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On the integration of human performance and collision risk simulation models of runway operation

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ON THE INTEGRATION OF HUMAN PERFORMANCE AND COLLISION RISK SIMULATION MODELS OF RUNWAY OPERATION

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Abstract

The integration of a human performance model (Air Man-machine Integration Design and Analysis System, Air MIDAS) and an accident risk assessment methodology (Traffic Organization and Perturbation AnalyZer, TOPAZ) was investigated in order to learn about the similarities and differences of their models, to demonstrate the feasibility of such integration, and the integration impact on accident risk assessment. The application example for this assessment is an airport surface operation in which a taxiing aircraft makes an unintended incursion into a departure runway. This paper describes the process for integrating the simulation based models of human performance for this example, and presents the result of this integration up to the level of risk of collision between two aircraft.[§]

1. Introduction

In the analysis and design of advanced operations in complex, dynamic, human-machine systems, accident risk assessment is a critical component of effective system engineering. Probability Risk Assessment (PRA) techniques typically model such complex system by assigning conditional probabilities of the success, or failure for system operations into fault and event trees (e.g. Kumamoto and Henley, 1996). Subsequently, an assessment of risk is undertaken by evaluating the combined effects of the conditional probabilities in these fault and event trees. The role and contribution of the human operator has proven to be a significant element to both accident risk (Hollnagel, 1993), and to system safety and effectiveness (Dekker 2001). The development of models that represent the contribution of the human operator to risk has been explored for some 30 years (Swain & Guttman 1983). The function of the human operator was either assigned a probability of success or failure, as would be provided for any system component, and the "integration" was the inclusion of those probabilities in the overall system success failure assessment. In a more sophisticated approach the process of assessment of human performance characteristics is based on the context of control as described by (Hollnagel, 1993). Here the conditional probabilities for human activities reflect the impact of the context on human operator control modes. Control mode selection refers to a qualitative shift in activities performed and the detailed characteristics of their performance. The parameters of performance such as time to react or time to visually detect a target would reflect the subject matter expert assessment of performance under stress. Typically, these performance characteristics are assigned based on expert knowledge elicitation regarding the impact of the context on human performance (such as probability of mishearing a clearance).

A serious limitation of fault and event tree based PRA is its inability to evaluate the effects of concurrent and dynamic behavior on accident risk. The remedy is to exploit stochastic dynamical modeling and Monte Carlo simulation of the concurrent and dynamic processes for accident risk assessment (e.g. Labeau et al., 2000), including the safety engineering directed modeling and simulation of a human operator (e.g. Cacciabue, 1998). In order to apply this approach to air traffic management, multiple human operators and their interactions with each other and with aircraft and ground systems have to be modeled and simulated.

This creates three kinds of challenges. First, the architecture of established risk assessment and fast-time system performance models has tended to be incompatible with interactive human performance model architectures. Second, the speed of human performance model-based simulations has been considered a bottleneck in the operation. Third, the granularity or degree of detail required to account for impact on human performance has been considered

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out of scale in consideration of large system operations with critical human cognitive capabilities in the millisecond range.

Both with the human performance model Air-MIDAS (Corker, 2000) and with the accident risk assessment methodology TOPAZ (Blom et al., 2001, 2003; Stroeve et al., 2003), significant and complementary headway has been made in successfully addressing these issues. This makes the integration of Air-MIDAS and TOPAZ a valuable topic of collaborative research in aviation safety assessment. The objective of this integration is to combine the significant advances established in individual human performance representation and human performance factors (human factors in general and human cognitive behavior in particular) through large-scale simulations for accident risk assessment. As an objective test for the success of this integration we hypothesize that this combination allows Air-MIDAS to provide simulation results for individual human operators which improves the accident risk assessment. In addition we hypothesize that an integrated accident risk simulation model is able to illuminate the Air-MIDAS model entities (either specific operators, functions within an operator, or interaction among individuals) which are most critical in managing the accident risk level. The aim of the current paper aims to study the first hypothesis. The testing of the second hypothesis will be addressed in a follow-up study.

Through several stages of development over a period of 4 years, the two modeling teams, NLR and San Jose State University have succeeded in identifying a method for integration of the two techniques, implemented that integration and applied it, as a demonstration, to a runway incursion and surface operation example. Such operations have been a particular focus both by Eurocontrol and by FAA (e.g. Cardosi&Yost, 2001). The aviation community continues to be concerned with accident risk and runway operations and several technologies have been under development to mitigate this risk. Given the relevance of these operations to both safety risk and human performance, an integrated simulation of the baseline conditions for runway incursion avoidance was undertaken by Air-MIDAS and TOPAZ simulation toolset TAXIR for this operation.

