



NLR Air Transport Safety Institute

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**SAFETY MODELLING AND ANALYSIS OF
ORGANIZATIONAL PROCESSES IN AIR TRAFFIC
- D8: FINAL REPORT
EUROCONTROL CARE INNOVATIVE
RESEARCH III**

S.H. Stroeve
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Executive summary

SAFETY MODELLING AND ANALYSIS OF ORGANIZATIONAL PROCESSES IN AIR TRAFFIC - D8: FINAL REPORT

EUROCONTROL CARE Innovative Research III

Problem area

Safety culture is broadly recognized as important for air traffic management (ATM) safety and various studies have addressed its characterization and assessment. However, relations between safety culture and formal and informal organizational structures and processes are yet not well understood. This impedes structured improvement of safety culture.

As a way forward, NLR Air Transport Safety Institute, Vrije Universiteit Amsterdam and EUROCONTROL have collaborated in a EUROCONTROL CARE Innovative Research III project. The aim of this project is to enhance safety analysis of organizational processes in air traffic by development of formal approaches for modelling, simulation and analysis of organizational relationships and processes. These models aim to provide a proper basis for understanding the causal relations between organizational

processes that influence safety culture, such that robust and flexible policies may be identified to improve and maintain a sufficient level of safety culture in an organization.

Description of work

This final report provides an overview and discussion of the results obtained in the project.

Based on a literature survey we identified a multi-view hybrid organizational modelling approach, which provides a broad repertoire of methods for modelling, simulation and analysis of organizational relations and processes. Using this approach we developed an agent-based organizational model for safety occurrence reporting at a specific air navigation service provider (ANSP) in relation to safety culture indicators. We validated the model by relating its predictions to results of a EUROCONTROL safety culture survey of this ANSP.

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Results and conclusions

We attained valid predictions of safety culture indicators with dedicated input data of the safety culture survey questionnaires. A sensitivity analysis of the organizational model provided valid results for important organizational factors influencing the safety culture indicators and related recommendations.

We conclude that the agent-based organizational modelling approach is a useful add-on to the EUROCONTROL safety culture survey approach. The major added advantage of the organizational modelling approach is that it provides a structured, formally-grounded means for analysis and improvement of safety culture. It defines explicit formal relations between safety culture indicators and organizational

processes and structures, thus enabling identification of important organizational aspects impacting safety culture by sensitivity analysis techniques. Insights in relations between safety culture indicators and organizational structures and processes can be used to further enhance safety culture questionnaires, prepare safety culture survey workshops and support decision making on organizational change processes at ANSPs. In addition, coupling of organizational modelling to risk modelling provides a future way for structured analysis of the effect of safety culture on safety performance.

Applicability

This research supports the understanding of the impact of formal and informal organizational processes on safety culture.

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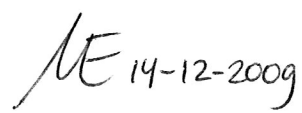

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I INTRODUCTION

I.1 CONTEXT AND AIM OF THE PROJECT

The importance of proper organizational processes to maintain the safety of complex operations is currently well realized. It is generally recognized that the level of safety achieved in an organization depends on the constraints and resources set by people working at the blunt end (e.g. managers, regulators), which determine the working conditions of practitioners who are directly controlling hazardous processes at the sharp end (e.g. pilots, controllers, maintenance operators). The recognition of the importance of organizational aspects for operational safety is reflected in the considerable number of publications on organizational and safety culture (Gordon et al., 2006; Mearns et al., 2008; Choudhry et al., 2007; Hopkins, 2006; Ek et al., 2007). Safety culture aims to keep the collective mind of an organization, through its entirety of individual minds, continually focused on safety (EUROCONTROL/FAA AP15 Safety, 2008). As a prelude to systemic changes in air traffic management (ATM) via SESAR in Europe and NextGen in the USA, EUROCONTROL, FAA and CANSO plan to see more and more air navigation service providers (ANSPs) go through safety culture measurement and improvement processes. Various studies have focused on characterization and assessment of safety culture (e.g., Mearns et al., 2008; Ek et al., 2007). However, the links of safety culture with organizational structures and processes are yet not well understood and this affects the determination of ways to improve safety culture.

As a way forward, NLR Air Transport Safety Institute, Vrije Universiteit Amsterdam and EUROCONTROL have collaborated in a EUROCONTROL CARE Innovative Research III project. The aim of this project is to enhance safety analysis of organizational processes in air traffic by development of formal approaches for modelling, simulation and analysis of organizational relationships and processes. These models aim to provide a proper basis for understanding the causal relations between organizational processes that influence safety culture, such that robust and flexible policies may be identified to improve and maintain a sufficient level of safety culture in an organization.

1.2 PURPOSE AND STRUCTURE OF THE REPORT

This report is the final report of the project. Its aim is to provide an overview of the main results that have been achieved by the organizational modelling approach followed in this study, to discuss these results in the context of safety culture assessment methods and other organizational modelling methods, to shed a light on possibilities for application and enhancement of the model and to discuss links of the modelling approach with risk assessment.

Section 2 introduces theory and methods on organizational modelling in general as well as for safety analysis. Section 3 presents definitions, models and assessment methods for safety culture. Section 4 highlights the main results of the development and validation of an organizational model for safety culture issues in relation to occurrence reporting at an ANSP. Section 5 presents the discussion as outlined above. Section 6 presents the conclusions of the study.

1.3 REPORTS AND PAPERS PRODUCED

In the project, the following reports were produced as deliverables:

- D1: Literature study (Stroeve et al., 2007a)
- D2: Application cases (Stroeve et al., 2007b)
- D3: Methods and requirements (Sharpanskykh and Stroeve, 2008a)
- D4: Model and initial simulation results (Sharpanskykh et al., 2008b)
- D5: Validation plan (Sharpanskykh and Stroeve, 2008b)
- D6: Model evaluation and improvement (Sharpanskykh and Stroeve, 2009a)
- D7: Validation (Stroeve and Sharpanskykh, 2009)
- D8: Final report (current report)

In addition, the research in this project supported the following publications:

- Paper at EUROCONTROL Safety R&D Seminar 2007 (Stroeve et al., 2007c)
- Paper at EUROCONTROL Innovative Research Workshop 2007 (Stroeve et al., 2007d)
- PhD-thesis at Vrije Universiteit (Sharpanskykh, 2008a)
- Paper at EUROCONTROL Innovative Research Workshop 2007 (Stroeve et al., 2008)
- Paper at EUROCONTROL Safety R&D Seminar 2009 (Stroeve et al., 2009a)
- Paper at EUROCONTROL Innovative Research Workshop 2009 (Stroeve et al., 2009b)
- Paper at the 10th International Conference on Enterprise Information Systems 2008 (Sharpanskykh et al., 2008a)

- Paper at the 21st International Conference on Industrial, Engineering & Other Applications of Applied Intelligent Systems 2008 (Sharpanskykh, 2008b)
- Paper at SocialCom-09/SIN-09 conference 2009 (Sharpanskykh and Stroeve, 2009b)
- Paper in the 4th International Conference on Intelligent Computing and Information Systems, 2009 (Sharpanskykh, 2009)
- Chapter in the “Intelligent Systems for Knowledge Management” book (Sharpanskykh, 2010)

Furthermore, at the time of writing of this final report we are preparing journal publications about the results achieved.

2 ORGANIZATIONAL MODELLING

This section provides an introduction on organization theory (Section 2.1), general methods for organizational modelling (Section 2.2) and some specific methods for organizational modelling in safety analysis (Section 2.3).

2.1 ORGANIZATION THEORY

Organization theory is a broad discipline that studies structures and dynamics of human organizations. The research methods that are used in organization theory stem from such disciplines as economics, psychology, sociology, political science, anthropology, and system theory. Related practical disciplines include human resources and industrial and organizational psychology. This overview focuses on the major theories and trends in the western sociological tradition.

2.1.1 DEFINITIONS

Depending on the perspective, different definitions for an organization are formulated in organization theory:

- An organization is defined as a planned, coordinated and purposeful action of human beings to construct or compile a common tangible or intangible product (Giddens, 2006).
- 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 (Scott et al., 1981).
- An organization is a structure that comprises sets of interrelated roles, which are intentionally organized to ensure a desired (or required) pattern of activities (Biddle, 1979).
- An organization is defined as a system that represents an organized collection of parts that are highly integrated in order to accomplish an overall goal (Kast and Rosenzweig, 1972).

The definitions by (Giddens 2006), (Scott et al., 1981) and (Biddle, 1979) are formulated from the positions of sociology. The definition by (Kast and Rosenzweig, 1972) is given from the perspectives of system theory.

Although the definitions given above reflect different aspects of the organizational reality, all of them are based on the concept of rationality that lies in the basis of organizational theory (Pfeffer 1982). According to the definitions,

organizations are created for certain purposes. To achieve these goals organizational activities are intentionally planned, coordinated and executed.

2.1.2 AGGREGATION LEVELS

In organization theory organizations are investigated at different aggregation levels. In particular, at the individual (micro) level the behaviour of organizational individuals and groups is investigated. At the level of the whole organisation (meso level) different aspects of the organisational structure and dynamics are considered. At the global (macro) level the interaction between the organization and its environment that includes other organizations, society, markets etc. is considered.

At the individual (micro) level the following aspects are considered:

- perception of an individual in the organizational context (Scott et al., 1981);
- work motivation and satisfaction (Vroom, 1964);
- the influence of personal and/or organizational values on the motivation and work-related behaviour of an individual (Yukl, 2006; Hackman, 1980);
- group formation (Campion et al., 1993);
- group norms and regulations (Scott et al., 1981);
- social influence and conformity (Yeatts and Hyten, 1998);
- leadership (Yukl, 2006);
- individual conflicts in organizations (March and Simon, 1967);
- power and influence in groups (Yukl, 2006).

At the meso level of the whole organization the following topics are of relevance:

- organization structure and behaviour (Blau and Schoenherr, 1971; Mintzberg, 1979; Morgan, 1996);
- organization authority and power structures (Scott et al., 1981; Mintzberg, 1979; Pfeffer, 1982);
- organization normative systems (Scott et al., 1981);
- intergroup conflict within an organization (March and Simon, 1967);
- organization reward system (Galbraith, 1978; Vroom, 1964);
- technology in organizations (Morgan, 1996; Scott, 1981);
- organizational change (Cummings and Worley, 2005).

At the global (macro) level the behaviour of organizations is investigated using the population ecology theory (Hannan and Freeman, 1977) and the resource dependence theory (Pfeffer and Salancik, 1978). The following topics are considered at this level:

- inter-organizational formations, such as mergers and consolidations, joint ventures and programs (Scott et al., 1981);
- governmental impact on organizations (Morgan, 1996);
- organizations and politics (Bacharach and Lawler, 1980);
- interactions between organizations and the society (Scott et al., 1981);
- organizations and markets (Langlois and Robertson, 1995);
- virtual organizations (Warner and Witzel, 2004).

2.1.3 ORGANIZATION TYPES

Classical organization theories (Mooney, 1947) provide insights into the functioning of mechanistic (or functional) organizations. This type of organizations comprises systems of hierarchically linked job positions with clear responsibilities that use standard well-understood technology and operate in a relatively stable environment.

In contrast to mechanistic organizations, a substantial group of modern organizations are characterized by a highly dynamic, constantly changing, organic structure with non-linear behaviour, which are known as organic organizations (Morgan, 1996). Such organizations can be investigated using modern organization theories. Modern theories are based on two essential frameworks: the systems framework (Walter, 1968) and the contingency approach (Donaldson, 2001).

The systems framework is based on the notion of interdependency, which implies that a change in one part of an organization has effect on the behaviour of all other parts. The systems framework is applied for studying matrix and network organizations (Morgan, 1996).

The contingency approach (Donaldson, 2001) focuses on external determinants of organizational structure and behaviour called contingencies. A contingency is any variable that moderates the effect of an organizational characteristic on organizational performance. The key thesis of the contingency theory is that to ensure the effectiveness and the efficiency of an organization, its structure and behaviour should be defined depending on particular environmental conditions. The contingency approach is claimed to be useful for studying a variety of organization types and to be particularly suitable for organization design.

Organization design is a special topic in the organization theory (Lorsch and Lawrence, 1970; Galbraith 1978). Galbraith (1978) stated that 'organization

design is conceived to be a decision process to bring about a coherence between the goals or purposes for which the organization exists, the patterns of division of labour and inter-unit coordination and the people who will do the work.’ The ideas of Galbraith and others are used extensively in the managerial practice to (re)design efficient and effective organizations (Romme, 2003). The literature on organizational design proposes an extensive set of factors identified at every level of representation of an organization (i.e., micro, meso, and macro), which influence the choice of specific design parameters (e.g., the group size, the task complexity, reporting relations, the number of employees) related to the organizational structure and dynamics.

