Accident Risk Analysis Benchmarking Monte Carlo Simulation versus Event Sequences

Henk A.P. Blom, Sybert H. Stroeve, Jelmer J. Scholte
National Aerospace Laboratory NLR
Amsterdam, The Netherlands
blom@nlr.nl; stroeve@nlr.nl; scholte@nlr.nl

Hans H. de Jong
DFS Deutsche Flugsicherung GmbH
Langen, Germany
hans.de.jong@dfs.de

***Abstract*—Fault and event trees are the dominantly used safety risk models in air traffic. Systemic accident risk assessment by Monte Carlo simulation is a more recent technique, the power of which is less explored. In this paper we compare the two approaches for an accident risk analysis of an active runway crossing operation that is supported by a runway incursion alerting system for the runway controller. For this example we show and explain remarkable differences in results obtained using the two approaches.**

Keywords- runway crossing; runway incursion; collision risk; stochastic systems; Monte Carlo simulation; event sequence analysis; alert system

I. INTRODUCTION

In following Hollnagel [11], accident models can be categorized in sequential models, epidemiological models, and systemic models.

Sequential accident models describe an accident as the result of a limited number of sequences of events that occur in a specific order. These models assume that there are well-defined cause-effect links that propagate the effects of chains of events leading to an accident. Examples of sequential accident models are the domino theory, event trees and fault trees. Many methods used in practice are based on the traditional fault/event tree. However, as argued by Hollnagel and several other leading researchers, e.g. [15], [16] and [18], they may not be adequate to account for the complexity of modern socio-technical systems. Sequential accident models are commonly known and often applied in system dependability and safety requirement studies in aviation and air traffic, e.g. [8].

Epidemiological accident models describe an accident in analogy with the spreading of a disease, i.e. as the outcome of a combination of factors, such as performance deviations, environmental conditions, barriers and latent conditions. Like sequential accident models, epidemiological accident models rely on cause-effect propagation in accidents. Epidemiological models provide a broader basis to represent the complexity of accidents than sequential models by better accounting for interactions between relevant factors. Epidemiological models have been used in aviation and air traffic, in methods such as the Human Factors Analysis and Classification System of Wiegmann and Shappel [21] and Bayesian belief networks, e.g. [1], [10], [13].

Systemic accident models describe the performance of a system as a whole, rather than at the level of cause-effect mechanisms or epidemiological factors. The systemic view considers accidents as emergent phenomena from the variability of a system, for instance due to the concurrent and interacting behaviour of multiple agents (humans, technical systems) in a safety critical and dynamic operation. In such case the interacting multiple agents together form a joint cognitive system (Hollnagel and Woods, [12]). Hollnagel [11] explains that the foundation of systemic models lies in systems, control and chaos theories. Subsequently, he describes the key principles of these theories in terms of an elegant functional resonance accident model. Leveson [15] directly exploits the control theory view for the development of a systemic accident modelling approach, named STAMP. Corker, Pritchett and co-workers [14], [17] have shown that agent based Monte Carlo simulation allows to predict emergent behaviour in advanced air transport developments. Blom et al. [4] exploit stochastic system and control theory to develop a multi-agent Monte Carlo modelling and simulation approach for the evaluation of safety critical air traffic scenarios, named TOPAZ. Stroeve et al. [19] show that this Monte Carlo modelling and simulation approach is of systemic accident type.

To practitioners of accident risk analysis of future air traffic management designs (e.g. in NEXTGEN and SESAR), the development of three rather different types of accident modelling types raises the question whether the developments beyond sequential models yield better safety analysis results or not. In the latter case the novel approaches would be nice to have only. In the former case, the novel approaches even may be of critical design value for the design of future air traffic management. In order to bring more clarity in this question, the aim of this paper is to compare a fault/event tree approach with a Monte Carlo simulation approach for an active runway crossing operation, that is supported for safety reasons by a runway incursion alert system (RIAS) for the runway controller. This active runway crossing example incorporates concurrent and interacting behaviour of pilots and controllers in the dynamics of the operation.

The paper is organized as follows. Section II presents the active runway crossing operation considered. Section III

ISBN: 978-0-615-20720-9

presents the safety relevant scenarios that have been identified for this operation, and the scenario selected for benchmarking. Section IV presents the risk assessment by the event sequence modelling and analysis. Section V presents the risk assessment through Monte Carlo modelling and simulation Section VI compares the accident risk results obtained by the two approaches. Finally, Section VII draws conclusions.

II. THE ACTIVE RUNWAY CROSSING OPERATION

The subject of our risk assessment is an active runway crossing operation proposed at Amsterdam Airport Schiphol. In this proposed operation, Runway 18C is used for departures, whereas taxiing aircraft have to pass it on their ways from the gate to departure from Runway 36L, or from landing on Runway 18R to the gate. Figure 1 shows Runway 18C/36C with surrounding taxiways.

During the early development of the infrastructure and operation for simultaneous use of the aforementioned runways, the air navigation service provider opted for crossings over an active Runway 18C/36C, to keep taxi times between airport centre and the far-off runway as low as possible. For this operation, a runway incursion alerting system (RIAS) was foreseen to give stop bar violation alerts and runway incursion alerts. In support of this early development phase, a safety requirements analysis has been performed using a functional hazard analysis (FHA) for, inter alia, the runway incursion alerting system and its usage by the runway controller (RC). In [9], a number of hazardous scenarios have been considered, such as collisions between a departing aircraft and an aircraft making a runway incursion, and between an aircraft sliding off the runway and an aircraft holding at a crossing point. The safety risk analysis of the runway incursion collision scenario delivered, inter alia, the following design requirements under poor visibility condition:

- The probability that the Runway incursion alert system (RIAS) fails to detect a runway incursion is at most 10^{-5};
- The probability that the runway controller fails to react appropriately to an alert is at most 5×10^{-5};
- The probability that it takes a minute for contingency procedures to become effective when the radio frequency is blocked, is at most 10^{-5}; and
- The probability that pilots of both aircraft fail to react to stop taxiing and cancel take-off/perform missed approach is at most 10^{-5}.

