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Human performance modelling for accident risk assessment of active runway crossing operation

S.H. Stroeve and H.A.P. Blom

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Summary

A human performance modelling approach is presented for risk assessment of operations with multiple, dynamically interacting agents. The approach is illustrated for a risk model of an incursion by a taxiing aircraft on an active departure runway. This model-based approach can provide detailed, systematically derived results regarding contributions to safety by human operators and technical systems in complex multi-agent environments.

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1 Introduction

Since capacity and efficiency are the drivers of the development of advanced air traffic operations, by now there is a broad consensus that appropriate accident risk assessment models are needed to assess safety in relation to capacity with the aim to optimise advanced air traffic operations (Wickens et al., 1998). Air traffic operations account for highly distributed and dynamic interactions between human operators, procedures and technical systems. As such, the safety of air traffic operations depends not only on the functioning of the individual elements in such multi-agent scenarios, but also on their complex interactions, especially in non-nominal situations. Because of this distributed control nature of air traffic, established techniques fall short in performing accident risk assessment. Blom et al. (2001) addressed this problem by development of a Monte Carlo simulation-based methodology that takes an integral approach towards human performance modelling and accident risk assessment for air traffic (Traffic Organization and Perturbation AnalyZer: TOPAZ).

The human performance modelling approach followed in TOPAZ is based on a contextual perspective in which human actions are the product of human internal states, strategies and the environment (Amalberti and Wioland, 1997; Hollnagel, 1993; Wickens and Holland, 1999; Cacciabue, 1998). The model for task performance of a human operator considers multiple tasks, human error and contextual control modes (Blom et al., 2003). Specifically, for a human operator

- the tasks of the human operator are identified,
- the most relevant cognitive control modes are identified,
- per identified cognitive control mode, the characteristics of the operator tasks are identified,
- clusters of tasks are formed,
- hierarchy and concurrency for the task clusters are identified.

In such performance modelling, parameter values are based on operational observation, real-time simulation and expert interviews. Corker et al. (2005) showed that an additional way of identifying parameter values is to make use of the more detailed human performance model of Air-MIDAS.

In air traffic, situation awareness problems are important contributing factors to many accidents. The concept of situation awareness addresses perception of elements in the environment, their interpretation and the projection of the future status (Endsley, 1995). In an air traffic environment with multiple human operators, these aspects and associated errors of situation awareness depend on human-human and human-machine interactions. A model for situation awareness evolution in a multi-agent air traffic environment was developed (Stroeve et al., 2003; Blom and Stroeve, 2004). Here, an agent is an entity, such as a human operator or a technical system, which may have situation awareness of its environment. The environment of an agent includes the complete group of agents. The situation awareness of each agent consists of time-dependent information of other agents, including identity, continuous state variables, mode variables and intent variables. Achieving, acquiring and maintaining situation awareness depends on processes as observation, communication and reasoning.

It is the goal of the current paper to elucidate the approach for multi-agent human performance modelling and illustrate it for simulation-based accident risk assessment of an active runway crossing operation. In the sequel of this paper, the risk assessment steps and the runway operation are described first, followed by methods and results of the simulation model with emphasis on human performance aspects.

2 Accident risk assessment steps

Following the TOPAZ methodology, assessment of the risk of an operation is performed in a number of steps:

1. *Determination of the scope:* In collaboration with operational experts, determine the scope of the operation. Determine safety criteria and methods of the risk assessment.
2. *Description of the operation*: Describe in sufficient detail the operation, including context, human roles and responsibilities, procedures and technical systems.
3. *Hazard identification*: Identify non-nominal events or situations possibly having adverse effects on the operation. Particularly of interest are brainstorm results on situations and events for which pilots and controllers have complementary opinions.
4. *Construction of conflict scenarios*: Hazards are related to conflict types and ordered with respect to root events, resolution events and effects. The resulting hazard structures are called conflict scenarios. Risk is divided into sub-risks related to the various conflict types. This enables efficient and orderly evaluation of risk.
5. *Argumentation-based evaluation*: Evaluate the risk based on the conflict scenarios, interviews with operational experts (pilots, controllers) and incident databases. This provides a first indication of the severity and frequency of conflict scenarios.
6. *Development of a simulation model*: Develop a mathematical accident risk model for conflict scenarios that are difficult to assess by argumentation-based evaluation. This stochastic dynamic model represents the performance and interaction of technical systems and human performance for a particular air traffic situation.
7. *Simulation-based evaluation*: Evaluate potentially safety-critical and uncertain risks by Monte Carlo simulations based on the developed simulation model and hierarchical simulation speed-up techniques.

