Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015)

A risk-based framework for assessment of runway incursion events

Sybert Stroeve, Bas van Doorn, Bert Bakker
Air Transport Safety Institute
National Aerospace Laboratory NLR
Amsterdam, The Netherlands
sybert.stroeve@nlr.nl, bas.van.doorn@nlr.nl, bert.bakker@nlr.nl

Pradip Som
Federal Aviation Administration
Office of Safety, Air Traffic Organization
Fort Worth (TX), USA
pradip.som@faa.gov

***Abstract*— Current safety management of aerodrome operations uses a severity-based categorization of runway incursion events. This severity assessment is mainly based upon the outcome of a runway incursion event, in particular on the closest distance attained. As such the severity depends to a considerable extent on uncontrolled random circumstances and we argue that it is not suitable as prime indicator for safety management of aerodrome operations. In this paper we present a new framework for the evaluation of runway incursion events, which is based on the risk of scenarios associated with the initiation of runway incursion events, rather than on the outcomes of the events. In support of this framework an inventory of scenarios is provided, which can represent most runway incursion events involving a conflict with an aircraft. A main step in the framework is the assessment of the conditional probability of a collision given a runway incursion scenario. This can be effectively achieved for large sets of scenarios by agent-based dynamic risk modelling. The results provide detailed feedback on risks of runway incursion scenarios, thus enabling effective safety management for the most safety-critical situations.**

Keywords - Safety management, agent-based dynamic risk modelling, runway incursion, severity, air traffic control, accident risk

I. INTRODUCTION

The safety of runway operations is one of the key focus points of air traffic management (ATM). It is well realized that runway incursions ("any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle, or person on the protected area of a surface designated for the landing and takeoff of aircraft" [1]) are to be avoided for the sake of safety of runway operations.

Safety programs such as [1-3] support the development of procedures, training and technical systems to reduce runway incursion risk. Considerable research has been done on human factors in runway incursion [4, 5] and on the development of runway incursion prevention systems in aircraft, air traffic control (ATC) tower, ground vehicles and aerodrome [6]. All such procedures, training programs and technical systems intend to improve runway safety by reducing the risk of runway incursions, either by reducing the probability of their occurrence or by mitigating their potential consequences (most prominently, preventing a collision).

Monitoring and controlling the safety of runway operations is part of the safety management system (SMS) of the stakeholders of aerodrome operations. A safety management system includes goal setting, planning, measuring and feeding back of operational safety in a plan-do-check-act cycle [7]. As an instrument for safety management of runway operations, runway incursion events need to be reported and analysed [1, 8]. Here and in the remainder of this paper we use the term 'runway incursion event' for runway incursions that actually occurred during operations.

The International Civil Aviation Organization (ICAO) recommends to classify the severity of runway incursion events by one of the following severity categories [1]:

A. A serious incident in which a collision was narrowly avoided;
B. An incident in which separation decreases and a significant potential for collision exists, which may result in a time-critical corrective/evasive response to avoid a collision;
C. An incident characterized by ample time and/or distance to avoid a collision;
D. An incident that meets the definition of runway incursion such as incorrect presence of a single vehicle/person/aircraft on the protected area of a surface designated for the landing and takeoff of aircraft but with no immediate safety consequences;
E. Insufficient information or inconclusive or conflicting evidence precludes a severity assessment.

In the USA, the Federal Aviation Administration (FAA) uses the ICAO recommended severity categories A to D to classify runway incursion events. Statistics on runway incursions and the associated severities are regularly published in runway safety reports and runway safety plans [2, 9]. In addition to such reports, FAA publishes the details of runway incursion events, including their severity categories, in a publicly accessible on-line database system, called FAA Aviation Safety Information Analysis and Sharing (ASIAS) [10]. In Europe, the European Aviation Safety Agency (EASA)

This research was financed by the Federal Aviation Administration.

provides statistics of safety occurrences, including runway incursions, in its annual safety review [11]. EASA uses generic severity categories (serious incident, major incident, significant incident, no safety effect, not determined) for all safety occurrences. In this paper we use data of runway incursions in the USA, but it is evident that the prevention of runway incursions and their potential consequences are relevant for air traffic operations all around the world.

Statistics of runway incursion events reported in the USA [2, 9, 10] show that in fiscal years 2008 to 2013, A and B events occurred between 2 and 13 times per year, whereas there were about 400 C events and 600 D events per year. Over these years, the mean rate of runway incursions was 2.0E-5 per airport operation (takeoff or landing). The A and B events contributed only about 0.6% each to the overall rate, which was dominated by C events (40%) and D events (59%).

The current severity categorization of runway incursion events is to a large extent based on the particular outcome of a runway incursion. In particular, the closest distance attained by the entities (aircraft / vehicle / person) in a runway incursion is the main driver of the severity determination. This closest distance attained depends to a considerable extent on uncontrolled random circumstances, such that in somewhat different circumstances the outcome might have been quite different. The consequence is that current safety management is driven by largely random outcomes, wherein lessons from events with less severe (C, D) outcomes may be undervalued and there may be an overreaction to severe (A, B) outcomes.