These FHA based design requirements subsequently formed the basis for the design of a RIAS supported active runway crossing operation of runway 18C/36C. As has been explained in [7], eventually this proposed RIAS supported runway crossing design of active runway 18C/36C has not been selected for implementation at Amsterdam Airport Schiphol. For the purpose of comparing two risk analysis methods, however, this RIAS supported runway crossing design forms a valuable example.

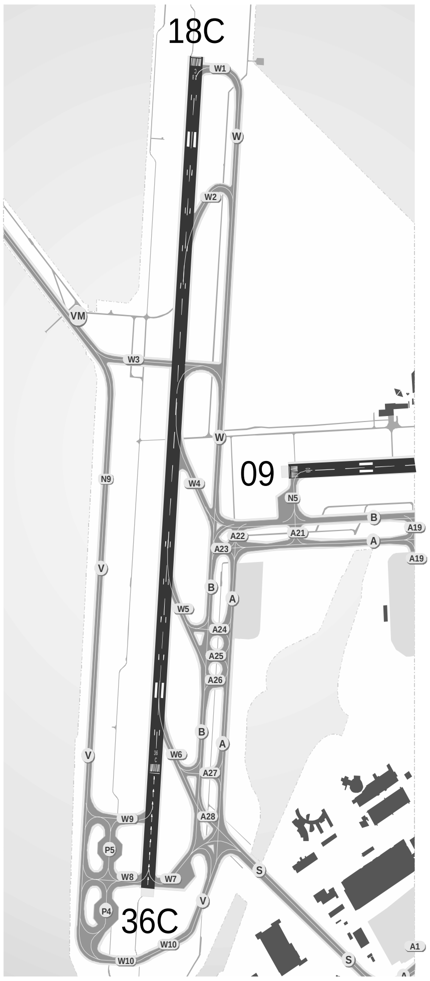

Figure 1. Runway 18C/36C and its surrounding at Amsterdam Airport Schiphol

III. COMMON ACCIDENT RISK ANALYSIS STEPS

In order to validate whether the RIAS supported design of the active runway crossing operation would be sufficiently safe, it has been evaluated following a formal risk assessment process. An overview of the steps taken in this safety risk assessment is given in Figure 2. This cycle has been developed over many years at NLR, and presented in [4]. This cycle is generic in the sense that it is used both in preparation of an event sequence-based assessment as well as a Monte Carlo simulation based assessment.

In step 0, the objective of the assessment is determined, as well as the safety management and regulatory context, the scope and the level of detail of the assessment. The actual safety assessment starts by determining the operation that is assessed (step 1). Next, hazards associated with the operation are identified (step 2), and aggregated into safety relevant scenarios (step 3), for which the potential severities are identified (step 4). The risk quantification is done in the frequency assessment (steps 5). Subsequently, the safety risk associated with each safety relevant scenario is classified (step 6). For each safety relevant scenario with a (possibly) unacceptable safety risk, the main sources (safety bottlenecks)

ISBN: 978-0-615-20720-9

contributing to safety risks are identified (step 7), which help operational concept developers to learn for which safety issues they should develop improvements in the ATM design. If the ATM design is changed, a new safety risk assessment cycle of the operation must be performed in order to investigate how much the risk posed by previous safety issues has been decreased, and to assess any new safety issues that may have been introduced by the enhancements themselves.

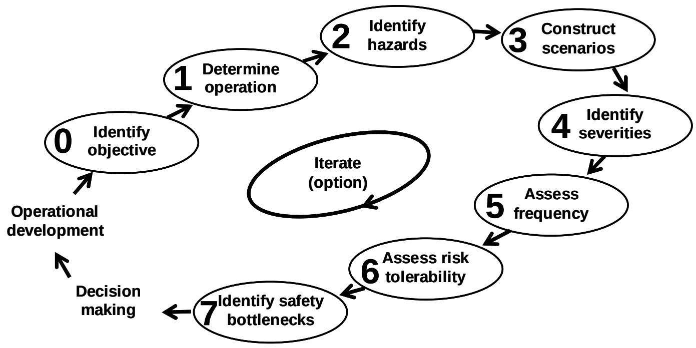

Figure 2. Safety risk assessment cycle.

Steps 0 through 4 are the common accident analysis steps for Monte Carlo simulation and fault/event tree based approaches in step 5. For the active runway crossing operation considered these common steps are described in the remainder of this section.

Step 0: Identify objective

Before starting the actual risk assessment, the objective and scope of the assessment are set. This is done in close co-operation with the decision makers and designers of the advanced operation. Also, the appropriate framework of safety management and safety regulations must be made clear, such that the assessment is performed in line with these.

An important issue in setting this context is the choice of risk tolerability criteria/Target Level of Safety (TLS) with respect to which the assessment is performed and the scope of risks to which these are applied. Depending on the application, such criteria are defined for particular flight condition categories (e.g. flight phases or sub-phases) and for particular severity categories (e.g. accident or serious incident). Typically, within the chosen context, these criteria define which flight condition/severity categories have to be evaluated and which frequency level forms the Target Level of Safety (TLS) threshold per flight condition/severity category.

