Modelling and Automated Analysis of Organisations from the Air Traffic Management Domain

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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, the paper 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 results obtained by automated analysis have been recognized as plausible by domain experts.

1. Introduction

An Air Traffic Organisation (ATO) ensures a safe and efficient flow of aircraft both at airports and in the air. Nowadays, an ATO represents a complex organisation that involves many parties with diverse goals performing for 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] 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. Agents are autonomous entities interacting with the environment are used here to model the behaviour of organisational actors (humans, hard/software). In [5] an agent-based system is used to represent and automate air traffic management processes. However, in this approach the ATO is represented as a plain society of agents, without considering the organisational layer that prescribes structures and behaviour on agents. Several approaches [8, 10] consider an influence of different organisational aspects on safety, however, without providing precise details. To create a model of the ATO in this paper the developed previously general organisation modelling and analysis framework [9] is used. On the one hand, this framework allows specifying the prescriptive structural and behavioural dependencies and the rules 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 [4, 11] this framework has the defined precisely 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) [3] is used for specifying dynamic aspects of organisations. To decrease the complexity of modelling the framework distinguishes four interrelated perspectives (or views): (1) the *performance-oriented view* that describes organisational goal structures, performance indicators structures, and relations between them; (2) the *process-oriented view* that describes organisational functions and processes, how they are related, ordered and synchronised and the resources they use and produce; (3) the *organisation-oriented view* that describes organisational roles, their authority, responsibility and interraction relations; (4) the *agent-oriented view* that describes agents' types with their capabilities, models of agent behaviour based on social theories, and principles of allocating agents to roles. In the framework organisational specifications can be represented and analysed at different levels of abstraction in order to handle complexity and increase scalability.

The framework proposes a number of analysis techniques, the application of some of which is demonstrated in this paper. More specifically, the constructed specification of the ATO is checked for correctness by applying the general and specific for particular views consistency verification techniques from [9]. Furthermore, the consequences of different types of agent behaviour that diverges from the prescriptive (formal) organisational specification are investigated by agent-based simulations.

The paper is organized as follows. Section 2 introduces the description of the ATO under consideration. The design process of a specification for the ATO is described in Section 3. The analysis results are given in Section 4. Section 5 concludes the paper.

2 Air Traffic Organisation in Focus

The ATO performs a variety of tasks: development and evaluation of new operations, movement of aircraft on the ground, incident reporting and investigation, etc. Due to the space limitation, in this paper we focus particularly on the ATO tasks related to movement of aircraft on the ground. More specifically, the taxiing of an aircraft to a designated runway and the subsequent take off from this runway are investigated. However, as it is demonstrated in [12], the developed organisational model is sufficiently complete to analyse also other processes of the ATO.

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 the 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 on the airdrome, each of which is guided by a Tower Controllers Supervisor. Through tower controllers supervisors interaction of the controllers with the management of the ANSP is carried out.

3 Modelling the Air Traffic Organisation

To perform analysis of the ATO's structures and processes should be developed: (1) the specification of the formal organisation; (2) the specifications of agents of different types and the principles of their allocation to the roles of the organisation. To design such specifications a sequence of design steps is identified[1]. The formal organisation specification is built by executing the steps 1-8 described below. Agents that cause performance variability in the ATO are specified at the step 9.

Step 1. The identification of the organisational roles

In this step organisational roles are identified, both simple and composite ones and subrole-relations between them are established. A *role* represents a (sub-)set of functionalities of (part of) an organisation, which are abstracted from specific agents (or actors) who fulfil them. Each role can be composed by several other roles, until the necessary detailed level of aggregation is achieved, where a role that is 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. Graphically, a role is represented as an ellipse with white dots (the input interfaces) and black dots (the output interfaces). The environment represents a special component of a model, which also has input and output interfaces. In the considered ATO, roles are identified at three aggregation levels, some of which are presented in Fig. 1 and 2.

