceived by controllers	[0, 0.48]	(0.48, 0.7]	(0.7, 1]
I7	Average commitment to safety of management as perceived by controllers	[0, 0.45]	(0.45, 0.63]	(0.63, 1]

As a basis for the derivation of survey-based safety culture indicator results, we defined relations between the indicators and related questions of the survey questionnaire (see Table 3). This was done before we received the outcomes of the questionnaire. For the cases where an indicator is related to multiple questions, a weight was assigned to each question, indicating our estimate of the degree of relevance of the question for the safety culture indicator. Next, we associated the weighted average of the survey-based safety culture indicator with the three classes Low/Medium/High. This association was based on the distribution of the means of the survey questions of a particular ANSP-2 (different from ANSP-3) and the above defined class distributions (Low 30%, Medium 55%, High 15%). This resulted in the following class ranges for the questionnaire results:

- Values in the range ≥1 and ≤3.25 are defined as Low;
- Values in the range >3.25 and ≤4.0 are defined as Medium;
- Values in the range >4.0 and ≤5.0 are defined as High.

After above preparatory steps we received the questionnaire results of ANSP-3 and we derived the resulting classes of the survey-based safety culture indicators as shown in Table 3. It can be observed that six indicators are Medium, indicator I6 is Low and indicator I2.1 could not be derived from the questionnaire data.

Table 3: Safety culture indicators based on survey questionnaire results

Safety culture indicator		Related safety culture survey questions	Weight	Survey result	Total
No.	**Description**				
I1.1	Reporting quality (ratio reported/observed) in the whole organization.	A.24 People understand the need to report incidents in order to identify trends and make changes to the system if required	0.5	3.7 Medium	3.7 Medium
		A.31. 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	3.3 Medium	
		A.32. If I do something unsafe I am aware that I may be asked to explain myself	0.2	4.1 High	
I2.1	Average quality of the processed notification reports produced by a controller in the whole organization.	No related question identified.	-	-	-
I3.1	Average quality of the received final safety occurrence assessment reports by controllers in the whole organization.	A.22 Appropriate responses are made after an incident to address why the incident occurred.	1	3.7 Medium	3.7 Medium
I4.1	Average quality of the monthly safety overview reports received by controllers in the whole organization.	A.24 People understand the need to report incidents in order to identify trends and make changes to the system if required	0.4	3.7 Medium	3.5 Medium
		A.29 Lessons learned from incidents are published in a de-identified manner in a newsletter or similar document	0.6	3.3 Medium	

Safety culture indicator		Related safety culture survey questions	Weight	Survey result	Total
No.	Description				
I5.1	Commitment to safety of a controller	B.10 Controllers would never compromise their responsibility to safety.	1	3.8 Medium	3.8 Medium
I5.2	Perceived commitment to safety of a team of controllers	A.4 My colleagues are committed to safety.	0.7	4.0 Medium	3.9 Medium
		A.11 Everyone at my Unit/Team feels that safety is their personal responsibility.	0.3	3.8 Medium	
I6	Perceived commitment to safety of supervisor.	B.16 My concern about safety would be acted on if I expressed them to my supervisor	1	3.0 Low	3.0 Low
I7	Perceived commitment to safety of management.	A.7 My management is committed to safety	1	3.4 Medium	3.4 Medium

In Phase 1, the safety culture indicators were predicted by the agent-based organizational model on the basis of evidence input values, which had been derived using organizational information of ANSP-3 consisting of interviews, SMS documents and general literature, as indicated in Section 3.2. The resulting values and classes of the safety culture indicators are listed in Table 4 and they can be compared with the survey-based indicators. It follows from Table 4 that according to the model all safety culture indicators except I3.1 are High. The Medium value of I3.1 indicates sub-optimal feedback provision on safety occurrences to air traffic controllers and/or insufficient amount of details in the safety occurrence assessment reports. The values of indicators I1.1 and I4.1 are High but close to the border of the class Medium, the other High indicators are well away from this border. Comparing the survey and model results, it is clear that the model results are consistently higher than the survey results, except for indicator I3.1.

Table 4: Comparison of the safety culture indicators obtained by the organizational model and the survey questionnaire data in Phase 1

Index	Safety culture indicator	Model		Survey
		Value	Class	
I1.1	Average reporting quality of controllers	0.80	High	Medium
I2.1	Average quality of the processed notification reports	0.65	High	–
I3.1	Average quality of the final safety occurrence assessment reports	0.23	Medium	Medium
I4.1	Average quality of the monthly safety overview reports received by controllers	0.70	High	Medium
I5.1	Average commitment to safety of controllers	0.72	High	Medium
I5.2	Average commitment to safety of a team as perceived by controllers	0.70	High	Medium
I6	Average commitment to safety of a supervisor as perceived by controllers	0.78	High	Low
I7	Average commitment to safety of management as perceived by controllers	0.76	High	Medium

4.4 Phase 2

In Phase 2, the safety culture indicators were predicted by the agent-based organizational model on the basis of organizational information of ANSP-3 in combination with survey questionnaire results. The applied survey questionnaire results had not already been used for the determination of the values of the safety culture indicators. For each input evidence variable we pursued to identify related survey questions:

- For 14 evidence input variables we identified one to six related survey questions;
- For five evidence input variables we did not identify any related survey question.

For the cases where we identified related survey questions, we averaged the scores and combined them with a priori knowledge on the organization in an updated value for the input evidence variable. Table 5 shows some examples of input evidence variables, related survey questions and updated values of the variable. For most of the evidence input variables this process led to a decrease in their values.