Step 1: Determine operation

Step 1 serves for the risk assessors to obtain a complete and concise overview of the operation, and to freeze this description during each cycle of analysis. Main input to step 1 is a description of the operational concept from the designers, while its output is a sufficiently complete, structured, consistent and concise description of the operation considered. The operation should be described in generic terms, it should provide any particular operational assumption to be used in the safety assessment, and it has to be verified by the operational concept designers. Typically during this step, holes and inconsistencies in the concept as developed are also identified and immediately fed back to the design team.

Step 2: Identify hazards

The term hazard is used in the wide sense; i.e. an event or situation with possibly negative effects on safety. Such non-nominal events or situations may evolve into danger, or may hamper the resolution of danger, possibly in combination with other hazards or under certain conditions. The goal of step 2 is to identify as many and as diverse hazards as possible. Hazard identification brainstorming sessions are used as primary means to identify (novel) hazards.

Based on the experience gained in using the hazard identification part of HAZOP in a large number of safety analyses and on scientific studies of brainstorming, NLR has developed a method of hazard identification for air traffic operations by means of pure brainstorming sessions. This method has been reported in [6]. In such a session no analysis is done and solutions are explicitly not considered. An important complementary source is formed by hazards identified in previous studies on related operations. Example hazards are mentioned in the explanation of step 3.

In total, about 100 hazards have been identified. A first ordering of these hazards is made by distinguishing

- root hazards, which describe safety relevant events and conditions that cause the initiation of a conflict in a safety relevant scenario, and
- resolution hazards, which describe events and conditions that influence resolution of the conflict, which is aimed at limiting the severity of consequences.

Step 3: Construct scenarios

When the list of hazards is as complete as reasonably practicable, it is processed to deal with duplicate, overlapping, similar and ambiguously described hazards. Then, per flight condition selected in Step 0, the relevant ‘conflict’ types which may result from the hazards are identified using a full list of potentially relevant conflict types, such as for instance ‘aircraft erroneously crossing and other aircraft in take-off’ and ‘collision between aircraft sliding off runway and aircraft near crossing’. Although these situations are simply called ‘conflicts’, it is important to note that not only ordinary conflicts between aircraft are considered; ‘conflict types’ rather indicate general potentially dangerous operational situations.

Each potentially relevant conflict type is subsequently used as crystallization point upon which all applicable hazards and their combined effects are fitted as elements of additional event sequences. If hazards cannot be appropriately addressed by the crystals developed so far, then additional conflict types need to be defined and corresponding scenarios developed. The output of such a crystallization process is a bundle of event/condition sequences and effects per conflict type/crystallization point, and each resulting crystal is referred to as a safety relevant scenario (see Figure 3). This way of constructing scenarios aims to bring into account all relevant ways in which hazards can play a role.

 ISBN: 978-0-615-20720-9

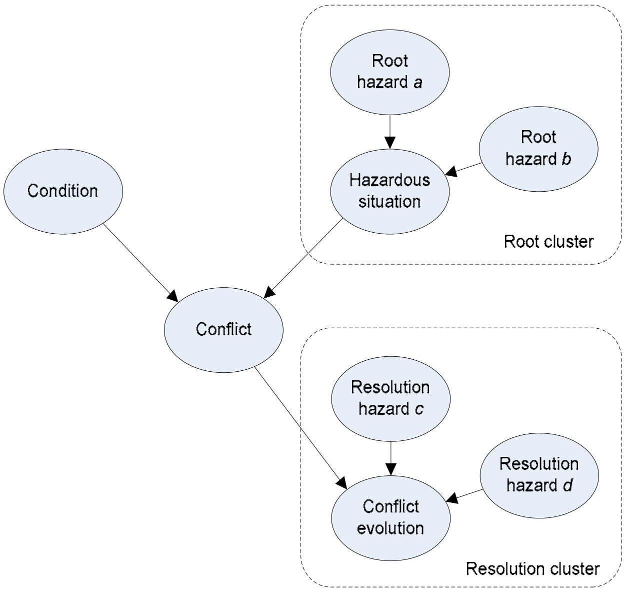

Figure 3. Generic diagram of a safety relevant scenario.

The outcome of this crystallization process are crystals for the following safety relevant scenarios of the active runway crossing operation:

- Scenario I: Aircraft erroneously in take-off and crossing aircraft on runway;
- Scenario II: Aircraft erroneously crossing and other aircraft in take-off;
- Scenario III: Aircraft taking off and runway unexpectedly occupied;
- Scenario IV: Aircraft crossing and runway unexpectedly occupied by aircraft;
- Scenario V: Aircraft crossing and vehicle on runway;
- Scenario VI: Collision between aircraft sliding off runway and aircraft near crossing;
- Scenario VII: Aircraft taking off and vehicle crossing;
- Scenario VIII: Jet-blast from one aircraft to another; and
- Scenario IX: Conflict between aircraft overrunning, or climbing out low, and an aircraft at a nearby taxiway.

Because Scenario II ranks high in expected safety risk, this scenario has been selected for the comparison of the two risk assessment approaches in this paper. Scenario II covers the situation where there is one aircraft that takes off from runway 18C, and has been allowed to do so, and there is one aircraft that crosses the runway while it should not, over the runway crossing position marked by ‘W3’, somewhat to the north of the middle of the runway (see Figure 1).

In the context of safety relevant scenario II, examples of its elements in figure 3 are:

- Root hazard a: Pilots react on clearance for another aircraft and start crossing;
- Root hazard b: Pilots cross without clearance;
- Hazardous situation: Aircraft crossing runway while it should not;
- Condition: Other aircraft has initiated take-off;
- Conflict: Aircraft is erroneously crossing the runway, while other aircraft is taking off;
- Resolution hazard c: Pilots of crossing aircraft do not frequently look for conflicting traffic;
- Resolution hazard d: Pilots of crossing aircraft are not tuned to frequency of runway controller; and
- Conflict evolution: Possible ways of evolution of the runway incursion conflict, e.g. leading to an accident or an incident of certain severity.