In this paper, we present a new framework for the analysis of runway incursion events, which does not use an outcome-based severity category, but which is strictly based on the risk of scenarios associated with the runway incursion event. A main step herein is the assessment of the probability of a collision due to a runway incursion, which accounts for a variety of probabilistic circumstances that influence the collision probability. In the framework, runway incursion events are considered as safety indicators for tracking accident risk levels of runway incursions. This provides the basis for safety management actions to mitigate the risks of the most safety-critical runway incursion scenarios.

The paper is structured as follows. Section II explains the current severity-based approach for assessment of runway incursion events and its limitations. Section III presents the development of an inventory of runway incursion scenarios, which forms the basis of the new framework. Section IV presents the steps in the new risk-based framework and provides some illustrative results. Section V discusses the methods and describes future research opportunities.

II. SEVERITY-BASED ASSESSMENT OF RUNWAY INCURSIONS

The assessment of the severity category of a runway incursion event is typically done by an assessment team. Its outcomes depend on the information available for the event and it may depend on the composition and the subjective judgements of the team. ICAO advises to use information on the following aspects to classify the severity of a runway incursion event [1]: proximity of the aircraft and/or vehicle; geometry of the encounter; evasive or corrective action; available reaction time; environmental conditions, weather, visibility and surface conditions; and factors that affect system performance.

Table 1: Examples of severity classifications of runway incursion events [10].

Ev.	Description	Sev.
1	*A flight of two, a Luscombe L8 and a Aeronca AR11 were holding short of runway 17L at taxiway A1 for departure. The L8 pilot reported ready and Ground Control told the pilot he was number one for departure and to monitor tower frequency. The L8 then entered runway 17L at A1 without clearance and conflicted with a Cessna C172 landing same runway. The C172 flew over the nose of the L8 as it was entering the runway by an estimated 50 feet vertical and landed normally approximately 1,000 feet down the runway. The AR11 did not enter the runway.*	A
2	*A Dehavilland DH8A was issued progressive taxi instructions to Runway 24R via Lima, Romeo, to hold short of Runway 24L. The DH8A pilot read back instructions and the hold short for Runway 24L. The DH8A switched to Local Control (LC) as instructed. LC attempted to stop the DH8A before entering runway 24L at Romeo due to a CANADAIR CRJ2 on short final runway 24L. The CRJ2 was crossing landing threshold and initiated a go-around on his own and flew over the DH8A with the closest proximity of 200 feet vertical. AMASS analysis shows that the DH8A was approximately 104 feet from runway centerline as the CRJ2 past Romeo in a climb. Runway width is 150 feet and CRJ2 wingspan of 70 feet.*	B
3	*A Piper PA28A was instructed to taxi to runway 27R at taxiway Romeo for departure. Ground Control advised the PA28A to contact Local Control (LC). The PA28A then entered runway 27R at Romeo without clearance thus conflicting with a Luscombe SP18 less than a mile final same runway. The SP18 was issued a go around at one quarter (.25) mile final. Distance from approach end runway 27R to Romeo is more than 2,000 feet.*	C
4	*A Bellanca BL17 was instructed to hold short of runway 33R which pilot read back correctly. Subsequently the BL17 crossed runway 33R at Hotel without clearance thus conflicting with a Cessna C172 less than a mile final same runway. The C172 was issued a go around at one quarter (.25) mile final.*	C
5	*A Pilatus PC12 was instructed to taxi into position and hold (TIPH) on runway 17 at taxiway G1. The PC12 instead TIPH on runway 12R at approach end thus conflicting with a CANADAIR CRJ7 on final same runway. The CRJ7 was issued a go around at one (1) mile final.*	D
6	*A Cessna C182 was issued IFR clearance and taxi instructions to runway 20C. Subsequently the C182 entered runway 20C and departed without clearance. No conflicts reported.*	D

Some typical examples of the evaluation of runway incursion events are shown in Table 1. Events 1 to 5 consider a conflict between an aircraft about to land and an aircraft taxiing on the runway without permission. In events 1, 3 and 5 the taxiing aircraft lined up on the runway, in events 1 and 3 the pilots may have erroneously thought that they were allowed to do so, in event 5 the pilot lined up at the wrong runway. In event 1 this led to the situation that the landing aircraft missed the taxiing aircraft by about 15 m vertically and the severity class was judged as A. In event 3 the landing aircraft was issued a go around when it was at about 1000 m horizontally and the severity was judged as C. In event 5 the landing aircraft was issued a go around when it was at about 1600 m horizontally and the severity was judged as D. In events 2 and 4 the taxiing aircraft crossed the runway, although in both cases the taxi instructions to hold short of the runway were read back correctly. A reason for the erroneous crossing is not provided in the descriptions. Maybe the pilots did not know that they were already at the runway crossing when they were, or they had forgotten or misinterpreted the hold-short instruction. In event 2 the landing aircraft initiated a missed approach and flew over the taxiing aircraft with a vertical distance of about 60 m and the severity was judged as B, whereas in event 4 a go-around was issued when the landing aircraft was at about 400 m before the runway threshold and the severity was judged as C. In event 6 an aircraft lined up and took off without clearance, wherein it did not come into conflict with other traffic, and the severity was judged as D.

