Agent-based Modelling and Analysis of Air Traffic Organisations

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Abstract. A modern Air Traffic Organisation (ATO) represents a complex organisation that involves many parties with diverse goals performing for a wide range of tasks. Due to the structural and behavioural complexity of ATOs, mistakes and performance problems are not rare in such organisations. Some of these faults may seriously affect safety, causing incidents. Therefore, the possibility to perform detailed and reliable analysis is of primary importance for ATOs. To this end, this chapter introduces an automated approach for modelling and analysis of complex ATOs. The developed model incorporates all important structural and behavioural aspects of an ATO. The approach is illustrated by a case study in which ATO's tasks related to movement of aircraft on the ground and to safety occurrence reporting are considered.

1. Introduction

An Air Traffic Organisation (ATO) ensures a safe and efficient flow of aircraft both at airports and in the air. An ATO represents a complex organisation that involves many parties with diverse goals performing a wide range of tasks. Among the ATO's participants are airports, air navigation service providers (ANSP), airlines, regulators, and the government. Due to the high complexity, inconsistencies and performance bottlenecks often occur in ATOs. Some of these faults may result into performance issues, whereas others can seriously affect safety, causing incidents. Therefore, the possibility to perform detailed and reliable automated analysis aiming at detecting safety hazards in ATOs is of primary importance in the air traffic domain. Currently, formal risk assessment approaches [6, 11] 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. Advantages of agent-based organisation modelling that allows investigating complex emergent dynamics of a system are increasingly recognized in the domain. In particular, agent-based modelling has been proposed as a means to assess safety risk of complex emergent dynamics of air traffic operations [15, 16]. These studies focus on the risk of air traffic operations and use a plain society of agents, without considering the organisational layer. Several approaches [8, 11] consider an influence of different organisational aspects on safety, however, without providing precise details. This chapter presents the first attempt to create a formal agent-based organisational model of an ATO using the developed previously organisation modelling and analysis framework [13] and the methodology from [16]. On the one hand, the framework allows specifying the prescriptive structural and behavioural dependencies of an organisation. On the other hand, it provides means to describe autonomous behaviour of the organisational actors. In contrast to many existing enterprise modelling approaches (CIMOSA [4]; ARIS [12]) this framework has a formal basis, which enables reliable analysis of models. More specifically, to express structural relations, sorted predicate logic-based languages are used, whereas the Temporal Trace Language (TTL) [2] is used for specifying dynamic aspects of organisations.

Also, more limited languages dedicated for automated modelling and analysis of particular aspects of organisations have been developed: process-oriented modelling techniques [18], organisational performance evaluation techniques [17]. However, modelling of particular organisational aspects does not allow defining interdependencies between different perspectives on organisations and to investigate a combined influence of factors from different perspectives on the organisational behavior. By considering multiple perspectives of organisations the designer is equipped with more rigorous and manifold analysis possibilities than by using analysis techniques dedicated to a particular view only.

In [5] an integrated framework for process and performance modelling is described that incorporates accounting/business parameters into a formal process modelling approach based on Petri-nets. However, key aspects as authority and power relations, organisational and individual goals, individual behavior are not considered. Another formal framework for business process modelling is described in [7] focusing on the formal goal-oriented modelling using situation calculus. Modelling and analysis of processes and other organisational concepts are not properly addressed in this framework. A formal framework for verifying models specified in Unified Enterprise Modelling Language (UEML) is proposed in [3]. It identifies a general idea to use conceptual graphs for verifying enterprise models; however, neither technical nor experimental results are provided to support this idea.

In the framework used in this chapter four interrelated views are distinguished: the *performance-oriented view* describes organisational goal structures, performance indicators structures, and relations between them; the *process-oriented view* describes organisational functions, processes, resources and relations between them; the *organisation-oriented view* describes organisational roles, their authority, responsibility and interraction relations; the *agent-oriented view* describes agents' types with their capabilities, and principles of allocating agents to roles.

The framework proposes a number of analysis techniques, the application of some of which is demonstrated in this chapter. Specifically, the constructed specification of the ATO is verified for correctness by applying the general and specific for particular views consistency verification techniques from [2, 13]. Further, the consequences of different types of agent behaviour that diverges from the prescriptive (formal) organisational specification are simulated.

The chapter is organized as follows. Section 2 introduces the description of the ATO under consideration. In Section 3 the developed model for the formal organisation is presented. A specification of the organisational agents is described in Section 4. The results of the correctness verification of the designed ATO specification are presented in Section 5. The results of the analysis by simulation are considered in Section 6. Section 7 concludes the chapter.

2 Case Study

The ATO performs a variety of tasks: development and evaluation of new air traffic operations (e.g., introduction of a new runway on an aerodrome), movement of aircraft on the ground, safety occurrence reporting and investigation, etc. In this paper we focus particularly on the ATO tasks related to movement of aircraft on the ground and safety occurrence reporting. More specifically, the taxiing of an aircraft to a designated runway and the subsequent take off from this runway are considered using input from [14, 15]. Furthermore, reporting of safety occurrences during taxiing operations near an active runway are investigated.

During the taxiing, an aircraft moves from one sector of the airport to another, until it reaches the runway designated for take off. The crew of an aircraft consists of the pilot-in-command and the second pilot. The monitoring and control over the traffic in a sector is performed by a dedicated ground controller. Also, the control over aircraft on a runway and in its surroundings is performed by a dedicated runway controller. During the taxiing control over an aircraft is handed over from one controller to another, depending on the physical position of the aircraft. Before crossing a runway on its way, the crew of a taxiing aircraft should request the controller responsible for the runway for clearance. Only when the clearance is provided, the aircraft is allowed to cross. The same holds for the take off operation. Controllers may be situated in the same or in different towers at the airdrome, each of which is guided by a Tower Controllers Supervisor.

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 organisational lines or via informal coordination. The formal organisation 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 in the case of a consistent series of less severe occurrences, the SIU may initiate an investigation for possible causes. The investigation results are reported to the operation management team at the ANSP.

The organisation 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 organisation). 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.