Step 4: Identify severities

For each of the safety relevant scenarios identified in step 3, it is determined which of the severity categories selected in step 0 are applicable to its possible effects. Usually, a range of severities applies to a safety relevant scenario. For all nine safety relevant scenarios, except scenario VIII, all four severities (minor, major, hazardous, accident) have been identified as being applicable [5]. For safety relevant scenario VIII, the severity of accident has been judged not to be applicable.

The sequel of this paper focuses on step 5 (assess frequency) of the safety analysis for the most severe possible effects of scenario II, i.e. accidents. In Section IV this is done using a fault/event tree analysis approach. Next, in Section V, this is done using a Monte Carlo modelling and simulation approach. Finally the results of both approaches are compared in Section VI.

IV. EVENT SEQUENCE BASED RISK ASSESSMENT

For safety relevant scenario II, the accident risk is modelled through a combination of fault and event trees. Two separate fault trees (see Figure 4) have been developed for two specific cases:

- Case p, i.e. pilot of taxiing aircraft starts crossing without contacting the runway controller (e.g. by misunderstanding the ground controller); and
- Case p-not, i.e. pilot of taxiing aircraft has contacted runway controller well, though starts crossing while it should not.

Subsequently, for each of these two fault trees an event tree has been developed. Both event trees make use of the following fixed sequence of twelve branching points:

- There is an aircraft on 18C in take-off (yes/no)
- Early recognition and resolution by pilots (yes/no)
- Early recognition by RC (yes/no)
- Stopbar violation alert and RC becomes aware of it (yes/no)
- Early communication by RC and pilot resolution (yes/no)
- Medium recognition and resolution by pilots (yes/no)
- Medium recognition by RC (yes/no)
- RIAS alert and RC becomes aware of it (yes/no)
- Medium communication by RC and pilot resolution (yes/no)
- Medium recognition by RC (yes/no)
- RIAS alert and RC becomes aware of it (yes/no)

ISBN: 978-0-615-20720-9

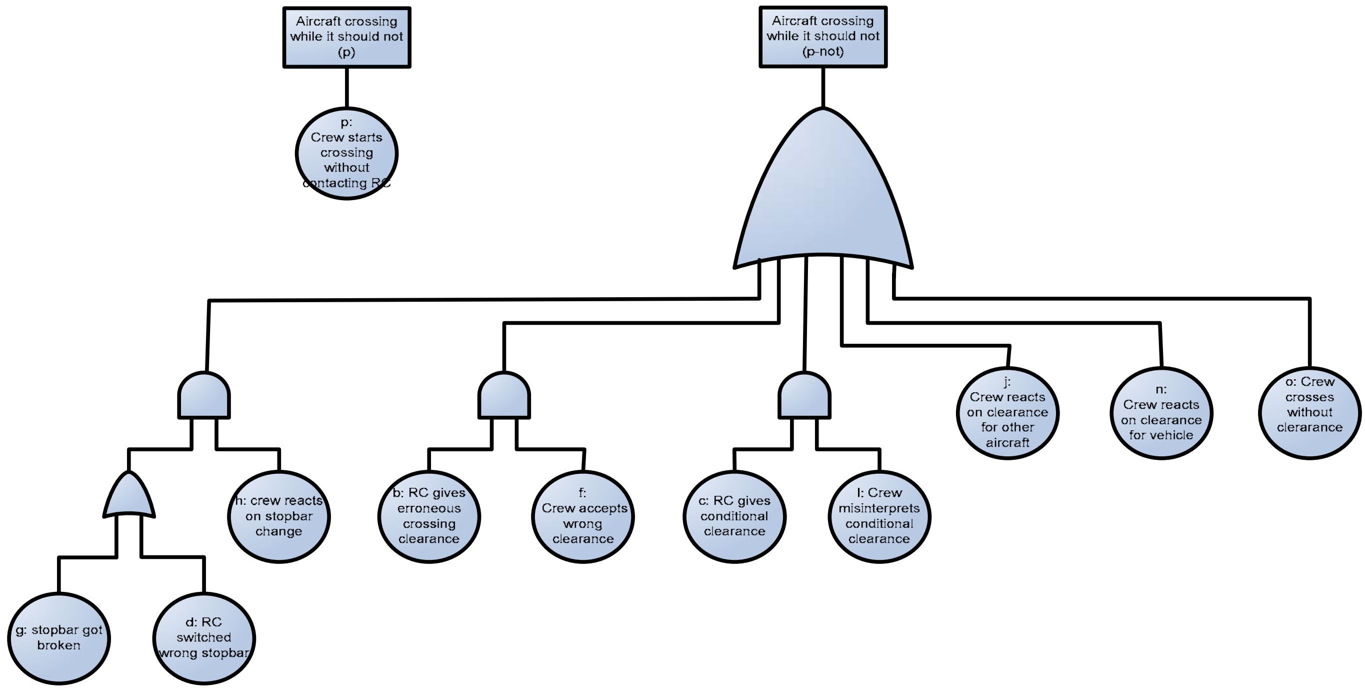

Figure 4: Fault Trees for safety relevant scenario II.