These examples illustrate that runway incursion events are considered to be more severe for smaller closest proximities attained in the event. A major limitation of such outcome-based assessment of runway incursion events is that it considerably depends on uncontrolled random circumstances. For instance, in all events 1, 3, 5 and 6 an aircraft lined up on the runway without permission by ATC, but the severity category depended on the random circumstance whether a landing aircraft was close to the runway at the time of the incursion. The type of error made was the same, but the severity was either A, C or D. In other words, if a landing aircraft would have been nearby in events 3, 5, or 6, then the severity could well have been A or B rather than C or D. It could even be argued that, other conditions being equal, the risk associated with the behaviour shown in event 6 is highest, since the pilot first lined up without a clearance and next initiated takeoff without a clearance, thus creating two possibilities for a conflict. Nevertheless, in the severity-based approach event 6 was considered as least serious. As another example, an aircraft crossed the runway without permission in both events 2 and 4, and this led to a difference in severity mainly due to the distance with the landing aircraft at the time of the initiation of the runway incursion. Given the large distinction in the statistics between the frequency of A and B events, on the one hand, and the frequency of C and D events, on the other hand, the focus on the outcome of runway incursions implies that lessons from the large majority of C and D events may be undervalued in the safety management cycle.

Another main limitation of the severity-based evaluation of runway incursion events is that it does not provide means to structure reasons of the runway incursion events and to evaluate the risk implications of such reasons. For instance, in both events 2 and 4, the taxiing aircraft crossed the runway erroneously, and a reason for this error was not provided in the description. It might be that (a) the pilots had misinterpreted the instruction of the controller or that (b) they were lost and they did not know to be heading to the active runway. If the runway incursion would be due to reason (a), the pilots knew to be crossing a runway and in such situation it can be expected that the visual monitoring performance of the pilots would be more prudent than in the situation of reason (b). As such it can be argued that the risk of a collision due to reason (a) would be smaller than the risk due to reason (b). Yet, the severity-based evaluation does not consider these kinds of different reasons for runway incursions, but primarily assesses the distance-based outcomes of the runway incursion events. Given the lack of systematic gathering of reasons of runway incursions in relation with their risk implications, identification of risk mitigating measures is not achieved effectively in current safety management.

III. INVENTORY OF RUNWAY INCURSION SCENARIOS

A. Scenarios for risk evaluation of runway incursions

To overcome the limitations of the outcome focused approach in the current assessment of runway incursion events, we have developed a risk-based approach. In general, risk considers uncertain and undesired future occurrences, and it is typically assessed by combining probability and severity levels of future occurrences. Note that there is no risk involved in runway incursion events as such, since they did occur and their consequences are known.

As a basis for the risk-based evaluation of runway incursion events we introduce the concept of a runway incursion scenario. A runway incursion scenario is a generic description of a situation on an aerodrome leading to a runway incursion. There can be a considerable variety of runway incursion scenarios. Given a particular runway incursion scenario it can be argued what its consequences may be and what the probabilities of these consequences are. We next discuss the relation between timing in runway incursion events and runway incursion scenarios, as well as the variety of scenarios needed to assess risk levels.

The description of a runway incursion event may include various time stamps. The start of a runway incursion (RI) event is defined at time t_0 : E^{RI}_{q,t_0}, where *q* is an event index. For instance, it may be the event that a taxiing aircraft passes the runway hold-short line without authorization, or the event that an aircraft starts the takeoff roll without authorization. In addition, runway incursion event reports often include information for $t < t_0$ about events and conditions leading to the runway incursion, e.g. “after landing the aircraft taxied towards the gate and took a wrong turn leading towards the runway” or “while the pilots had acknowledged to hold short of the runway they continued taxiing towards the runway”. We denote the events and conditions up to the start of the runway incursion as $E^{RI}_{q,t\leq t_0}$. The final stage of a runway incursion event is defined at time t_f : E^{RI}_{q,t_f} . In runway incursion event reports the final stage is typically described by phrases such as "both aircraft stopped, the nose of aircraft A was 10 feet before the runway edge, the lateral distance between the aircraft was 1000 feet" or "aircraft A flew over aircraft B at a height of 100 feet". As argued, the current practice of severity assessment of runway incursion events is in practice mainly based upon the final outcome.

The new risk-based framework for evaluation of runway incursion events is based on $E^{RI}_{q,t \le t_0}$. It means that a runway incursion scenario is defined by information only that is available up to the initiation of the runway incursion. Conditions and acts that may occur after the initiation of a runway incursion are not considered in the definition of the scenario, but they are evaluated probabilistically in a risk assessment given the scenario.

The potential adverse consequences of a runway incursion considered in our risk assessment framework are a collision and the consequences of a collision. The description of runway incursion scenarios should be sufficiently broad, such that differences in the probabilities of these adverse consequences that may be due to conditions at the start of a runway incursion are accounted for by differences in the scenarios. However, the number of scenarios should not be exceedingly large as this could complicate the risk assessment of the scenarios and it might complicate the practical inclusion in a safety management framework.