2. Integration of complementary human modeling approaches

Because of the complementary objectives and separate developments of Air-MIDAS and TOPAZ their human performance modeling approaches show similarities and differences. Their potentially complimentary functions form the reason why this integration is so useful and challenging at the same time. In the course of the integration study the complementary human performance modeling details of both approaches have become clear. A short explanation of this is given next, including an overview in Table 1.

Table 1 Human performance modeling in Air-MIDAS and TOPAZ

		Air-MIDAS	TOPAZ
A	Management modes	Max-load or Even-load	None
	Control Modes	Matching with Rasmussen's SRK (Skill, Rule, Knowledge)	Matching with Hollnagel's tactical and opportunistic control modes
	Switching between modes	Fixed thresholds	Thresholds with hysteresis
B	Task Scheduling	Goal oriented subtask scheduling	Priority rules for aggregated tasks
	Resources model	Multiple: Visual, Auditory, Cognitive, Psychomotor	Aggregation on the basis of time-critical tasks/resources combinations
	Memory model	Procedural (with decay) Declarative (with decay) Knowledge (no decay)	Aggregated (no decay)
C	SA model	SA of one human only	Multi Agent SA and interactions
D	Human error	Is result of detailed modelling	Amalberti's error recovery model is added
E	Behaviour of Non-human entities	Nominal	Nominal & Non-Nominal
F	Specification language	Air-MIDAS specific, based on LISP	Dynamically Coloured Petri Nets (DCPN)

A. Control Modes: In TOPAZ the control modes are chosen to represent the tactical and opportunistic control modes of Hollnagel, whereas Air-MIDAS uses Rasmussen's SRK modes. In TOPAZ the control modes are primarily responsible for the task processing speed and the error probability, while in Air-MIDAS, the control mode defines the task scheduling mechanism. In Air-MIDAS the cognitive control mode switching and activity selection depends on the available time to complete the tasks, where the available time is called the look-ahead time in Air-MIDAS. In TOPAZ, the cognitive control mode switching depends on the number of tasks to be processed at a given time. Switching between control modes happens in Air-MIDAS without any hysteresis, and with significant hysteresis in TOPAZ. Air-MIDAS uses management modes for the goal scheduling, while TOPAZ has no management modes.

B. Task scheduling/Resources/Memory: Air-MIDAS uses task analysis and Wickens' model for multiple resources. TOPAZ uses Wickens also, however subtasks and resources are aggregated in a fixed pattern, according to the time critical task/resources combinations. Hence, for each task, information regarding the result of the task is modeled and not the resources leading towards this result. Air-MIDAS also has a rather detailed memory model, which includes memory decay. TOPAZ does not model human memory decay.

C. SA Model: TOPAZ aims to address all combinations of SA differences between the multiple agents in the model. Air-MIDAS models individual awareness in its upadateable world representation, but currently does not include awareness among operators.

D. Human error characteristics of Air-MIDAS is the emergent result of the detailed modelling under A and B. In TOPAZ the characteristics are added on top of A and B, using literature and expert knowledge on human error types, error recovery and frequencies.

E. Behaviour of Non-human entities: Only nominal behaviour is modelled in Air-MIDAS, whereas TOPAZ models both nominal and non-nominal levels.

F. Specification language: Air MIDAS uses a dedicated LISP-based model notation, whereas TOPAZ uses a Petri Net based model specification language (Everdij & Blom, 2005).

For an effective integration of Air-MIDAS and TOPAZ the complementary modeling approaches should be taken into account. In order to accomplish this, integration applies at the following three levels:

- Context level: This ensures that similar application contexts are being considered. This requires clarity about issues such as boundaries, operation and task analysis.
- Model level: In order to ensure that the model integration is done appropriately, there is need for an understanding how Air-MIDAS and TOPAZ models complement each other.
- Parameter level: In order to ensure that similar parameter values are being used, there is a need to use Air-MIDAS detailed output as input by TOPAZ simulations.

Integration at the model level ensures that the simulation scenario under examination is jointly represented in the two modeling systems. This allows identification of values for specific parameters of human performance in the TOPAZ simulation model to be supplied by the Air MIDAS simulation. These parameter values are generated in Monte Carlo runs of the human performance model and subsequently supplied as input to improving TOPAZ simulations. In so far as the modeling paradigms allow similar representation, this parameter exchange is straightforward. For example, simulation of pilot reaction time to recognition of an incursion by the taxiing aircraft is represented in both modeling processes, hence reaction time is a straight forward parameter value to exchange.