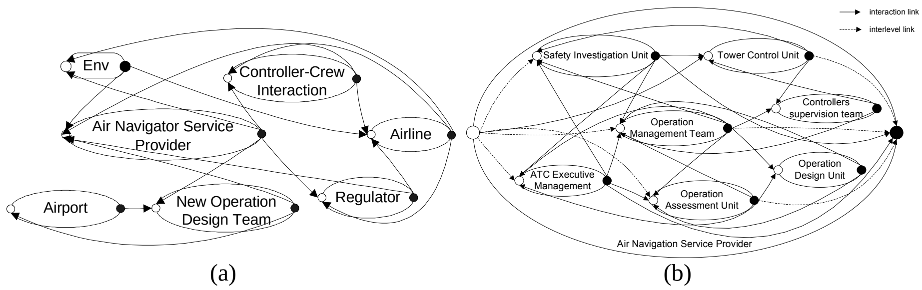

Fig. 1. Interaction relations in the ATO considered at the aggregation level 1 (a) and in the composite role Air Navigator Service Provider considered at the aggregation level 2 (b).

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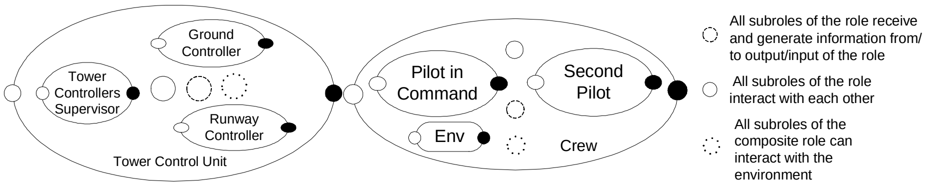
[1] Although the specifications are based on the formal languages, for better readability in this paper they are given in textual form, for the complete formal specifications we refer to [12].



(a) (b)

Fig. 2. 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 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. 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). 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 and 2).

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 effectively and readily their knowledge for tasks performance. As an example the following requirements for the air traffic controller role are defined: (1) passed a rigid 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; (8) ability to stand stress.

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 10.1, 10.2, 10.3, 10.4, 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.

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
10.1	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.
10.2	It is required to maintain a high (sufficient) level of proficiency of pilots	the level of proficiency of pilots
10.3	It is required to maintain a high (sufficient) level of proficiency of controllers	the level of proficiency of controllers
10.4	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
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

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.

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: 13.2, 14.1, 14.3, 24.1.1, 14.2, 23.1, 20				
1.2	Switching to the frequency of another controller	data about the new frequency	-	Min: 1 sec Max: 5 sec
Goal: 14.1, 14.3, 14.2				
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: 14.1, 14.3, 14.2				
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: 13.1, 22.1, 24.1.1, 23.1, 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: 14.1, 14.3, 23.1, 14.2, 20				

Step 7. The specification of the authority relations

In this step authority relations (i.e., formal 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.

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. A workflow example for the ATO is given in Fig. 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				

