ORGANIZATIONAL MODELING AND ANALYSIS OF SAFETY OCCURRENCE REPORTING IN AIR TRAFFIC

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Abstract: An Air Traffic Organization (ATO) is a complex organization that involves many parties with diverse goals performing a wide range of tasks. Due to this high complexity, inconsistencies and performance bottlenecks may occur in ATOs. By analysis, such safety- and performance-related problems of an ATO can be identified. To perform reliable and profound analysis automated techniques are required. A formal model specification that comprises both prescriptive aspects of a formal organization and autonomous behavioral aspects of agents forms the basis for such techniques. This paper describes how such a model specification is developed and analyzed in the frames of a simulation case of incident reporting in the ATO

1 INTRODUCTION

In many modern human organizations prescriptive aspects of a formal organization are combined with (some degree of) autonomy of organizational actors. For example, an Air Traffic Organization imposes numerous prescriptions on its actors, but also provides them decision-making freedom to deal with complex contextual conditions in air traffic operations, e.g., for crews for aircraft taxiing, for controllers for issuing of instructions.

Due to high complexity, many existing organizations contain inconsistencies and performance bottlenecks, which can be identified by analysis. To perform reliable and profound automated analysis, a formal specification of an organization is required that comprises both prescriptive aspects of the formal organization and autonomous behavioral aspects of actors. This paper describes how such a specification can be built for the case of incident reporting in an ATO. To define the prescriptive aspects, the general organization modeling framework from (Sharpanskykh, 2008) is used. In contrast to many existing enterprise modeling frameworks (CIMOSA (1993); ARIS (Scheer & Nuettgens, 2000)) this framework has a precisely defined formal basis: to express structural relations sorted predicate logic-based languages are used, whereas the Temporal Trace Language (TTL) is used for specifying dynamic aspects of organizations. In this framework, formal organizations are considered from three interrelated perspectives: the performance-oriented, the process-oriented, and the organization-oriented.

The organizational actors are modeled in this paper as agents, i.e., autonomous entities able to make decisions and to interact with the environment. To specify the characteristics and autonomous behavior of agents, knowledge from the air traffic domain is used. A specification of the formal organization extended with agents forms a basis for analysis of organizational behavior by simulation. In this paper a simulation approach is described by which the path of informal incident reporting in the ATO is investigated and compared with the one prescribed by the formal organization.

The paper is organized as follows. Section 2 considers related literature. Section 3 describes the organization under investigation. The specification of the formal organization is given is Section 4. Section 5 describes the characteristics and behavior of agents used in simulation. Section 6 presents the simulation results. Section 7 concludes the paper.

2 RELATED LITERATURE

Currently, formal risk assessment approaches (e.g. Eurocontrol, 2004) are based predominantly on fault/event trees used for sequential cause-effect reasoning for accident causation. However, such trees do not encounter for complex, non-linear dependencies and dynamics inherent in ATOs. Agent-based modeling has been proposed as a means to assess safety risk of complex emergent dynamics of air traffic operations (Blom and Stroeve, 2004). This study focuses on the risk of air traffic operations and uses a plain society of agents, without considering the organizational layer. Several approaches (Le Coze, 2005; Reason, 1997) consider influence of various organizational aspects on safety at a rather conceptual level, without providing precise details.

To provide a precise specification for a formal organization, a number of reference architectures have been proposed in the area of Enterprise Information Systems (e.g., CIMOSA, ARIS). Due to the lack of properly defined formal foundations, such architectures provide only limited possibilities for automated analysis of enterprise models. Partially this is due to the high expressive power of the specification languages of architectures. However, also more limited languages dedicated to automated analysis of particular aspects of organizations have been developed: process-oriented modeling techniques (Van der Aalst & Van Hee, 2002), organizational performance evaluation (Tham, 1999). However, modeling of particular organizational aspects does not allow defining interdependencies between different perspectives on organizations and to investigate a combined influence of factors from different perspectives on the organizational behavior.