Table 5: Examples of the update of evidence input variables, based on survey questionnaire results (full list in [70])

Ev.	Description	Related safety culture survey questions	Survey result	Ev. variable	
				Old	New
e1	Priority of safety-related goals in the role description	A.1. Balancing safety against the other requirements of my job is a challenge	3.5	0.90	0.70
		A.5. Safety is a responsibility shared throughout the organization	3.7		
		A.12. The other people in the organization do not understand the safety roles we fulfil	3.0		
e4	Influence of a controller on safety activities	B.2 Our opinion and input into safety assessments are actively sought after.	2.8	0.70	0.50
		B.12 We are consulted about changes to the technical/engineering system that impact on the way we do our work	3.2		
		B.15 I have the opportunity to provide input in the ATC systems development or acquisition process.	2.9		
e9	Availability of reliable and ergonomic technical systems for controllers	B.8 I trust the ATC equipment that I use in my job.	3.9	0.90	0.75
e10	Sufficiency and timeliness of training for changes	A.28. Information about changes to procedures or the system is easily accessible	3.4	0.80	0.60
		A.26 There are so many changes that it is hard to keep track of the current situation	2.8		
		A.30. I am kept informed of changes that have been made to procedures or systems	3.7		

Based on the updated values of the input evidence variables, new model simulation results were obtained. Table 6 shows the updated model results in relation with the (unchanged) survey-based results. All safety culture indicators are now in the class Medium, except for indicator I2.1. Indicators I1.1 and I7 are close to the class boundary with High, all other indicators are well off from a class boundary. It follows from a comparison of the original model results in Table 4 and the updated model results in Table 6 that all indicators transferred to a lower class, except for indicators I2.1 and I3.1. Comparison of the model and survey results in Table 6 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. As a result of the input updating, the consistency between the model and the survey-based results for the safety culture indicators has thus increased considerably.

Table 6: Comparison of the safety culture indicator classes for the survey data and for the organizational model with updated model input values (Phase 2)

Index	Safety culture indicator	Model		Survey
		Value	Class	
I1.1	Average reporting quality of controllers	0.74	Medium	Medium
I2.1	Average quality of the processed notification reports	0.54	High	–
I3.1	Average quality of the final safety occurrence assessment reports	0.20	Medium	Medium
I4.1	Average quality of the monthly safety overview reports received by controllers	0.58	Medium	Medium
I5.1	Average commitment to safety of controllers	0.56	Medium	Medium
I5.2	Average commitment to safety of a team as perceived by controllers	0.55	Medium	Medium
I6	Average commitment to safety of a supervisor as perceived by controllers	0.60	Medium	Low
I7	Average commitment to safety of management as perceived by controllers	0.61	Medium	Medium

4.5 Phase 3

In Phase 3 we employed a sensitivity analysis to predict organizational factors at ANSP-3 that are important for its safety culture indicators and on the basis of these factors we proposed a number of organizational improvement options as ways to improve the safety culture. Next we compared these results with issues and recommendations that were identified earlier in workshops of the EUROCONTROL safety culture survey at ANSP-3. In coordination with the EUROCONTROL experts who performed the safety culture survey we reached conclusions about the level of agreement between the model- and the survey-based results.

4.5.1 Sensitivity analysis

The sensitivity analysis method used in this study is Monte Carlo filtering [76]. It aims to identify the model parameters of which the variation according to associated credibility intervals leads to significant differences in attained model output classes. It was applied in the following way.

For the complete set of model parameters, lower and upper bounds of credibility intervals of their values were determined. These bounds are based on the variability in and the level of applicability of related safety culture questionnaire results and on our understanding of the level of uncertainty of the modelled aspects. Next, Monte Carlo simulations were performed, where in each simulation the parameters were chosen uniformly within their credibility interval bounds. The number of performed Monte Carlo simulations was sufficient to obtain stable results (8000 simulations of three years periods each appeared sufficient). For each parameter x_i two sets of values were determined:

- $x_i \mid B$, containing all values of x_i that produced a High safety culture indicator, and
- $x_i \mid \underline{B}$, containing all values of x_i that produced a Low or Medium safety culture indicator.

A Smirnov two sample test was performed for each input factor independently. The applied test statistic is

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

where F_B and $F_{\underline{B}}$ are marginal cumulative probability distribution functions calculated for the sets $x_i \mid B$ and $x_i \mid \underline{B}$, respectively, and Y is the output. A low level of $d(x_i)$ supports the null-hypothesis $H_0 : F_B(x_i \mid B) = F_{\underline{B}}(x_i \mid \underline{B})$, meaning that the parameter 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. To obtain a convenient overview over the sensitivity analysis results, we use a tripartite classification:

- If $\alpha \le 0.01$, then the sensitivity for x_i is High;
- If $0.01 < \alpha \le 0.1$, then the sensitivity for x_i is Medium;
- If $\alpha > 0.1$, then the sensitivity for x_i is Low.

Table 7 shows the results of the sensitivity analysis for all input evidence variables for each safety culture indicator, according to above methodology. We calculated a total safety culture sensitivity index 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 for a particular parameter. There are eight evidence input variables with a total safety culture sensitivity index of at least four (which will be discussed in Section 4.5.2). 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 evidence variables. Only 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, achieved a similar large effect on the safety culture indicators.

Table 7: Results of the sensitivity analysis for the input evidence variables. The following data are shown for each input evidence variable: its nominal value and credibility interval, the sensitivity class (Low/Medium/High) for each safety culture indicator and a total sensitivity index (where values ≥4 are shaded).