- Medium communication by RC and pilot resolution (yes/no)
- Late recognition and resolution by pilots (yes/no)
- Late recognition by RC and pilot resolution (yes/no)
- Late communication by RC and pilot resolution (yes/no)

The branching points in the event tree differentiate between early, medium, and late recognition of the conflict by the pilots and RC. This approach was chosen as a systematic means to get hold on the large variety in the timing of particular events to happen in combination with the timing of stop bar violation and RIAS alerts and the remaining braking distance.

Of all feasible branching point combinations, there are six ending at accident. All others end at late, medium or early resolution of the conflict. The estimation of the yes/no probability values per branching point has been done on the basis of statistical data and expert based estimates, for each of the two cases (p and p-not) separately [5]. This way, for each branching point both expected, and upper/lower bound probability values have been assessed. Subsequently, the quantified fault and event trees have been used to calculate accident risk in terms of expected value, and upper and lower bound values. The rsulting upper bound accident probability values for scenario II are given in Table I.

TABLE I. RESULTS OF THE EVENT SEQUENCE-BASED RISK ASSESSMENT FOR THE TWO CASES CONSIDERED. THE PROBABILITIES ARE UPPER BOUND VALUES PER TAKE-OFF.

Case	Conflict probability	Conditional accident probability given conflict	Accident probability
p-not	$3\ 10^{-4}$	$1.6\ 10^{-5}$	$4.8\ 10^{-9}$
P	$6\ 10^{-5}$	$7.3\ 10^{-5}$	$4.4\ 10^{-9}$
Total	$\mathbf{3.6\ 10^{-4}}$	$\mathbf{2.6\ 10^{-5}}$	$\mathbf{9.2\ 10^{-9}}$

In Figure 5 it is shown which branching points play a role in the accumulation of contributions to the accident probability. For contributions to case p, the risk is dominated by situations in which RC is alerted by stopbar violations. For contributions to case p-not, the risk is dominated by situations in which RC is not yet aware of the conflict after a stopbar violation alert.

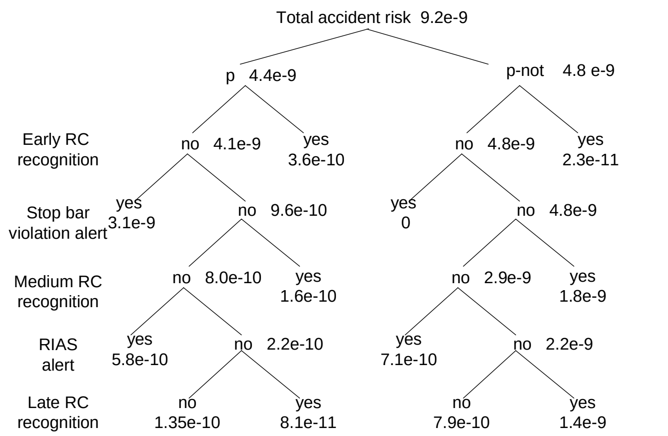

Figure 5. Contributions to the collision risk for events related to early, medium or late RC recognition of the conflict, and the occurrence of stopbar violation or RIAS alert. The probabilities are upper bound values per take-off.

V. MONTE CARLO BASED RISK ASSESSMENT

A. *Monte Carlo simulation model*

Prior to running Monte Carlo simulations for accident risk analysis, a simulation model is developed that captures the nominal and non-nominal (stochastic and dynamic) behaviour of the aircraft, the relevant technical systems, the relevant

ISBN: 978-0-615-20720-9

human operators (pilots and runway controller), and the interactions between all these entities. Figure 6 gives an overview of the main entities and their interactions for the runway incursion Monte Carlo simulation model [4], [19], [20]. An arrow from one entity to another entity indicates that the former (directly) influences the latter.

For the development of the models for the human operators, the key aspects are taken into account, such as situation awareness / task performance / task scheduling of a human operator, flight phases / performance modes of aircraft, and availability / status of an alert system. Subsequently, the interactions between human operators and/or technical entities are also modelled, e.g. the effect of task performance of a pilot on the flight phase of an aircraft, or the effect of an alert on the situation awareness of a controller. The resulting human performance models and their interactions have been calibrated and validated through a comparison with an Air-Midas model for surface operations [2], [3]. A complementary validation approach consisting of a systematic bias and uncertainty assessment has been provided in [19].

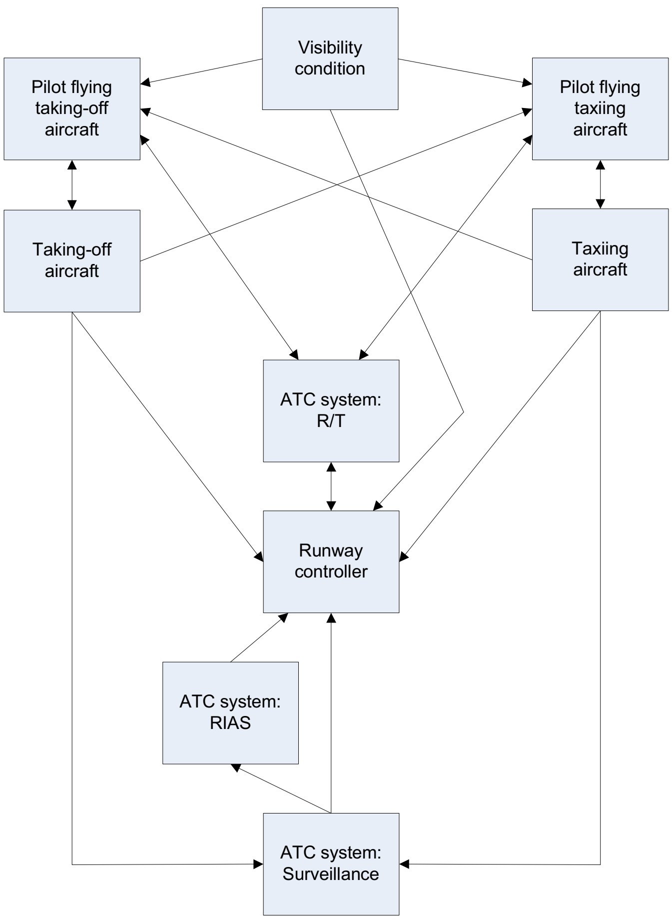

Figure 6. Interactions between the main entities of the runway incursion simulation model: aircraft, pilots flying, runway controller, visibility condition and ATC system (R/T, RIAS and surveillance).