3. Integration at the three levels

3.1 Application context

The following operational concept for crossing of an active runway is being considered. A simplified representation of the runway configuration is used, as shown in Figure 1. It consists of one runway with a crossing at a length y_3^b from the runway start threshold. The crossing has remotely controlled stopbars on both sides of the runway. The runway is being used for taking off aircraft. The traffic crossing over the runway accounts for traffic between apron(s) and a second runway. The involved human operators include the start-up controller, the ground controller, per runway a runway controller, the departure controller, and the pilots flying and pilots not flying of taking-off aircraft and crossing aircraft.

Communication between controllers and aircraft crews is via standard VHF R/T. Communication between controllers is supported by telephone lines. Monitoring by the controllers can be by direct visual observation and is supported by radar track plots. Monitoring by the aircraft crews is by visual observation and is supported by the VHF R/T party-line effect.

In the runway crossing operation considered, the control over the crossing aircraft is transferred from the ground controller to the controller of the runway to be crossed. If the runway controller is aware that its runway is not used for a take-off, the crew of an aircraft intending to cross is cleared to do so. The pilot not flying of the crossing aircraft acknowledges the clearance and then the pilot flying initiates the runway crossing. As soon as the crossing aircraft has vacated the runway, then the pilot not flying reports this to the controller of that runway. Next the control over the aircraft is transferred from this runway controller to either another runway controller or to the ground controller.

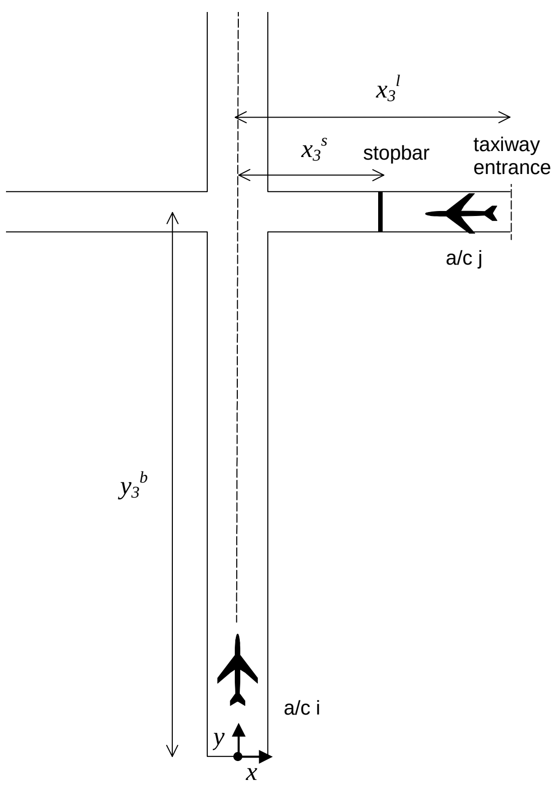

Figure 1: Configuration of active runway crossing operation considered. Aircraft i and j respectively take off from a position at the runway start and taxi along a taxiway leading to a runway crossing at a given distance from the runway start.

3.2 Joint model for integrated simulations

The TOPAZ and Air-MIDAS simulation models consider the following human agents: pilots flying for both the taxi aircraft and the taking off aircraft, and the runway controller. The most important elements of these human and other entities are shortly described below.

Pilot flying of taking-off aircraft

Initially, the pilot flying (PF) of the taking-off aircraft has the situation awareness (SA) that take-off is allowed and initiates a take-off. During the take-off the PF visually monitors the traffic situation on the runway. During a monitoring action the PF may not observe the crossing aircraft, because of a limited gaze angle or the distance with the crossing aircraft exceeds a viewing threshold, or occasional heads-down time for engine parameter sampling. The monitoring process includes distance dependent error components. Furthermore, the PF monitors the VHF communication channel. The PF of the taking-off aircraft starts a collision avoiding braking action if (s)he observes the crossing aircraft within a critical distance of the runway centre-line or in reaction to a controller clearance, and (s)he decides that braking will stop the aircraft in front of the crossing aircraft.