8. *Evaluation of model assumptions*: Assess the effect on the modelled risk of assumptions made in the modelling process. This step accounts for the recognition that a model differs by definition from reality. It includes an analysis of bias and uncertainty in assumptions as well as a risk sensitivity analysis, and results in an evaluation of bias and uncertainty bounds of the risk of the operation.
9. *Risk criteria*: Compare the evaluated risk with risk criteria to assist decision-makers in their evaluation of the acceptability of the operation.

Here, operational experts are actively involved during hazard identification, argumentation-based evaluation and evaluation of model assumptions.

3 Active runway crossing operation

The active runway crossing operation enables traffic to cross an active departure runway (named Runway A) in order to taxi between the aprons and a second runway (named Runway B). Each crossing has remotely controlled stopbars on both sides of the runway. The operation includes a large number of interacting agents (see also Figure 1):

- aircraft (taking off or taxiing),
- aircraft's flight management systems (FMS),
- pilots flying (PF's),
- pilots not flying (PNF's),
- Runway A controller,
- Runway B controller,
- ground controller,
- departure controller,
- start-up controller,
- ATC system, which is broadly defined to include
  - airport manoeuvre control systems,
  - surveillance systems,
  - airport configuration,
  - environmental conditions,
  - communication systems.

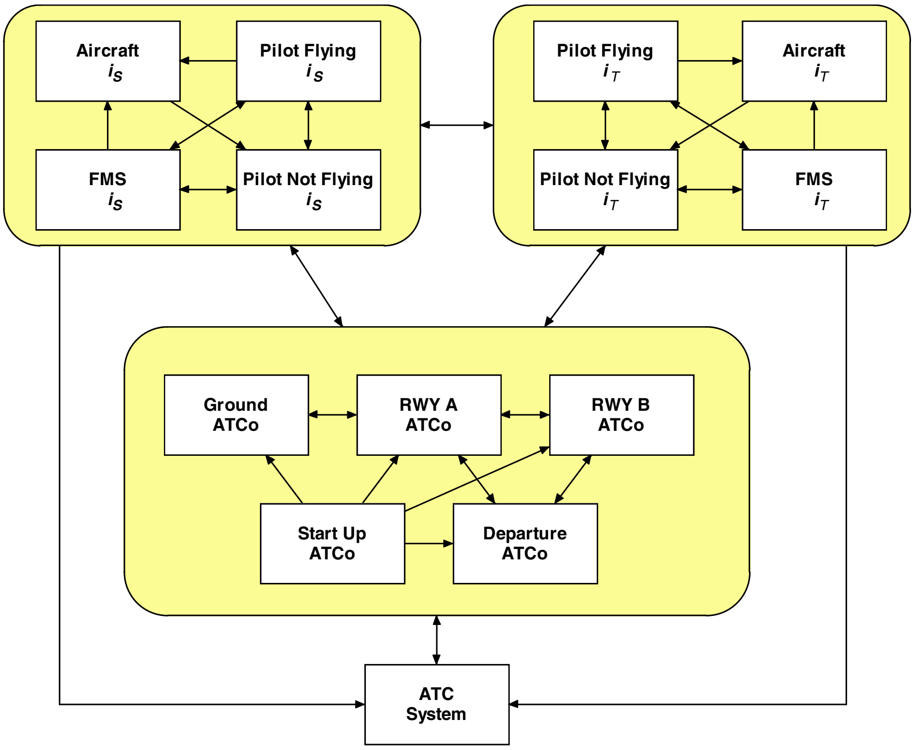

Figure 1: Relations between agents identified for the active runway crossing operation.