B. Development of a scenario inventory

The development of a suitable scenario inventory requires an iterative process, which balances the requirements from events representation, risk modelling, and safety management. In this paper we present a first version of a runway incursion scenario inventory. This inventory focuses on runway incursion scenarios that describe conflicts between two physical entities on a runway, of which at least one is an aircraft. The development was done on the basis of runway safety literature and by studying runway incursion events with severity A, B and C at US airports.

The runway incursion scenarios are described by a number of scenario descriptors. For ease of referencing we distinguish main scenario descriptors and subcase descriptors. Main scenario descriptors consider

- runway configuration: single / intersecting runway(s);
- types of involved physical entities (PE's): aircraft / vehicle / person / helicopter;
- operations of the involved PE's: takeoff / land / taxi / any;
- runway incursion initiating PE: PE1 / PE2;
- encounter direction: opposite / same / intersect;
- encounter relative position: in front / behind;
- intent of human operator of PE: takeoff / land / cross runway / lineup / taxi along taxiway / taxi along runway / stop at runway holding point / any.

There exist dependencies between the descriptors, limiting the possible values. For instance, if a PE is a vehicle it cannot have a takeoff operation. The inclusion of the intent of human operators enables to represent causes of runway incursion initiations and to account for varying intent-based performance of human operators during the evolution of a runway incursion.

Subcase descriptors are:

- sizes of PE's: small / large / heavy / tow / other / any;
- location on runway: start / middle / end;
- runway hold position (w.r.t. runway centerline): small / medium / large;
- visibility condition: 1 / 2 / (3 or 4) [12].

In combination, these scenario descriptors can represent runway incursion scenarios $S_{i,j}$, with main scenarios *i* and subcases *j*. Some examples of scenarios are:

1. *Main scenario*: Single runway, involving two aircraft, where PE1 is taking off and PE2 is taxiing, PE2 initiates the runway incursion, the pilots of PE2 have the intent to taxi over a normal taxiway, PE2 moves on a taxiway intersecting the runway, in front of PE1.
   Subcase: PE1 is a large aircraft, PE2 is a small aircraft, the taxiway used by PE2 is in the middle of the runway, the runway hold position is at a medium distance to the runway centerline, and the visibility is good (VC1).
2. *Main scenario:* Single runway, involving an aircraft (PE1) and a vehicle (PE2), where PE1 is about to land, PE1 initiates a runway incursion (e.g. lands on the wrong runway), the vehicle driver has the intent to taxi along an inactive runway, PE2 is moving in the same direction as PE1, in front of PE1.
   Subcase: PE1 is a small aircraft, the vehicle has a normal size (not a tow), the vehicle is at the approach end of the runway (start), the runway hold position if large, the visibility condition is 1.
3. *Main scenario*: Intersecting runways, involving two aircraft, PE1 taking off, PE2 landing, PE1 initiates a runway incursion (e.g. starts takeoff without clearance), PE2 is in front of PE1.
   Subcase: PE1 is a large aircraft, PE2 is a large aircraft, the intersection point is at the end of runway 1 and in the middle of runway 2, visibility condition is 2.

By combining the scenario descriptors there are 169 main scenarios involving at least an aircraft landing, taking off, or lining up, including

- 61 main scenarios where an aircraft is taking off and comes into conflict with an aircraft, vehicle, person, or helicopter;
- 56 main scenarios where an aircraft is landing and comes into conflict with an aircraft, vehicle, person or helicopter, excluding aircraft taking off; and
- 52 main scenarios where an aircraft is lining up on the runway and comes into a conflict with an aircraft, vehicle or person that is taxiing or moving on the runway (excluding aircraft taking off or landing).

The number of subcases in a main scenario depends on the main scenario considered and can be up to 243 subcases per scenario. For instance, the main scenarios of examples 1 and 3 contain 243 subcases (3 values for each of the 5 indicators of the subcases) and the main scenario of example 2 has 162 subcases (2 values for the size of a vehicle and 3 values for the 4 other indicators).

C. Mapping of events to the scenario inventory

To obtain insight in the completeness of the runway incursion scenario inventory, a mapping was made of runway incursion events to the scenarios. This was done for all A and B events in the US in fiscal years 2004 to 2010 and for part of the C events in fiscal year 2010. Using the narratives for each event the applicable descriptors of the runway incursion scenario inventory were identified. On this basis we distinguished the following cases of the number of main scenarios that apply to an event:

- The event cannot be described by any of the main scenarios.
- The event can be described uniquely by one main scenario.
- The event can be described by multiple main scenarios. This is the case if there is not sufficient information to decide uniquely on the applicable main scenario descriptors.

Table 2: Overview of the number of runway incursion main scenarios (none / one / multiple) that are associated with runway incursion events of severity categories A, B and C.

Scenarios	A		B		C		Total	
None	3	3.3%	0	0.0%	0	0.0%	3	1.3%
One	66	72%	45	72%	44	57%	158	68%
Multiple	23	25%	18	29%	33	43%	71	31%
Total	92	100%	63	100%	77	100%	232	100%

Table 2 provides an overview of the mapping of the runway incursion events to the main scenarios. It follows from the mapping of runway incursion events that 98.7% of the 232 analyzed events could be mapped to one or several main scenarios of the inventory. The events that could not be mapped consider a conflict between physical entities that are both not a fixed-wing aircraft (two helicopters), a conflict involving a physical entity not in the inventory (balloon) and a conflict involving an operation not in the inventory (low approach).