2.2 ORGANIZATIONAL MODELLING METHODS

2.2.1 TRADITIONAL ORGANIZATIONAL MODELLING METHODS

The first formal computational organization modelling approaches have been developed in the areas of the system dynamics theory (Forrester, 1961) and operation research (Marlow, 1993).

Organizational models specified in system dynamics (SD) are based on numerical variables and equations that describe how these variables change over time (e.g., a set of differential equations that describe the dynamics of a labour market from a global perspective). In Figure 1 the graphical representation of a system dynamics model is given as an example, which describes the change of the firm population over time. In this representation, level variables are represented by rectangles, rate of change variables - by valve symbol, and constants and auxiliary variables - by a point or name of the constant. Cloud symbols represent respectively source and sink, where the flow originated and vanished (e.g., the environmental sources). Blue arrows represent influences of level variables on other variables.

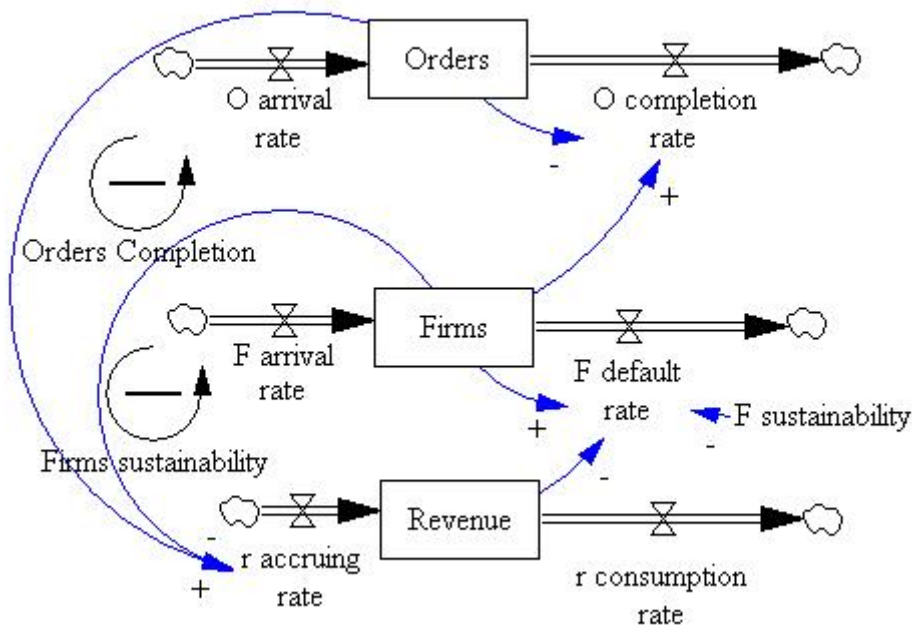


Figure 1: Example of a system dynamics model of firms population (Merlone et al., 2008)

Operation research proposes mathematical methods for identifying best possible solutions to problems related to coordination and execution of the operations within an organization that improve or optimize the organizational performance (Marlow, 1993), e.g., an optimisation of a production line in an organization.

Both system dynamics- and operation research-based 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 (e.g., market fluctuations, general trends of the organizational development). However, they provide little help for 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 results from a large number of diverse local interactions among organizational actors, the examination of an organization at detailed levels may help identifying causes of organizational malfunctioning and inefficiencies at more general levels.

Another traditional organization modelling approach that allows behavioural representations at the level of organizational individuals is discrete-event modelling (Banks, 2005). Discrete-event models represent the dynamics of a system as a time ordered discrete sequence of events. Each event occurs at an

instant in time and indicates a change of state in the system. Discrete-event models were used in organisation modelling to analyze the performance and reliability of organizations (Ranky, 1994; Ajaefobi and Weston, 2009). However, some organizational and individual processes are best described by continuous equations such as systems of differential or difference equations (e.g., cognitive processes of individuals, dynamics of the environmental entities such as markets), which is not possible in discrete-event models. To address this issue and incorporate both discrete and continuous aspects of an organization in one model, hybrid modelling techniques are required.

2.2.2 AGENT-BASED ORGANIZATIONAL MODELLING

Agent-based modelling approaches take into account the local perspective of a possibly large number of separate components and their specific behaviours (i.e., 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 such as organizations. Currently many definitions exist for the concept of an agent, including:

- An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors (Russell and Norvig, 1995);
- An agent is an active object with the ability to perceive, reason, and act (Huhns and Stephens, 1999);
- An autonomous agent is a system situated within and a part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future (Franklin and Graesser, 1996).

In general, most of the definitions agree that an agent is an entity that is able to perceive its environment and to act upon this environment. In the area of multi-agent systems the agent environment is understood as the agent surroundings that include both passive and active entities including other agents (Figure 2).

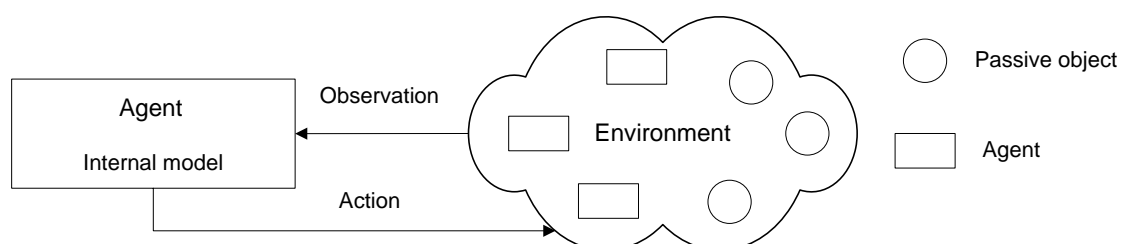


Figure 2: The classical model of an agent situated in the environment

In the area of multi-agent systems the organizational paradigm is used to improve computational properties of distributed algorithms, based on agent systems (Bresciani et al, 2004, Ferber and Gutknecht, 1998, Hannoun et al, 2004, Omicini, 2000). In particular, representation of a multi agent system as an organization consisting of roles and groups can facilitate handling high complexity and poor predictability of the dynamics in a system, and thus, allows building better algorithms (Horling and Lesser, 2005). Organization-oriented models of multi-agent systems have also been used to support processes of real organizations: goal-related aspects of organizations are considered in (Giorgini et al., 2006; Maiden et al., 2006), models for different types of organizational interactions are described in (Horling and Lesser, 2005), an approach to coordinate the execution of tasks is shown in (Decker, 1996). Although organization-oriented models developed in the area of multi-agent systems can be computationally effective for particular tasks, those known to the authors lack the ontological expressivity required to conceptualize a wide range of concepts and relations of human organizations. Furthermore, such frameworks only rarely use the extensive theoretical basis from organization theory. Many agent-based approaches that incorporate findings from social science are considered in the area of computational organization theory.

In the area of computational organization theory (Carley, 1996) computational and mathematical techniques are applied for the investigation of human organizations; development, testing and improvement of organization theories. Many models in this area are based on the agent paradigm. Such models aim at the representation, investigation and prediction of processes in organizations considered at three representation levels: (1) the macro level that focuses on an organization as a whole and its relations with the environment; (2) the meso level that focuses on the interaction between individuals and/or groups in the organizational context; and (3) the micro level that focuses on an individual of an organization, his/her characteristics and behaviour in an organization. Organizational factors that exert an influence on the behaviour of agents are diverse: norms and regulations related to the task execution and to communication, a power (authority) system, a reward/punishment system. Furthermore, organizational factors are interrelated (e.g., a power structure influences the execution of tasks). However, often models used in computational organization theory consider only a limited number of the organizational aspects directly related to the considered research problem and do not reveal (inter-) dependencies that exist between these and other (indirectly related) organizational aspects. Neglecting indirect relations between aspects may result

into limited evaluation possibilities of different organizational processes and may undermine the practical feasibility of organizational models.

To perform a profound evaluation of the organizational performance and to enable analysis and prediction of organizational behaviour under different environmental influences, more sophisticated modelling and analysis techniques are required that employ concepts and relations between them across different perspectives on organizations and establish relations between different representation levels (i.e., micro, meso and macro).

2.2.3 MULTI-VIEW HYBRID ORGANIZATIONAL MODELLING

In this project the generic organization modelling and analysis framework from (Sharpanskykh, 2008a) was applied. By using multiple views and hybrid techniques for organizational modelling (Figure 3), it aims to overcome the restrictions of other organizational modelling approaches discussed above.

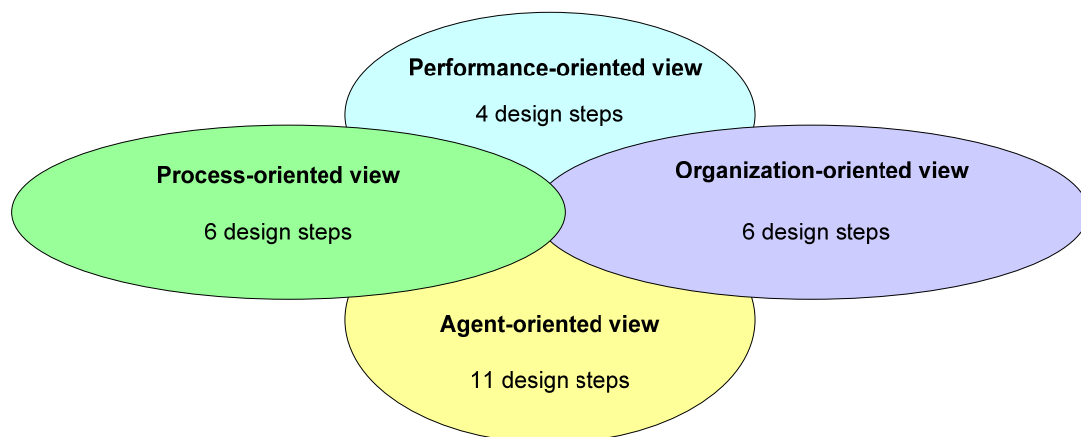


Figure 3: Views considered in the multi-view hybrid organizational modelling approach

This framework includes the following key issues.

- (1) *Expressivity*: The modelling methods provide languages with sufficient expressivity to represent different structural and behavioural aspects of organizations of different types; furthermore, relations between different aspects of the organizational reality are specified explicitly. The framework includes four interrelated modelling views: *the performance-oriented view* describes organizational goal structures, performance indicator structures, and relations between them; *the process-oriented view* contains information about the organizational functions and processes, how they are related, ordered and synchronized and the resources they use and produce; within

the organization-oriented view organizational roles, their authority, responsibility and power relations are defined; in *the agent-oriented view* different types of agents with their capabilities are identified, models of agent behaviour are specified based on social theories, and principles of allocating agents to roles are formulated. Specification of the views is formalized using sorted predicate logic-based languages. These languages provide high expressivity for conceptualizing a variety of concepts and relations and allow expressing both quantitative and qualitative aspects of different views. To express temporal relations in specifications of the views, the dedicated languages of the views are embedded into the Temporal Trace Language (TTL). TTL is a hybrid modelling language, it allows expressing the behaviour of both discrete and continuous components of an organization.

- (2) *A strong connection to social science*: The meaning attached to the introduced modelling concepts and the rules of correct use of these concepts in organizational specifications are specified based on the literature from social science.
- (3) *Automated formal analysis*: The languages used for the formalization of organizational specifications allow rigorous automated formal analysis of these specifications (e.g., by simulation, verification and validation) both within particular views on organizations and across multiple views.
- (4) *Complexity*: Since specifications for real organizations may be very complex, means to handle a high complexity and to increase scalability of modelling and analysis have been developed in the framework.
- (5) *Support for the execution of organizational scenarios*: The developed methods allow designing organizational specifications that form a basis for enterprise information systems, which support and control the execution of organizational scenarios.
- (6) *Usability*: The framework is aimed to be usable and convenient for organizational practitioners: modellers, designers, analysts, etc.

2.3 ORGANIZATIONAL MODELLING FOR SAFETY ANALYSIS

2.3.1 STAMP

It is recognised by Leveson (2004) that often applied sequential accident models, which explain accidents in terms of multiple events sequenced as a chain over time, and related reliability engineering techniques do not effectively account for (1) social and organizational factors in accidents, (2) system accident and software errors, (3) human error, and (4) adaptation over time. To account for these aspects, Leveson (2004) presents a model based on system and control

theory: STAMP (Systems-Theoretic Accident Model and Processes). In the underlying concept of safety, accidents occur when external disturbances, component failures, or dysfunctional interactions among system components are not adequately handled by the control system. Here, the terms systems and control are used in a broad context, referring to all aspects and levels of a socio-technical organization. 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.