Input evidence variables			Sensitivity of safety culture indicators								Total sensitivity
No.	**Description**	**Values**	**I1.1**	**I2.1**	**I3.1**	**I4.1**	**I5.1**	**I5.2**	**I6**	**I7**	
			Reporting quality	Quality of notification reports	Quality of occurrence assessment	Quality of monthly safety overview	Commitment to safety of a controller	Safety commitment of team	Perceived safety commitment of supervisor	Perceived safety commitment of managament	
e1	Priority of safety-related goals in the role description	0.60 [0.50, 0.70]	M	M	L	M	H	H	H	H	5.5
e4	Influence degree of controllers on safety arrangements	0.50 [0.40, 0.60]	H	L	L	L	H	H	H	H	5
e7	Sufficiency of number of safety investigators	0.50 [0.40, 0.60]	M	L	H	H	H	H	H	H	6.5
e8	Sufficiency of the number of controllers	0.60 [0.40, 0.80]	H	H	H	H	H	H	H	H	8
e9	Availability of reliable and ergonomic technical systems for controllers	0.75 [0.65, 0.85]	M	H	L	L	H	H	H	H	5.5
e10	Sufficiency and timeliness of training for changes	0.60 [0.45, 0.75]	L	L	L	L	H	H	H	H	4
e11	Regularity of safety meetings	0.75 [0.60, 0.90]	L	L	L	L	M	L	H	H	2.5
e12	Developed and implemented SMS	0.60 [0.40, 0.80]	M	M	L	L	H	H	H	H	5
e14	Level of development of managerial skills	0.60 [0.40, 0.80]	H	H	H	H	H	H	H	L	7
e19	Self-confidence for ATC task	0.85 [0.75, 0.95]	L	M	M	M	H	H	L	L	3.5

e20	Commitment to perform ATC task	0.80 [0.70, 0.90]	M	M	L	L	H	H	L	L	3
e21	Development level of skills for ATC task	0.80 [0.70, 0.90]	L	L	M	L	L	L	L	M	1
e25	Sufficiency of the number of maintenance personnel	0.75 [0.60, 0.90]	L	M	H	H	M	L	L	M	3.5
e26	Quality of formal procedures for system checks and repairs	0.75 [0.60, 0.90]	L	M	L	L	L	L	L	L	0.5
e35	Intensity of informal interactions in the team of controllers	0.65 [0.50, 0.80]	L	L	L	L	L	L	L	L	0
e36	Quality of the formal occurrence assessment procedure	0.85 [0.75, 0.95]	L	L	L	L	L	L	L	L	0
e40	Quality of the communication channel between controllers and safety investigators	0.50 [0.30, 0.70]	L	L	H	L	L	L	L	L	1
e44	Average commitment to safety of the agents involved in safety analysis	0.65 [0.50, 0.80]	L	L	L	H	M	L	L	L	1.5
e61	Individualism index of a controller	0.8 [0.7, 0.9]	L	L	L	L	L	L	L	L	0
e62	Power distance index of a controller	0.4 [0.3, 0.5]	L	L	L	L	L	L	L	L	0
e63	Masculinity index of a controller	0.15 [0.05, 0.25]	L	L	L	L	L	L	L	L	0
e64	Uncertainty avoidance index of a controller	0.5 [0.4, 0.6]	L	L	L	L	L	L	L	L	0
e71	Formal support for confidentiality of reporting	0.65 [0.55, 0.75]	L	L	L	L	L	L	L	L	0

4.5.2 Major organizational factors

Based on the sensitivity analysis of the model for ANSP-3, we identified eight major organizational factors (MOFs) with a large effect on safety culture based on the input evidence variables with a total sensitivity index larger or equal than four in Table 7. Earlier, in the EUROCONTROL safety culture survey of ANSP-3, a range of safety culture issues had become clear from the results of the questionnaire and the safety culture workshops at ANSP-3. In coordination with the EUROCONTROL personnel who had performed the safety culture survey at ANSP-3, we compared the major organizational factors found by the sensitivity analysis with related issues identified in the workshops. Table 8 provides an overview of this comparison. It was concluded that there is some agreement for two factors (MOF-1, 4) and good agreement for the remaining six factors (MOF-2, 3, 5, 6, 7, 8). For instance, for MOF-1 (Sufficiency of number of controllers) it was expressed in the survey workshops that with the current reduction in traffic volume there is no shortage in controller resources, but it may be a problem in contingency situations and in the long term. In general, the issues identified by the survey study provide more detailed information about the organizational context of the safety culture issues. For instance, in relation to MOF-2 details related to leadership roles, selection based on an adequate competence profile and coordination within the organization became clear from the survey workshop.

Table 8: Overview of the major organizational factors identified by the agent-based organizational model and the related issues identified in the safety culture workshops