B. Risk assessment results

Table II shows the values assessed for the event probabilities and conditional accident probabilities of the runway crossing operation considered, at a distance of 1000 m from the runway threshold. Two non-nominal situation awareness (SA) conditions for the pilot of the taxiing aircraft are distinguished*):

- The pilot flying of the taxiing aircraft believes to be proceeding on a normal taxiway (without being aware to be heading to a runway crossing), and
- The pilot flying of the taxiing aircraft starts to cross the runway without being aware that crossing is currently not allowed.

Table II shows that the conditional accident probability value is 35 times higher when the PF of the taxiing aircraft believes to be proceeding on a taxiway rather than being crossing a runway.

Through a deeper analysis of the Monte Carlo simulation results, the reasons of this large difference appeared to be as follows. When a pilot aims to cross a runway, then he will stop prior to the runway and expecting a clearance before actually starting the crossing. However, when a PF aims to proceed on a taxiway then there is no reason to stop, and its aircraft maintains taxiing speed. Moreover, being unaware of the runway, the pilot has no reason to frequently scan this runway. As a result of this, at the moment that a pilot detects the runway incursion, then the time period that is left to stop the aircraft is much shorter than the time period that would be available when the aircraft starts from a hold before crossing the runway, first has to build up taxiing speed, and where the pilot frequently scans this runway.

TABLE II. MONTE CARLO SIMULATION BASED RISK ASSESSMENT FOR RUNWAY CROSSING AT 1000M FROM TAKE-OFF STARTING POINT. THE VALUES ARE POINT ESTIMATES PER TAKE-OFF.

SA by PF of Taxiing aircraft	Probability of event	Event conditional accident probability	Accident probability
Cross runway	$2.3\ 10^{-4}$	$4.8\ 10^{-6}$	$1.1\ 10^{-9}$
Proceed taxiway	$3.5\ 10^{-5}$	$1.7\ 10^{-4}$	$6.0\ 10^{-9}$
Total	$\mathbf{2.7\ 10^{-4}}$	$\mathbf{2.6\ 10^{-5}}$	$\mathbf{7.1\ 10^{-9}}$

Figure 7 provides a view on various contributions to the collision risk, such as the influence of situation awareness conditions of the pilot of the taxiing aircraft (Cross runway/Proceed runway), and the functioning of ATC alert and communication systems (Up/Down). These results show that accident risk is dominated by situations where a pilot flying of a taxiing aircraft is not aware of the nearby runway due to erroneous situation awareness, whereas neither failure of alert systems for ATC, nor failure of communication systems contribute noticeably to collision risk per departure.

*) The identification of these non-nominal SA conditions is in fact a direct result of the systematic modelling of multi-agent SA within our Monte Carlo simulation model [20].

 ISBN: 978-0-615-20720-9

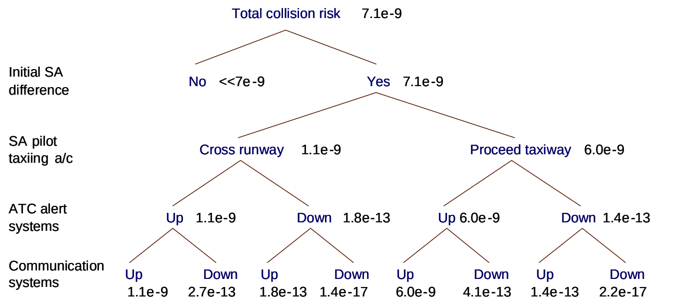

Figure 7. Contributions to the collision risk for various combinations of events related to pilot situation awareness and functioning of ATC alert and communication system, for crossing distance of 1000 m, under good visibility.

C. *Conditional risk increase under hypothetical assumptions*

Using the Monte Carlo simulation model, it also is possible to attain insight in the conditional risk increase when the monitoring capability of any of the involved human operators or ATC alert system is assumed to be out of the loop. Table III shows the conditional collision risks obtained for the hypothetical situation where an aircraft taxies towards a runway crossing while the pilot believes to taxi on a normal taxiway. The conditional collision risks in Table III refer to hypothetical cases where traffic conflict monitoring by specific human operators, or ATC alerting system are assumed to be within the model ('yes') or out of it ('no'). A risk increase factor is determined by comparing the conditional collision risk with the situation in which none of the human operators are taken out of the loop.

Table III shows that out-of-the-loop placing of monitoring function by PF of taxiing aircraft ranks highest on risk increase. Second ranks risk increase due to out-of-the-loop placing of monitoring by PF of taking-off aircraft. Third ranks risk increase due to out-of-the-loop placing of monitoring by RC, and fourth ranks risk increase due to out-of-the-loop placing of ATC alert systems.