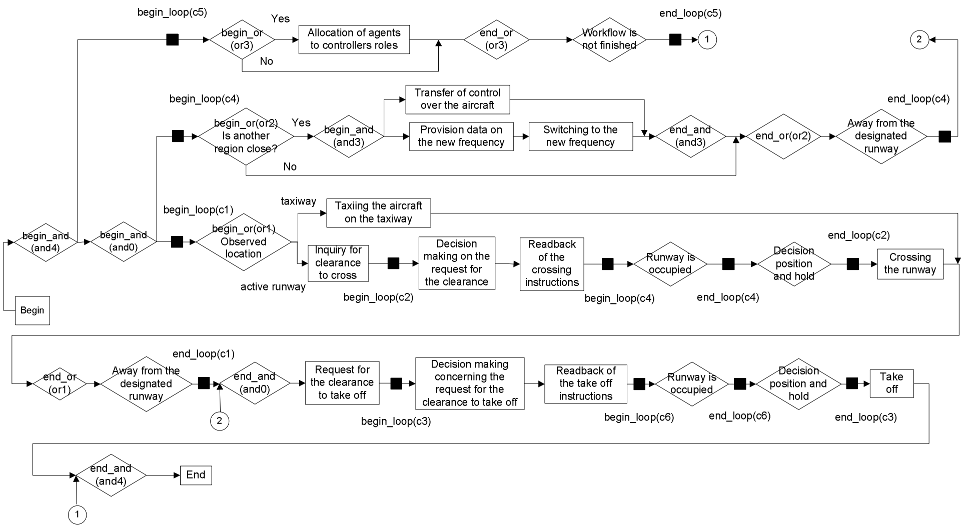


Fig. 3. Workflow for an aircraft taxiing to and taking-off from a designated runway

Step 9. The specification of the characteristics and behaviour of agents, and the agent allocation principles.

The performance variability in an organisation is represented by specifications of agents that are allocated to organisational roles. 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. For the ATO a number of agent types have been identified, such as Controller, Pilot, and Manager. Then, particular agents of these types with varying capabilities and traits have been defined. For example, the agent allocated to Tower Controllers Supervisor role in comparison to the agent allocated to some Ground Controller role has a higher level of development of the technical and interpersonal skills and additionally has the developed managerial skills. The behaviour of an agent is considered as goal-driven. Goals of an agent may be in line with the organisational goals or may, sometimes, contradict them. Other internal states of agents allocated to organisational roles are represented as beliefs. A belief of an agent is created based on: an observation from the environment; a communication provided to/obtained from another agent, and an action performed by the agent in the environment.

Step 10. 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 represented by a logical theory expressed using the formal languages of the framework. An organisational specification is *correct* if the corresponding theory of constraints is satisfied by 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 two.

4 Analysis results

In this Section first the results of the correctness verification of the designed ATO specification are presented (Section 4.1). Then, the analysis by simulation of a combined specification with agents allocated to the roles is described (Section 4.2).

4.1 Correctness verification

As a result of the automated analysis a number of inconsistencies have been identified. In particular, several (potential) conflicts have been found in the goal structure: between goals 10.3 and 4.4; between goals 11.2 and 4.4; between goals 20 and 10.1; and between goals 23 and 10.1. The goals that are in conflict cannot be satisfied at the same time. For example, goal 10.1 ensures adherence of the roles to the safe-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 ensure that constraint C5 defined in step 10 of Section 3 is satisfied, the organisation should have a sufficient number of properly trained agents to be allocated to all the roles of the organisation. The analysis based on the amount of agents currently employed by the organisation identified many situations in which the same agent-controller should be allocated to more than two 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.

4.2 Analysis by simulation

Using the developed model of the ATO, simulation of different scenarios can be performed, one of which is described in this Section. 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). 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 (e.g., incorrect situation awareness, mistakes) associated with the probability values from the studies [1, 7] (for details see [12]). 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 [2]. The obtained simulation traces have been analyzed using the checking environment [3]. 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.

The analysis results point at a significant risk that exists, when an active runway is situated on the way to other runways. In this case the safety re-evaluation of the new operation (i.e., the new runway introduction) is required.

5 Conclusions

The modelling and analysis of the ATO using the framework from [9] proved to be practicable and useful for the understanding of the organisational functioning, identification of errors and inconsistencies, and for the investigation of the organisational dynamics in different environmental settings. The modelling framework allowed the identification of diverse aspects of the considered organisation at a detailed level. Using the automated analysis techniques the missing and the conflicting parts of the ATO specification have been identified. In particular, many of the conflicts identified at the level of organisational goals stem from the principal difference between performance and safety objectives of the organisation. To survive and to make profit in the highly competitive environment ATOs often strive for (a high degree of) the satisfaction of the performance-related goals. This often results into a decrease of the satisfaction of some safety-related goals, which may bring to an incident or even to an accident. Another analysis type by simulation allowed to evaluate how different types of divergent agent behaviour may result into delays in executions of processes and even into incidents. In the future also posivite influences of agent behavior on the organisational performance will be investigated.

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