Major organizational factor	Related issues identified in workshops
MOF-1: Sufficiency of the number of controllers	• Currently, there is a reduction in traffic volume and as such there is no shortage of controller resources. • In contingency situations, there may be insufficient controller resources. • It is recognized that the balance between safety and capacity may be a problem. • There is a lack of confidence regarding the long term planning of resources.
MOF-2: Level of development of managerial skills of supervisors	• There is a lack of leadership role for the supervisor to brief and motivate people. • There is a lack of authority of supervisors. • Not all supervisors encourage feedback on safety events. • The competence profile of supervisors is based on old role profiles, which do not reflect the current organization. • The selection process of supervisors is not defined according to an appropriate profile. • There is a lack of managerial skills of supervisors regarding interaction with their peer supervisors and the management.
MOF-3: Sufficiency of the number of safety investigators	• More resources on the investigation side and safety assessments side are required. • People in the organization do not well know how they can effectively contribute to the investigation process.
MOF-4: Priority of safety-related goals in the role description	• People in the organization believe that pressure and conflicting goals are obstacles that force management to set priorities that are not always in favour of safety. • Safety messages are not always well processed by the middle management, for instance the severity of messages may get diluted.
MOF-5: Availability of reliable and ergonomic technical systems for controllers	• The implementation of a new system was perceived as being rushed. • During the development of a new system the safety argument was felt to be misused. • The prevailing culture that 'change is good' is questionable.
MOF-6: Influence of a controller on safety activities	• Controllers do not feel they are consulted enough about major changes affecting safety of operations. • The impression that controllers' opinions are not listened to is due to the fact they do not see actions deriving from the concerns they raise and adequate feedback about these concerns is not provided.
MOF-7: Developed and implemented Safety Management System (SMS)	• The SMS is seen as an asset and at an advanced level. • The transmission of safety concerns upwards in the organization does not appear to be working, nor is the top-down communication being effectively translated through the levels.
MOF-8: Sufficiency and timeliness of training for changes	• On-job-training is not optimally organized. • Controllers receive adequate ATC training, although the high number of students has meant that some of them are controlling together on the same sector. • Training issues related to changes may be underestimated. More realistic assessments of training requirements should be put in place. This is the major point in relation to training.

4.5.3 Organizational improvement options

The insights obtained by the sensitivity study can be used as basis for recommendations to improve the organization. In the case study, we proposed the following five organizational improvement options.

OIO-1: More involvement of controllers in safety assessment for development of new systems and procedures (MOF-4, 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 (MOF-1, 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 OIO-1 with involvement of controllers.
(c) A result of these guidelines may be that the number of controllers should increase.

OIO-3: Improve the quality of management by supervisors (MOF-2)

(a) The quality of the management by supervisors should be improved.
(b) The quality of management may be improved by further development of the managerial skills and techniques of supervisors.
(c) The quality of management may be improved by developing clear guidelines that support supervisors in their decisions for dealing with capacity-safety issues in nominal and non-nominal conditions. The development of such guidelines may be achieved in coordination with OIO-1 and OIO-2.

OIO-4: Improve coherence and communication in the safety management system (MOF-3, 7)

(a) The coherence and communication in the safety management system should be improved.
(b) Improvement of the coherence means that safety assessment (prior operation) and safety monitoring (during operation) should be more consistent, such that safety indicators and safety requirements formulated in the safety assessment are well captured in the safety monitoring phase.
(c) Improvement of the communication means, on the one hand, that voicing about safety issues is encouraged, and on the other hand, that that there should be a structured way to always provide feedback on the safety issues raised (either prior or during operation). Therefore, OIO-4 should be addressed in good coordination with OIO-1.

OIO-5: Improve the communication about and training for changes (MOF-8)

(a) The communication about changes to systems, procedures or working conditions should be improved.

(b) Appropriate training should be considered for changes to systems, procedures or working conditions.
(c) In such communication and training there should be reference to the conclusions of the safety assessments conducted in line with OIO-1, explaining the reasons for the change and its assessed impact.

It was concluded in the safety culture model workshop that the organizational improvement options of the model-based study are consistent with the recommendations of the survey study. The recommendations of the survey study tend to reflect the larger detail in the organizational context as has emerged in the survey workshops at ANSP-3. 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 ANSP-3.

5 Discussion

The onset of this paper described the need for methods towards a better understanding of the implications of the material aspects of an organization for safety culture as well as their interactions with the immaterial characteristics. To this end we developed an agent-based organizational modelling approach that considers the formal organization as well as the value- and belief-driven behaviour of individuals in this organization, and that facilitates simulation-based analysis. The model was developed for and applied to the organization of safety occurrence reporting and processing of reported occurrences at a particular West-European Air Navigation Service Provider (ANSP-3) and the model results were compared with reference results of a EUROCONTROL safety culture survey study of ANSP-3. Next, Section 5.1 discusses the achieved model results and Section 5.2 discusses the possibilities of organizational modelling for safety culture analysis.

5.1 Achieved model results

In summary, the following results were obtained in the three study phases:

- In Phase 1, the input values of the model were completely based on organizational information available prior to the survey questionnaire results. The model predicted safety culture indicators which were mostly higher than the survey questionnaire results. In particular, for six out of the seven relevant indicators a higher class was predicted by the model.
- In Phase 2, the input values of the model were based on a combination of organizational information and survey questionnaire results. The model predicted safety culture indicators which were mostly equal to the survey questionnaire results. In particular, for six out of seven indicators the same class was predicted by the model.
- In Phase 3, major organizational factors affecting the safety culture indicators and related organizational improvement options were inferred from a sensitivity analysis of the organizational model. Next these results were compared with safety culture issues and recommendations stemming from safety culture survey workshops. The major organizational factors and organizational improvement options identified by the model-based sensitivity study were largely consistent with the safety culture issues and the recommendations arrived at via the workshops in the survey study. The survey results included more details of the organizational context and revealed some additional aspects that were out of the scope in the organizational model.