In the operation, communication between controllers and aircraft crews is via standard R/T. Monitoring by the controllers is via direct visual observation and is supported by radar track plots. The runway crossing operation over Runway A is under the responsibility of the Runway A controller. The Runway A controller is supported by a runway incursion alert system and a stopbar violation alert system. The Runway A controller manages the remotely controlled stopbars and the runway lighting. Monitoring by the aircraft crews is by visual observation and may be supported by the VHF R/T party-line effect.

4 Simulation model

An initial argumentation-based evaluation of the risk of the active runway crossing operation showed that of all identified conflict scenarios, there are three conflict scenarios that may pose unacceptable safety effects. In this paper, we focus on the details of an accident risk model for one of these conflict scenarios. In this conflict scenario there is one aircraft that takes off and has been allowed to do so and there is one aircraft that crosses the runway while it should not. Taxiing along a straight line over a standard runway crossing is considered. Hence, in the illustrative example of this paper, emphasis is placed on the models of the aircraft, pilot flying, Runway A controller and ATC system agents. A high-level overview of these models is specified next.

Aircraft

A taking-off aircraft initiates take-off from a position at the beginning of the runway. A crossing aircraft initiates crossing at a position close to the remotely controlled stopbar with a normal taxiing speed or from a hold state.

Pilot flying of taking-off aircraft

Initially, the pilot flying (PF) of a taking off aircraft has the SA that take-off is allowed and initiates a take-off. During the take-off the PF monitors the traffic situation on the runway visually and via the VHF communication channel. The PF starts a collision avoidance braking action if a crossing aircraft is observed within a critical distance from the runway centre-line or in reaction to an ATCo clearance, and it is decided that braking will stop the aircraft in front of the crossing aircraft.

Pilot flying of crossing aircraft

Initially, the PF has the intent SA that the next airport way-point is either a regular taxiway or a runway crossing. In the former case the PF proceeds taxiing and in the latter case the PF may have the SA that crossing is allowed. The characteristics of the visual monitoring process of the PF depend on the intent SA. In case of awareness of a conflict, either due to own visual observation or due to an ATCo call, the PF stops the aircraft, unless it is already within a critical distance from the runway centre-line.

Runway controller

The Runway A controller visually monitors the traffic and has support from a stopbar violation alert and a runway incursion alert. If the ATCo is aware that a crossing aircraft has passed the stopbar, a hold clearance is specified to both the crossing and the taking off aircraft.

ATC system

The ATC system includes communication systems, tracking systems, a stopbar violation alert, a runway incursion alert and remotely controlled stopbars.

Hazard Representation

The model of the active runway crossing procedure accounts for intent-dependent and cognitive mode-dependent error-prone perception processes of pilots flying and the Runway A controller. Table 1 shows how a number of situation awareness related hazards of the operation considered were accounted for in the accident risk model.

Table 1: Examples of the representation of hazards in the accident risk model of the active runway crossing procedure.

Hazard	Model representation
Runway incursion alert is active, but runway controller has wrong 'picture' of the situation, and therefore reacts too late, not or wrongly.	In response to an alert there is a chance that the runway controller does not observe the conflict and therefore does not react.
Pilots get confused because of complexity of the taxiways in the new operation.	The PF of a taxiing aircraft may be aware that the aircraft is taxiing on a regular taxiway while it actually is on a runway crossing.
Pilot reacts not, wrongly, too late or cannot react to conflict solving clearance of runway controller.	There is a chance that the PF does not or only after a long time becomes aware of a clearance.

5 Performance model of pilot flying

The various human performance submodels are integrated into a simulation model. As an illustrative example, a model is presented of the pilot flying of an aircraft that taxies towards the runway crossing. A high-level overview of the model elements of the pilot flying agent is shown in Figure 2. The human operator model includes the following groups of model elements.