3 Modelling the Formal Air Traffic Organisation

To perform analysis of the ATO's structures and processes both the specification of the formal organisation and the specifications of agents and the principles of their allocation to the roles should be developed. To design such specifications a sequence of design steps is identified in [16]. The formal organisational specification is built by executing the steps 1-9 described below. Agents that cause performance variability in the ATO are specified in the next section.

In general, organisation modelling is a challenging task that requires a close investigation of organisational documents (e.g., policies, job prescriptions), interaction with organisational actors (e.g., by organising interviews and formulating questionnaires).

Step 1. The identification of the organisational roles

In this step organisational roles are identified, both simple and composite ones and subrole-relations are established. A *role* represents a set of functionalities of (part of) an organisation abstracted from specific actors who fulfil them. Each role can be composed by several other roles. A role composed of subroles is called a composite role. In the considered organisation roles can be represented at three aggregation levels (see Fig. 1-3). For example, at the aggregation level 1 the Air Navigation Service Provider is considered as one composite role interacting with other roles. The subroles of the Air Navigation Service Provider (e.g., the Control Unit) are described at the aggregation level 2, and so forth. Note that based on the introduced generic roles role instances may be defined for particular applications (e.g., in simulations). Each role has an input and an output interface facilitating in interaction with other roles.

A special role type is the environment (env). The environment for the case study consists of two sectors of an airdrome, 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.

Step 2. The specification of the interactions between the roles

In this step, interaction relations between roles, roles and the environment are identified. To specify interaction relations, the interfaces of the roles and the environment are formalised by interaction ontologies. For a role, input and output ontologies are specified referred to as interface ontologies, which are used to describe interactions with other roles. Generally speaking, an input ontology determines what types of information are allowed to be transferred to the input of a role (or of the environment), and an output ontology predefines what kinds of information can be generated at the output of a role (or of the environment). For specifying communications the interface ontologies for all roles include the following predicate:

communication_from_to: ROLE x ROLE x MSG_TYPE x CONTENT

Here the first argument denoted the role-source of information, the second – the role-recipient of information, the third argument denoted the types of the communication (which may be one of the following {observe, inform, request, decision, readback}) and the fourth – the content of the communication. The sort ROLE is a composite sort that comprises all subsorts of the roles of particular types (e.g., CONTROLLER). The sort CONTENT is also the composite sort that comprises all names of terms that are used as the communication content. Such terms are constructed from sorted constants, variables and functions in the standard predicate logic way.

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. It represents information transition between two adjacent aggregation levels. The interaction relations for the ATO have been identified and formalised at each aggregation level (see Fig. 1-3). An ANSP interacts with Crews of aircraft being guided by air traffic controllers. A regulator performs safety assessment of ANSP's operations and procedures regularly. In some ANSPs Ministry of Justice may be involved in the safety investigation of severe occurrences.

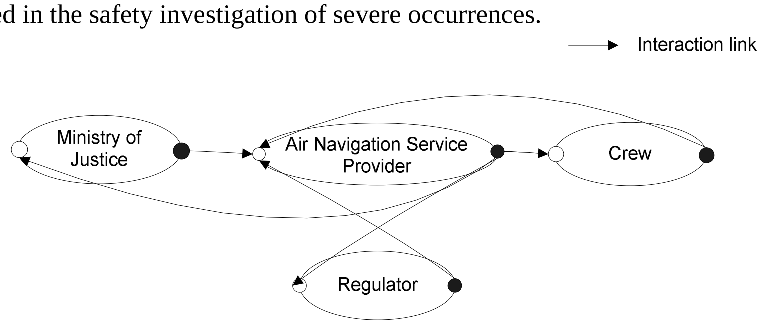


Fig. 1. The interaction relations between the generic roles at the aggregation level 1

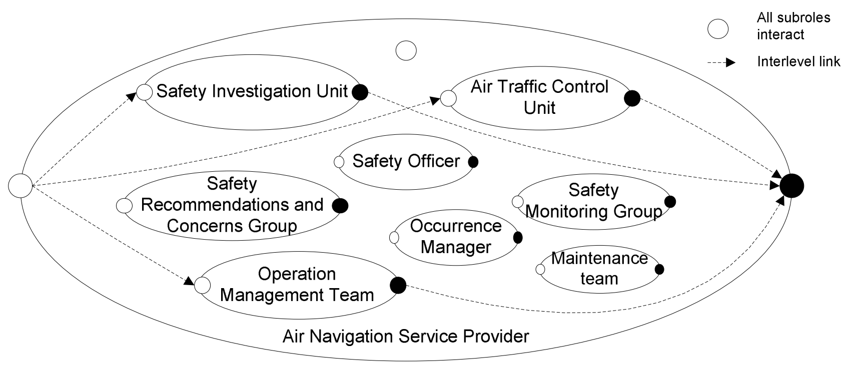
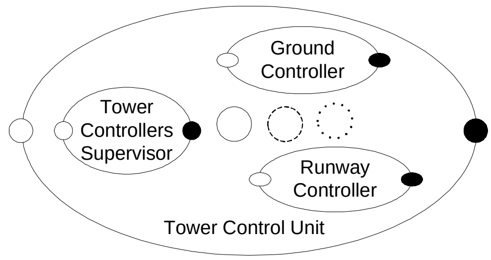
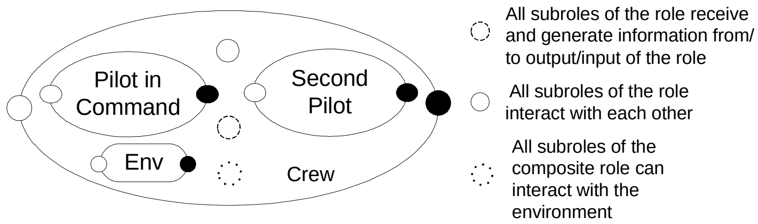


Fig. 2. The role Air NavigationService Provider considered at the aggregation level 2



(a)



(b)

Fig. 3. Interaction relations at the aggregation level 3: (a) within the Tower Control Unit (subrole of the ANSP) and (b) within Crew role (subrole of the Airline).