Comparing the results of Phases 1 and 2, there is a clear difference in the attained consistency between the survey questionnaire and model results. This difference is due to the differences in the values of the input evidence variables of the model. The overall higher values used in Phase 1 led to safety culture indicator classes that were mostly higher in Phase 1 than in Phase 2, and that were mostly inconsistent with the survey questionnaire results in Phase 1 and mostly consistent in Phase 2. The (higher) values of the evidence input variables in Phase 1 were based on organizational information stemming from interviews with a safety manager and a safety investigator at ANSP-3, and from the SMS of ANSP-3. The (lower) values of the evidence input variables in Phase 2 were based on the questionnaire-aggregated opinions of a large number of employees with a variety of roles.

The consistent results in Phase 2 show that the model structure and other parameters are such that the agent-based organizational model can predict the safety culture indicators reasonably well. In other words, given part of the data on the attitudes of a broad set of people in the organization, the integrated material and immaterial characteristics have been represented such in the model, that it predicted the safety culture indicators that are consistent with another part of the attitude dataset. This provides a positive indication of the validity of the organizational model. Nevertheless, a limitation of this comparison is that both the reference outputs and the evidence input values were based on the survey questionnaire results. Although different questions were used for these two classes, the responses to groups of questions reflect similar tendencies in safety culture dimensions at ANSP-3, and as such the values for the inputs and reference outputs may have been correlated. In addition to Phase 2, the comparison in Phase 3 using independent data sources is therefore important to obtain a more complete view.

The results in Phase 3 show that the outcomes based on the sensitivity analysis of the model are mostly consistent with the results of the safety culture survey workshops. Both the model and the workshop used results of the survey questionnaire as input, but the processes for achieving their results were completely different and independent. As such, the consistency in their results indicates that the organizational model well captured key aspects of the safety culture. The observed limitation in the detail of the organizational context and the scope of the model results is, on the one hand, a fundamental modelling issue, in the sense that a model is always an abstraction of reality and it focuses on selected aspects. On the other hand, the range of organizational aspects that are considered in detail in the model may be enhanced, as is discussed in Section 5.2.

5.2 Organizational modelling for safety culture analysis

We developed and applied an agent-based organizational modelling approach for the analysis of safety culture. Such agent-based modelling is a new approach in safety culture research. Core reasons for taking an agent-based modelling approach are that it is well capable of representing individuals in an organization and that it takes into account the beliefs, values and norms of such individuals that form an important basis of the organizational and safety culture. The beliefs, values and norms of individuals are influenced by and/or have effect on the processes, goals, policies and structures of the organization. Thus the integration of material and immaterial characteristics of organizational culture takes place at the level of the individual.

This focus on the individual in the agent-based organizational modelling can be contrasted with recently developed organizational models with an emphasis on system dynamics (SD), such STAMP [53] and SoTeRiA [56]. In general, SD models tend to abstract from single events, entities and actors of organizations and to use an aggregate view on the organizational dynamics. On the one hand, using such aggregate views may be simpler as it restricts the model complexity by focusing on presumed key aspects in the organization. On the other hand, it may be difficult to map actual organizational structures and processes to abstract aggregated model variables. By doing so, the link to the behaviour of organizational individuals and their interactions may be lost, such that the level of analysis is reduced. Moreover, a high complexity of social dynamics of interacting organizational actors may result in unexpected emergent effects in the organization, which may not be observed in models using aggregated organizational views. In this paper we showed that in spite of the modelling complexity it is feasible to develop an agent-based organizational model that provides predictions consistent with survey-based results.

Notwithstanding the importance of agents in the organizational modelling, it is only one of the views of the applied multi-view hybrid organizational modelling framework [52] and its three other views are needed to describe the formal organizational context in which the agents perform. In particular, these other views describe organizational aspects such as the organization of roles, authority relations, responsibility relations, goals, performance indicators, tasks and processes. A wide repertoire of organizational perspectives thus helps to perform the analysis from a broad scope without neglecting possibly relevant organizational aspects prematurely. Furthermore, it helps assuring that the agents' behaviour is considered in a valid organizational context, i.e. a context that well represents the structures and processes of the organization under study. The multi-view organizational modelling [52] supported a suitable representation of the formal organizational context in the case study, such as indicated by the largely consistent predictions obtained.

For the development and use of the model, information on both the material and the immaterial characteristics of an organization is needed. Information on the material characteristics (such as roles, processes, responsibilities) can be obtained by e.g. management documentation, process observation or interviews; in the case study we used documentation of the SMS and interviews on the ways of working. Information on the immaterial characteristics (values, beliefs, norms) is more difficult to obtain. As noted in the Introduction questionnaires are predominantly used in safety culture research to reveal related attitudes of people in the organization. In the case study questionnaire-based information was used as model input and on this basis consistent model predictions of the safety culture indicators could be achieved, as discussed in Section 5.1. This research is not focused on the quest for the best way to reveal values, beliefs and norms of people in the organization, but it manifests that information on these immaterial characteristics is essential model input. After all, organizations with similar material characteristics may have different organizational cultures.

The case study showed that the model could achieve predictions of safety culture indicators that are consistent with questionnaire-based indicators. However, the aim of the organizational modelling is not the prediction of safety culture indicators as such. As discussed in the previous paragraph, information on immaterial characteristics is necessary model input and thus the added value of the prediction of indicators using the same type of information would be low. The aim of the modelling is to improve the understanding of the relations between the material and immaterial characteristics of safety culture, as a basis for structured determination of ways towards better safety culture. The logical structure of the organizational model offers the basis to systematically reason about the complex relations between aspects of the formal organization and the behaviour, values and beliefs of actors in the organization. As the organizational model considers a variety of complex interactions, such as agent relations, dynamics, stochasticity and feedback loops, computer simulations are needed to evaluate the resulting behaviour of the model. The results of such simulations provide insights in the relations between material and immaterial characteristics of organizational culture and can be used to evaluate various organizational (improvement) scenarios. As an example, the studied case showed the effective use of a sensitivity analysis to identify organizational factors that have a strong impact on safety culture.