Pilot flying of taxiing aircraft

Initially, the PF of the taxiing aircraft has the SA that either (s)he is taxiing on a regular taxiway, which does not cross a runway or (s)he is taxiing on a taxiway approaching the runway crossing. In the latter case the PF may have the SA that crossing is allowed. Both in the case that the PF has the SA that (s)he is taxiing on a regular taxiway and in the case that the PF is aware that a runway crossing is allowed, the PF proceeds on the runway crossing. During taxiing the PF visually monitors the traffic situation. The characteristics of the monitoring process depend on the SA of the PF concerning the next airport waypoint (either runway crossing or taxiway). After passage of the stopbar the PF may receive a hold clearance by the runway controller. There is a probability that the controller message is not properly understood by the PF. In response to a hold clearance or an observed conflict the PF initiates braking of the aircraft, unless the cockpit of the crossing aircraft is estimated to be already within a critical distance of the runway centre-line.

Runway controller

The runway controller visually monitors the traffic situation on the runway. There is a probability that during monitoring an aircraft is not observed. In response to an alert, the controller directly monitors the traffic situation and the TOPAZ controller model updates the SA. If the controller is aware that the crossing aircraft has passed the stopbar then (s)he specifies a hold clearance to both the crossing and the taking-off aircraft.

3.3 Parameters jointly represented

As noted, the representations that the two simulation modeling systems provide are in some ways similar and in others different. Upon examination of the similarities and differences of the models used for the surface operation considered by Air MIDAS and by the TOPZ-TAXIR toolset, a list of model parameters to be affected by the joint runs was identified. These parameters are grouped and provided as follows:

- braking initiation times of pilots flying;
- inter-monitoring time of pilot flying of taxiing aircraft;
- duration of visual observation of pilots flying.

4. Air-MIDAS results and use by TOPAZ-TAXIR

4.1 Braking initiation time of PF's

This parameter group includes the braking initiation times of pilots flying of taking-off or taxiing aircraft in either tactical of opportunistic mode, when they have become aware of a conflict with the other aircraft. In Figure 2 an overview is provided of the probability density functions (PDF's) and related parameter values for Air-MIDAS and the original and the modified TOPAZ-TAXIR. In all three models equal PDF types and parameter values for the braking initiation times are chosen for the pilots flying of the taking-off and taxiing aircraft, regardless of their cognitive control modes.

It can be observed that in comparison to Air-MIDAS, the original TOPAZ-TAXIR has a smaller mean braking initiation time, and a larger tail (probability of more than 5 s initiation time). In order to improve on these aspects, for the modified TOPAZ-TAXIR model the Rayleigh PDF has been selected. The improvements are:

- its shape better fits to the Air-MIDAS data,
- it supports positive values only,
- has a more realistic tail than Gaussian PDF

The parameter value of the Rayleigh PDF has been chosen such that its standard deviation equals the standard deviation of the PDF chosen in Air-MIDAS.

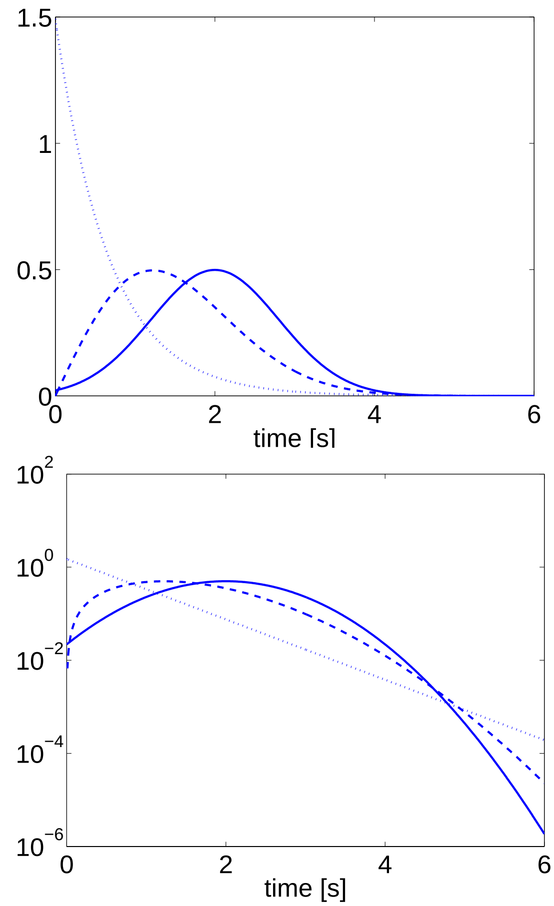

Figure 2: Probability density functions for braking initiation time on a linear scale (top figure) and a logarithmic scale (lower figure). Air-MIDAS (continuous line): Gaussian PDF with μ=2, σ=0.8. Original TOPAZ-TAXIR (dotted line): exponential PDF with μ=0.67, σ=0.67. Modified TOPAZ-TAXIR (dashed line): Rayleigh PDF with μ=1.53, σ=0.8.