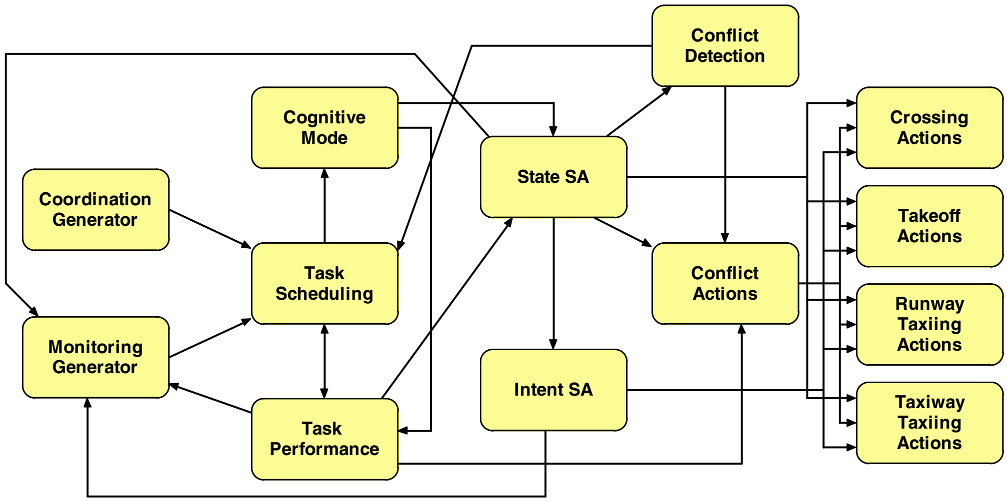

Figure 2: High-level overview of the model elements of the pilot flying agent.

Task triggering

Task triggering processes specify times at which it is desired to complete a task. They may depend on other processes, such as task performance and situation awareness. For example, the model blocks *Monitoring Generator* and *Coordination Generator* in Figure 2 represent task triggering processes of a pilot flying and specify times at which monitoring of the traffic situation and coordination with the pilot not flying is desired, respectively. These model blocks receive several inputs. For instance, the dependence of *Monitoring Generator* from *Intent SA* enables an intent-dependent visual updating frequency.

Task scheduling

Task scheduling processes determine which tasks should currently be processed by the human operator. Task scheduling processes may depend on other processes, e.g., task triggering, task performance and situation awareness processes. For example, in Figure 2 the *Task Scheduling* block represents a scheduling process with a fixed hierarchy and concurrency structure.

Task performance

Task performance processes describe the development of the progress of a task. They may, e.g., depend on task scheduling and cognitive mode processes. For example, in Figure 2 *Task Performance* depends on *Cognitive Mode*, resulting in a faster task performance in the opportunistic control mode with respect to the tactical control mode of the pilot flying.

Cognitive control mode

Cognitive control mode processes describe the cognitive control mode of the human operator. They may, e.g., depend on the number and types of scheduled tasks. See, for instance, the *Cognitive Mode* block in Figure 2.

Situation Awareness

Situation awareness model elements represent the state SA and intent SA, as outlined before. In Figure 2, the model blocks *State SA*, *Intent SA* and *Conflict Detection* represent SA components, where the latter block represents the detection process and the SA of a conflict. In Figure 2, *State SA* depends *Cognitive Mode*, representing that (errors in) the state SA updating process can depend on the cognitive mode.

Task Specific Actions

Task specific actions represent particular elements of tasks of a human operator. For instance, for a pilot flying these may include (see Figure 2) *Crossing Actions*, *Takeoff Actions*, *Runway Taxiing Actions, Taxiway Taxiing Actions* and *Conflict Actions.*

6 Conditional Monte Carlo simulations

An accident risk assessment includes a risk decomposition, which supports efficient evaluation of the collision risk and promotes insight in the risk contributions. The evaluation of the collision risk is based on the probabilities and the conditional collision risks of combinations of event sequences, as have been identified in the decomposition process. The decomposition process considers whether alert systems, remotely controlled stopbar and communication systems are functioning well or not. The decomposition process considered in the example includes

- the aircraft type of each aircraft to be either a medium-weight *A320* or a heavy-weight *B747*;
- the intent SA of the PF of a crossing aircraft concerning the next way-point (*Taxiway / Crossing*) and concerning allowance of runway crossing (*Allowed / Not Allowed*);
- whether alert systems are functioning well or not;
- whether the remotely controlled stopbar is functioning well or not;
- whether communication systems are functioning well or not.