Based on above findings, the proposed organizational modelling approach can be considered as part of a set of safety culture analysis methods, which specifically aims at an integrated and systematic evaluation of material and immaterial characteristics of socio-technical organizations. By using this approach an organization is able to gain a deeper understanding of causes of diverse problems and inefficiencies both in the formal organization and in the behaviour of organizational agents, and to systematically identify and evaluate improvement options. Given the broad perspective of the organizational modelling framework, such improvement options may cover a broad range, e.g. roles, responsibilities, goals, processes, working conditions (some specific examples achieved in the case study are listed in Section 0), thus promoting organizational learning at various levels and beyond single-loop learning. The effects of organizational changes may be evaluated by follow-up analyses, using feedback of attitudes and other related organizational performance indicators. Such feedback may also support further improvement of the organizational model.

The application of the modelling approach is not a free lunch. It requires a good understanding of the modelling methods and their bases in organization theory, social psychology and cognitive science, as well as a considerable effort to analyse and formalize relevant aspects of the material and immaterial characteristics of the organization. In addition, the performance of model simulations requires that appropriate values need to be determined for large number of parameters and by the nature of the modelling the uncertainty of these parameter values may well be high. In the sensitivity analysis of the case study it was illustrated how the Monte Carlo filtering technique is able to select the most important factors in spite of the uncertainty in the parameter values.

This paper presented a new agent-based organizational modelling approach for integrated and systematic evaluation of material and immaterial characteristics of a socio-technical organization in safety culture analysis. Future developments may further strengthen and broaden the approach. Such enhancements may include:

- Extension of the set of agent modelling constructs to allow evaluation of a broader range of safety culture issues. For instance, trust-related safety culture issues may be evaluated using trust modelling approaches from [77][78]; issues related to emotions and feelings can be addressed by techniques from [79][80].
- More direct coupling of the organizational modelling with other safety culture analysis methods. For instance, development of safety culture questionnaires

with questions that are directly linked to variables in the model or that are based on important issues identified by the model; preparation of safety culture workshops on the basis of organizational factors identified by the model.

- Broadening the scope of the modelling. For instance, in the case 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 modelled at a high (abstract) level. The level of modelling detail of such other processes may be enhanced, thus enabling more specific results for these organizational layers and the air traffic control operations.
- Coupling of organizational modelling to risk modelling may provide a future way for structured analysis of the effect of safety culture on safety performance. A stimulus of safety culture studies is the premise that a good safety culture has a positive effect on the safety risk of the work performed at the organization; for an ANSP this would mean that better safety culture supports lower ATM-related risk levels. A way forward for the analysis of this important link consists of modelling of the effect of safety culture on the way operations are being performed, and next, assessing the risk of the safety culture influenced performance by risk modelling methods that explicitly account for the performance of human operators, e.g. as has been done in agent-based dynamic risk modelling [57][58]. Such modelling allows for explicitly arguing about relations between safety culture and safety performance, which can be supported by sensitivity analysis at the level of safety risks.

Acknowledgements

This research was supported by the EUROCONTROL CARE Innovative III project. We are grateful to Marinella Leone and Eve Grace-Kelly of EUROCONTROL for their contribution to the safety culture model workshop, and to the interviewees at ANSP-3 and EUROCONTROL Head Quarters for their cooperativeness. We thank the reviewers of Reliability Engineering and System Safety, their comments helped to improve the paper considerably.

6 References

[1] Reason J. Managing the risk of organizational accidents. Ashgate, Aldershot, England, 1997
[2] Gordon R, Kennedy R, Mearns K, Jensen CL, Kirwan B. Understanding safety culture in air traffic management. EUROCONTROL, report EEC Note No. 11/06, 2006
[3] Choudhry RM, Fang D, Mohamed S. The nature of safety culture: A survey of the state-of-the-art. Safety Science 45:993-1012, 2007
[4] Hopkins A. Studying organizational cultures and their effects on safety. Safety Science 44:875-889, 2006
[5] Ek A, Akselsson R, Arvidsson M, Johansson CR. Safety culture in Swedish air traffic control. Safety Science 45(7):791-811, 2007
[6] EUROCONTROL/FAA Action Plan 15 Safety. Safety Culture in Air Traffic Management: A white paper. December 2008
[7] Uttal B. The corporate culture vultures. Fortune 17:66-72, 1983
[8] Woods DD, Hollnagel E. Joint cognitive systems: Patterns in cognitive system engineering. CRC Press, Boca Raton (FL), USA, 2006
[9] Hollnagel E, Woods DD, Leveson N (eds.). Resilience engineering: Concepts and precepts. Ashgate, Aldershot, England, 2006
[10] Woods DD, Johannesen L, Cook RI, Sarter N. Behind human error: Cognitive system, computers and hindsight. Wright-Patterson AFB, OH: Crew Systems Ergonomics Information Analysis Center, 1994
[11] Cooper MD. Towards a model of safety culture. Safety Science 36: 111-136, 2000
[12] Mearns K, Kirwan B, Kennedy R, Gordon R. The EUROCONTROL safety culture measurement approach. Proceedings EUROCONTROL Safety R&D Seminar, Southampton, UK, 22-24 October 2008
[13] Guldenmond FW. The use of questionnaires in safety culture research – an evaluation. Safety Science 45:723-743, 2007
[14] Grote G, Künzler C. Diagnosis of safety culture in safety management audits. Safety Science 34:131-150, 2000
[15] Grote G. Understanding and assessing safety culture through the lens of organizational management and uncertainty. Safety Science 45:637-652, 2007
[16] www.eurocontrol.int/eec/public/standard_page/proj_CARE_INO_III_Safety_M.html
[17] Sharpanskykh A, Stroeve SH. An agent-based approach for structured modeling, analysis and improvement of safety culture. Computational and Mathematical Organization Theory, in press