TABLE III. CONDITIONAL RISK INCREASE FACTORS ACHIEVED IN THE SIMULATION MODEL DUE TO OUT OF THE LOOP ASSUMPTIONS OF MONITORING BY HUMAN OPERATORS OR ATC ALERT SYSTEM, WHEN THE PF OF A TAXIING AIRCRAFT INTENDS TO PROCEED ON A NORMAL TAXIWAY UNDER GOOD VISIBILITY (CROSSING IS AT 1000 M FROM RUNWAY THRESHOLD)

	Monitoring in the loop of					
Hypothetical Case	**PF taxi**	**PF take-off**	**RC**	**ATC alert systems**	**Conditional risk**	**Increase Factor**
0	Yes	yes	yes	yes	$1.7\ 10^{-4}$	1
1	no	yes	yes	yes	$9.4\ 10^{-3}$	55
2	Yes	no	yes	yes	$4.0\ 10^{-4}$	2.4
3	Yes	yes	no	yes	$2.3\ 10^{-4}$	1.4
4	Yes	yes	yes	no	$2.2\ 10^{-4}$	1.3

VI. COMPARISON OF RESULTS

For scenario II, the upper bound of estimated accident risk assessed by the event sequence approach equals $9.2\ 10^{-9}$ per take-off [5]. This means that the upper bound value estimated by the event sequence approach is almost equal to the Monte Carlo simulation based point estimate value of $7.1\ 10^{-9}$ per take-off.

Comparison of the values in Table I with the values in Table II, shows that the conditional collision risk total/mean values also are about the same for the scenario based upper bound estimates and the Monte Carlo simulation based point estimates. Through a bias and uncertainty assessment conducted in [19], it has been shown that the Monte Carlo simulation based upper bound value of the conditional risk is almost a factor five larger than the point estimated value. This means that the event sequence approach in Section IV leads to a significantly lower accident risk level per take-off than the Monte Carlo simulation approach in Section V.

In order to better understand the reason of this difference, Table IV compares conditional risk increase factors under MC simulation and event sequence approaches for the hypothetical cases of Table III plus two combinations, i.e. case 1&2 and case 1&2&3 respectively. The Monte Carlo simulation-based results are given for the case that the pilots of the taxiing aircraft believe to be proceeding on a taxiway and the event sequence-based results are given for event p 'Pilot starts crossing without contacting RC (e.g. by misunderstanding the ground controller)'. These two conditions have in common that they both imply that pilots of the taxiing aircraft are not aware of the need to be in contact with the runway controller, which makes their comparison particularly relevant.

TABLE IV. COMPARISON OF CONDITIONAL RISK INCREASE FACTORS DUE TO ASSUMING (COMBINATIONS) OF HUMAN OPERATOR MONITORING OUT-OF-THE-LOOP. IN THE MC SIMULATION RESULTS THE PILOT OF THE TAXIING AIRCRAFT (ERRONEOUSLY) BELIEVES TO TAXI ON A NORMAL TAXIWAY. THE EVENT SEQUENCE BASED RESULTS ARE UPPER BOUND ESTIMATES THAT APPLY TO EVENT P.

case	**Monitoring in-loop-of**			**MC simulations**		**Event sequences**	
	PF taxi	**PF take-off**	**RC**	**Conditional risk**	**Factor**	**Conditional risk**	**Factor**
0	yes	yes	yes	$1.7\ 10^{-4}$	1	$7.3\ 10^{-5}$	1
1	no	yes	yes	$9.4\ 10^{-3}$	55.3	**)	**)
2	yes	no	yes	$4.0\ 10^{-4}$	2.35	**)	**)
3	yes	yes	no	$2.3\ 10^{-4}$	1.35	$1.2\ 10^{-3}$	17
1&2	no	no	yes	*)	*)	$1.4\ 10^{-2}$	200
1&2&3	no	no	no	$8.9\ 10^{-2}$	530	$2.5\ 10^{-1}$	3400

*) In the MC simulation approach, not monitoring by pilots of both aircraft was not evaluated

**) In the event sequence approach, distinction between pilots of different aircraft was not modelled

The event sequence results in Table IV show that the product of the risk increase factor for the case without monitoring of the controller (case 3) and the risk increase factor for the case without monitoring of the pilots of both aircraft (case 1&2), is equal to the risk increase factor for the case where pilots and controller do not monitor (case 1&2&3). This reflects that in the event sequence approach the risk reducing contributions of pilots and controller are considered to be independent. In contrast, for the Monte Carlo simulation results, it follows from Table IV that the product of the risk

ISBN: 978-0-615-20720-9

increase factors due to not monitoring of individual human operators (case 1, case 2 and case 3) is considerably smaller than the risk increase factor for the case when both pilots and controller are not monitoring (case 1&2&3). This reflects that in the Monte Carlo simulation approach, the risk reducing contributions of pilots and controller are interdependent, such that the risk increase due to not monitoring by one of the actors is moderated by the performance of the others. In particular, Table IV shows that the increase in the conditional collision risk by excluding monitoring by RC is much higher in the event sequence approach (factor 17.1) than it is in the Monte Carlo simulation approach (factor 1.35). It is the simulation based approach that makes clear that although RC identifies a good share of conflicts, its contribution to avoiding a collision is much smaller than the event sequence based approach predicted. Deeper analysis yields that a significant proportion of the instructions issued by the runway controller arrive late, hence these instructions either concern conflicts that are already solved by the pilots, or even arrive too late for any of the pilots involved to successfully avoid a collision.

VII. CONCLUSION

In safety risk analysis literature there is an ongoing debate regarding the advantage of systemic modelling over sequential modelling for complex safety critical socio-technical systems, such as future air traffic management. In order to contribute in a concrete way to this debate, we performed a benchmark of both approaches for the same demanding application, i.e. accident risk analysis of active runway crossing operation. The sequential modelling approach considered is fault/event tree modelling. The systemic modelling approach considered is Monte Carlo modelling and simulation.