4.2 Inter-monitoring time of PF of taxiing aircraft

It is assumed in TOPAZ-TAXIR that the inter-monitoring time of the pilot flying of the taxiing aircraft is independent from the cognitive control mode of the pilot. In the original model this time was represented by an exponential probability density function. Simulations of Air-MIDAS resulted in a data-set of 536 inter-monitoring times of the taxiing pilot flying. An histogram of this data-set is shown in Figure 3. It can be observed that this histogram can be well represented by an exponential PDF. Therefore, in the modified model the inter-monitoring times of the taxiing PF are also chosen from an exponential PDF with a mean equal to the estimated mean of the Air-MIDAS data.

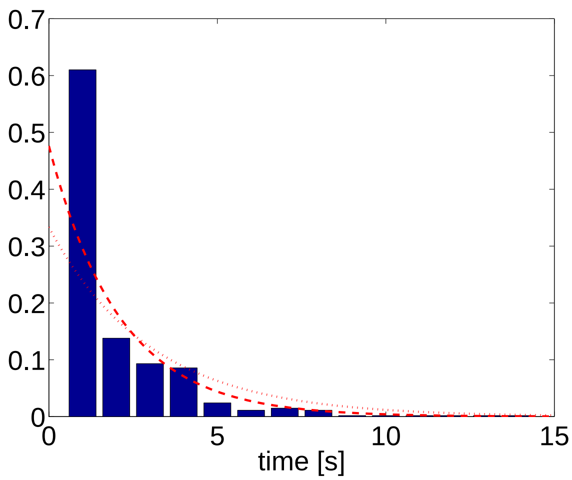

Figure 3: Data of inter-monitoring times of the PF of taxiing aircraft. Air-MIDAS (bars): normalized histogram of data ($\hat{\mu}=2.1, \hat{\sigma}=1.8$). Original TOPAZ-TAXIR (dotted line): exponential PDF with μ=3.0, σ=3.0. Modified TOPAZ-TAXIR (dashed line): exponential PDF with μ=2.1, σ=2.1.

4.3. Duration of visual observation of PF's

This parameter group includes the visual observation times of pilots flying for the taking-off or taxiing aircraft in either tactical of opportunistic mode. The PDF's of these times in the original model are exponential PDF's with a mean that is smaller in the opportunistic mode than in the tactical mode.

Air-MIDAS simulations provided data on the duration of the tasks:

- 'Monitor Out The Window' for the PF of the taking-off aircraft, and
- 'Decide Action - Decide Take-off Spotted' for the PF of the taxiing aircraft.

These tasks were found to be in good agreement with the visual observation tasks of the pilots flying of the taking-off and taxiing aircraft, respectively. These data were provided for the three control modes used in Air-MIDAS.

Histograms of the Air-MIDAS data are shown in Figure 4. In these data there are no statistically significant differences between the visual observation times for the two control mode categories. Hence, for the modified TOPAZ-TAXIR model it is assumed that the shape of the probability density functions does not depend of the control mode.

It can be observed in Figure 4A,B,C that the histograms of the visual observation time of the PF of the taking-off aircraft can be reasonably approximated by uniform PDF's with a lower bound of 0.5 and an upper bound of 1.5. Therefore this simple representation was chosen in the modified model (see Figure 5). For the PF of the taxiing aircraft, the Air-MIDAS data indicate that the variance of the visual observation duration is smaller than for the PF of the taxiing aircraft (see Figure 4.D,E,F), whereas their means are about equal. To not unduly complicate the TOPAZ-TAXIR model and since there are no manifest reasons why the PDF of the visual observation duration should be different for pilots flying of the taking-off and taxiing aircraft, the PDF for the taxiing aircraft case is chosen equal to PDF for the taking-off aircraft case.

5. Integration Impact on Collision Risk Model

In Table 2 the collision risk results of both versions of TOPAZ-TAXIR are shown for three values of the distance of the runway crossing with respect to the runway start threshold. It follows from these results that the collision risks as evaluated by the modified model are smaller than those evaluated by the original model and that the relative differences in collision risk tend to get larger for larger crossing distances. In all cases, the difference between the results is within a factor two.

Table 2: Collision risks evaluated by the original and modified TOPAZ-TAXIR models for three crossing distances.