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. Knowledge-related requirements define facts and procedures that must be well understood by an agent. Skills describe developed abilities of agents to use their knowledge for tasks performance. For example the following requirements for the air traffic controller role are defined: (1) passed a medical examination; (2) 2 or 4 year college degree before initiation of training; (3) thorough knowledge of the air traffic management system and the flight regulations; (4) computer training; (5) air traffic control training; (6) excellent listening and communication skills; (7) quick decision-making skills.

Step 4. The identification of the organisational performance indicators and goals
In this step, organisational goals, performance indicators (PIs) and relations between them and organisational roles are identified. A *PI* is a quantitative or qualitative indicator that reflects the state/progress of the company, unit or individual. PIs can be hard (e.g., taxiing time) or soft, i.e., not directly measurable, qualitative (e.g., level of collaboration between controllers). PIs can be related through various relationships. The following relations are considered in the framework: (strongly) positive/negative causal influence of one PI on another, positive/negative correlation between two PIs, aggregation – two PIs express the same measure at different aggregation levels.

Goals are objectives that describe a desired state or development and are defined as expressions over PIs. The characteristics of a goal include, among others: *priority*; *horizon* – for which time point/interval should the goal be satisfied; *hardness* – hard or soft (for which instead of satisfaction, degrees of *satisficing* are defined). A goal can be refined into subgoals forming a hierarchy. Some examples of the goals and PIs of the ATO are given in Table 1. Here goals 25, 26, 27, 28, 16 and 21 are subgoals of goal 10, and the PIs, on which these subgoals are based, are related to the PI of goal 10 by the aggregation relation. Goals are related to roles. For example, goal 10 is associated with Airline, Tower Control Unit and Safety Investigation Unit roles.

Step 5. The specification of the resources

In this step organisational resource types and resources are identified, and characteristics for them are provided, such as: *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.

Table 1. Examples of goals and PIs of the ATO

#	Goal	Based on the PI
10	It is required to maintain a high level of safety of execution of tasks related to the air traffic management	The level of safety of execution of tasks related to the air traffic management
16	It is required to maintain a high level of robustness and unambiguousness of the control (coordination) structure for the execution of tasks	The level of robustness and unambiguousness of the control (coordination) structure for the execution of tasks
20	It is required to maintain a sufficient level of autonomy of decision making and the operation execution for the roles involved into the air traffic management	The level of autonomy of decision making and the operation execution for the roles involved into the air traffic management
21	It is required to maintain unambiguousness, consistency, correctness and timeliness of information exchanged between agents	The unambiguousness, consistency, correctness and timeliness of information exchanged between agents
23	It is desired to increase the volume of passengers, departing/arriving from/to an airport	The volume of passengers, departing/arriving from/to an airport
25	It is required to maintain a high level of conformance of all roles involved into the air traffic management to the formal norms and regulations defined for their tasks	The level of conformance of all roles involved into the air traffic management to the formal norms and regulations defined for their tasks.
26	It is required to maintain a high (sufficient) level of proficiency of pilots	The level of proficiency of pilots
27	It is required to maintain a high (sufficient) level of proficiency of controllers	The level of proficiency of controllers
28	It is required to maintain the high quality and reliability of the hardware used in the air traffic control management	The quality and reliability of the hardware used in the air traffic control management

Step 6. The identification of the organisational tasks, the relations between the tasks, and relations between the tasks, the resources and the goals

A *task* represents a function performed in the organisation 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 organisation should contribute to the satisfaction of one or more organisational goals. Examples of the ATO's tasks in relation to goals and resources are given in Table 2.

Table 2. Examples of the tasks of the ATO in relation to goals and resources

#	Task name	Uses	Produces	Durations
1	Taxiing the aircraft to the designated runway	All resources of the subtasks	All resources of the subtasks	Depends on the durations of subtasks
1.1	Taxiing the aircraft on a taxiway	Airport's diagram, the taxi instructions, compass, radar, aircraft	-	Depends on a particular taxiway
Goal: 29, 30, 31, 32, 33, 34, 20				
1.2	Switching to the frequency of another controller	Data about the new frequency	-	Min: 1 sec Max: 5 sec
Goal: 30, 31, 33				
1.3	Inquiry for the clearance for crossing an active runway	Observations, the taxi instructions,communication R/T system	A request for clearance	Min: 2 sec Max: 5 sec
Goal: 30, 31, 33				
1.4	Making and communicating the decision on a request for crossing a runway	Data about the current state of the runway, a request for for clearance to cross, communication R/T system	'Position and hold' or 'clearance is provided'	Min: 3 sec Max: 11 sec
Goal: 35, 36, 32, 34, 20				
1.5	Crossing a runway	Clearance to cross, airport's diagram, taxiing instructions, radar	'Clear of the runway'	Min: 30 sec Max: 60 sec
Goal: 30, 31, 34, 33, 20				
2	Safety occurrence reporting and the report handling	All resources of the subtasks	All resources of the subtasks	Depends on the duration of the subtasks
2.1	Create a notification report	The observation from the environment of an occurrence that may be classified as an incident/accident, the incident classification database	A notification report	Min:3 min Max: 24 hours
2.2	Preliminary assessment of an occurrence	A processed notification report	A preliminary safety occurrence assessment report	For severe occurrences: Max: 48 hours For less severe occurrences: Max: 72 hours

2.3	Investigation of an occurrence	A preliminary safety occurrence assessment report, additional data about the occurrence (optional)	An interrim safety occurrence assessment report	Min: 3 days Max: 90 days

Step 7. The specification of the authority relations

In this step authority (i.e., informal power) relations of an organisation are identified: superior-subordinate relations on roles with respect to tasks, responsibility relations, control for resources, authorization relations. Organisational roles may have different rights and responsibilities with respect to different aspects of task execution, such as execution, passive monitoring, consulting, making technological decisions (i.e., decisions that concern technical questions related to the task content) and making managerial decisions (i.e., decisions that concern general organisational issues related to the task). Examples of responsibility relations in the air traffic organisational model are presented in Table 3.