In (Dalal et al., 2004) an integrated framework for process and performance modeling is described that incorporates accounting/business parameters into a formal process modeling approach based on Petri-nets. However, key aspects as power relations, organizational/individual goals, individual behavior are not considered. Another formal framework for business process modeling is described in (Koubarakis & Plexousakis, 2004) focusing on the formal goal-oriented modeling using situation calculus. Modeling and analysis of processes and other organizational concepts are not properly addressed in this framework.

Since individuals often exert a significant influence on the organizational dynamics, also aspects related to human behavior should be considered in organization modeling approaches. The extensive theoretical basis on modeling humans in organizational context developed in social science (e.g., theory of needs, expectancy theory (Pinder, 1998)) is largely ignored in the existing enterprise modeling approaches.

3 ORGANIZATION IN FOCUS

In this study reporting of safety occurrences during taxiing operations near an active runway of an airport are investigated. Traffic movements on the runway and surrounding taxiways are under control of a runway controller and ground controllers, respectively. In this operational context, safety-relevant events may occur, e.g. taxiing aircraft initiates to cross due to misunderstanding in communication. To support safety management, such events should be reported by the involved pilots and controllers. In this case, we consider reporting that occurs either via formal organizational lines or via informal coordination. The formal organization considers safety occurrence reporting at the air navigation service provider (ANSP) and at airlines, the informal path considers coordination between air traffic controllers.

The formal occurrence reporting at the ANSP starts by the creation of a notification report by the involved controller(s). This notification report is examined and possibly improved by the supervisor. The notification report is processed by the safety investigation unit (SIU) of the ANSP. The severity of the occurrence is assessed and a description of the event is stored in a safety occurrences database. In the case of single severe occurrences or of a consistent series of less severe occurrences, the SIU may initiate an investigation for possible causes.

The organization of the safety occurrences processing at the airline starts with a notification report created by the pilots. This notification report may be provided to the airline’s safety management unit or it may be directly provided to the regulator (a governmental organization). The airline’s safety management unit examines and potentially improves the report and it informs the regulator about safety occurrences at the airline. The regulator may decide on further investigation of safety occurrences by itself or by a facilitated external party.

The informal safety occurrence reporting path at the ANSP considers that controllers discuss during breaks the occurrences that happened in their shifts. If they identify potential important safety issues they inform the head of controllers, who is a member of the operation management team. This team may decide on further investigation of the issue.

4 SPECIFICATION OF THE FORMAL ORGANISATION

To create a specification of the formal organization a design methodology has been developed that uses the modeling languages from (Sharpanskykh, 2008) and identifies the following sequence of design steps:

Step 1. The identification of the organizational roles. A *role* is a set of functionalities of an organization, abstracted from specific agents who fulfill them. Each role can be composed by several other roles, until the necessary level of details is achieved. A role composed of (interacting) subroles is called a composite role. Each role has an input and an output interface, which facilitate in the interaction with other roles. The environment is a special component of a model that also has input and output interfaces. In the ATO, roles are identified at three aggregation levels (see Figure 1).

Step 2. The specification of the interactions between the roles. Relations between roles are represented by interaction and interlevel links. An *interaction link* is an information channel between two roles at the same aggregation level. An *interlevel link* connects a composite role with one of its subroles. The interaction relations for the ATO have been identified at each level (see Figure 1).

Step 3. The identification of the requirements for the roles. In this step the requirements on knowledge, skills and personal traits of the agent implementing a role at the lowest aggregation level are identified. A prerequisite for the allocation of an agent to a role is the existence of a mapping between the capabilities and traits of the agent and the role requirements.

Step 4. The identification of the organizational performance indicators and goals. A performance indicator (PI) is a quantitative or qualitative indicator that reflects the state/progress of the company, unit or individual. PIs can be hard (e.g., occurrence investigation time) or soft, i.e., not directly measurable, qualitative (e.g., level of collaboration between controllers).