This safety concept has led to the development of system modelling methods for risk analysis, which aims at understanding the dynamic risk contributions of technical and organizational factors, where ‘dynamic’ refers to the risk effects of changes in organizational and technical factors over time. In such analysis, models of relevant organizational aspects are developed using system dynamics methods (Section 2.2.1). For example, in a model for NASA’s safety culture sub-models such as Launch Rate, System Safety Resource Allocation, Perceived Success by Management, and System Safety Status were used (Leveson et al., 2005; Dulac et al., 2007). In this example, emergent properties include perceived concern for performance, perceived concern for safety, level of risk, and fraction of corrective action to fix systemic problems. Another example of an application is the analysis of organizational processes in a water contamination accident (Leveson, 2004).

Some illustrative archetypes for organizational safety based on control systems thinking are presented in (Marais et al., 2006). It presents (high-level) control diagrams for organizational issues, such as stagnant safety practices in the face of technological advances, decreasing safety consciousness, unintended side-effects of safety fixes, fixing symptoms rather than root causes, and vicious cycle of bureaucracy. The variables in these models are at the meso and macro organizational levels, rather than at the (micro) levels of individuals. As an example, the control diagram of vicious cycle of bureaucracy is shown in Figure 4. It consists of a reinforcing loop $R_{\{\text{bureaucracy}\}}$, which leads to a continuing increase in bureaucracy by management trying to improve (safety) performance by formalisation, a balancing loop $B_{\{\text{control devices}\}}$, which tries to regulate the performance by control devices, and a balancing loop $B_{\{\text{make them feel better}\}}$, which tries to counteract dysfunctional reactions in an organization by human relation treatments.

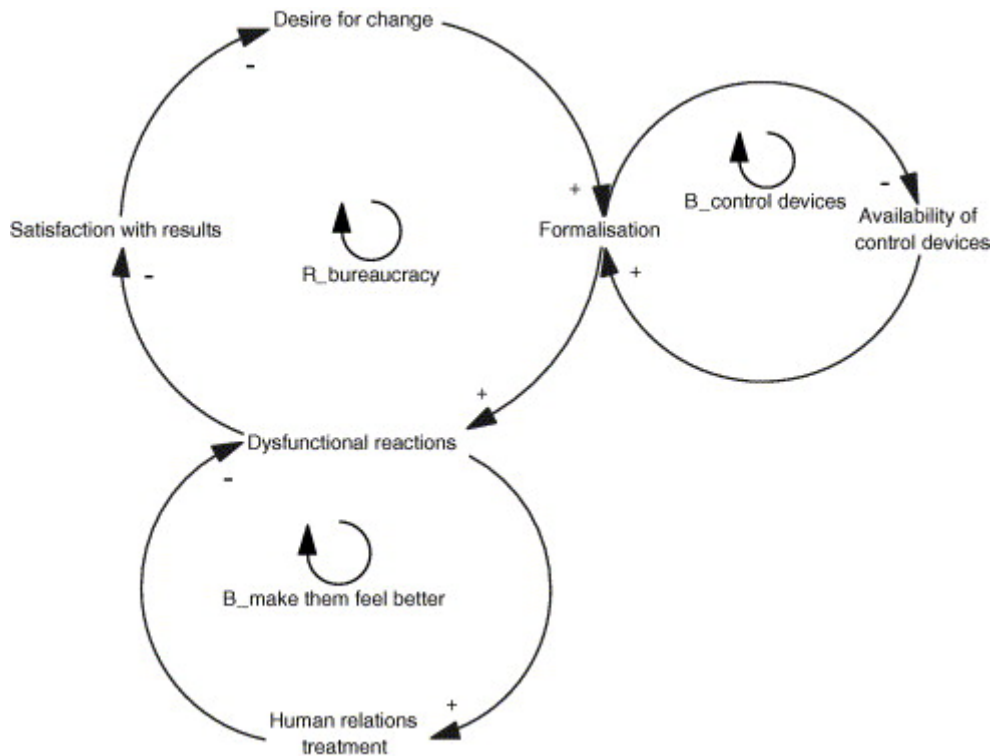


Figure 4: Control diagram for vicious cycle of bureaucracy (Marais et al., 2006)

2.3.2 SoTERIA

Mohaghegh and Mosleh (2009) presented a wide list of principles of organizational risk analysis, which cover requirements for the development process and the characteristics of models for organizational risk analysis. The foundations for these principles span diverse disciplines, such as risk analysis, industrial/organizational psychology, organizational theory and human reliability. Based on these principles, they developed the Socio-Technical Risk Analysis (SoTeRiA) framework, which is represented schematically in Figure 5. It describes the forward and feedback loops of a variety of organizational factors impacting system risk.

Mohaghegh et al. (2009) propose a hybrid technique that uses three types of modelling techniques to specify a SoTeRiA model:

- Stock and flow diagrams from system dynamics (SD). Mathematically, these describe sets of ordinary differential equations. They are used to formulate deterministic dynamics in the model, such as delays and grow and decay processes.
- Ordinary Bayesian Belief Networks (BBNs) or Qualitative-Quantitative (QQ) BBNs. Ordinary BBNs represent conditional probabilities between variables in a directed acyclic graph. QQ BBNs include qualitative scales (e.g. low,

- medium, high) and a mapping mechanism to quantitative scales. They are used to represent probabilistic relations between organizational factors.
- Event Sequence Diagrams (ESDs) and Fault Trees (FTs). These classical Probabilistic Risk Assessment Techniques are used to describe relations between conditions, failures and errors in risk scenarios, leading to probability estimates of hazardous events.

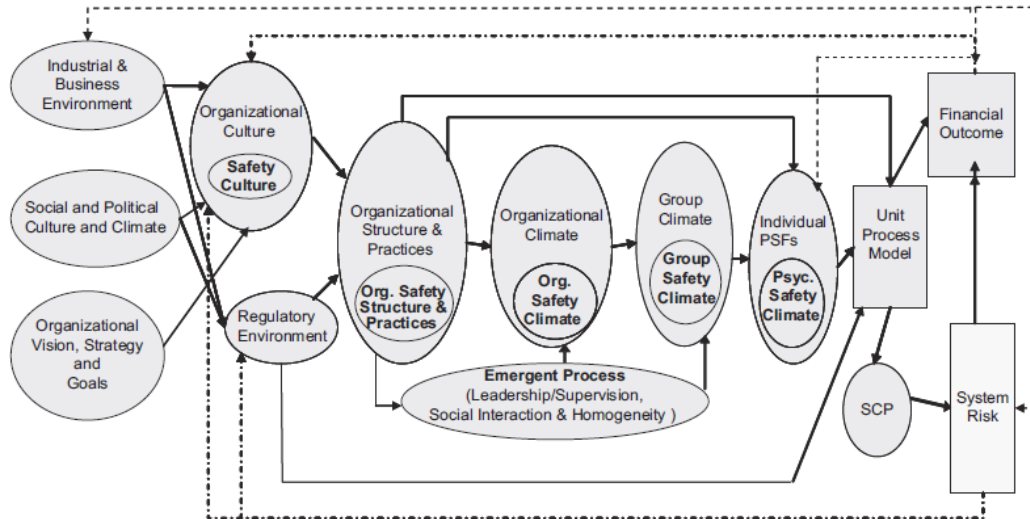


Figure 5: Schematic representation of SoTeRiA (Mohaghegh et al., 2009)

The application of this hybrid technique is illustrated by an example of aircraft maintenance and the effects of its quality on aircraft airworthiness and accident risk. This application includes SD models for 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 (Mohaghegh et al., 2009) 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

Motivated by stochastic system and control theory, researchers at NLR have developed a systemic accident model methodology for the evaluation of air traffic risk. This methodology uses Monte Carlo simulations and uncertainty evaluations to analyse the safety risk of air traffic operations. In (Blom et al., 2001a,b, 2003a,b) an initial version of this methodology has been introduced under the name TOPAZ (Traffic Organization and Perturbation AnalyZer).

Subsequently, this methodology has been extended with multi-agent situation awareness modelling (Stroeve et al., 2003), an integrated qualitative safety risk assessment cycle (Blom et al., 2006a), risk bias and uncertainty assessment (Everdij et al., 2006a), and compositional specification of accident models by Petri nets (Everdij et al., 2006b).

Key in TOPAZ risk assessments are Monte Carlo simulations of accident models for air traffic scenarios. These accident models uniquely define the stochastic dynamics of the relevant agents (human operators and technical systems) by a compositional specification approach using a stochastic dynamic extension of the Petri net formalism (Everdij and Blom, 2006b). Within this Petri net formalism a hierarchically structured representation of the agents in the air traffic scenario is developed. In this systemic accident modelling approach, the performance of human operators and technical systems in an environment is thus represented in an integrated way by coupled stochastic dynamic models. The human performance modelling is based on a contextual perspective in which human actions are the results of the interaction between human internal states, strategies and the environment (Hollnagel, 1998; Wickens and Hollands, 1999). The multi-agent situation awareness model describes the situation awareness of each agent as time-dependent information on other agents, including identity, continuous state variables, mode variables and intent variables (Blom and Stroeve, 2004; Stroeve et al., 2003). Achieving, acquiring and maintaining situation awareness depends on processes as observation, communication and reasoning, which are part of the tasks of the human operator model.

As an integrated part of TOPAZ, a bias and uncertainty assessment method has been developed (Everdij et al., 2006a). This method supports identification of differences between the Monte Carlo simulation model and reality, and subsequent evaluation of the bias and uncertainty in the risk due to these differences. This evaluation includes assessment of the size of the differences and the associated risk sensitivity. Typically, feedback from operational experts is an important source of information in the bias and uncertainty assessment.

TOPAZ has been applied to a range of air traffic safety studies, including:

- collision risk analysis of parallel en-route lanes (Blom et al. 2003a,b,c),
- collision risk analysis of simultaneous missed approaches on converging runways (Blom et al. 2003d),
- collision risk analysis of incursion on active runway crossings (Stroeve et al. 2003, 2009c)
- collision risk analysis of airborne separation assurance system-based (free flight) concepts (Blom et al. 2006b).

3 SAFETY CULTURE

The organizational model that has been developed and validated during this study is focused on safety culture. As an introduction to this concept Section 3.1 provides some definitions, Section 3.2 presents some related models and Section 3.3 presents methods for assessment of safety culture.

3.1 DEFINITIONS OF ORGANIZATIONAL AND SAFETY CULTURE

There are various definitions of organizational culture, including

- A pattern of basic assumptions – invented, discovered, or developed by a given group as it learns to cope with its problems of external adaptation and internal integration; that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems (Schein, 1992);
- Shared values (what is important) and beliefs (how things work) that interact with a company's people, organizational structures and control systems to produce behavioral norms (the way we do things around here) (Uttal, 1983);
- A relatively stable, multidimensional, holistic construct shared by (groups of) organizational members that supplies a frame of reference and which gives meaning to and/or is typically revealed in certain practices (Guldenmond, 2000);
- The way we do things around here (Hopkins, 2006).

The definition of Schein stems from sociology, Uttal's one is from management theory, the definition of Guldenmond is based on a review of a range of definitions, and the functional one of Hopkins reflects a practitioner's view.

In addition to the concept of organizational culture, some authors use the term organizational climate. Guldenmond (2000) and Hopkins (2006) argue that the terms organizational culture and organizational climate have been used in various not always distinguishable ways. Currently, the term organizational climate usually indicates the overt manifestation of organizational culture. Cox and Cox (1996) compare the culture and climate of an organization with, respectively, the personality and mood of an individual.

Safety culture reflects safety-relevant aspects of organizational culture. A wide range of definitions are provided in reviews by Guldenmond (2000) and Choudhry et al. (2007), including:

- The set of beliefs, norms, attitudes, and social and technical practices that are concerned with minimising the exposure of employees, managers, customers and members of the public to conditions considered dangerous or injurious (Pidgeon, 1991);
- The product of individual and group values, attitudes, perceptions, competencies, and patterns of behaviour that determine the commitment to, and the style and proficiency of the organization's health and safety management (Lee, 1996);
- The attitudes, beliefs and perceptions shared by natural groups as defining norms and values, which determine how they act and react in relation to risk and risk control systems (Hale, 2000).

Hopkins (2006) notes that there is confusion about the meaning of safety culture. He argues that the study of organizational culture should be distinguished from the impact of organizational culture on safety; as such there is no need to use the term safety culture.