Table 3. The responsibility relations of the roles on different aspects of some identified tasks

Task	Execution	Monitoring	Consulting	Technological decisions	Managerial decisions
1.1	Crew	Ground Controller, Tower Controllers Supervisor	Ground Controller	Crew	Ground Controller, Tower Controllers Supervisor
1.2	Crew		Ground Controller	Crew	
1.3	Crew				
2.1	Safety Investigator	Safety Manager; Safety Investigator	Safety Manager	Safety Investigator	
2.3	Safety Investigator	Safety Manager, Occurrence Manager	Safety Manager	Safety Investigator	

Step 8. The specification of the flows of control

In this step dynamic structures (called workflows or flows of control) are defined that represent temporal execution sequences of processes of an organisation in particular scenarios. The framework allows representing all commonly used workflow templates described in [18]. In Fig.4 a worklow is given that describes the process of taxiing of an aircraft to and taking-off from a designated runway. Fig. 5 describes the execution of the formal occurrence reporting initiated by a controller.

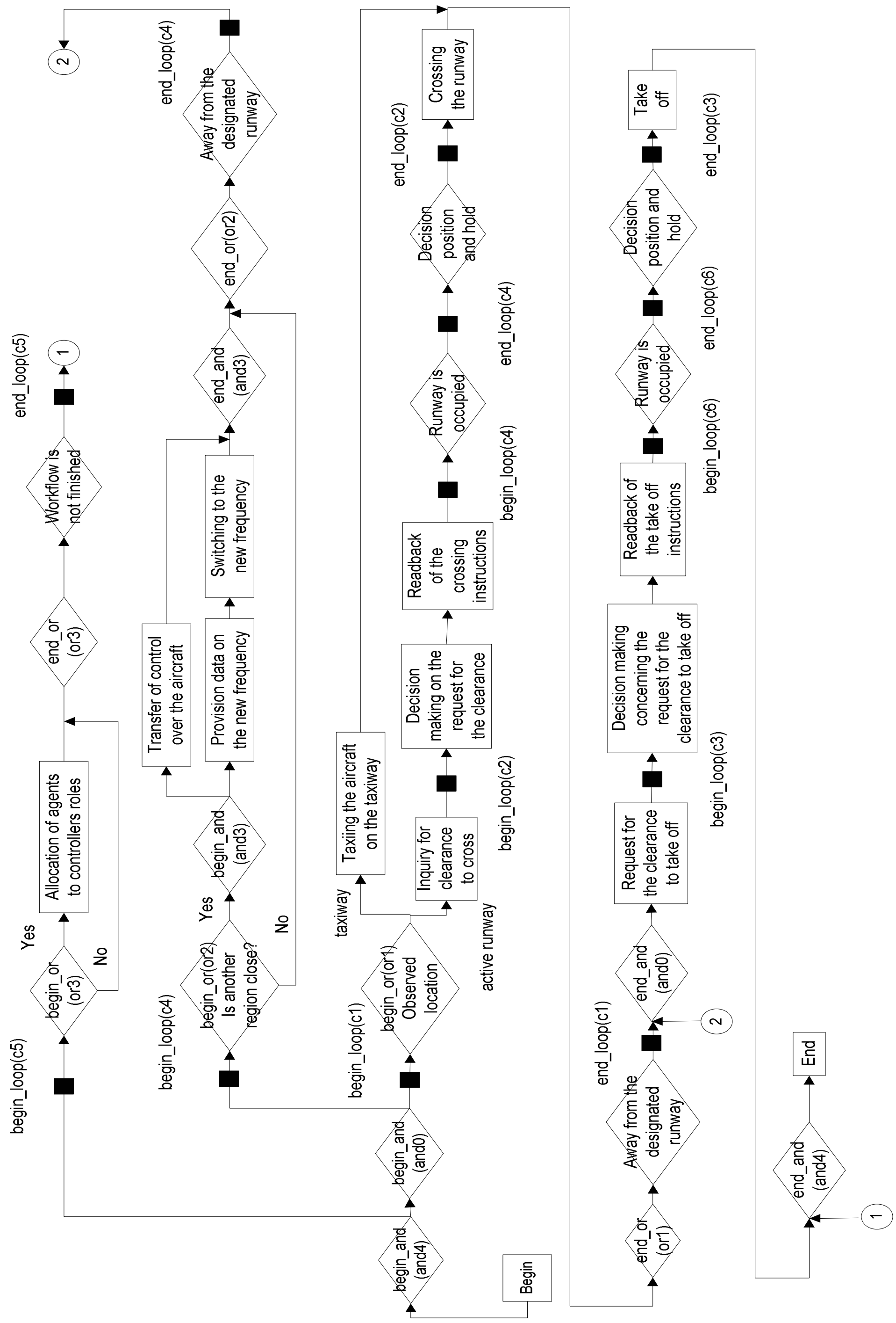


Fig. 4. Workflow for an aircraft taxiing to and taking-off from a designated runway