Crossing distance	**Original Collision Risk** (occurrence per take-off)	**Modified Collision Risk** (occurrence per take-off)
500 m	$1.3\ 10^{-8}$	$1.2\ 10^{-8}$
1000 m	$1.1\ 10^{-8}$	$7.1\ 10^{-9}$
2000 m	$8.0\ 10^{-9}$	$4.4\ 10^{-9}$

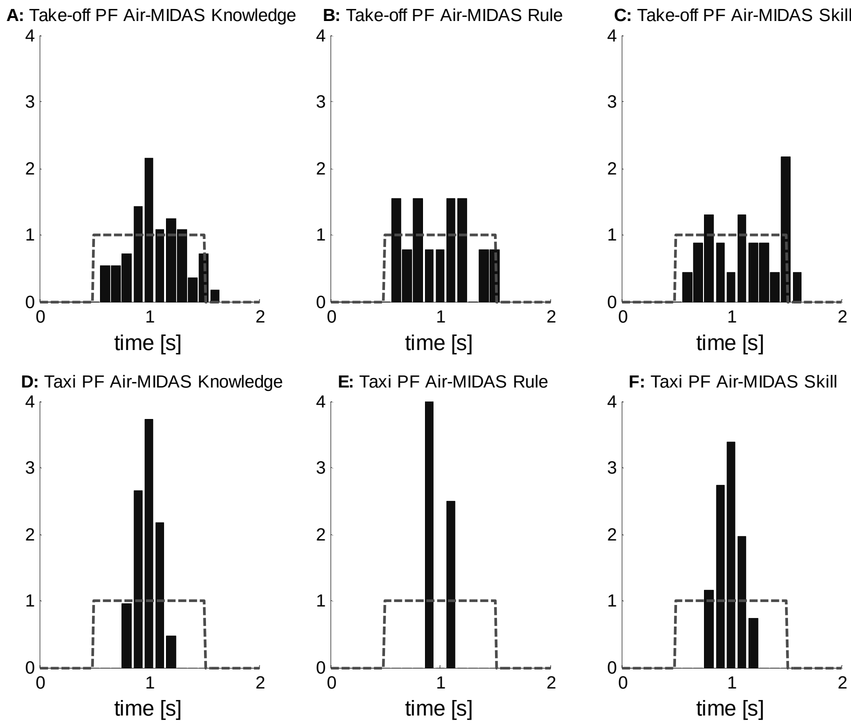

Figure 4: Air-MIDAS data of visual observation times of the PF's of taking-off aircraft (upper figures) and taxiing aircraft (bottom figures), when control mode are Knowledge-based (left), Rule-based (centre) or Skill-based (right). The dashed lines picture the uniform density fits adopted versus the normalized histograms.

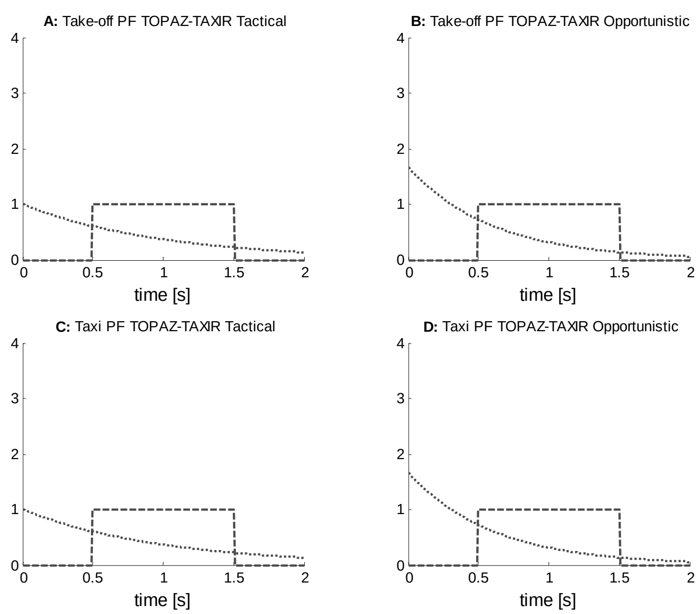

Figure 5: TOPAZ-TAXIR probability density functions of visual observation times of the PF's of taking-off aircraft (upper figures) and taxiing aircraft (bottom figures), while the control mode is similar to tactical (left) or opportunistic (right). Original (dotted lines): exponential PDF's. Modified (dashed lines): uniform PDF's.