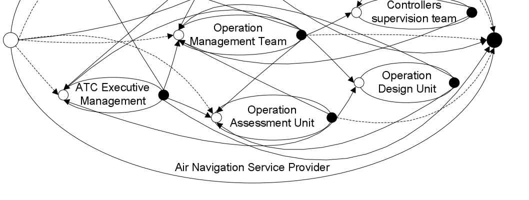

Figure 1: Interaction relations in the ATO (level 1)

Goals are objectives that describe a desired state or development and are defined as expressions over PIs. A goal can be refined into subgoals forming a hierarchy. For example, goal G18 'It is required to maintain timeliness and a high quality of occurrence investigation' is based on two PIs 'timeliness of occurrence investigation' and 'quality of occurrence investigation'. This goal is refined in several subgoals among which: G18.2 'It is required to maintain a sufficient level of details of notification reports', G18.3 'It is required to maintain the timely investigation of an occurrence' and G18.4 'It is required to maintain a high level of thoroughness of occurrence investigation'. To ensure the satisfaction of G18, the (sufficient degree of) satisfaction of its subroles is required. Goals are related to roles. E.g., G18 is attributed to Safety Investigation Unit and Regulator roles of the ATO.

Step 5. The specification of the resources. Resource types are characterized by: *name*, *category*: discrete or continuous, *measurement unit*, *expiration duration*: the time interval during which a resource type can be used; *location*; *sharing*: some processes may share resources. Examples of resource types of the ATO are: airport's diagram, aircraft, incident classification database, clearance to cross a runway, an incident investigation report.

Step 6. The identification of the tasks and relations between the tasks, the resources and the goals. A task represents a function performed in the organization and is characterized by *name*, *maximal* and *minimal duration*. Tasks can be decomposed into more specific ones using AND- and OR-relations forming hierarchies. Each task performed in an organization should contribute to the satisfaction of one or more organizational goals. For example, the ATO task T4 'Occurrence reporting based on the data provided by a controller' is refined into more specific tasks, among which T4.1 'Create a notification report', T4.4 'Investigation of the occurrence based on the notification report'. Task T4.4 is related to resources: it uses a processed notification report and produces an occurrence investigation report. Furthermore, T4.1 contributes to the satisfaction of goal G18.2, and T4.4 contributes to goals G18.3 and G18.4.

Step 7. The specification of the authority relations. The following types of authority relations are distinguished: superior-subordinate relations on roles w.r.t to tasks, responsibility relations, control for resources, authorization relations. Roles may have different rights and responsibilities with respect to different aspects of task execution, such as execution, passive monitoring, consulting, making technological decisions and making managerial decisions. E.g., Safety Investigator role is responsible for execution of and making technological decisions

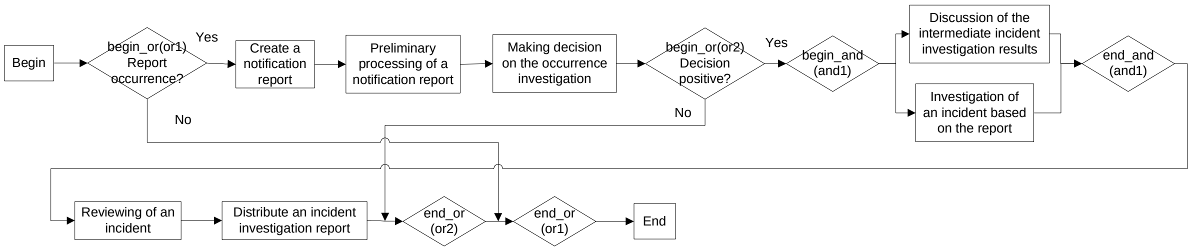

Figure 2: The flow of control that defines the execution of the formal occurrence reporting path initiated by a controller

w.r.t. task T4.4, Head of Safety Investigation Unit is responsible for monitoring, consulting and making managerial decisions related to T4.4.

Step 8. The specification of the flows of control. Flows of control describe temporal ordering of processes of an organization in particular scenarios. The framework allows representing all commonly used workflow templates. Figure 2 describes the execution of the formal occurrence reporting initiated by a controller.