The majority (68%) of the events is mapped to a single main scenario. It follows from the results for the severity categories in Table 2 that relatively larger fractions of events of category A and B are mapped to a single main scenario than the category C events. This is explained by the typically more detailed narratives of more severe events, which provides a better basis for a unique scenario selection.

A considerable part (31%) of the events is mapped to multiple (up to 4) main scenarios. In these cases sufficient information was not available to uniquely select the runway incursion scenario descriptors. Frequently missing information in the narratives of the runway incursion events was the intent of a pilot or vehicle driver that has led to the runway incursion. Whereas the situation awareness and reasoning of controllers was typically well explained in the narratives, this was often missing for pilots or vehicle drivers causing a runway incursion. There were a considerable number of runway incursion event narratives, where the pilot or driver seemed to be acting and responding normally from the viewpoint of the involved air traffic controller, but unexpectedly passed the hold-short line towards the runway. What was the situation awareness of the pilot or driver that led to the runway incursion? For instance, did a pilot intend to cross the runway after a misunderstanding of a clearance to do so, or did a pilot think to be taxiing along a normal taxiway without knowledge on the active runway crossing, or did a pilot know that he should stop, but failed to do so at the appropriate location? Another example of missing information in event narratives is the direction of the movement of a vehicle in a conflict.

IV. Steps in the risk-based framework

A. Global overview of the steps

Building on the scenario inventory, the risk-based framework for assessment of runway incursion events consists of the following five steps.

1. Mapping of a runway incursion event to one or multiple runway incursion scenarios. This step is done for every runway incursion event, using only information up to its initiation.
2. Assessment of the probabilities of runway incursion scenarios, expressed as rates per airport movement (takeoffs, landings), using statistics of associated runway incursion events.
3. Assessment of the conditional probabilities of a collision given runway incursion scenarios. These probabilities are assessed using a risk model, independently of a runway incursion event.
4. Assessment of the conditional probabilities of the human and material collision impact categories given a collision in a runway incursion scenario. These probabilities are assessed using a risk model, independently of a runway incursion event.
5. Evaluation of runway incursion risk by combining the results of Steps 2, 3 and 4, and comparison with safety criteria.

Details of each of these steps are provided next.

B. Step 1: Mapping of events to scenarios

Step 1 in the runway incursion risk modeling framework sets the basis by mapping of runway incursion events to runway incursion scenarios. A runway incursion event is mapped to a single runway incursion scenario if the event can be uniquely described by the runway incursion scenario. However, as explained in Section III.C, there is not always sufficient information available to map an event to a single scenario. To incorporate multiple possible scenarios for an event, a probabilistic approach is followed. This implies that for a runway incursion event $E^{RI}_{q,t\le t_0}$ the conditional probabilities $P(S^{RI}_{i,j} \mid E^{RI}_{q,t\le t_0})$ of all runway incursion scenarios $S^{RI}_{i,j}$ are assessed, with $\sum_{i,j} P(S^{RI}_{i,j} \mid E^{RI}_{q,t\le t_0}) = 1$. If the event can be mapped uniquely to a single scenario the conditional probability is assessed equal to 1 for that scenario. If several scenarios may apply, conditional probabilities larger than zero are assessed for these scenarios.

C. Step 2: Assessing probabilities of scenarios

The objective of Step 2 is to assess the probability of a runway incursion scenario $P(S^{\mathrm{RI}}_{i,j})$, expressed as rate per airport operation (landing / takeoff). Step 2 of the framework primarily uses data on runway incursion events and airport operations data, and as a secondary means it uses expert judgment to decide on dependencies between scenarios and subcases, and to provide lower bounds for probabilities of scenario without associated events.

An estimate of the probability of a runway incursion scenario, expressed per airport operation, is the empirical probability

$$P(S_{i,j}^{\mathrm{RI}}) = \frac{1}{N^{\mathrm{AO}}} \sum_{q=1}^{N^{\mathrm{RI}}} P(S_{i,j}^{\mathrm{RI}} \mid E_{q,t\le t_0}^{\mathrm{RI}}),$$

where N^{RI} is the number of runway incursion events and N^{AO} is the number of airport operations in a given period, and $P(S_{i,j}^{\mathrm{RI}} \mid E_{q,t\le t_0}^{\mathrm{RI}})$ are derived in Step 1. Estimates of the probability of a main scenario can be achieved by summation over its subcases. Examples of results for FAA runway incursion statistics are provided in Figure 1 of Section IV-F.

D. Step 3: Assessing collision probabilities of scenarios

Step 3 in the runway incursion risk modeling framework concerns the assessment of the conditional probability of a collision given a runway incursion scenario $P(E^{\mathrm{coll}} \mid S_{i,j}^{\mathrm{RI}})$. In our framework, agent-based dynamic risk modelling (DRM) is chosen as the primary method to assess these probabilities.