The collision risk value that result from the TOPAZ-TAXIR simulations is composed of risk contributions from combinatorially many event sequences (Stroeve et al., 2003). In particular, the event sequence classes include the status of technical systems, such as alerting systems and communication systems, aircraft types, and human operator situation awareness. Since the adaptations of TOPAZ-TAXIR in the integration process with Air-MIDAS all consider assumptions regarding the behaviour of pilots flying, it is interesting to compare the risk decomposition for a pilot flying in the original and modified models. In particular, in Figure 6, collision risk results are shown for the situations that

- the pilot flying of the taxiing aircraft believes to be on a regular taxiway, or
- The pilot flying of the taxiing aircraft believes that runway crossing is allowed.

In the first case the pilot is lost, in the second case the situation awareness corresponds well with the actual position of the aircraft.

It can be observed in Figure 6 that in both the original and the modified model, the risk contribution for the situation that the pilot is aware to be on a regular taxiway exceeds the risk contribution for the situation that the pilot is aware to be on a runway crossing. However, the difference between those risk contributions is smaller in the modified model than in the original model.

On the one hand, the reduced difference in the risk contributions between the model versions is due to an increase in the risk contribution for the situation that the pilot flying is aware to be on a runway crossing in the modified model. The model modifications that may effect this risk increase concern the braking initiation times by the pilots flying of both aircraft, and the duration of the visual observation tasks of the pilots flying of both aircraft.

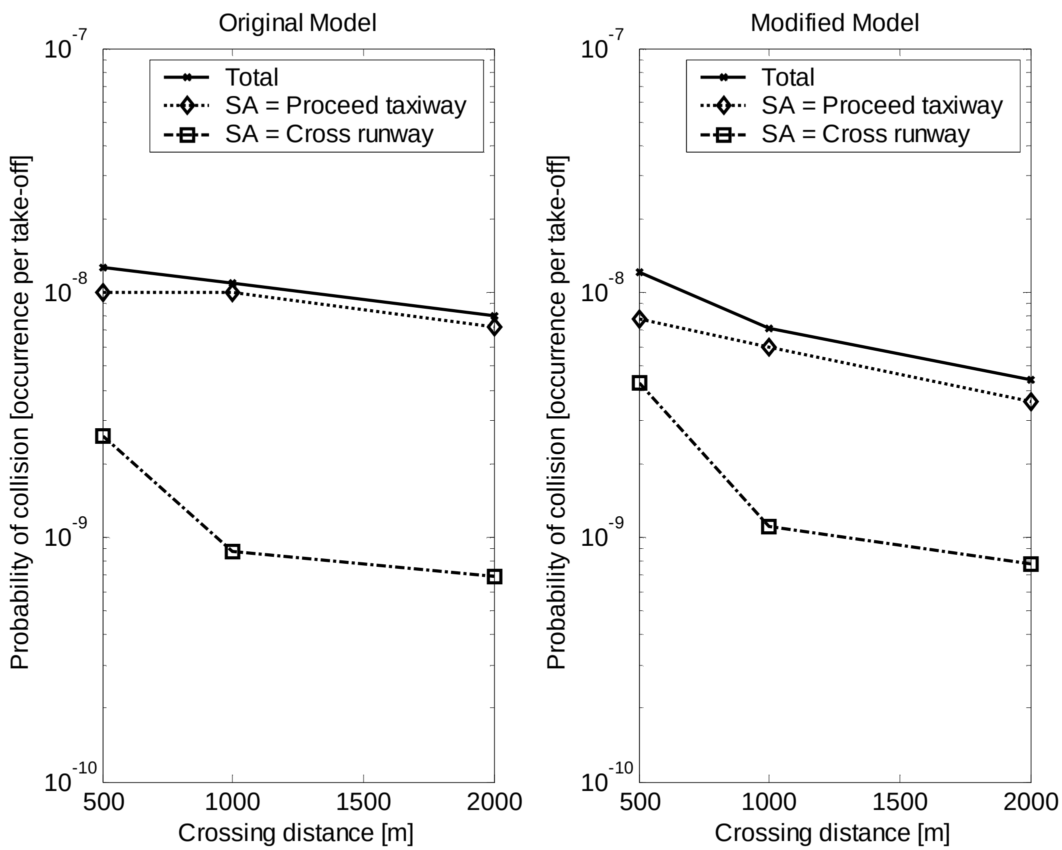

Figure 6: Total risk per take-off aircraft to collide with a crossing aircraft and contributions to this by correct and incorrect SA by the PF of the crossing aircraft; left for the original, right for the modified TOPAZ-TAXIR model.