Step 9. The identification of the generic and domain-specific constraints. Constraints are imposed on organizational specifications to ensure their internal consistency and integrity, and validity with respect to the domain. An organizational specification is *correct* if the corresponding set of constraints is satisfied by this specification. The framework used provides means for automated checking of the correctness of a specification. Consider examples of the domain-specific constraints of the ATO:

C1: When an aircraft is approaching to a runway, the pilots should cease all processes not related to the taxiing.

C2: The pilots of a crew should verbally share information about the instructions of controllers.

C3: Each observed incident should be reported by a crew.

C4: Perform allocation of controllers to aircraft monitoring processes in such way that the number of processes executed at the same time by each controller is less than 7.

5 MODELING AGENTS IN THE INFORMAL REPORTING PATH

The specification of a formal organization forms a part of an overall organizational specification. Another part describes characteristics and behavior of agents and their allocation to roles.

Agents are characterized by sets of skills and personal traits that influence their behavior and performance in the organization. The behavior of an agent is considered as goal-driven. For the case considered it is assumed that the goals of the agents are in line with the organizational goals. For the ATO a number of agent types have been identified, among which: Controller, Pilot, and Manager. Based on agent type Controller, 7 instances have been defined with varying development levels of the skills. All the agents-controllers possess the aggregated air traffic control skill (atc), which allows them to be assigned either to Runway or Ground Controllers roles. The agent ag_controllerG also possesses the skill employee management, which allows allocating this agent to role Tower Controllers Supervisor. Based on observations in the air traffic domain, it is assumed that the development level of the atc skill forms the basis for informal power of controllers: the higher the development level of the controller's atc, the more influence s/he has in the organization. In particular, the level of influence of an agent-controller plays an important role in the propagation of information about potential safety problems to the management level of the ANSP.

In the considered case study, the behavior of agents is investigated in the context of execution of the taxiing and incident reporting tasks described in Section 3. Both the formal and informal incident reporting paths are modeled, simulated and compared. The physical environment represented in the simulation case consists of two sectors of the airodrome, each of which is controlled by the corresponding ground controller role. The sectors adjoin a runway that is in control of the runway controller role. In the simulation at the beginning of each day, three agents controllers are chosen randomly to be allocated to two ground controllers and the runway controller roles. The traffic flow in the surroundings of the runway is assumed to be 30 aircraft per hour, 12 hours per day. For each aircraft a crew role is introduced, to which properly qualified agents pilots are assigned.

Controllers and crews are able to react to 6 types of safety-related occurrences that may happen during the execution of taxiing operations.

Table 1 shows the events and the probability values assumed in this simulation study.

Table 1: Safety-relevant events and their probability values per taxiing operation.

Event	*Probability*
(*a*) Aircraft rejects take-off as result of a runway incursion	5e-6
(*b*) Taxiing aircraft stops progressing on the runway crossing only after the stopbar and due to a call by the runway controller	2e-5
(*c*) Taxiing aircraft makes wrong turn and progresses towards the runway crossing	1e-4
(*d*) Taxiing aircraft makes wrong turn and progresses on a wrong taxiing route	2e-4
(*e*) Taxiing aircraft has switched to a wrong frequency	1e-3
(*f*) Taxiing aircraft initiates to cross due to misunderstanding in communication	1e-4

Some event types can be observed by the agents allocated to particular roles only. Moreover, agents may not always recognize and report observed events correctly. This is specified by probability values assigned to corresponding events (for details see (Sharpanskykh, 2008)).A sufficient number of observed occurrences of a particular type results into the initiation of a formal reporting process, more specifically: 1 event of type (a); 3 of (b), 6 of (c), 55 of (d), 55 of (e), and 6 of (f).

To model the informal occurrence reporting path, the role Discussion is introduced that contains subroles Participant 1…N. The agent controller with the highest influence level in Discussion role has also a joint allocation to subrole Problem Informant in Problem Communication role. Thus, this agent represents Discussion role in the interactions with Operational Management Team role (OMT).