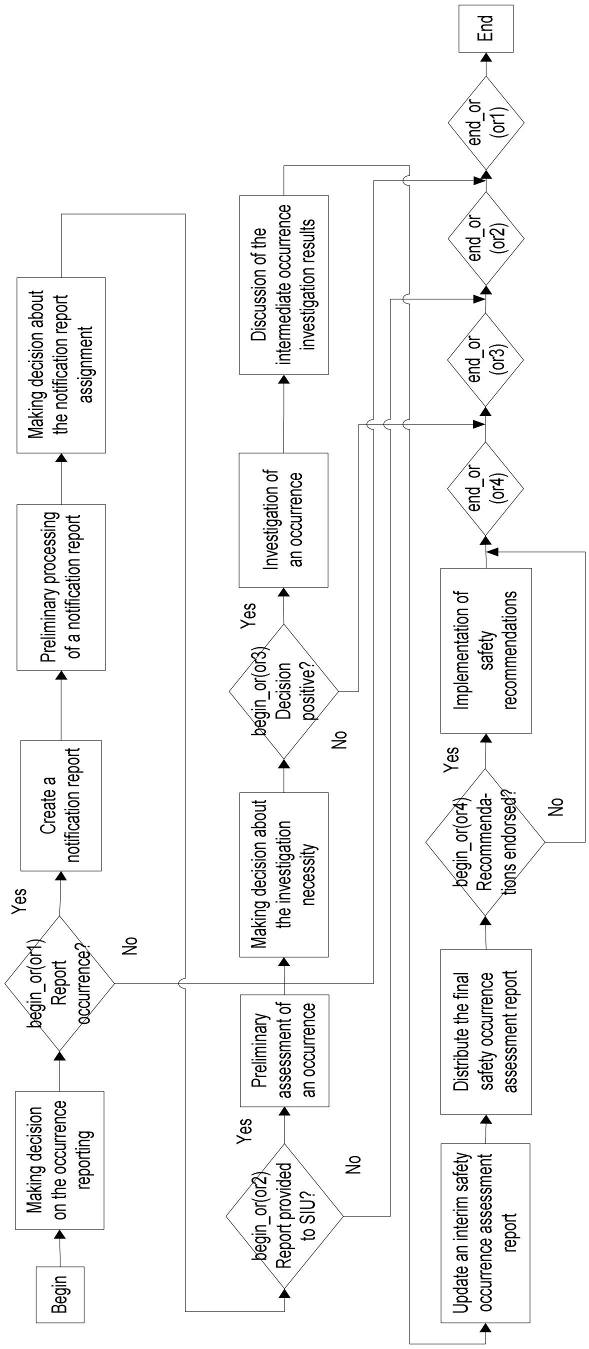


Fig. 5. The workflow that defines the execution of the safety occurrence reporting and the report handling task initiated by a controller

Step 9. The identification of the generic and domain-specific constraints

In this step generic and domain-specific constraints imposed on a formal organisational specification are identified. Generic constraints need to be satisfied by any organisational specification. Domain-specific constraints are dictated by the application domain and may be changed by the designer. A set of constraints imposed on an organisational specification is expressed using the formal languages of the framework. An organisational specification is *correct* if every constraint in the corresponding set is a logical consequence of this specification. The framework provides means for automated checking of the correctness of a specification. Consider examples of the domain-specific constraints of the ATO obtained from the formal regulations of a controller and of a pilot:

C1: When an aircraft is approaching to an active 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: A controller may guide maximum two aircrafts at the same time.

C4: A controller is not allowed to issue any new clearances for some runway until this runway is vacated by the aircraft that had received the last clearance from the controller.

C5: Perform the allocation of agents-controllers to the aircraft monitoring processes in such a way that the number of processes executed at the same time by each controller is less than four.

Furthermore, the ANSP's reprimand policies related to reporting were formalized as constraints.

4 Modelling of Agents

The specification of a formal organisation forms a part of an overall organisational specification. Another part describes characteristics and behavior of agents and their allocation to the organisational roles. Thus, an overall organisational specification combines prescriptive aspects of a formal organisation with the specification of the autonomous behavior of agents. Using such specifications, investigations of different scenarios of organisational behavior can be performed by simulation.

Agent models are formally grounded in order-sorted predicate logic with finite sorts. More specifically, the static properties of a model are expressed using the traditional sorted first-order predicate logic, whereas dynamic aspects are specified using the Temporal Trace Language (TTL) [2, 13], a variant of the order-sorted predicate logic. In TTL, the dynamics of a system are represented by a temporally ordered sequence of states. Each state is characterized by a unique time point and a set of state properties that hold, specified using the predicate at: STATE_PROPERTY x TIME. Dynamic properties are defined in TTL as transition 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 eventually perform a, is formalized in TTL as:

∀t:TIME [at(internal(ag, belief(reward_for_action(r, a))), t) →
∃t1 > t at(output(i, performed_action(a)), t1)]

The behavior of an agent can be considered from external and internal perspectives. From the external perspective the behavior can be specified by temporal correlations between agent's input and output states, corresponding to interaction with other agents and with the environment. An agent perceives information by observation and generates output in the form of communication or actions.

From the internal perspective the behavior is characterized by a specification of direct causal relations between internal states of the agent, based on which an externally observable behavioral pattern is generated. It is assumed that agents create time-labeled internal representations (*beliefs*) about their input and output states, which may persist over time:

∀ag:AGENT ∀p:STATE_PROPERTY ∀t:TIME at(input(ag, p), t)→ at(internal(ag, belief(p, t), t+1))

Information about observed safety occurrences is stored by agents as beliefs: e.g., belief(observed_occurrence_with(ot:OCCURRENCE_TYPE, ag:AGENT)), t: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 (such as expectancies and instrumentalities from the following section):

belief(occurs_after(p1:STATE_PROPERTY, p2:STATE_PROPERTY, t1:TIME, t2:TIME), t:TIME), which expresses that state property p2 holds t' (t1 < t' < t2) time points after p1 holds.

In social science behavior of individuals is considered as *goal-driven*. It is also recognised that individual goals are based on *needs*. Different types of needs are distinguished: (1) *extrinsic needs* associated with biological comfort and material rewards; (2) *social interaction* needs that refer to the desire for social approval and affiliation; in particular own group approval and management approval; (3) *intrinsic needs* that concern the desires for self-development and self-actualization; in particular contribution to organisational safety-related goals and self-esteem, self-confidence and self-actualization needs. Different needs have different priorities and minimal acceptable satisfaction levels for individuals.

Table 4. Skills and influence of the agents-controllers.

Agent	Skill(development level)	Influence
ag_controllerA	atc (2)	0.3
ag_controllerB	atc (3)	0.6
ag_controllerC	atc (2)	0.3
ag_controllerD	atc (4)	1
ag_controllerE	atc (3)	0.6
ag_controllerF	atc (4)	1
ag_controllerG	employee management(4) atc (4)	1

Furthermore, agents are characterised by sets of skills and personal traits that influence their behavior and performance in the organisation. 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 given in Table 5. All the agents-controllers possess the aggregated air traffic control skill (atc), which allows them to be assigned either to Runway or Ground Controller 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 control domain, it is assumed that the development level of the atc skill forms the basis for influence (informal power) of controllers: the higher the development level of the controller's atc, the more influence s/he has in the organisation (the assumed influence levels for this study are given in Table 4). For plausible modelling of the organisation authority structure both informal power (influence) and formal power (authority) of the organisation (identified in Step 7 in Section 3) should be considered explicitly, as they both influence the execution of tasks.

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.

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. In the considered case study at the beginning of each day, three agents controllers from Table 4 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.