For a further evaluation of the effects of these modifications a sensitivity analysis is required. As a preliminary finding, the risk increase is especially due to the increase in mean braking initiation times and may be to a smaller extent due to the increase in mean visual observation time in the opportunistic mode.

On the other hand, the reduced difference in the risk contributions between the model versions is due to a decrease in the risk contribution for the situation that the pilot flying is aware to be on a regular taxiway in the modified model. The risk decrease in this situation is effected by all model modifications. The combined effect of the changes in the braking initiation times and the visual observation times is a risk increase. The decrease in the mean inter-monitoring time of the pilot flying of the taxiing aircraft leads to a risk decrease because it causes the pilot to monitors for conflicting traffic more often. The combined effect turns out to decrease risk.

6. Conclusions

The results showed that the Air-MIDAS based adaptation did lead up to a factor two reduction in assessed collision risk level. This result alone demonstrates that it is feasible and useful to couple Air-MIDAS and TOPAZ. More importantly this means that we have now running two human performance simulations for more or less the same situation. This gave us the unique chance to make further comparisons between the two simulation approaches.

We examined the change in collision risk assessment resultant from the integration of these two models. In the scenario examined, the actions of the flight crew and ATC are largely perceptual-motor response to runway incursion. The impact assessment reported reflects the change in those characteristics. More complex decision making or coordinated action among agents and safety augmentation technologies would require full representation of the models of those more complex interactions.

In order to recognize the logical pattern in these differences, one should be aware that both are aimed to assess quite different top-level metrics. Air-MIDAS top-level metric is the behavioral pattern of human operators; while TOPAZ top-level metric is collision risk. The implied focal attention in TOPAZ is on performance, error making and error propagation among multiple agents versus memory and task scheduling and performance in Air-MIDAS. For error mechanisms the error recovery model of Amalberti & Wioland (1997) has been reported for two types of stress levels. This is reflected by the two control modes of TOPAZ and avoids the need to model a lot of memory and task performance characteristics. In Air-MIDAS the adoption of the Skill Rule Knowledge (SRK) model of Rasmussen for task performance leads to three control modes, and with this the need to model memory and task scheduling and performance in detail. The complementarity of TOPAZ and Air-MIDAS makes it so interesting to compare simulation results obtained by both approaches.

Both for Air-MIDAS and TOPAZ, a proper work breakdown and scheduling mechanism of subtasks is very important in order to make effective use of the human resources available in the model. The more complete task breakdown within Air-MIDAS yields a greater level of detail, and cognitive psychological expertise is often used to fill in the parameter values. The nice thing about this is that the model can partly be validated by walkthroughs by cognitive psychologists. However the larger detail also implies that there also is more to be validated than with the less detailed approach of TOPAZ.

From a validation perspective both approaches have much in common: they produce results on basis of carrying out simulations with a mathematical/computational model and by its very nature, a mathematical/computational model differs from reality. In order to validate a mathematical/computational model in a systematic way, the following activities should be performed:

- Identification of the differences between the mathematical model and the reality, and
- Assessment of the effect of these differences on the value of the output metric(s).

This validation process termed bias and uncertainty assessment is scheduled to be undertaken for the integrated simulations of Air-MIDAS and TOPAZ-TAXIR for the runway operation considered.

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List of keywords

Discrete Event Modeling, Human Performance Modeling, Model Integration, Accident Risk Assessment, Surface Movement, Validation, Runway Incursion, Monte Carlo Simulation

Biographies

Kevin Corker is currently an Associate Dean of the College of Engineering and a Professor in the Industrial and Systems Engineering Department, San Jose State University. He received his Ph.D. in a joint program in Cognitive Psychology and Engineering Systems from the University of California, Los Angeles. His major areas of research interest include computational cognitive modeling, human performance, human-system measurement methodologies, human-automation system integration and issues in control and display in large-scale dynamic systems.

Henk Blom is Principal Scientist at National Aerospace Laboratory NLR in Amsterdam. He received a PhD from Delft University of Technology on Bayesian estimation for decision-directed stochastic control. His major research interests include modeling and analysis of uncertain and distributed systems involving multiple agents (human and automata) and with applications to multi-source data fusion and to the management of safety critical operations.

Sybert Stroeve is Senior Scientist in air transport safety at National Aerospace Laboratory NLR, The Netherlands. He received his Ph.D. for modeling neuromuscular control of human arm movements from Delft University of Technology. His current research interests include human performance modeling, accident risk assessment and accident risk management.