[18] Stroeve SH, Sharspanskykh A, Blom HAP. Literature survey of safety modelling and analysis of organisational processes: EUROCONTROL CARE Innovative research III. National Aerospace Laboratory NLR, report CR-2007-156, 2007
[19] Giddens A. Sociology, 5th ed., Polity, Cambridge, 2006
[20] Scott WG, Mitchell TR, Birnbarum PH. Organization theory: a structural and behavioural analysis, Richard D. Irwin Inc., Illinois, USA, 1981
[21] Biddle B. Role Theory: Concepts and Research. Krieger Publishing Co., 1979
[22] Kast FE, Rosenzweig JE. General systems theory: applications for organization and management. Academy of Management Journal December: 447-465, 1972
[23] Vroom VH. Work and motivation. Wiley, New York, 1964
[24] Yukl G. Leadership in organizations, 6th ed., Englewood Cliffs, NJ: Prentice-Hall, 2006
[25] Hackman JR. Work redesign and motivation. Professional Psychology 11: 445-455, 1980
[26] Campion MA, Medsker GJ, Higgs AC. Relationship between work group characteristics and effectiveness: implications for designing effective work groups. Personnel Psychology 46: 823-850, 1993
[27] Yeatts DE, Hyten C. High-performing self-managed work teams: A comparison of theory to practice. Sage, Thousand Oaks, 1998
[28] March, JG, Simon, HA. Organizations, John Wiley & Sons Inc., 1967
[29] Blau PM, Schoenherr RA. The structure of organizations, Basic Books Inc., New York London, 1971
[30] Mintzberg H. The Structuring of Organizations, Prentice Hall, Englewood Cliffs, 1979
[31] Morgan G. Images of organizations, SAGE Publications, Thousand Oaks London New Delhi, 1996
[32] Pfeffer J. Organizations and organization theory, Pitman Books Limited, Boston London Melbourne Toronto, 1982
[33] Galbraith JR. Organization design, Addison-Wesley Publishing Company, London, 1978
[34] Cummings TG, Worley CG. Organization development and change. Thomson/South Western, 2005
[35] Bacharach SB, Lawler EJ. Power and politics in organizations, Jossey-Bass, San Francisco, 1980
[36] Langlois RN, Robertson PL. Firms, Markets, and Economic Change: A Dynamic Theory of Business Institutions. London: Routledge, 1995
[37] Warner M, Witzel, M. Managing in Virtual Organizations, Thomson Learning, 2004
[38] Forrester JW. Industrial dynamics, Waltham, MA: Pegasus Communications, 1961

[39] Marlow WH. Mathematics for Operations Research. New York: Dover, 1993
[40] Russell S, Norvig P. Artificial Intelligence: A Modern Approach. Prentice-Hall, Inc.
[41] Huhns MN, Stephens LM. Multiagent Systems and Societies of Agents, in Multiagent Systems: A Modern Approach to Distributed Artificial Intelligence, Gerhard Weiss, editor, MIT Press, Cambridge, MA, 1999
[42] Carley KM. A comparison of artificial and human organizations. Journal of Economic Behavior & Organization, 31(2), 175-191, 1996
[43] Zambonelli F, Jennings NR, Wooldridge M. Developing multiagent systems: the Gaia Methodology, ACM Transactions on Software Engineering and Methodology, vol. 12 (3): 317-370, 2003
[44] Ferber J, Gutknecht O. A meta-model for the analysis and design of organizations in multi-agent systems. Proceedings of Third International Conference on Multi-Agent Systems (ICMAS'98), IEEE Computer Society, 128-135, 1998
[45] Omicini A. SODA: Societies and infrastructures in the analysis and design of agent-based systems. Proceeding of AOSE’00, 185-193, 2000
[46] Hannoun M, Boissier O, Sichman JS, Sayettat C. MOISE: An Organizational Model for Multi-agent Systems. Proceedings of the International Joint Conference, 7th Ibero-American Conference on AI: Advances in Artificial Intelligence, LNCS, vol. 1952, 156 - 165, 2000
[47] Bresciani P, Giorgini P, Giunchiglia F, Mylopoulos J, Perini A. Tropos: An Agent-Oriented Software Development Methodology, Journal of Autonomous Agent and Multi- Agent Systems, vol. 8(3): 203-236, 2004
[48] Giorgini P, Kolp M, Mylopoulos J. Multi-Agent Architectures as Organizational Structures. Journal of Autonomous Agents and Multi-Agent Systems. Kluwer Academic Publishers, 13(1), 3-25, 2006
[49] Maiden NAM, Kamdar N, Bush D. Analysing i* system models for dependability properties: The Uberlingen accident, Proceedings REFSQ'2006 Mini-Conference, in conjunction with CaiSE'2006, Luxembourg, 2006
[50] Horling B, Lesser V. A survey of multi-agent organizational paradigms. The Knowledge Engineering Review, Vol. 19(4) 281-316, 2005
[51] Decker K. TAEMS: A Framework for Environment Centered Analysis & Design of Coordination Mechanisms. Foundations of Distributed Artificial Intelligence, Chapter 16, O'Hare, G. and Jennings, N. (eds.), Wiley Inter-Science, 429-448, 1996
[52] Sharpanskykh A. On computer-aided methods for modeling and analysis of organizations. PhD Thesis Vrije Universiteit Amsterdam, The Netherlands, 2008
[53] Leveson N. A new accident model for engineering safer systems. Safety Science 42:237-270, 2004