Based on the simulation model and the accident risk decomposition, Monte Carlo simulation software is developed to evaluate the conditional collision risk for the events resulting form the decomposition process.

7 Accident risk results of the model

This section presents results of the simulation-based risk evaluation for a generic runway in good visibility conditions. Figure 3 shows the accident risk as function of the distance of the runway crossing with respect to the runway threshold. The probability of a collision decreases for larger crossing distances. Figure 3 also shows the decomposition of the total risk for the cases that the pilot flying of the taxiing aircraft either intends to proceed on a normal taxiway (without being aware to be heading to a runway crossing) or intends to cross the runway (without being aware that crossing is currently not allowed). The largest contribution to the risk is from the situation that the pilot intends to proceed on a normal taxiway. The relative size of this contribution depends on the crossing distance and varies from 64% for crossing at 500 m to about 83% for crossing at 1000 m or 2000 m.

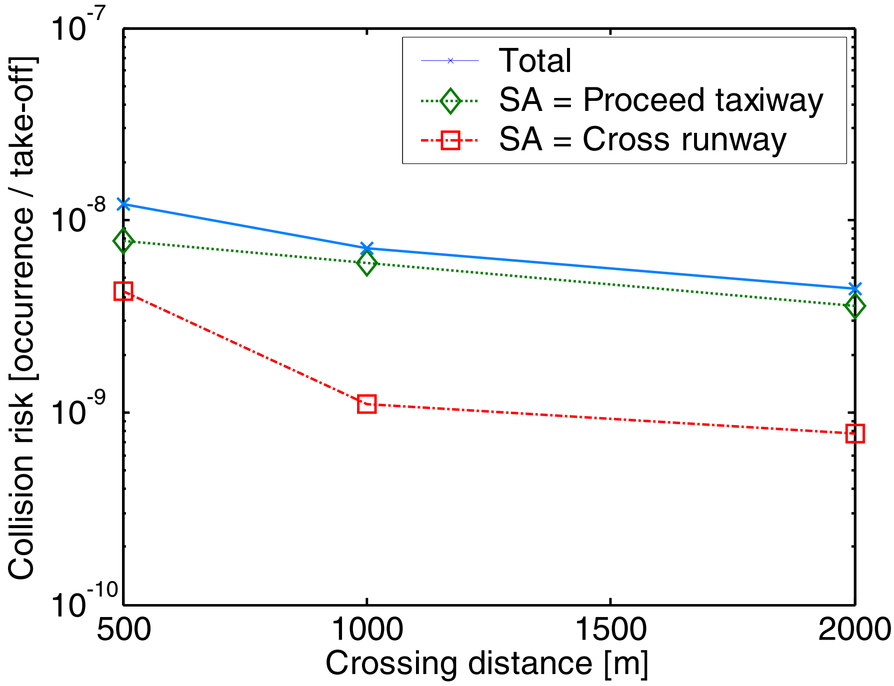

Figure 3: Contributions to the total collision risk by the simulation model for the cases that the SA of the PF of the taxiing aircraft is to proceed on a taxiway, or to cross the runway.

Table 2: SA Dependent collision risk by the simulation model for crossing at a distance of 1000 m (event condition is not distant dependent).

Probability per take-off	**SA by PF of taxiing aircraft**	
	Proceed taxiway	*Cross runway*
Probability of event	3.5 10^{-5}	2.0 10^{-4}
Conditional collision risk	1.7 10^{-4}	5.5 10^{-6}
Collision risk	6.0 10^{-9}	1.1 10^{-9}

The collision risk in Table 2 depends on the probability of the particular SA condition and the probability of a collision given this condition, for a crossing distance of 1000 metres. The probability of the situation that a pilot taxies across the stopbar not knowing he is approaching the runway, is assumed to be a factor 5.7 smaller than the probability of the situation that the pilot starts crossing the runway while not allowed to do so. Nevertheless, the largely enhanced conditional collision risk leads to a larger collision risk in the former case. The reduced conditional collision risk in the latter situation is due to better monitoring process of the pilot flying of the taxiing aircraft, if its crew is aware to be heading towards a crossing of an active runway.