Controller and crew agents are able to react to 6 types of safety-related occurrences that may happen during the execution of taxiing operations. Table 5 shows the events with the probability values of their occurrence assumed in the simulation studies considered in Section 6.

Table 5. Safety-relevant events and their probability values per taxiing operation.

Event	Probability
(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

Table 6. The observation possibilities of safety-relevant events by controllers and crews.

Event	Identification by			
	Runway Controller	Ground Controller	Crew takingoff	Crew taxiing
a	Yes	No	Yes	Yes
b	Yes	Maybe	Yes	Maybe
c	Yes	Maybe	Maybe	No
d	No	Maybe	Maybe	No
e	Maybe	Maybe	Maybe	No
f	Yes	No	Maybe	Maybe

Table 7. The probability values for recognition and registration of events by controllers and crews.

Event	Probability of correct event recognition		Probability of the event registration	
	Controller	Crew	Controller	Crew
a	$1 - 10^{-5}$	$1 - 10^{-5}$	$1 - 10^{-5}$	$1 - 10^{-5}$
b	$1 - 10^{-5}$	$1 - 10^{-5}$	0.99	0.99
c	0.99	0.98	0.9	0.9
d	0.95	0.8	0.5	0.5
e	0.7	0.9	0.5	0.5
f	0.99	0.9	0.99	0.99

Some event types can be observed by the agents allocated to particular roles only (see Table 6). Moreover, agents may not always recognize and report observed events correctly (see Table 7). 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 type (b), 6 of type (c), 55 of type (d), 55 of type (e), and 6 of type (f).

According to the formal organisation a shift of a controller consists of three sessions. The duration of each session is 1 hour. After each session, a break with the duration 1 hour follows. During breaks controllers discuss occurrences observed during their shifts. Since the results of such discussions may initiate the path of informal occurrence reporting, interaction between controllers during such discussions should be modeled explicitly. To this end, the role Discussion is introduced that contains subroles Participant 1…N. The agent controller with the highest influence level in Discussion role has also the joint allocation to subrole Problem Informant in Problem Communication role (see Fig. 6).

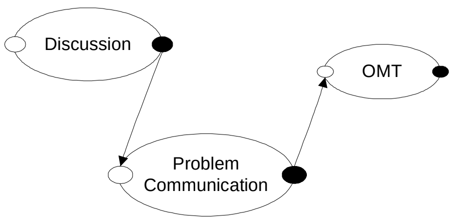


Fig. 6. Interaction relations in the ATO considered at the aggregation level 1

Thus, this agent represents Discussion role in the interactions with the management (more specifically, Operational Management (OMT) role). OMT has the formally defined authority to make decisions based on information provided by controllers (e.g., the decision about the beginning of an occurrence investigation). 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 [9] is used. The motivation model defines the motivational force of an agent to perform some action as:

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

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/the desire level) 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 (see Fig. 7). In the model two second-level outcomes are identified related to the needs of a controller: positive impact on the organisational goals (intrinsic needs) and group acceptance (social interaction needs). The parameters of the motivation are defined as follows: instrumentalities I11 and I12 are assigned high values (0.9), as the controllers involved in the discussion believe that the identified safety related issue will contribute to the satisfaction of the organisational safety-related goals. Both second-level outcomes have a high level of priority for the controllers (valence value = 1).

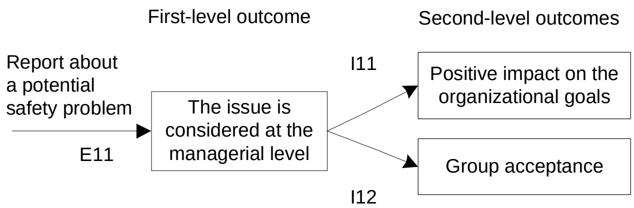


Fig. 7. The motivation model of a controller for reporting about a potential safety problem

Expectancy E11 is proportional to the influence levels of the controllers in the discussion as well as to the quotient of the number of occurrences required for the investigation and the number of occurrences observed by the controllers involved in the discussion so far:

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

where CD is the set of the controllers involved in the discussion and ac(occur_type) is defined as:

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

with N(occur_type) the number of occurrences of the type occur_type required for the investigation (the same as for the formal incident reporting) and $N(occur\_type)_{curr}$ 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

$$F(occur\_type, CD) = 1.8 * E11(occur\_type, CD)$$

If F(occur_type, CD) > 1.8, the problem will be reported to the management by the controller representative of Discussion role. After that, the problem will be discussed at the nearest OMT meeting and the occurrence investigation will be initiated.

5 Correctness Verification

In this Section the results of the correctness verification of the designed ATO specification are presented. As a result of the automated analysis a number of inconsistencies have been identified. In particular, identification of (potential) conflicts in the goal structure has been performed using the corresponding PI structure based on the following principle. If goals are related by a refinement relation, then the PIs corresponding to these goals are related by a certain (positive or negative) causality relation. To determine the exact type of causality, goal expressions should be analyzed. Typically a goal is defined based on a PI expression in the form of (a conjunction of) clauses in the form [pi op value], where op is one of the relations =, <, or >, and in the form of individual PIs involved in the optimized goal pattern. By analyzing a goal expression target/unsatisfactory values of the PI that contribute to the satisfaction/failure of the goal can be determined on the PI's scale. For example the target value of the PI 'the level of safety of execution of tasks related to the air traffic management' from goal 10 'It is required to maintain a high level of safety of execution of tasks related to the air traffic management' is 'high', whereas the unsatisfactory values of the PI are 'average' and 'low' (given a three-valued qualitative scale).

When the target and unsatisfactory values of a PI are identified, a label ('↑' indicating growth of a PI; '↓' indicating decrease of a PI) may be determined for the PI that indicates the dynamics of change of the PI, when the goal's satisfaction degree changes from denied (failed) to satisfied. For example, for the PI 'the level of safety of execution of tasks related to the air traffic management' of the goal 10 label ↑ is identified. A PI used for a goal pattern of the type minimize (maximize) can be labelled by ↓ (↑) even without considering its values. Note that in some cases additional information is required to identify the label. For example, for the goal 'it is required to maintain the density of traffic = 100' the target value of the PI is 100, whereas the unsatisfactory values are in principle all values on the PI's scale ≠ 100 (i.e., on the scale used both PI values > 100 and < 100 are possible). To determine the label in this case, information is needed, for example, on the unsatisfactory PI's values that can actually be observed in reality.