Similarly to the current notion of organizational climate, the term safety climate is sometimes used to indicate the overt manifestation of safety culture.

3.2 MODELS OF ORGANIZATIONAL/SAFETY CULTURE

Regarding layers or levels of organizational/safety culture, Glendon and Stanton (2000) and Guldenmond (2000) describe a three-layered model going from an outer layer to a core. The outer layer refers to observable behaviour, e.g. meetings, inspection reports, protective equipment, procedures. At a middle layer are espoused attitudes and perceptions, which are not directly observable but may be inferred from behaviour or by questioning. At the core level are basic assumptions, e.g. about the nature of reality and truth, which are not easily assessed (ethnographic methods may be required).

A related three-level model of safety culture is proposed by Gordon et al. (2006). They regard safety culture as reflecting the actual level of commitment of norms set by safety management procedures. The safety culture model used specifies the relations between 'what is believed', 'what is said' and 'what is done'. Discrepancies between these safety culture aspects are relevant for safety assessment and management.

In recognition of interactive contributions from psychological, situational and behavioural factors in accident causation, Cooper (2000) proposes a reciprocal safety culture model, which gives a multi-faceted view of safety culture (see

Figure 6). In this approach, the internal psychological factors (i.e. attitudes and perceptions) are assessed via safety climate questionnaires, actual ongoing safety-related behaviour is assessed via checklists developed as a part of behavioural safety initiatives, and the situational features are assessed via safety management system audits/inspections.

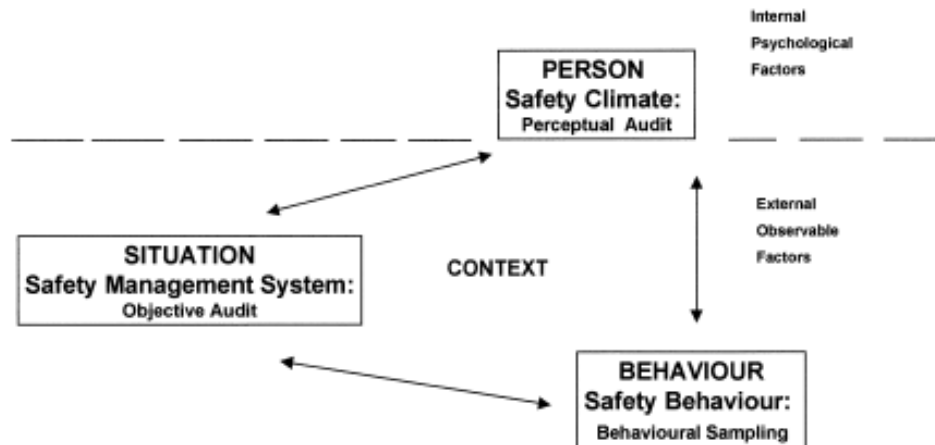


Figure 6: Reciprocal safety culture model (Cooper, 2000)

Ek et al. (2007) use a 9-dimensional model of safety culture, addressing 1) learning culture, 2) reporting culture, 3) just culture, 4) flexibility, 5) communication, 6) safety-related behaviours, 7) attitudes towards safety, 8) working situation, and 9) risk perception. They used this model in a survey-based analysis of safety culture in Swedish air traffic control and correlated the safety culture results with a 10-dimensional model of organizational climate. They found that the organizational climate dimensions Support for ideas (overall attitude towards new ideas) and Conflicts (presence of personal and emotional tensions) to be, respectively, positively and negatively related to many of the safety culture aspects.

Parker et al. (2006) provides a characterization of five levels of safety culture (from bad to good): pathological, reactive, calculative, proactive, generative. Part of the provided characteristics refers to concrete organizational aspects, e.g. auditing, incident/accident reporting, contractor management, work-site job safety techniques. Other characteristics refer to ‘abstract’ organizational aspects, e.g. ‘how do safety meetings feel?’, balance between HSE and profitability, ‘who causes accidents in the eyes of the management?’.

Based on a review of safety culture literature, Montijn and De Jong (2006) identified six categories of safety culture aspects, which include 13 safety culture characteristics. Table 1 provides an overview of their results.

Table 1: Categorized safety culture characteristics (Montijn and De Jong, 2006)

Category	Characteristics	Description
Commitment to safety	Attitudes towards safety	Reflects the extent to which the organization's members and groups have a positive attitude towards the importance of safety and actually take personal responsibility for safe operations.
	Organizational commitment	Reflects the extent to which management identifies safety as a core value and guiding principle of the organization; demonstrates a positive attitude towards safety; and invests resources and effort in the implementation of safety improving activities.
	Employee empowerment	Reflects the extent to which (front-line) employees are empowered in keeping a high level of safety, by increased motivation and means in making the right decisions concerning safety issues.
Behaviour with respect to safety	Working situation	Reflects the extent to which the working situation promotes safe operations. The working situation includes team work, job pressure, job satisfaction, trust in colleagues and equipment.
	Safety related behaviours	Reflects the extent to which actions related to safety are taken by the organization's members and groups.
	Management involvement	Reflects the extent to which management is involved in keeping a high level of safety throughout the entire organization.
Adaptability	Learning	Reflects the extent to which the organization's members and groups are actively willing to learn from past experience regarding safety issues.
	Flexibility	Reflects the extent to which the organization is able to reconfigure itself when facing safety issues.
Awareness	Risk perception	Reflects the extent to which the organization's members and groups are aware of the risk they and their surroundings are subjected to.
	Wariness	Reflects the extent to which the organization's members and groups are maintaining a high degree of vigilance with respect to safety issues.
Information	Communication	Reflects the extent to which work related (thus not exclusively safety related) information is communicated to the right people within the organization.
	Reporting	Reflects the extent to which the organization's members and groups are willing to report safety concerns, and to which they will not fear reprisals when doing so.
Justness	Justness	Reflects the extent to which safe behaviour and reporting of safety issues are encouraged or even rewarded, and unsafe behaviour is discouraged.

3.3 ASSESSMENT OF SAFETY CULTURE

Surveys (questionnaires, interviews) are often used to study organizational culture and their effect on safety (e.g. Ek et al. 2007, Montijn and De Jong 2006, Gordon et al. 2006). They can be used to study organizational practices, as well as attitudes. It has been noted as a drawback of surveys that they tend to provide relatively superficial descriptions of organizational culture, since many practices are too complex and dynamic to be effectively captured in survey questions (Hopkins, 2006). Furthermore, people may use questionnaires to show a picture they want to show for company political reasons, rather than indicating their true perception. Hopkins argues that ethnographic research, where a researchers study the organization from within, can provide a much richer account of organizational culture than surveys. Hopkins advocates the use of major accident inquiries for studying organizational culture and its impact on safety.

EUROCONTROL has developed a safety culture survey approach along a number of steps, which are illustrated in Figure 7 and which are discussed in detail in (EUROCONTROL/FAA AP15, 2008). Main steps in this approach are safety culture questionnaires and workshops. 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 answers are provided via a five-point scale as illustrated in Figure 8. The data of the questionnaires are analysed and key safety culture issues are identified on the basis of the statistics. Next, there are several workshops with small groups of people from different parts of the organization. The aims of the workshops are to ensure that the interpretation from the questionnaire results are complete and correct, to discuss organizational causes underlying the safety culture issues, and to identify candidate solutions for these issues. The EUROCONTROL safety culture survey approach has now been applied at a large number of ANSPs in Europe. Data derived by this survey approach has been used in this study as will be outlined in Section 4.



Figure 7: Steps in the EUROCONTROL safety culture survey approach (EUROCONTROL/FAA AP15, 2008)

	Strongly disagree	Disagree	Neither	Agree	Strongly agree
1. Appropriate responses are made after an incident to address the reasons why the incident occurred.	1	2	3	4	5
2. Everyone at my Unit feels that safety is their own responsibility - there is proactive participation by all staff in safety initiatives.	1	2	3	4	5
3. People who raise problems are seen as trouble-makers.	1	2	3	4	5
4. Even if the system fails, we are still expected to achieve the targets that are set for us.	1	2	3	4	5
5. The organization says "it is committed to safety" but actually has other higher priorities.	1	2	3	4	5
6. Only my manager has responsibility for safety.	1	2	3	4	5

Figure 8: Examples of part of a safety culture questionnaire (EUROCONTROL/FAA AP15, 2008)

4 MODELLING AND VALIDATION OF SAFETY CULTURE AT A SPECIFIC ANSP

4.1 INTRODUCTION

Based on a literature survey on safety modelling and analysis of organizational processes reported in (Stroeve et al., 2007a) and highlighted in Section 2, we found that the organizational modelling framework proposed by Sharpanskykh (2008a) presents the widest repertoire of desired organizational modelling features. Therefore this method was employed for the development of an organizational model for the analysis of safety culture aspects in relation to safety occurrence reporting at a particular ANSP, referred to as ANSP-3. The model results were compared with the results of a EUROCONTROL safety culture survey study of ANSP-3. The modelling and validation study 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.

Section 4.2 presents general safety culture issues, which were identified as a starting point for the model development. Section 4.3 highlights key features of the developed agent-based organizational model. Sections 4.4, 4.5 and 4.6 present the model and validation results of Phases 1, 2 and 3, respectively. Section 4.7 discusses the obtained results for the application case.

4.2 IDENTIFICATION OF SAFETY CULTURE ISSUES

To identify safety culture aspects relevant for the occurrence reporting, EUROCONTROL safety culture survey results of two ANSPs (ANSP-1, ANSP-2) and

safety culture data from the literature have been analysed, and interviews have been conducted with experts at EUROCONTROL Head Quarters and at a third ANSP (ANSP-3). As result of this analysis, a categorised set of safety culture issues that impact safety occurrence reporting has been determined. For each issue in the identified set, required organization modelling aspects have been identified. Then, based on a number of criteria, the selection of the most relevant modelling aspects has been performed for further inclusion in the model.

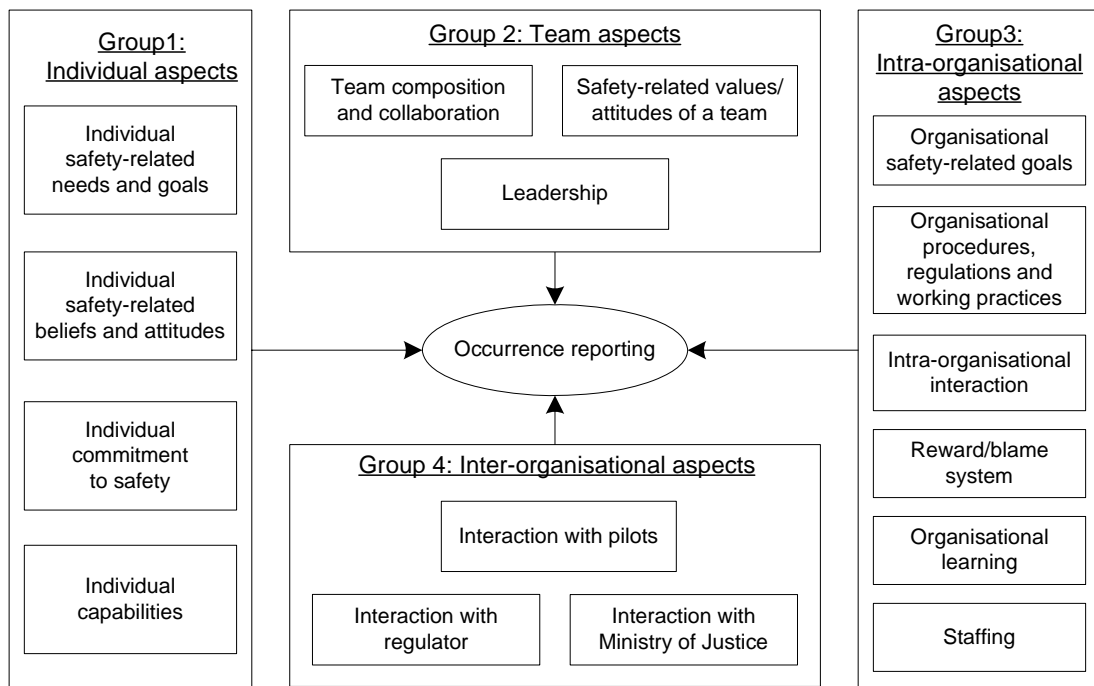


Figure 9: Identified groups of aspects that influence safety occurrence reporting

Figure 9 shows the categorization of factors that influence occurrence reporting (Sharpanskykh and Stroeve, 2008a). It discerns four aggregation levels for the organization of safety occurrence reporting at an ANSP:

1. The level of an individual in the organisation (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 an organisation (i.e. intra-organisational structures, as departments in an ANSP);
4. The level of inter-organisational interaction (i.e. influences from other organisations on an ANSP).