The provision of relevant and reliable information about safety-related occurrences to OMT depends greatly on the informal influence relations that exist among controllers. More specifically, the relevant information is propagated if the controllers involved in the discussion are sufficiently influential and possess sufficient knowledge about occurrences. To create a quantitative model for informal incident reporting, the motivation model by Vroom (Pinder, 1998) is used. The motivation model defines the motivational force of an agent to perform some action as:

$$F_i = f\left(\sum_{j=1}^{n} E_{ij} \times V_j\right), \quad V_j = \sum_{k=1}^{m} V_{jk} \times I_{jk} \qquad (1)$$

Here, E_{ij} is the strength of the expectancy (belief) that act i will be followed by outcome j; V_j is the valence (i.e., perceived importance) of first-level outcome j; V_{jk} is the valence of second-level outcome k that follows first-level outcome j; I_{jk} is perceived instrumentality (belief about the likelihood) of outcome j for the attainment of outcome k.

This model is used to represent the motivation of the agent allocated to a participant role (within Discussion role) with the highest influence level to propagate information about a safety-related issue. The parameters of the motivation are defined as follows: instrumentalities $I11$ and $I12$ are assigned high values (0.9). Both second-level outcomes have a high level of priority for the controllers (valence value = 1). Expectancy $E11$ is defined as:

$$E11(\text{occur\_type}, CD) = ac(\text{occur\_type}) \times \sum_{C_i \in CD} \text{influence\_level}(C_i)$$

where CD is the set of the controllers involved in the discussion and $ac(\text{occur\_type})$ is defined as:

$$ac(\text{occur\_type}) = \begin{cases} 1, & N(\text{occur\_type}) \le N(\text{occur\_type})_{curr} \\ \dfrac{N(\text{occur\_type})_{curr}}{N(\text{occur\_type})}, & N(\text{occur\_type}) > N(\text{occur\_type})_{curr} \end{cases}$$

with $N(\text{occur\_type})$ the number of occurrences of the type occur_type required for the investigation (the same as for the formal incident reporting) and $N(\text{occur\_type})_{curr}$ the number of occurrences of the type occur_type observed by the controllers involved in the discussion so far.

Thus, the motivation force to report about a possible problem based on the observations of events of type occur_type is calculated using (1) as:

$$F(\text{occur\_type}, CD) = (1*0.9 + 1*0.9) * E11(\text{occur\_type}, CD)$$

If $F(\text{occur\_type}, CD) > 1.8$ (i.e., agent's expectancy $E11$ that the reported issue will be considered in $OMT > 1$), then the problem will be reported to OMT by the representative of Discussion role. Then, the problem will be discussed at the nearest OMT meeting and the occurrence investigation will be initiated.

6 SIMULATION RESULTS

Based on the specification constructed in Sections 4 and 5, 100 stochastic simulations with a simulation time of maximum 3 years (12 operational hours per day) each have been performed using the simulation tool LEADSTO (Bosse et al., 2007). When the formal or informal safety occurrence reporting has lead to the identification of a safety problem and a further investigation thereof, the simulation was halted. As a result of each simulation trial, a trace is generated by the LEADSTO. Then, such traces can be automatically analyzed using the TTL Checker software (Bosse et al., 2006). In this case study a number of properties has been checked automatically on 100 generated traces, two of which are described in the following. The first property calculates the number of traces, in which the safety problem has been found based on the reported occurrences of some type. Another property calculates the mean time of the problem recognition on all traces in which the problem of a particular type has been found. The simulation results for both formal and informal reporting are shown in Table 2.

Table 2: Results of the simulation experiments.