[54] Dulac N, Owens B, Leveson N et al. Demonstration of a new dynamic approach to risk analysis for NASA's constellation program. MIT SCRL Report, March 2007
[55] Mohaghegh Z, Mosleh A. Incorporating organizational factors into probabilistic risk assessment of complex socio-technical systems: Principles and theoretical foundations. Safety Science 47:1139-1158, 2009
[56] Mohaghegh Z, Kazemi R, Mosleh A. Incorporating organizational factors into probabilistic risk assessment (PRA) of complex socio-technical systems: A hybrid technique formalization. Reliability Engineering and System Safety 94:1000-1018, 2009
[57] Blom HAP, Bakker GJ, Blanker PJG, Daams J, Everdij MHC, Klompstra MB. Accident risk assessment for advanced air traffic management. In: Donohue GL and Zellweger AG (eds.), Air Transport Systems Engineering, AIAA, pp. 463-480, 2001
[58] Stroeve SH, Blom HAP, Bakker GJ. Systemic accident risk assessment in air traffic by Monte Carlo simulation. Safety Science 47: 238-249, 2009
[59] Blom HAP, Bakker GJ, Everdij MHC, Van der Park MNJ. Collision risk modelling of air traffic. Proceedings European Control Conference 2003 (ECC03), Cambridge, UK, 2003
[60] Blom HAP, Bakker GJ, Klein Obbink B, Klompstra MB. Free flight safety risk modeling and simulation. Proc. Int. Conf. on Research in Air Transport (ICRAT), Belgrade, Servia, 2006
[61] Hollnagel E. Barriers and accident prevention. Ashgate, Aldershot, England, 2004
[62] Sträter O. Cognition and safety: An integrated approach to system design and assessment. Ashgate, Hampshire, England, 2005
[63] Montijn C, De Jong H. Safety culture in air transport: Definition, characteristics, indicators and classification scheme. National Aerospace Laboratory NLR, memorandum ATSF-2006-150, 2006
[64] Burt RS. Social Contagion and Innovation: Cohesion Versus Structural Equivalence Source: The American Journal of Sociology, 92, 6, pp. 1287-1335. The University of Chicago Press, 1987
[65] ESARR 2. Safety Regulatory Requirement ESARR 2: Reporting and assessment of safety occurrences in ATM. Edition 2.0, 3-11-2000
[66] EC Directive 42-2003. On occurrence reporting in civil aviation, 13 June 2003.
[67] Sharpanskykh A, Stroeve SH. Safety modelling and analysis of organizational processes in air traffic - D3: Methods and requirements. National Aerospace Laboratory NLR, report NLR-CR-2008-299, 2008
[68] Sharpanskykh, A., Treur, J., Automated Analysis of Compositional Multi-Agent Systems, International Journal of Agent-Oriented Software Engineering, 4(2), pp. 174-221

[69] Sharpanskykh A, Stroeve SH, Van Lambalgen R. Safety modelling and analysis of organizational processes in air traffic – D4: Model and initial simulation results. National Aerospace Laboratory NLR, report NLR-CR-2008-407, 2008
[70] Stroeve SH, Sharpanskykh A. Safety modelling and analysis of organizational processes in air traffic – D7: Validation. National Aerospace Laboratory NLR, report CR-2009-305, 2009
[71] Wooldridge M, Jennings N. Intelligent agents: Theory and practice. Knowledge Engineering Review 10(2), 1995
[72] Pearl J. Causality: Models of Reasoning and Inference. Cambridge University Press, 2000
[73] Griffin RW, Bateman TS. Job satisfaction and organizational commitment. In: Cooper CL, Robertson I (Eds), International Review of Industrial and Organizational Psychology 1986, Wiley, New York, pp. 157-188
[74] Pinder CC. Work motivation in organizational behavior. Upper Saddle River, NJ: Prentice-Hall, 1988
[75] Hofstede G. Cultures and Organizations. McGraw-Hill, 2005
[76] Saltelli A, Ratto M, Tarantola S, Campolongo F. Sensitivity analysis practices: Strategies for model-based inference. Reliability Engineering and System Safety 91:1109-1125, 2006
[77] Castelfranchi C, Falcone R. Trust theory : a socio-cognitive and computational model. Chichester : John Wiley & Sons, 2010.
[78] Sharpanskykh A. Integrated Modeling of Cognitive Agents in Socio-Technical Systems, In: Jedrzejowicz P, Nguyen NT, Howlett RJ , Jain LC (eds.), KES AMSTA 2010 Proceedings of the 4th International KES Symposium on Agents and Multi-agent Systems. Springer Verlag, pp. 262-271. 2010.
[79] Sharpanskykh A, Treur J. Adaptive Modelling of Social Decision Making by Affective Agents Integrating Simulated Behaviour and Perception Chains. In: Pan J-S, Chen S-M, Kowalczyk R (eds.), Proceedings of the Second International Conference on Computational Collective Intelligence, ICCCI'10. Lecture Notes in Artificial Intelligence, Springer Verlag, 2010.
[80] Chown E, Jones RM, Henninger AE. An architecture for emotional decision-making agents. AAMAS, pp. 352-353, 2002.