Examples of the identified safety culture issues for these four aggregation levels are shown in Table 2. These issues form a basis for the development of the agent-based organizational model, which will be discussed in the next section.

Table 2: Examples of identified safety culture issues; a full list is in (Sharpanskykh and Stroeve, 2008a)

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 with an actor may decrease after s/he has been involved in a (serious) incident
Problems are not raised as actors do not want to be seen as trouble-makers
Group 3: Intra-organizational aspects
Importance of safety-related goals may be threatened by performance-related goals
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 comes 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 Regulator
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 Ministry of Justice may decide to investigate (severe) occurrences and decide to prosecute involved organisations or human operators. In investigation and prosecution, occurrence reports may be used

4.3 AGENT-BASED ORGANIZATIONAL MODEL

For modelling the safety occurrence reporting in an ANSP the modelling framework and methodology from (Sharpanskykh, 2008a) was used, which comprises a sequence of organization design steps. This framework allows modelling institutional (prescriptive) aspects of the formal organization, as well as the social behaviour of organizational actors (agents). This section provides an overview of the developed agent-based organization model, where Section 4.3.1 focuses on the formal organization and Section 4.3.2 describes the performance of agents in the organization. A detailed description of the model can be found in associated reports (Sharpanskykh et al., 2008b; Sharpanskykh and Stroeve, 2009a).

4.3.1 SPECIFICATION OF FORMAL ORGANIZATION

A specification of the formal organization is provided along three interrelated views: organization-oriented view, performance-oriented view and process-oriented view. The methodology for the model development along these views includes various steps, which can be read in (Sharpanskykh, 2008a; Sharpanskykh et al., 2008b; Stroeve et al., 2007b, 2008).

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, 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. An example of interactions between roles is illustrated in Figure 10.

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.

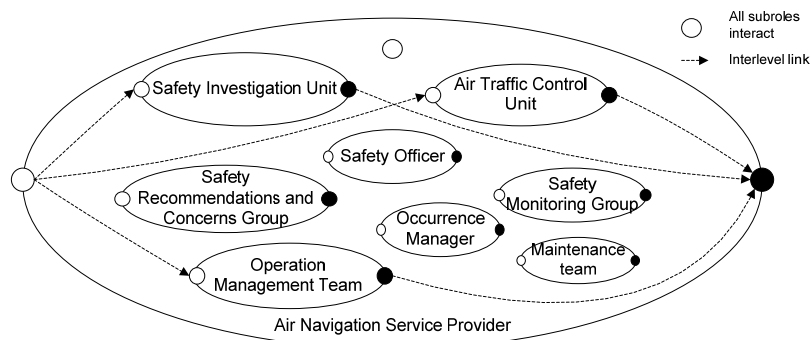


Figure 10: Example of interactions between roles in an ANSP

Safety occurrence reporting is a key process in the organizational model and the workflow for its tasks is shown in Figure 11 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. The workflow is a product of the process-oriented view and it has interactions with both the organization- and performance

oriented views. In relation with the organization-oriented view, the responsibilities of the roles for the tasks in the workflow are defined, e.g., the Controller role is responsible for execution of and decision making with respect to the task 'Create a notification report', the Controller Supervisor is responsible for monitoring and consulting for this task. In relation with the performance-oriented view, goals that are pursued by tasks in a workflow are addressed, e.g. goals to achieve particular reporting quality levels.

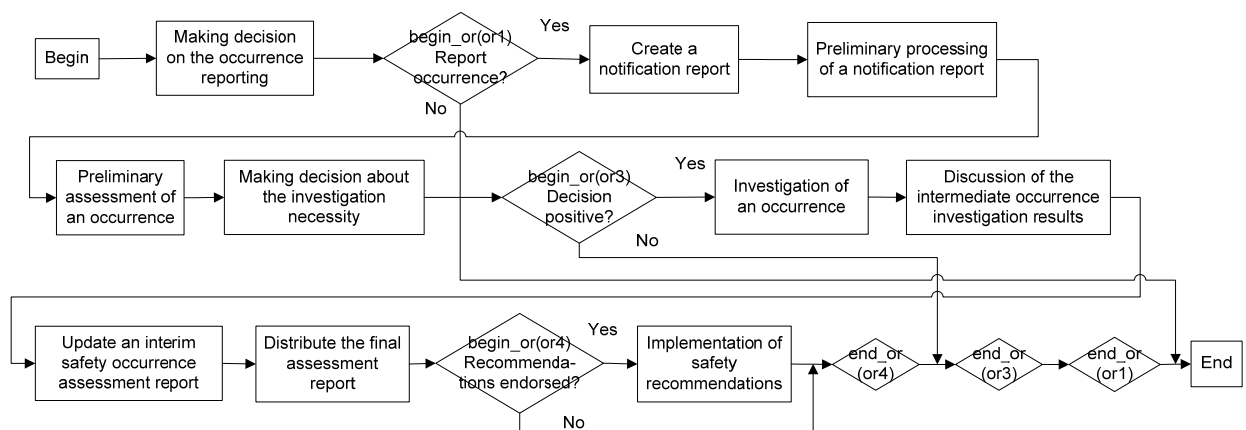


Figure 11: Workflow example: occurrence reporting

4.3.2 SPECIFICATION OF AGENTS

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, corresponding to interaction with other agents and with the environment in a multi-agent organization (Figure 12). An agent perceives information by observation or communication and generates output in the form of communication or actions.

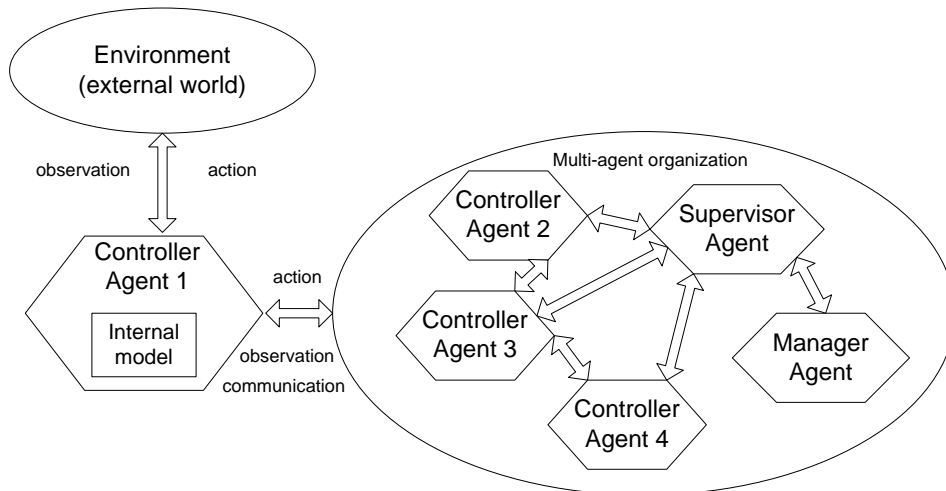


Figure 12: External perspective of an agent in a multi-agent organization

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 13). The internal states of an agent include information attitudes (e.g. belief, knowledge) and pro-attitudes (e.g. desire, intention, obligation, commitment) (Wooldridge and Jennings, 1995). 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.

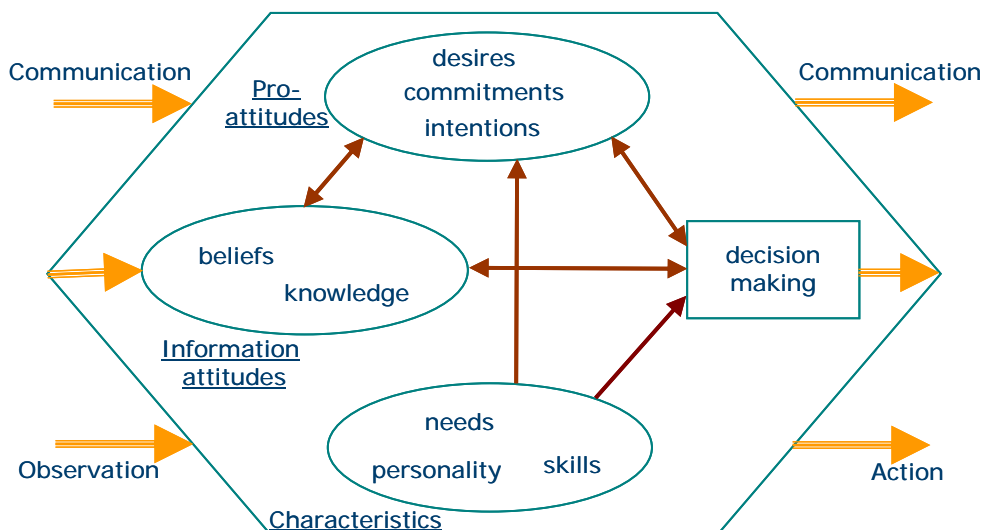


Figure 13: Internal perspective of an agent

Agent's information attitudes and pro-attitudes

Agents create time-labelled internal representations (beliefs) about their input and output states, which may persist over time. Besides beliefs about single states, an agent forms beliefs about dependencies between its own states, observed states of the environment, and observed states of other agents. In the developed model we use the Temporal Trace Language (TTL) (Sharpanskykh, 2008a) to represent temporal relations between state properties. For example, the property that for all time points if an agent *ag* believes that action *a* is rewarded with *r*, then *ag* will after 30 time units perform *a*, is formalized in TTL as:

$$\forall t:\text{TIME} [\text{at}(\text{internal}(\text{ag}, \text{belief}(\text{reward_for_action}(r, a))), t) \rightarrow \text{at}(\text{output}(\text{ag}, \text{performed_action}(a)), t+30)]$$

In our study relations between agent's states are mostly modelled by causal networks (Pearl, 2000), which describe weighted static mappings between 'evidence variables', which take on values in the range from 0 to 1. As an example Figure 14 shows the causal network for the commitment to safety of a controller. According to this causal network, 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 (Burt, 1987; Griffin and Bateman, 1986). The rounded boxes in Figure 14 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 the level of training of the agent and the quality of feedback on occurrence reporting received by the agent. By interconnection of causal networks feedback loops exist in the model.

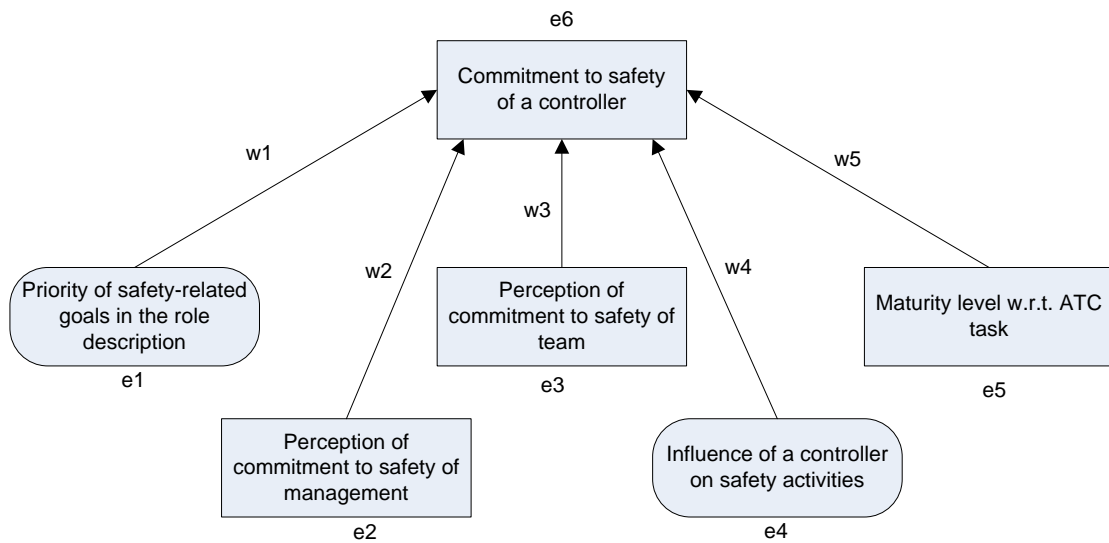


Figure 14: Causal network for 'Commitment to safety of a controller'

Agent's needs

Social science considers behaviour of individuals as 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. Different needs have different priorities and minimal acceptable satisfaction levels for individuals in different cultures. In this study we use the cultural classification framework of Hofstede (2005), which considers three indices: individualism index reflects the degree to which individuals are not integrated into groups; power distance index is the extent to which the less powerful members of an organization accept and expect that power is distributed unequally; and uncertainty avoidance index deals with individual's tolerance for uncertainty and ambiguity. The model uses values for these indices that are suitable for Western European culture (Hofstede, 2005). 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.