If the same labels are identified for the PIs of a goal and of its subgoal, then one may assume that the PIs are related by a positive causality relation, in case of different labels the PIs are related by a negative causality relation. The higher the degree of influence of a subgoal on its parent goal, the higher the confidence that the identified relation indeed holds.

Note that since the designer has a lot of freedom in specifying goal expressions, there is no guarantee that inconsistencies identified in a PI structure are valid. Therefore, all automatically identified inconsistencies in goal and PI structures still need to be confirmed by the designer. Below the algorithm is given to verify the consistency of goal and PI structures by processing individual subgoal relations in the goal hierarchy.

Algorithm to verify the consistency of goal and PI structures

For each subgoal relation from the goal hierarchy perform the following steps:

1. If the goal pattern of the subgoal is of type minimize (maximize), then the PI of the subgoal is labelled by ↓ (↑); proceed with Step 4.
2. Identify the target and unsatisfactory values of the PI of the subgoal.
3. Identify the label for the PI of the subgoal. If the label is unknown, return UNKNOWN.
4. If the goal pattern of the parent goal is of type minimize (maximize), then the PI of the parent goal is labelled by ↓ (↑); proceed with Step 7.
5. Identify the target and unsatisfactory values of the PI of the parent goal.
6. Identify the label for the PI of the parent goal. If the type is unknown, return UNKNOWN.

7a. If the labels of the PIs of the subgoal and of its parent goal are the same,
and the subgoal has a high degree of influence on its parent goal (i.e., the goals are related by satisfices or is_subgoal_of relations),
and the PIs of the subgoal and the parent goal are related by a negative causality relation in the PI structure,
then return INCONSISTENT_HIGH_CONFIDENCE (i.e., inconsistency is identified that concerns the considered subgoal relation and the relation from the PI structure between the PIs on which the goals are based)
else
7b. If the labels of the PIs of the subgoal and of its parent goal are the same,
and the subgoal has a low degree of influence on its parent goal (i.e., the goals are related by contributes_to relation),
and the PIs of the subgoal and the parent goal are related by a negative causality relation in the PI structure,
then return INCONSISTENT_LOW_CONFIDENCE
else
7c. If the labels of the PIs of the subgoal and of its parent goal are opposite,
and the subgoal has a high degree of influence on its parent goal,
and the PIs of the subgoal and the parent goal are related by a positive causality relation in the PI structure
then return INCONSISTENT_HIGH_CONFIDENCE
else
7d. If the labels of the PIs of the subgoal and of its parent goal are different,
and the subgoal has a low degree of influence on its parent goal,
and the PIs of the subgoal and the parent goal are related by a positive causality relation in the PI structure
then return INCONSISTENT_LOW_CONFIDENCE
else
7e. return CONSISTENT

Using this algorithm several (potential) conflicts have been identified in the goal structure from the case study: between goals 27 and 37; between goals 38 and 37; between goals 20 and 25; and between goals 23 and 25. The goals that are in conflict cannot be satisfied at the same time. For example, goal 25 ensures adherence of the roles to the safety-related norms, which may not always be optimal from the performance point of view (goal 23). Besides execution of tasks, the formal authority relations influence the satisfaction of organisational goals. For example, to achieve the satisfaction of the goal 20, the crews and the controllers should be provided sufficient decision making power with respect to their tasks.

To check the constraints introduced in step 9 in Section 3 a number of dedicated algorthims have been developed. In particular, consider the algorithm for checking constraint C5 for a controller role r.

Algorithm to verify the constraint C5

1. Identify the set of processes for which the role is responsible: PROC_REL={p:PROCESS| ∃a∈ ASPECT is_responsible_for(r,a, p)}

2. For each process p∈ PROC_REL identify the execution interval $[est_p, let_p]$ and write the values est_p and let_p in a new row of the allocation matrix M of role r. If a role has an allocation for a part of the execution interval of a process, then the time points of the beginning and end of this allocation is written in M.

3. Process the obtained allocation matrix M row by row. For each row identify the existence of non-empty intersections with intervals represented by other rows of M. An intersection of the intervals represented by rows i and j is nonempty if $\neg((m_{i2} < m_{j1}) \vee (m_{j2} < m_{i1}))$ is true. When a row is processed, it is not taken into account in any other evaluations. If for a row the amount of non-empty intersections is greater than 4, then **C5 is not satisfied**, **exit**.

4. When all rows are processed, **C5 is satisfied.**

The presented algorithm proceeds under the assumption that any organisational process p may be executed at any time point during the interval $[est_p, let_p]$. Thus, the satisfaction of constraint C5 is checked for all possible executions (combinations of intervals) of the processes allocated to an agent. To this end, instead of the calculation of combinations of processes at each time step (as in state-based methods), the algorithm establishes the existence of non-empty intersections of the complete execution intervals of processes in a more efficient way. As shown in [10] the time complexity for the calculation of the execution bounds for all processes of a workflow for the worst case is not greater than $O(|P|^2 Cw)$, where P is the set of processes of the workflow, and Cw is the set of constraints on the workflow.

The automated verification of this constraint identified many situations in which the same controller role was allocated to more than four aircraft's monitoring processes, thus violating constraints C3 and C5, and sacrificing the satisfaction of goals 10 and 24. Sometimes the management to keep the satisfaction of C5, allocates not (completely) qualified agents to the controller roles, thus, causing the dissatisfaction of goal 10. Obviously, the satisfaction of the important safety-related goal 10 is sacrificed in both solutions. The lack of the consideration for the safety-related goals may cause incidents or even accidents.

6 Analysis by simulation

Using the developed model of the ATO, simulation of different scenarios can be performed. In section 6.1 the simulation results of the runway incursion scenario considered in the case study are presented. Then, the simulation results of the safety occurrence reporting scenario are considered in section 6.2.

6.1 Simulation results for the runway incursion scenario

In this scenario based on the joint decision of the Airport's Management, the ANSP and the largest airlines, the new runway runway1 has been introduced. Due to its physical position, most of the aircraft taxiing to other runways need to cross runway1 on its way (runway1 can be crossed at one place only, whereas may be approached using two taxiways situated in two different sectors of the airport) (see Fig. 8 below).