Agent-based DRM uses an agent-based perspective on air traffic scenarios, the development of stochastic dynamic models on the basis of this perspective, and rare event Monte Carlo simulation of these stochastic dynamic models, to arrive at collision risk for the scenarios [13, 14]. Agent-based DRM for risk assessment of runway incursions scenarios between aircraft taking off and taxiing, and between aircraft landing and taxiing is presented in [15-17]. Agent-based DRM explicitly represents the processes and interactions of agents in runway incursion scenarios and the conditional collision probability given a scenario emerges from rare event Monte Carlo simulations. For instance, the agent-based DRM of runway incursion scenarios between aircraft landing and taxiing of [17] includes models describing aircraft dynamics during final approach, landing and taxiing, models of situation awareness updating and aircraft maneuvering actions by pilots, models of situation awareness updating and control actions by a runway controller, models of surveillance and communication systems, and models of the aerodrome infrastructure, visibility and wind conditions. These models represent stochastic and dynamic variability in the processes (e.g. timing of human operator actions, aircraft speed variation), and various modes of the agents (e.g. failure and error modes, aircraft size, visibility conditions).

For the assessment of the conditional probabilities of a collision given a specific runway incursion scenario in Step 3, parameter values associated with the scenario descriptors are set in the agent-based model (e.g. for aircraft sizes, human operator intent, location on runway). Next, conditional collision probabilities can be attained for each of the scenarios by rare event Monte Carlo simulation. As an example, Table 3 shows conditional collision probabilities given subcases of a specific main scenario S9, which were attained by Monte Carlo simulations of an extension of the model presented in [17]. This main scenario considers the situation that an aircraft lands and another aircraft lines up on the runway erroneously, while its pilots think they are allowed to line-up. The subcases consider the sizes of both aircraft, the location of the taxiway with respect to the runway threshold, the distance of the runway hold short position, and the visibility condition. All these subcase indicators have 3 values, such that in total there are 243 subcases. Table 3 shows the risks for only 8 subcases, but risk values have been obtained for each of the 243 subcases. The results for subcases 1, 2, and 3 show that the risk decreases if the hold short position is further from the runway. Subcases 4 and 5 show that the collision risk is higher for larger aircraft, due to their larger volume and larger final approach speed. Subcase 6 indicates that the risk is reduced if the taxiway is located near the middle rather than near the start of the runway. Subcases 7 and 8 show that the risk increases in poorer visibility conditions. The results in Table 3 illustrate that there are considerable differences between the conditional collision probabilities of the various subcases. These differences are due to differences in the assumed performance of agents and the interdependencies between the agents in the risk model.

Table 3: Illustration of conditional collision probabilities given subcases of scenario S9, attained by agent-based DRM.

#	**Size land ac**	**Size taxi ac**	**Loc.**	**Vis.**	**Rwy hold dist**	**Cond coll prob**
S9: *Aircraft lands and other aircraft lines up on the runway erroneously, while its pilots think they are allowed to line-up*						
1	Large	Small	Start	1	Small	3.0E-3
2	Large	Small	Start	1	Medium	8.3E-5
3	Large	Small	Start	1	Large	1.0E-6
4	Large	Large	Start	1	Medium	1.5E-4
5	Heavy	Small	Start	1	Medium	4.6E-4
6	Large	Small	Middle	1	Medium	3.8E-5
7	Large	Small	Start	2	Medium	4.3E-3
8	Large	Small	Start	3/4	Medium	5.7E-2
...	...	...	...	...	...	...
243 subcases in total						

E. Step 4: Assessing consequences of a collision

Given that a collision would occur as result of a runway incursion, the consequences of such a collision may vary considerably. For instance, the consequences of a collision between two small aircraft at low speed wherein only the wing tips touch, is likely to be limited to some minor damage without serious injuries or fatalities, whereas the consequences of a collision between two large jet aircraft that hit each other centrally at high speed, would likely be many fatalities and hull loss of the aircraft. The objective of Step 4 is to assess the probability of potential consequences of a collision given a scenario.

For the potential consequences we consider the human and material impact of a collision and we define a number of severity categories for human impact C_k^{Hu} and material impact C_k^{Ma}. With regard to human impact, we differentiate between collisions involving many fatalities (e.g. involving large aircraft), collisions involving some fatalities (e.g. involving small aircraft), serious injuries, and no serious injuries or fatalities. For the assessment of the material impact of a collision also four categories are used: hull loss, substantial damage, minor damage, and no or negligible damage.

Step 4 assesses the probabilities of attaining these human and material impact categories given a collision and a scenario: $P(C_k^{\mathrm{Hu}} \mid E^{\mathrm{coll}}, S_{i,j}^{\mathrm{RI}})$ and $P(C_k^{\mathrm{Ma}} \mid E^{\mathrm{coll}}, S_{i,j}^{\mathrm{RI}})$. For such collision consequences assessment a modelling approach has been developed, which considers a collision between an aircraft landing or taking-off with a taxiing aircraft. Input of the collision consequences model with regard to the position, speeds and masses of the aircraft at the time of a collision is obtained from the Monte Carlo simulations of the agent-based dynamic risk model in Step 3.