Agent's decision making process

The decision making model of agents is based on the expectancy theory by Vroom (Pinder, 1998) and it is illustrated in Figure 15. According to Vroom's theory, when a human evaluates alternative possibilities to act, the following

factors are explicitly or implicitly taken into account: valence, expectancy and instrumentality.

- Expectancy refers to the individual's belief about the likelihood that a particular act will be followed by a particular outcome (called a first-level outcome). For example in Figure 15, the expectancy E12 refers to the agent's belief of the likelihood that reporting of an occurrence will be followed by an administrative reprimand.
- Instrumentality is a belief concerning the likelihood that a first level outcome results into a second level outcome, which represents a (un)desirable state as reflected by the agent's needs. For example in Figure 15, the instrumentality I32 refers to the belief about the likelihood that own group appreciation of the action results in own group approval.
- Valence refers to the strength of the individual's desire for an outcome or state of affairs. The values of valences depend on the degree of satisfaction of the agent's need: the more a need is satisfied, the less is its valence.

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

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

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

instrumentality of outcome j for the attainment of outcome k . The agent's decision making model considers two forces for reporting or not reporting; the alternative with the greatest force is performed.

Expectancies, instrumentalities and valences 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 events and on related evidence variables. For example in Figure 15, the 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 (instrumentalist/social learning); and E16 is adjusted based on the feedback from the safety investigator agent on previously reported occurrences and the observed implementation of safety recommendations for previous reports (instrumentalist learning), as well as safety information informally provided by other controllers during breaks (social learning).

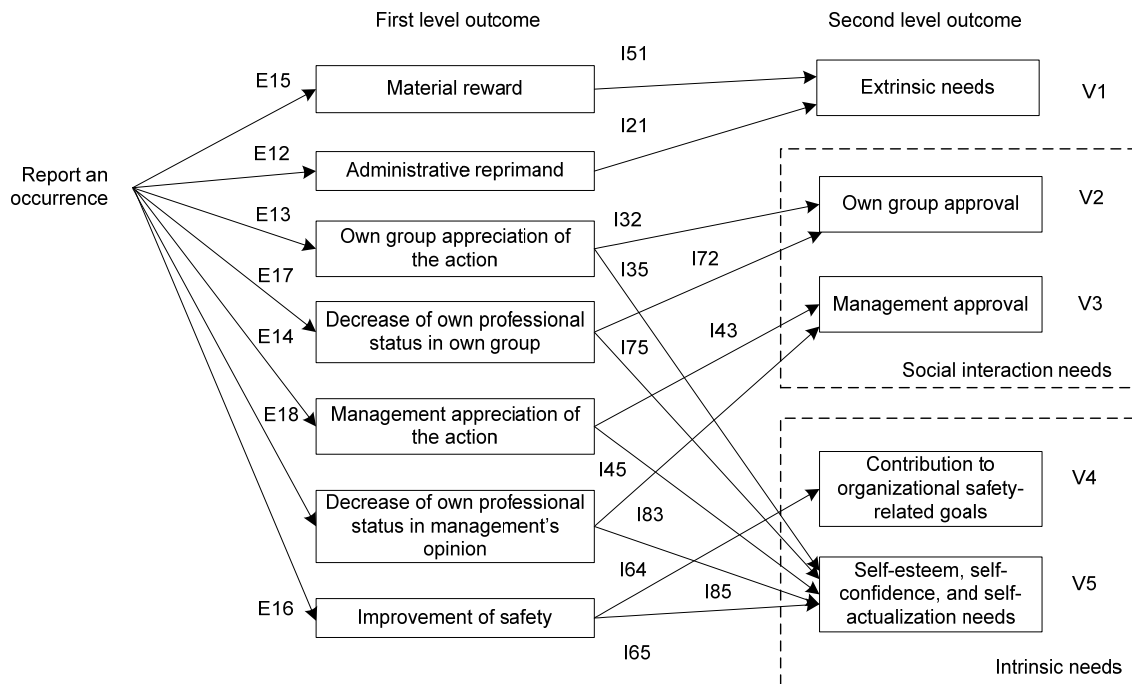


Figure 15: Decision making model for reporting an occurrence (E's are expectancies, I's are instrumentalities and V's are valences)

4.3.3 MODEL PARAMETERS AND OUTPUTS

The dynamics of the agent-based organizational model depend on the model structure such as outlined in the previous sections and on a range of parameter values. We distinguish the following types of parameters:

- Evidence input variables, which are the independent inputs of the causal networks in the model (Table 3 provides a list of all 22 evidence input variables);
- Weights, which reflect the importance of mappings between the evidence variables in the causal networks (the model contains 60 weights);
- Task durations, which refer to the (limits of) task durations in workflows (the model contains upper and lower bounds for 16 tasks);
- Decision making, which are related to Vroom's decision making model (28 parameters);
- Other (55 parameters).

In this study we used two sets of parameter values, which will be discussed later.

Table 3: Model input evidence variables

Variable	Description
e1	Priority of safety-related goals in the role description
e4	Influence of a controller on safety activities
e7	Sufficiency of the amount of safety investigators
e8	Sufficiency of the amount of controllers
e9	Availability of reliable and ergonomic technical systems for controllers
e10	Sufficiency and timeliness of training for changes
e11	Regularity of safety meetings
e12	Developed and implemented safety management system (SMS)
e14	Level of development of managerial skills
e19	Self-confidence for ATC task
e20	Commitment to perform ATC task
e21	Development level of skills for ATC task
e25	Sufficiency of the number of maintenance personal
e26	Quality of formal procedures for system checks and repairs
e35	Intensity of informal interactions in the team of controllers
e36	Quality of the formal safety occurrence assessment procedure
e40	Quality of the communication channel between controllers and safety investigators
e44	Average commitment of the agents involved in the safety analysis
e61	Individualism index of a controller
e62	Power distance index of a controller
e63	Masculinity index of a controller
e64	Uncertainty avoidance index of a controller
e71	Formal support for confidentiality of reporting

Based on a broad list of safety culture issues related to occurrence reporting that we identified in (Sharpanskykh and Stroeve, 2008a), Table 4 shows the eight safety culture indicators that are observable in the agent-based organizational model; these are the model outputs.

Table 4: Model output safety culture indicators

Index	Safety culture indicator
11.1	Average reporting quality of controllers. It refers to the ratio of reported versus observed occurrences.
12.1	Average quality of the processed notification reports. It refers to the correctness and completeness of information about the reported occurrences.
13.1	Average quality of the final safety occurrence assessment reports. It refers to the completeness of the occurrence report with respect to the causes of the occurrence.
14.1	Average quality of the monthly safety overview reports received by controllers. It refers to the completeness of the report with respect to the safety trends.

Index	Safety culture indicator
15.1	Average commitment to safety of controllers.
15.2	Average commitment to safety of a team as perceived by controllers.
16	Average commitment to safety of a supervisor as perceived by controllers.
17	Average commitment to safety of management as perceived by controllers.

4.4 MODEL AND VALIDATION PHASE I

In Model and Validation Phase 1, the safety culture indicators were predicted by the agent-based organizational model on the basis of organizational information of ANSP-3, without any knowledge of the safety culture survey results of ANSP-3. The organizational information used in this phase was based on interviews with a safety manager and a safety occurrence investigator of ANSP-3, as well as documentation about the Safety Management System of ANSP-3. In combination with general scientific knowledge about psychological, sociological and organization cultural aspects, this specific information was used to develop the model structure (as explained in Sections 4.3.1 and 4.3.2), and it was used for setting up values for the parameters (listed in Section 4.3.3).

As a basis for the validation in Phase 1 we used results of the safety culture survey questionnaire at ANSP-3. In the validation plan (Sharpanskykh and Stroeve, 2008b), which was written before we received any questionnaire results, we defined relations between safety culture indicators and particular questions in the survey questionnaire. Table 5 shows some examples of questions that are related to the safety culture indicators. For the cases where an indicator is related to multiple questions, a weight is assigned to each question indicating the degree of importance of the question for the safety culture indicator.

Table 5: Examples of coupling between safety culture indicators and safety culture survey questions

Safety culture indicator		Related survey questions	Weight
No.	Description		
11.1	Average reporting quality of controllers	A.24 People understand the need to report incidents in order to identify trends and make changes to the system if required	0.5
		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
		A.32. If I do something unsafe I am aware that I may be asked to explain myself	0.2

Safety culture indicator		Related survey questions	Weight
No.	Description		
15.2	Average commitment to safety of a team as perceived by controllers	A.4 My colleagues are committed to safety.	0.7
		A.11 Everyone at my Unit/Team feels that safety is their personal responsibility.	0.3
16	Average commitment to safety of a supervisor as perceived by controllers	B.16 My concerns about safety would be acted on if I expressed them to my supervisor	1

Different types of results are obtained by the safety culture survey questionnaires and the agent-based organizational model. The questionnaire results include mean scores for the level of agreement to statements on a scale from 1 (“fully disagree”) to 5 (“fully agree”). The model results for safety culture indicators range on scales from 0 to 1. Since the questionnaire and model scales are different and the results for neither of them can be expected to be uniformly distributed along the full scales, we introduce three classes for the values of the indicators: Low / Medium / High. Table 6 shows our definition of these classes for the questionnaire result scales. It follows from a analysis of survey questionnaire results of a particular ANSP-2 (different from ANSP-3) that for this ANSP the Low boundary cuts the first 30% of the safety culture indicator values, the following 55% of the values belong to the class Medium and the remaining 15% belongs to the class High.

Table 6: Definition of attributes of safety culture indicator value classes

Class of value of safety culture indicator	Range of average value in survey questionnaire	Relative contribution ANSP-2
Low	[1, 3.25]	30%
Medium	(3.25, 4]	55%
High	(4, 5]	15%

To analyse the range of results for the safety culture indicators that can be obtained by the model, we performed Monte Carlo simulations for variations in the settings of the evidence input variables. In particular, all evidence input variables listed in Table 3 were varied over their full range, except the national culture variables (e61-e64) which were associated with Western European culture. Figure 16 provides examples of histograms for the Monte Carlo simulation results for two safety culture indicators. Next, on the basis of these Monte Carlo simulation results, we associated ranges of values for each safety culture indicator to the classes High / Medium /Low: the upper 15% is High, the middle 55% is Medium and the lower 30% is Low, in line with the relative contributions of

ANSP-2. Table 7 shows the resulting boundaries of the model results for the class definitions.

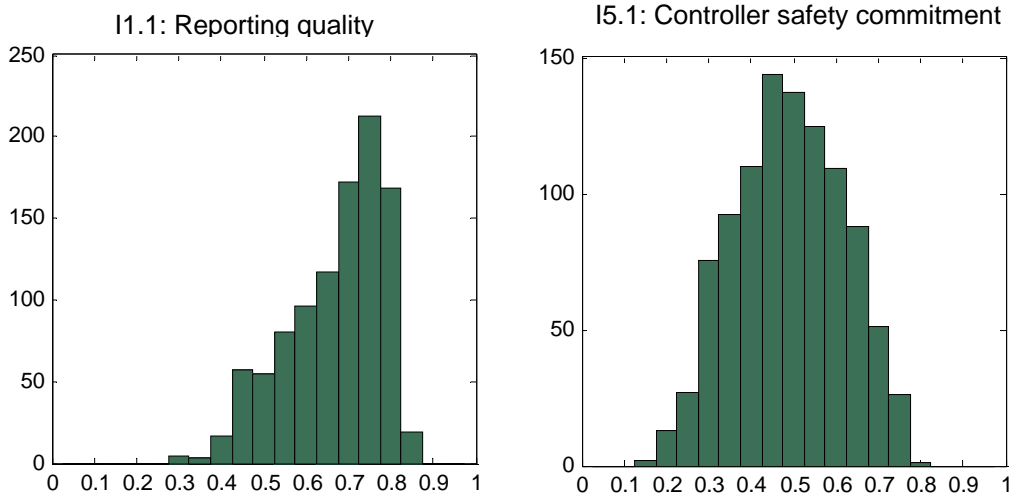


Figure 16: Examples of distributions of safety culture indicators (Monte Carlo simulation results)

Table 7: Class definitions for the model output values

Safety Culture Indicator		Low	Medium	High
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]