Based on results of the accident risk model, it is possible to attain insight in the accident risk reducing performance of involved human operators and technical systems. Table 3 shows conditional collision risks for the situation that an aircraft taxies towards a runway crossing at a distance of 1000 m from the runway threshold while the pilot is aware to taxi on a normal taxiway. The conditional collision risks in Table 3 refer to cases in which the involved human operators either do ('yes') or do not ('no') actively monitor for traffic conflicts. A risk reduction percentage is determined by comparing the conditional collision risk with the situation in which none of the human operators is actively monitoring. In this case, a collision is only avoided by the lucky circumstances that the taxiing aircraft just passes in front of or behind the taking-off aircraft (case 0 in Table 3).

Table 3: Risk reduction achieved in the simulation model by various combinations of involved human operators for the situation that the pilot flying of the taxiing aircraft intends to proceed on a normal taxiway. See main text for further explanation.

Case	**PF taxiing aircraft**	**PF taking-off aircraft**	**Runway controller**	**Conditional collision risk**	**Risk reduction**
0	no	no	no	$8.9\ 10^{-2}$	-
ATC alert systems on					
1	yes	yes	yes	$1.7\ 10^{-4}$	99.8%
2	yes	no	yes	$4.0\ 10^{-4}$	99.6%
3	no	yes	yes	$9.4\ 10^{-3}$	89.4%
4	yes	yes	no	$2.3\ 10^{-4}$	99.7%
ATC alert systems down					
5	yes	yes	yes	$2.2\ 10^{-4}$	99.8%
6	yes	no	yes	$1.7\ 10^{-3}$	98.1%
7	no	yes	yes	$1.1\ 10^{-2}$	87.9%
8	yes	yes	no	$2.3\ 10^{-4}$	99.7%

A number of model-based insights can be attained by comparing the results of Table 3.

- It follows from case 1 that 99.8% of the accidents can be prevented by the combined effort of all human operators and alert systems.
- It follows from a comparison of cases 1 and 5 that in the normal situation that all human operators are actively monitoring, ATC alert systems (runway incursion or stopbar violation) almost have no effect on the achieved risk.
- It follows from a comparison of cases 1 and 4, and cases 5 and 8, that the risk reduction that can be achieved by the tower controller in addition to the risk reduction of both pilots is very small.

- It follows from comparison of cases 1 and 3, and cases 5 and 7 that the pilot of the taxiing aircraft has the largest capability to prevent a collision in this context.

8 Discussion

The accident risk assessment methodology and the associated human performance modelling approach that are discussed in this paper, provide a systematic approach to risk assessment of operations with multiple, dynamically interacting agents. The combined effect of dynamically interacting agents is hard to assess by static or single-agent approaches. As an example, during an argumentation-based risk assessment of the discussed active runway crossing operation, pilots and controllers were asked to estimate their potential to prevent a collision as result of a runway incursion. Especially the contribution of the tower controller was overestimated, because this expert-based evaluation had difficulty to account well for the timing of actions of the pilots and controller. Through Monte Carlo simulations it has become clear that in good visibility conditions, a large part of conflicts is recognised and handled by the pilots before the controller can react.

By definition a model is unequal to reality. Hence, application in a risk assessment of the discussed models requires an evaluation of the effect on the risk of the assumptions adopted in the modelling process (Everdij and Blom, 2002). This evaluation takes into account the particular context of the operation assessed and will be conducted in a follow-up study. Then interviews with pilots and controllers will be conducted to obtain their feedback on the assumptions made. In these interviews, typically asked questions will refer to single-agent tasks and aspects such as task duration. These kind of questions can be more easily estimated than small probability values (e.g., conflict resolution probability estimates in a multi-agent environment) such as typically included in interviews for argumentation-based risk assessment.

The feasibility of using human performance modelling in accident risk assessment for a conflict scenario with a considerable number of interacting humans and technical systems has been illustrated for an active runway crossing operation. The model results stress the importance of proper situation awareness of the pilots flying for minimising runway incursion risk.

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