Event	*Percentage of traces, in which the investigation began*		*Mean time of the problem recognition (days)*	
	Formal	*Informal*	*Formal*	*Informal*
a	22%	21%	155.1	134.9
b	5%	15%	168.1	123.9
c	28%	50%	194.6	149.6
d	0%	0%	-	-
e	0%	3%	-	278.9
f	45%	11%	185.9	184.7
total	100%	100%	180.8	150.4

Table 2 shows that for both the formal and informal handling of safety occurrences in all simulation traces a safety investigation is initiated, however, the mean time until start of the investigation is 181 days in the formal case, whereas it is 150 days in the informal case. Considering the simulation results for the particular events, the mean time of recognition is smaller for all event types in the informal reporting path.

A main reason underlying the difference in the time until recognition of the safety problem is that situations like event b and event c are often recognized by both ground and runway controllers and thus feed common situation awareness on safety-critical aspects in informal discussions between controllers, whereas such events are just single occurrence reports in the formal incident reporting case. It remains to be validated whether this model predicted behavior concurs with practice.

7 CONCLUSIONS

This paper describes an automated formal approach for modeling and analysis of organizations and its application in the air traffic management domain. On the one hand, the approach allows specifying prescriptive aspects of a formal organization using the framework from (Sharpanskykh, 2008). On the other hand, it provides possibilities to specify stochastic behavior of organizational actors and the environment. By performing simulation, different scenarios of organizational behavior can be analyzed using the automated software.

An example of such analysis, in which the formal and informal occurrence reporting paths of the ATO are investigated, is provided in this paper. The analysis results show that the informal safety-occurrence reporting path results in faster identification of safety-related problems than the formal reporting path. Next research steps will focus on assessing the model validity and on evaluating whether this important feedback on safety occurrence reporting processes is recognized in actual air traffic organizations and may be a basis for organizational change.

REFERENCES

Blom, H.A.P., Stroeve, S.H., 2004. Multi-agent situation awareness error evolution in air traffic. *Proc. 7th Conference on Probabilistic Safety Assessment & Management*, Berlin, Germany

Bosse, T., Jonker, C.M., Meij, L. van der, Treur, J., 2007. A Language and Environment for Analysis of Dynamics by Simulation. *International Journal of Arificial Intelligence Tools*, 16: 435-464.

Bosse, T., Jonker, C.M., Meij, L. van der, Sharpanskykh, A., Treur, J., 2006. Specification and Verification of Dynamics in Cognitive Agent Models. In *Proceedings of the 6th Int. Conf. on Intelligent Agent Technology, IAT'06*. IEEE Computer Society Press, 247-255.

CIMOSA – *Open System Architecture for CIM*, 1993. ESPRIT Consortium AMICE, Springer-Verlag, Berlin.

Dalal, N., Kamath, M., Kolarik, W., Sivaraman, E., 2004. Toward an integrated framework for modeling enterprise processes, *Communications of the ACM*, 47(3), 83-87.

Eurocontrol: Air navigation system safety assessment methodology, 2004. SAF.ET1.ST03.1000-MAN-01, edition 2.0.

Koubarakis, M., Plexousakis, D., 2002. A formal framework for business process modeling and design. *Information Systems*, 27(5), 299–319.

Le Coze, J, 2005. Are organizations too complex to be integrated in technical risk assessment and current safety auditing? *Safety Science*, 43:613-638.

Pinder, C. C., 1998. *Work motivation in organizational behavior*. Upper Saddle River, NJ: Prentice-Hall.

Reason J., 1997 *Managing the risk of organizational accidents*. Ashgate, Aldershot, England

Scheer, A-W., Nuettgens, M., 2000. *ARIS Architecture and Reference Models for Business Process Management*. LNCS 1806, Springer, 366-389.

Sharpanskykh, A., 2008. On Computer-Aided Methods for Modeling and Analysis of Organizations. PhD Dissertation. Vrije Universiteit Amsterdam.

Tham, K.D., 1999. *Representation and Reasoning About Costs Using Enterprise Models and ABC*, PhD Dissertation, University of Toronto.

Van der Aalst, W.M.P., Van Hee, K.M., 2002. *Workflow Management: Models, Methods, and Systems*, MIT press, Cambridge, MA.