Based on the model, its setting and the methods for classifying the results of the model and the survey questionnaire, the results of the model and the survey are shown in Table 8. It follows from this table 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

model values of indicators I1.1 and I4.1 are close to the border of the class Medium, the other High indicators are well away from this border. Table 8 shows that the safety culture indicators based on the survey questionnaire results are all Medium, except for indicator I6, which is Low. The questionnaire-based scores are not close to the class edges. 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 8: Comparison of the classes of the safety culture indicators obtained by the organizational model and the survey questionnaire data in Phase 1

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

4.5 MODEL AND VALIDATION PHASE 2

In Model and Validation 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 for the safety culture indicators (i.e. different questions were used than as used in the process indicated in Table 5). For each input evidence variable we pursued to identify related survey questions:

- For fourteen 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 in an updated value for the input evidence variable. Table 9 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 9: Update of evidence input variables, based on survey questionnaire results

Variable	Description	Related survey questions	Value of 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	0.90	0.70
		A.5. Safety is a responsibility shared throughout the organization		
		A.12. The other people in the organization do not understand the safety roles we fulfil		
e4	Influence of a controller on safety activities	B.2 Our opinion and input into safety assessments are actively sought after.	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		
		B.15 I have the opportunity to provide input in the ATC systems development or acquisition process.		
e9	Availability of reliable and ergonomic technical systems for controllers	B.8 I trust the ATC equipment that I use in my job.	0.90	0.75

Based on the updated values of the input evidence variables, new model simulation results were obtained. Table 10 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 8 and the updated model results in Table 10 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 10 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 10: Comparison of the safety culture indicator classes for the survey data and for the organizational model with updated model input values

Index	Safety culture indicator	Model	Survey
11.1	Average reporting quality of controllers	Medium	Medium
12.1	Average quality of the processed notification reports	High	-
13.1	Average quality of the final safety occurrence assessment reports	Medium	Medium
14.1	Average quality of the monthly safety overview reports received by controllers	Medium	Medium
15.1	Average commitment to safety of controllers	Medium	Medium
15.2	Average commitment to safety of a team as perceived by controllers	Medium	Medium
16	Average commitment to safety of a supervisor as perceived by controllers	Medium	Low
17	Average commitment to safety of management as perceived by controllers	Medium	Medium

4.6 MODEL AND VALIDATION PHASE 3

In Model and Validation Phase 3 we predicted 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 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 a conclusion about the level of agreement between the model- and the survey-based results.

The basis for the model-based identification of Major Organizational Factors is a sensitivity analysis, which is presented in Section 4.6.1. The identified Major Organizational Factor and the comparison with the safety culture survey results are presented in Section 4.6.2. The identified Organizational Improvement Options and the comparison with the recommendations in the safety culture survey study are presented in Section 4.6.3.

4.6.1 SENSITIVITY ANALYSIS

The sensitivity analysis method used in this study is Monte Carlo filtering (Saltelli, 2006, 2008). The aim of Monte Carlo filtering is to identify the model parameters of which the variation according to associated credibility intervals lead to significant differences in attained model output classes. It consists of two steps, which are presented next.

Step 1: MC simulations

For the complete set of model parameters as presented in Section 4.3.3, 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, on our knowledge of the ANSP-3 organization and on our knowledge about the uncertainty in 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 of the sensitivity analysis (8000 simulations of three years periods each appeared sufficient).

For each input factor x_i two sets of values were determined:

- $x_i | B$, containing all values of x_i from the simulations that produced a High safety culture indicator (as defined in Table 7), and
- $x_i | \underline{B}$, containing all x_i values that produced a Low or Medium safety culture indicator.

Step 2: Smirnov test

A Smirnov two sample test was performed for each input factor independently.

The applied test statistics are

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

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

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

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

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

Table 11 shows examples of the importance of evidence input variables for each safety culture indicator, according to above methodology.

Table 11: Importance of input variables classified by categories High / Medium / Low for the ANSP3 model (examples)

Input variables		Safety Culture Indicators							
		11.1	12.1	13.1	14.1	15.1	15.2	16	17
		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 management
e1	Priority of safety-related goals in the role description	M	M	L	M	H	H	H	H
e4	Influence degree of controllers on safety arrangements	H	L	L	L	H	H	H	H
e7	Sufficiency of number of safety investigators	M	L	H	H	H	H	H	H
e8	Sufficiency of the number of controllers	H	H	H	H	H	H	H	H
e10	Sufficiency and timeliness of training for changes	L	L	L	L	H	H	H	H
e11	Regularity of safety meetings	L	L	L	L	M	L	H	H
e12	Developed and implemented SMS	M	M	L	L	H	H	H	H

A total safety culture sensitivity index is defined by firstly setting a value 0 for Low sensitivity, a value 0.5 for Medium sensitivity and a value 1 for High sensitivity, and subsequently summing those values over all safety culture indicators for a particular factor.

Table 12 shows all evidence input variables, their nominal values and the credibility interval ranges used in the sensitivity analysis, and their total safety culture sensitivity indices based on above mapping procedure. All evidence input variables with values larger than or equal to four are marked. There are eight evidence input variables that have such important effect on the safety culture indicators.

For all other types of parameters in the model (as listed in Section 4.3.3), 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 for one weight, which describes the relation between the commitment of a supervisor to safety and the perception of the commitment to safety in a team, a total safety culture index of 4 is achieved in the sensitivity analysis. All other parameters are less important.

Table 12: Total safety culture sensitivity index for the evidence input variables of the ANSP-3 model

Variable	Description	Value	Total SC sensitivity index
e1	Priority of safety-related goals in the role description	0.60 (0.50-0.70)	5.5
e4	Influence of a controller on safety activities	0.50 (0.40-0.60)	5
e7	Sufficiency of the amount of safety investigators	0.50 (0.40-0.60)	6.5
e8	Sufficiency of the amount of controllers	0.60 (0.40-0.80)	8
e9	Availability of reliable and ergonomic technical systems for controllers	0.75 (0.65-0.85)	5.5
e10	Sufficiency and timeliness of training for changes	0.60 (0.45-0.75)	4
e11	regularity of safety meetings	0.75 (0.60-0.90)	2.5
e12	Developed and implemented SMS	0.60 (0.40-0.80)	5
e14	Level of development of managerial skills	0.60 (0.40-0.80)	7
e19	Self-confidence for ATC task	0.85 (0.75-0.95)	3.5
e20	Commitment to perform ATC task	0.80 (0.70-0.90)	3
e21	Development level of skills for ATC task	0.80 (0.70-0.90)	1
e25	Sufficiency of the number of maintenance personal	0.75 (0.60-0.90)	3.5
e26	Quality of formal procedures for system checks and repairs	0.75 (0.60-0.90)	0.5
e35	Intensity of informal interactions in the team of controllers	0.65 (0.50-0.80)	0
e36	Quality of the formal safety occurrence assessment procedure	0.85 (0.75-0.95)	0
e40	Quality of the communication channel between controllers and safety investigators	0.50 (0.30-0.70)	1
e44	Average commitment of the agents involved in the safety analysis	0.65 (0.50-0.80)	1.5
e61	Individualism index of a controller	0.8 (0.7-0.9)	0
e62	Power distance index of a controller	0.4 (0.3-0.5)	0

Variable	Description	Value	Total SC sensitivity index
e63	Masculinity index of a controller	0.15 (0.05-0.25)	0
e64	Uncertainty avoidance index of a controller	0.5 (0.4-0.6)	0
e71	Formal support for confidentiality of reporting	0.65 (0.55-0.75)	0

4.6.2 IDENTIFICATION AND VALIDATION OF MAJOR ORGANIZATIONAL FACTORS

Based on the sensitivity analysis of the model for ANSP-3, we identified eight Major Organizational Factors with a large effect on safety culture. In the EUROCONTROL safety culture survey of ANSP-3, a range of safety culture issues became clear from the results of the questionnaire and the safety culture workshops. In a safety culture model workshop with EUROCONTROL personnel who performed the safety culture survey at ANSP-3, we identified for each Major Organizational Factor the range of related results of the safety culture survey, and we reached a conclusion about the agreement between the results of the model and the safety culture survey.

The list of Major Organizational Factors identified via the model in order of importance is:

- MOF-1: Sufficiency of the number of controllers
- MOF-2: Level of development of managerial skills of supervisors
- MOF-3: Sufficiency of the number of safety investigators
- MOF-4: Priority of safety-related goals in the role description
- MOF-5: Availability of reliable and ergonomic technical systems for controllers
- MOF-6: Influence of a controller on safety activities
- MOF-7: Developed and implemented Safety Management System (SMS)
- MOF-8: Sufficiency and timeliness of training for changes

It was concluded in the safety culture model workshop that in the comparison of the eight model-based Major Organizational Factors with issues identified in the survey workshops at ANSP-3, 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). In particular, 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 controllers resources, but it may be a problem in contingency

situations and in the long term. For MOF-4, no lack of priority of safety-related goals in the role description of controllers was identified in the workshops, but for some other roles in the organization the safety-related goals are not always appropriately understood. 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. This detailed information was mainly obtained in the workshop phase of the safety culture survey, where the personnel was asked to discuss particular safety culture issues with low scores in the safety culture questionnaire.

4.6.3 IDENTIFICATION AND COMPARISON OF ORGANIZATIONAL RECOMMENDATIONS

The identified Major Organizational Factors, which have a strong effect on the safety culture indicators, provided the basis for the proposition of the following five Organizational Improvement Options in the model-based study.

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 to 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 there should be a structured way to always provide feedback on the safety issues raised (either prior to 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 SC 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.

4.7 DISCUSSION OF RESULTS

In summary, the following results were obtained in the three phases of this model and validation study:

- 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 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 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. It follows from the survey questionnaire results that the thus determined values for these variables were too optimistic. The survey questionnaire results provided

an overview of the opinions of a large number of employees with a variety of roles, as such they give a considerably broader basis for the evaluation of the evidence input variables than what can be achieved by interviews.

The results in Phase 2 show that given appropriate model inputs, the model output results for the safety culture indicators are mostly consistent with the survey questionnaire results. This shows that the model structure and other parameters are such that the model can well predict the safety culture indicators for appropriate input evidence variables. A limitation of the validation exercise in Phase 2 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. Moreover, we know from the sensitivity analysis that there are various input evidence variables that have a strong effect on the output safety culture indicators. All in all, the consistent prediction in Phase 2 is a positive indication that a valid model has been developed, but due to the same basis for input and reference output not a strong proof though.

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 is a good indication of the model's validity. The 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. In the current study, the model development was focused on the occurrence reporting cycle and other processes such as management actions, engineering activities and traffic management actions by controllers were 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.

5 DISCUSSION

This section presents a general discussion of the organizational modelling approach applied in this study. Section 5.1 discusses the relation of the agent-based organizational modelling method and the EUROCONTROL safety culture survey approach. Section 5.2 presents some potential extensions of the developed organizational model. Section 5.3 compares the applied modelling approach with other safety-related modelling approaches. Section 5.4 describes possibilities to link the model with risk assessment.

5.1 RELATION WITH SAFETY CULTURE SURVEY APPROACH

The application and validation of the organizational modelling approach was done in conjunction with results achieved for a particular ANSP by the EUROCONTROL safety culture survey approach (described in Section 3). The results presented in Section 4 show that to achieve valid predictions of the safety culture indicators by the model, we needed input data from the safety culture survey questionnaire, and on this basis the sensitivity analysis provided valid results for important organizational factors influencing the safety culture indicators and related recommendations. In general, the developed model has a range of input variables that reflect attitudes and opinions of people in the organization, and a safety culture survey questionnaire is a suitable tool to obtain an overview for these. As such, the agent-based organizational modelling approach may be used in addition to safety culture questionnaires and workshops.

We found that the major added advantage of agent-based organizational modelling is that it provides a structured, formally-grounded means for analysis and improvement of safety culture. It defines explicit formal relations between safety culture indicators and organizational processes and structures, thus enabling identification of important organizational aspects impacting safety culture by sensitivity analysis techniques. Insights in relations between safety culture indicators and organizational structures and processes may be used to further enhance safety culture questionnaires and prepare safety culture survey workshops.

5.2 POTENTIAL EXTENSIONS OF THE ORGANIZATIONAL MODEL

The developed organizational model has a restricted scope, which may be broadened in several ways. Some possible extensions are presented next.