F. Step 5: Combination and evaluation of risk results

Step 5 in the scenario-based runway incursion risk assessment framework combines the results of Steps 1, 2, 3 and 4. This entails combining the results for the probabilities of scenarios associated with runway incursion events, for the conditional probabilities of collisions given the scenarios and for the conditional probabilities of collision consequence categories given the scenarios. These combined results can be evaluated by comparison with associated safety criteria. Next we discuss the evaluation of single runway incursion events and the aggregated risk results obtained by series of events.

Single events

The evaluation of single events is based on results of Steps 1 and 3, and optionally on results of Step 4. In particular, the conditional probabilities of scenarios given an event (Step 1) and the conditional probabilities of a collision given scenarios (Step 3) are used to determine the conditional probability of a collision given the initiation of the runway incursion event:

$$P(E^{\mathrm{coll}} \mid E_{q,t\le t_0}^{\mathrm{RI}}) = \sum_{i,j} P(E^{\mathrm{coll}} \mid S_{i,j}^{\mathrm{RI}}) \cdot P(S_{i,j}^{\mathrm{RI}} \mid E_{q,t\le t_0}^{\mathrm{RI}}) .$$

Herein it is assumed that the runway incursion scenarios provide a complete characterization of the collision probability. By inclusion of the results of Step 4, additionally the probabilities of human and material impact categories given a runway incursion event can be determined.

The conditional probabilities given a runway incursion event for a collision or for the human/material impact categories may be judged on the basis of safety criteria. For instance, the probability values may be mapped to a low / medium / high risk categorization, such that class feedback is obtained about the risk level.

An illustration of the conditional probabilities of a collision given the initiation of the runway incursion events of Table 1 is provided in Table 3. For each of the events with severity outcomes in the range from A to C, the associated scenarios are described, and the collision probabilities following from Monte Carlo simulations for an agent-based dynamic risk model are provided. The risk results provide quite a different view than those of the severities associated with the outcomes of the events. The largest collision risks are associated with events 2 and 4, which had B and C severity outcomes. The relatively large risk values are due to the possibility that the pilots of the taxiing aircraft did not know that they were entering an active runway, which is associated with less carefully monitoring for aircraft landing or taking off in the risk model. The risk associated with event 1, having the most severe outcome, is considerably lower than those of events 2 and 4. The lowest risk is attained for event 3, which is associated with a scenario similar to that for event 1, except here the aircraft lines up in the middle of the runway rather than at its start.

Table 4: Evaluation of conditional probability of a collision given the initiation of a runway incursion for events 1-4 of Table 1.

Ev.	Scenario(s)	Coll. Prob.	Sev.
1	Aircraft (small) lands and taxiing aircraft (small) lines up erroneously near the runway start; distance of hold-short line is medium; visibility is VC1	3.0E-5	A
2	Aircraft (large) lands and taxiing aircraft (large) enters runway erroneously, since its pilots have the intent to cross the active runway and think they are allowed to do so, or since its pilots have the intent to taxi over a normal taxiway or an inactive runway; distance of hold-short line is large; location is near the runway start; visibility is VC1	6.0E-3	B
3	Aircraft (small) lands and taxiing aircraft (small) lines up erroneously near the middle of the runway; distance of hold-short line is medium; visibility is VC1	6.6E-6	C
4	Aircraft (small) lands and taxiing aircraft (small) enters runway erroneously, since its pilots have the intent to cross the active runway and think they are allowed to do so, or since its pilots have the intent to taxi over a normal taxiway or an inactive runway; distance of hold-short line is medium; location is near the runway start; visibility is VC1	3.6E-3	C

Series of events

The results for a series of runway incursion events obtained by Steps 1, 2 and 3, and optionally by Step 4 can be combined to achieve an overview of risk levels over a particular period (e.g. year, series of years). A key aggregated risk result is the probability of a collision due to a runway incursion. This probability is determined by combining the runway incursion scenario probabilities obtained in Step 2 (using results of Step 1) and the conditional probabilities of a collision given the scenarios obtained in Step 3:

$$P(E^{\text{coll}}) = \sum_{i,j} P(E^{\text{coll}} \mid S_{i,j}^{\text{RI}}) \cdot P(S_{i,j}^{\text{RI}}) .$$

Note that as the overall collision probability is derived by the summation over all scenarios, the contributions to the collision probabilities of all individual scenarios are readily known. This provides detailed safety management feedback on what kinds of runway incursions contribute mostly to the probability of a collision due to a runway incursion. These results also explain the contributions of the frequencies of incursion scenarios and the risks given the scenarios. By inclusion of the results of Step 4, additionally the probabilities of human and material impact categories due to a runway incursion and a collision can be evaluated.

The derived probabilities for collisions due to a runway incursion and for the human / material impact categories can be evaluated against safety criteria. For instance, comparison with a target level of safety may be used to decide whether the collision probability is acceptable, tolerable only, or not acceptable. In the case of non-acceptable risk levels, the main contributions to such high levels can be obtained by the risk distribution. Introduction of safety criteria for human and material impact provides the possibility to have more stringent criteria for scenarios with potentially higher stakes for human lives. This may for instance imply that safety criteria for large jets with many occupants are more stringent than those for small aircraft with only a few people on board of the aircraft.