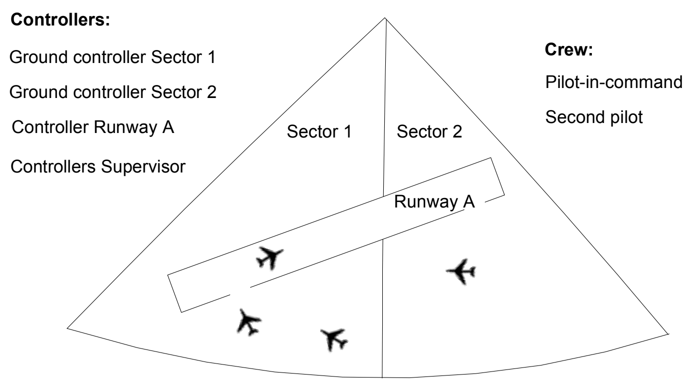


Fig. 8. A graphical layout for the airport situation considered in the scenario

The purpose of this study was to investigate the safety issues that may be caused by the introduction of runway1. Both the normal and the critical configurations have been investigated. In the normal configuration the number of aircraft guided by each controller is less than 3, whereas in the critical - the number ≥ 6 and constraint C5 cannot be satisfied for some controllers. The number of agents-controllers in both configurations is limited to 4, 1 of which is always allocated to Tower Controllers Supervisor role. This agent sees to the satisfaction of constraint C5. It is assumed that the agents are properly qualified for their roles. The behaviour of the allocated agents is defined by the ATO formal specification extended with the behavioural deviations, some of which are identified in [15] (e.g., incorrect situation awareness, mistakes) associated with the probability values. Some of these values are dependant on the agents' workload: the higher the agent's workload, the more chance of its error. In the study only serious occurrences were considered, such as an incursion of aircraft on a runway. One hundred simulation trials with the simulation time 3 years and simulation step 1 hour have been performed in the LeadsTo simulation environment [1]. The obtained simulation traces have been analyzed using the the TTL Checker software [2]. By the analysis the following results have been obtained:

(1) The agent allocated to Controller Runway1 role in all traces most of the time was monitoring at least 4 aircraft (i.e., was overloaded).

(2) The ground controller of the sector 1 was also overloaded, guiding in average three aircrafts at the same time.

(3) The incursion event on the runway1 occurred in 36 traces from 100.

(4) The number of incursions caused by the combination of the events a (the crew mistakenly recognized the runway as a taxiway) and c (the responsible ground controller forgot to inform the crew about the frequency change because of the high workload) is 30.

(5) The number of incursions caused by mistakes of the runway controller in the calculation of the separation distance between aircrafts is 5.

(6) There is only one incursion caused by a crew mistakenly reacting to the clearance for some other crew.

In the future a precise validation of the obtained results will be performed.

6.2 Simulation results for the safety occurrence reporting scenario

For the safety occurrence reporting both the formal and informal reporting paths were simulated and compared. Based on the developed model of the ATO 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. 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. Besides the logical analysis, the tool allows statistical post-processing of traces. For this the following functions are used:

case(logical_formula, value1, value2): if logical_formula is true, then the case function is mapped to value1, otherwise – to value2.

sum([summation_variables], case(logical_formula, value1, 0)): logical_formula is evaluated for every combination of values from the domains of each from the summation_variables; and for every evaluation when the logical formula is evaluated to true, value1 is added to the resulting value of the sum function.

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. Formally, for the occurrence type a:

sum([γ:TRACE], case(∃t:TIME holds(state(γ, t, environ), problem_found_based_on(a)), true), 1, 0)) > 0

Another property calculates the mean time of the problem recognition on all traces in which the problem of a particular type has been found. Formally, for the occurrence type a:

sum([γ:TRACE], case(∃t:TIME holds(state(γ, t, environ), problem_found_based_on(a)), true), t, 0)) / sum([γ:TRACE], case(∃t:TIME holds(state(γ, t, environ), problem_found_based_on(a)), true), 1, 0))> 0

The simulation results for both formal and informal reporting cases are presented in Table 8.

Table 8. 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

The mean time value of the identification of a safety related problem with respect to some event type is calculated over all traces, in which the occurrences of events of this type caused the incident investigation.

Table 8 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* ("Taxiing aircraft stops progressing on the runway crossing only after the stopbar and due to a call by the runway controller") and event *c* ("Taxiing aircraft makes wrong turn and progresses towards the runway crossing") are often recognized by both ground and runway controllers and thus feed common situation awareness on safety-critical aspects in informal discussions, whereas such events are just single occurrence reports in the formal incident reporting case.

7 Conclusions

The paper presents the first attempt to create a formal agent-based organisational model of an ATO using the framework of [13]. A typical ATO has high structural and behavioural complexities that present a challenge both for modelling and analysis of such an organisation. All important aspects of the considered organisation have been identified at four complementary levels, i.e. performance-oriented, process-oriented, organisation-oriented and agent-oriented. The modelling framework used allows scalability by distinguishing four interrelated organisational views and by specifying an organisational model at different aggregation levels and identifying relations between these levels. However, for complex organisations (such as ATOs) specifications of lower aggregation levels still may be very elaborated.

Using the automated analysis techniques from [2, 13] missing and conflicting parts of the ATO model can be identified. Some examples of application of these techniques are provided in the paper. The scalability of analysis is achieved by applying dedicated techniques for verification of specifications of particular organisational views and by distinguishing aggregation levels. Another analysis type demonstrated in the paper is by simulation. It allows to evaluate how different types of divergent agent behaviour in simulation models may result into delays in executions of processes up to the level of incidents. In comparison with the simulation approach of [14, 15], the novel approach considers the organisational layer of the ATO explicitly, however at the expense of not simulating beyond the incidents. Another example of such analysis, in which the formal and informal occurrence reporting paths of the ATO were investigated, is provided in this chapter. 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 whether this important feedback on safety occurrence reporting processes is recognized in actual air traffic organisations and may be a basis for organisational change.

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