- The modelling scope was focused on safety culture at the particular ANSP-3. Similar models may be developed for other ANSPs. To this end, the organizational structures and processes at other ANSPs should be studied and as a result the model structure may need to be adapted to be consistent with the specific organizational aspects at the other ANSPs. In addition, suitable input data should be obtained as basis for the estimation of the parameter values in the model. As was illustrated in this study, the safety culture questionnaires provide a useful source for this estimation.
- In the current study, the scope of the model was focused on safety culture issues in relation to occurrence reporting. In line with the broad scope of the safety culture dimensions adhered to in the EUROCONTROL safety culture survey approach, the range of safety culture issues may be enhanced. To this end, additional organizational processes may need to be modelled, such as the organization of training, the maintenance department or management layers.
- The characteristics of the controller agents in the organizational model include the four dimensions of national culture, as formulated by Hofstede (2001, 2005): Power Distance, Individualism, Masculinity and Uncertainty Avoidance. It has been shown in an extensive survey study in the aviation domain with more than 8,000 pilots of 26 countries that national culture has significant effects on pilot performance (Helmreich, 2000). In this study, we achieved model results showing manifest effects of Western versus Eastern European culture on safety culture indicators (Sharpanykh et al., 2008b; Stroeve et al., 2008). The effect of national culture on safety culture is worthwhile to study further, thus advancing on those early steps.
- The decision-making process by controller agents whether to report or not report observed occurrences has a central role in the model. These process of individual agents are adapted in response to the way reported occurrences are processed and fed back in the organization and by team and management interactions. These adaptations are manifestations of individual and team learning in relation to the occurrence reporting process. The organizational modelling approach can be used to analyse the effects of a larger variety of goal-directed organizational change processes. Examples are new reporting procedures, new rostering schemes, new management structures, etc. The learning effects can be studied at different aggregation levels, including individuals, teams, units and institutions.

5.3 COMPARISON WITH OTHER SAFETY-RELATED ORGANIZATIONAL MODELLING APPROACHES

In Section 2 we concisely presented the safety-related organizational modelling approaches STAMP, SoTeRiA and TOPAZ. Here we compare the multi-view hybrid organizational modelling approach applied in this study with those approaches.

Multi-view hybrid organizational modelling (this study)

The multi-view hybrid organizational modelling framework used in this study provides methods for modelling the formal, prescriptive organization as well as the social behaviour of organizational actors along four interrelated views: organization-, performance-, process- and agent-oriented views. Within these views several techniques are used, such as agent-based modelling, causal networks, cognitive modelling and logic-based modelling. The modelled organizational structure discerns roles (a set of defined functionalities in the organization abstracted from the actors performing them), role instances (description of performance of generic actors that may fulfil the role) and agents (individuals allocated to role instances). The model that was developed in this study by this approach uses a mix of variables. A part of these variables is at an aggregated level, e.g. e44 'Average commitment of the agents involved in the safety analyses'. The largest part of the variables is at the level of individuals, e.g. beliefs and intentions of agents. Both continuous and event-based dynamics can be represented, where the event times may be deterministic or stochastic. The model developed was focused on a number of safety culture indicators, e.g. reporting quality and commitment. These are quality indicators for the safety of the organization, but they do not directly relate to safety risk levels. The consistency of the model is checked using automated logic-based analysis methods (in particular TTL checking (Sharpanskykh, 2008a)). The model is evaluated by MC simulations that reflect a large number of instantiations (thousands in this study) of several years (three years in this study) of organizational performance. Simulation-based sensitivity analysis provides insights in the key factors that impact the safety culture indicators.

STAMP

The Systems-Theoretic Accident Modeling and Processes (STAMP) methodology uses system dynamics (SD) to describe interactions and dynamics between organizational processes and their effect on safety. The variables in such models are at an aggregated organizational level, rather than at the level of individuals in the organization. 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. The STAMP model in (Dulac et al., 2007) describes relations between a large number of organizational variables, including 'Safety of operational system'. However, the model does not provide probability estimates of adverse safety events (incidents/accident). The model is evaluated via simulation runs and these show dynamic traces of relevant variables regarding e.g. costs, scheduling and safety. By varying model settings, the effects of conditions and decisions on dynamic traces for variables of interest can be evaluated.

SoTeRiA

The Socio-Technical Risk Analysis (SoTeRiA) framework uses a hybrid set of modelling techniques, including system dynamics, Bayesian Belief Networks, Event Sequence Diagrams and Fault Trees. In the example model of (Mohaghegh et al., 2009) relations between organizational aspects are mostly represented by System Dynamics models, whereas the relation with risk levels is mostly achieved by the BNNs, ESDs and FTs. Similar to STAMP, the variables in the model are mostly at aggregated organizational levels, rather than at the level of individuals. Also similarly to STAMP, the dynamics of the model are continuous time-based with some triggering events. An extension with respect to STAMP is that SoTeRiA provides as outputs system safety probability estimates. Similar to STAMP, the model is evaluated via simulation runs and these show dynamic traces of relevant variables, which include (in addition to STAMP) risk probability estimates. By varying model settings, the effects of conditions and decisions on dynamic traces for variables of interest can be evaluated.

TOPAZ

TOPAZ (Traffic Organization and Perturbation AnalyZer) 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. The development of TOPAZ models has been focused on the organization at the operational level, 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. For instance, about 10 million variations of operational scenarios are

simulated and speed-up factors of about 10,000 are used, such that accident risks in the order of 1E-9 can be well evaluated per operational scenario. 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.

Discussion

A summary of the presented characteristics of these methods is provided in Table 13. Next, we discuss implications of these characteristics.

Table 13: Summary of characteristics of discussed methods

	This study	STAMP	SoTeRiA	TOPAZ
Methods	Prescriptive organization, agents using logic-based languages	SD	SD, BNN, ESD, FT	DCPN, agents
Scope	Organization	Organization	Organization	Operation
Variables	Aggregated, agent-level	Aggregated	Aggregated	Agent-level
Agent types	Individuals	-	-	Role instances, systems
Dynamics	Continuous time, event-based	Continuous time	Continuous time	Continuous time, event-based
Model evaluation	MC simulation	Simulation	Simulation	MC simulation, speed-up techniques
Sensitivity analysis	Sensitivity of SC indicators	Variety of dynamic traces	Variety of dynamic traces	Sensitivity, bias & uncertainty in safety risk
Safety output	Safety culture indicators	Safety indicators	Risk probabilities	Risk probabilities

STAMP and SoTeRiA are similar in their application of System Dynamics 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 System Dynamics 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 (Hollnagel, 2004; Sträter, 2005; Stroeve et al., 2009c; Everdij and Stroeve, 2009).

In contrast with STAMP and SoTeRiA, both TOPAZ and the multi-view hybrid organizational modelling method of the current study use agent-based models to describe the performance of people, systems or organizational units. These agent models intend to directly describe the behaviour of such organizational entities and therefore do not require the type of aggregation used in SD modelling. As a result of the agents' interactions, emergent behaviour exists at the level of the organization or the operation. Via sensitivity analysis the key factors contributing to safety culture of risk can be traced.

Differences between TOPAZ and the organizational modelling of this study include

- The focus on (safety-critical) operational scenarios in TOPAZ and on the organization of safety occurrence reporting in this study;
- The use of agents at the level of role instances (e.g. Pilot Flying, Runway Controller) and agents at the level of individuals (e.g. controller Peter) in this study;
- The attainment of risk probability values by TOPAZ and of safety culture quality indicators in this study.

5.4 COUPLING ORGANIZATIONAL AND RISK MODELS

The agent-based organizational model that we developed in this study has a number of safety culture indicators as output. A stimulus of safety culture

studies is the (implicit) premise that a good safety culture has a positive effect on the safety risk of the work performed by the organization; for an ANSP this would mean that good safety culture supports lowering ATM-related risk levels. However, there is yet little evidence that explicitly supports such relation between safety culture and safety performance. 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. 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. On this basis, measurements of organizational or operational factors that are found to be important for the safety risk can be defined and applied in safety monitoring. The way this coupling may be effectuated in practice depends on the type of risk model chosen. Next, we discuss coupling with (1) FT, ESD and BNN risk assessment models and (2) agent-based DRM.

FT, ESD, BNN

Fault Trees, Event Sequence Diagrams and Bayesian Belief Networks are methods frequently used in risk assessments to describe probabilistic relations between conditions, failures, errors and consequences in safety-relevant scenarios. Similarly as has been done in SoTeRia (Mohaghegh et al., 2009), safety culture quality variables of the organizational model may be used as Performance Shaping Factors (PSFs) in these risk assessment models. For instance, these PSFs may influence probabilities of the occurrence of human operator errors, as is usual in the field of Human Reliability Assessment. More generally, they may influence probabilities of particular occurrences (errors, failures, conditions) in the risk model, e.g. an increase in system failure probability due to low commitment at the maintenance department.

In this way of coupling between organizational and risk assessment models, it can be envisioned that aggregated variables in the organizational model (e.g. commitment of a group of controllers) are used rather than the performance characteristics of individual agents. Furthermore, in such coupling it should to a reasonable extent be feasible to describe the event probabilities as function of safety culture quality variables. We note that it may be difficult to accurately analyse the risk of air traffic scenarios with concurrently acting entities by traditional risk models (Stroeve et al., 2009c; Everdij and Stroeve, 2009). Since the operational risk model is not agent-based there is not a direct link from the operational model back to the organizational model.

Agent-based DRM

Agent-based Dynamic Risk Modelling (DRM) is an advanced method to assess the risk of complex air traffic scenarios; it is used in the TOPAZ risk assessment methodology. Such models describe the variability in the dynamic performance of operators, systems and environmental conditions of safety-relevant scenarios. The risk effects emerging from the variably performing and interacting agents are evaluated by Monte Carlo simulations. Coupling between the DRM and the organizational (safety culture) model can be envisioned at the level of roles or at the level of individuals.

In coupling at the role level, safety culture quality variables for specific role instances can be used to modify parameter values for these agent roles in the DRM. Since in the organizational model, roles are typically performed by a number of individuals, the safety culture quality variables are aggregated over these individuals (e.g. group average). Similar to the PSFs for the traditional risk models, error or failure probabilities may be described as function of safety culture quality variables. In addition to these traditional PSFs, the dynamic performance of agents in DRM can be influenced in a broad variety of ways (e.g. other task initiation timing, task duration, system velocity, system accuracy, etc.). This larger variety of influencing options may make it possible to describe the influencing relations more accurately than for event probabilities. In this coupling option, the simulations of the organizational model and the DRM can be performed separately and the complexity of the coupling is considered to be moderate.

In coupling at the level of individuals, the agents in the DRM should describe the performance of individuals in their operational roles, and under this condition, the agent-based dynamic risk and organizational safety culture models can be directly coupled. In this type of coupling, the influence of the organization on the individuals working in it, and vice versa, is modelled, as well as the way that this organizational influence has impact on the operational performance of the operator. For instance, agent Peter has got training for a failure condition, a while later agent Peter encounters this failure condition during operation and (as a result of the training) agent Peter reacts in a particular time, and this has effect on the safety-criticality of the air traffic scenario. This type of coupling holds the possibility to specify organizational aspects and operational effects, and their interactions, at a large level of detail. As such, it supports a high level of analysis detail. The modelling complexity for this coupling option is high.

6 CONCLUSIONS

It was set out as aim of this project to enhance safety analysis of organizational processes in air traffic by development of formal approaches for modelling, simulation and analysis of organizational relationships and processes. In particular, these models should support the understanding of causal relations between organizational processes that influence safety culture, such that robust and flexible policies may be identified to improve and maintain a sufficient level of safety culture in an organization.

We claim that this aim has been achieved based on the following arguments.

- Based on a literature survey we identified a multi-view hybrid organizational modelling approach, which provides a broad repertoire of methods for modelling, simulation and analysis of organizational relations and processes.
- We showed that it is feasible to apply this organizational modelling approach to the ATM domain by developing a model for the organization of the reporting and processing of safety occurrences at an ANSP.
- We showed that we could validate the model by relating its predictions to results of a EUROCONTROL safety culture survey of a particular ANSP.
- We showed that we could attain valid predictions of safety culture indicators with dedicated input data of the safety culture survey questionnaires.
- We showed that the sensitivity analysis of the organizational model provided valid results for important organizational factors influencing the safety culture indicators and related recommendations.

Based on above findings, we argue that the agent-based organizational modelling approach is a useful add-on to the EUROCONTROL safety culture survey approach. The major added advantage of the organizational modelling approach is that it provides a structured, formally-grounded means for analysis and improvement of safety culture. It defines explicit formal relations between safety culture indicators and organizational processes and structures, thus enabling identification of important organizational aspects impacting safety culture by sensitivity analysis techniques. Insights in relations between safety culture indicators and organizational structures and processes can be used to further enhance safety culture questionnaires, prepare safety culture survey workshops and support decision making on organizational change processes at ANSPs. In addition, coupling of organizational modelling to risk modelling provides a way for structured analysis of the effect of safety culture on safety performance.

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