Within the dynamics of an active runway crossing operation, the concurrent and interacting behaviours of pilots and controllers make that accident risk analysis on the basis of an event sequence based approach may be more demanding than what can be managed in a controlled way. The introduction of a differentiation between early, medium and late responses did not prevent a significant underestimation of (conditional) collision risk contributions of up to an order in magnitude. More specifically, for the runway incursion scenario considered, the event sequence based approach provided results which would imply that, under good visibility conditions, RIAS support to RC could serve as an effective means of reducing accident risk by an order in magnitude. The Monte Carlo simulation approach, however, showed that the effective contribution of RIAS support is almost zero for the simple reason that the pilots often will receive a RIAS triggered instruction from RC at a moment that one of the pilots already has recognized and started to resolve the conflict. Nevertheless, in such case, RC may perceive him/herself to have played a key role in resolving the conflict well.

The key difficulty is that coping with time and dynamic dependencies within event sequence modelling, is complicated by the interactions and concurrencies that play a key role in runway incursion. The power of a Monte Carlo simulation approach is that it can handle concurrency and interactions well.

VIII. REFERENCES

[1] Ale BJM, Bellamy LJ, Cooke RM, Goossens LHJ, Hale AR, Roelen ALC, Smith E. Towards a causal model for air transport safety - an ongoing research project. Safety Science Vol. 44 (2006):657-673

[2] Blom HAP, Corker KM, Stroeve SH, Van der Park MNJ. Study on the integration of Air-MIDAS and TOPAZ: Phase 3 Final Report. National Aerospace Laboratory NLR, report CR-2003-584, October 2003

[3] Blom HAP, Corker KM, Stroeve SH. Study on the integration of human performance and accident risk assessment models: Air-MIDAS & TOPAZ. 6th USA/Europe ATM R&D Seminar, 2005, Baltimore, USA

[4] Blom HAP, Stroeve SH, De Jong HH. Safety risk assessment by Monte Carlo simulation of complex safety critical operations. In: Redmill F, Anderson T (eds.), Developments in risk-based approaches to safety, Springer-Verlag, London, 2006, pp. 47-67

[5] De Jong HH, Tump RS, Blom HAP, Van Doorn BA, Karwal AK, Bloem EA. Qualitative safety assessment of a RIASS based operation at Schiphol Airport including a quantitative model: Crossing of departures on 01L/19R under good visibility conditions. National Aerospace Laboratory NLR, Memorandum LL-2001-017, May 2001

[6] De Jong HH. Guidelines for the identification of haz-ards; How to make unimaginable hazards imaginable? NLR Contract report 2004-094 for EUROCONTROL, March 2004 (included in EUROCONTROL, 2006: FHA, Ch. 3, GM B.2)

[7] De Jong HH, Blom HAP, Stroeve SH. Unimaginable hazards and emergent behavior in air traffic operations. Proceedings ESREL 2007, 25-27 June 2007, Stavanger, Norway

[8] Eurocontrol. A-SMGCS Levels 1 and 2 Preliminary Safety Case. Edition 2.0, 2006.

[9] Gleave DP, Thompson KS. Amsterdam Airport Schiphol Risk Assessment of Runway 18/36 Taxiway Options, Report No: 72/98/R026R, July 1998, Issue 1, Roke Manor Research Limited, 1998

[10] Greenberg R, Cook SC, Harris D. A civil aviation safety assessment model using a Bayesian belief network (BNN). The Aeronautical Journal, November 2005, pp. 557-568

[11] Hollnagel E. Barriers and accident prevention. Ashgate, Hampshire, UK, 2004

[12] Hollnagel E, Woods DD. Joint cognitive systems: Foundations of cognitive systems engineering. CRC Press, Boca Raton (FL), USA, 2005.

[13] Kardes E, Luxhoj JT. A hierarchical probabilistic approach for risk assessments of an aviation safety product folio. Air Traffic Control Quarterly, Volume 13 (2005), pp. 279-308.

[14] Lee SM, Pritchett AR, Corker KM. Evaluating transformations of the air transportation system through agent-based modeling and simulation. 7th USA/Europe ATM R&D Seminar, Barcelona, Spain, 2007.

[15] Leveson N. A new accident model for engineering safer systems. Safety Science, Volume 42 (2004), pp. 237-270.

[16] Pariès J.. Complexity, emergence, resilience... In: Hollnagel E, Woods DD, Leveson N (eds.). Resilience engineering: Concepts and precepts. Ashgate, Aldershot, England, 2006.

[17] Shah AP, Pritchett AR, Feigh KM, Kalaver SA, Jadhav A, Corker KM, Holl DM, Bea RC. Analyzing air traffic management systems using agent-based modelling and simulation. 6th USA/Europe ATM R&D Seminar, Baltimore, USA, 2005.

[18] Sträter O. Cognition and safety: An integrated approach to system design and assessment. Ashgate, Hampshire, England, 2005.

[19] Stroeve SH, Blom HAP, Bakker GJ. Safety risk impact analysis of an ATC runway incursion alert system. Eurocontrol Safety R&D Seminar, Barcelona, Spain, 25-27 October 2006

[20] Stroeve SH, Blom HAP, Van der Park MNJ. Multi-agent situation awareness error evolution in accident risk modelling. Proceedings of the 5th USA/Europe ATM R&D Seminar, Budapest, Hungary, 2003

[21] Wiegmann DA, Shappel SA. Human error analysis of aviation accidents: Application of the Human Factors Analysis and Classification System (HFACS). Aviation, Space, and Environmental Medicine, Volume 72 (2001), pp. 1006-1016.

ISBN: 978-0-615-20720-9