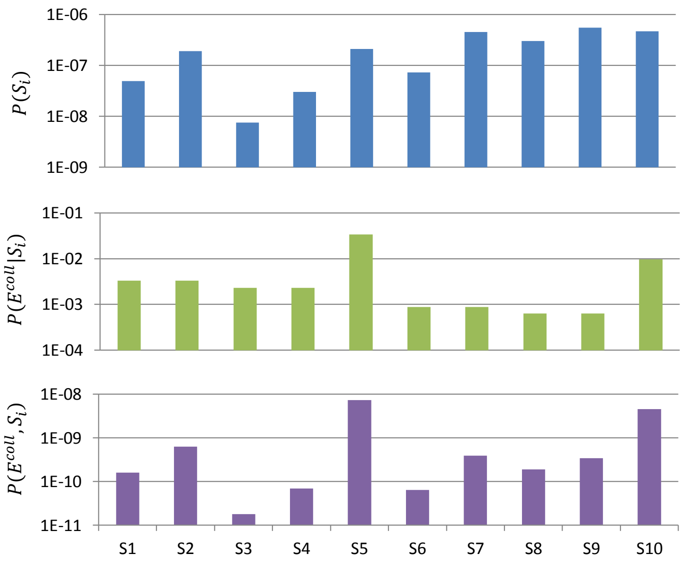

Figure 1. Illustration of aggregated risk results (per airport operation) for a number of main scenarios: scenario probabilities (top figure), conditional probabilities of a collision given scenarios (middle figure), probabilities of collision for scenarios (bottom figure).

An illustration of aggregated risk results is shown in Figure 1. It shows risk results for ten main scenarios, consisting of the probability of the scenario, the conditional probability of a collision given the scenario, and the probability of a collision and the scenario. In this example, the main scenarios have occurrence rates between 8E-9 and 6E-7 per airport operation. The overall (summed) rate for this set of scenarios is 2.3E-6. The probabilities of a collision given a main scenario vary between 6E-4 and 3E-2. In combination this provides probability estimates for a collision due to a main scenario in the range from 2E-11 to 7E-9 per airport operation. The total probability of a collision for this set of scenarios is 1.4E-8 per airport operation. Although there are six scenarios that occur at a rate of more than 1E-7 in the example of Figure 1, the overall probability of a collision is mainly due to the two main scenarios S5 and S10. In an effort to reduce the probability of a collision due to a runway incursion, effective safety management would thus best focus on mitigating measures for reducing the probability of occurrence and/or the conditional probability of a collision for scenarios S5 and S10. Note that this specific safety management feedback cannot be obtained by an overall rate of runway incursions (as is known in existing safety management), nor by incursion rates of individual scenarios, but only from the combination of incursion rates and conditional collision probabilities for a range of scenarios.

V. Discussion

In current safety management of airport operations, runway incursion events are evaluated using severity categories, such as A to E [1], A to D [2], or Serious incident to Not determined [11]. Such severity assessment is to a large extent based on the outcome of the runway incursion events, in particular on the closest distance attained in the event. A main limitation of this outcome-based evaluation is that the attained closest proximity depends on uncontrolled random circumstances, such as another aircraft being nearby at the time of the initiation of the runway incursion. In events that are judged as being less severe (C, D) typically the same types of errors lead to the runway incursion initiation and the distinction with more severe (A, B) events is only due to some uncontrolled circumstances. Given the focus of safety management on more severe outcomes this may imply that lessons from events with less severe outcomes are undervalued, and that there may be overacting to severe events. Another main limitation of the severity-based evaluation of runway incursions is that it does not provide means to structure reasons of the runway incursion events and to evaluate the risk implications of such reasons.

In this paper we have presented a new framework for the analysis of runway incursion events, which does not use an outcome-based severity category, but which is strictly based on the risk of scenarios associated with runway incursion events. This risk evaluation uses information up to the initiation of the event only; it refrains from using information on the particular evolution of the event after the initiation of the runway incursion. As such the safety evaluation of a runway incursion event is not biased by its particular outcome, and similar kinds of errors leading to runway incursions in similar conditions at their initiation are evaluated equally.

The basis of the risk-based framework is an inventory of runway incursion scenarios. On the one hand, such inventory should be sufficiently broad to represent the variety of runway incursions that may occur and especially the scenarios with different risk implications. On the other hand, the inventory should not be too extensive, such that application by a user is feasible and implementation of the associated risk assessments can be well achieved. In this paper we have presented a first version of such inventory, which includes a variety of descriptors for aspects such as runway configuration, types of involved entities, types of operations, intents of human operators, aircraft sizes, and visibility conditions. For conflicts between an aircraft taking off, landing or lining up with another aircraft, vehicle or person, combination of the scenario descriptors in this inventory provides 169 main scenarios with up to 243 subcases per main scenario.

It was shown for a set of more than 200 A, B and C events that almost 99% of these events could be described by the scenario inventory. This indicates that it is able to describe the large majority of events involving a conflict, leaving out only some special cases, such as incursions with balloons or between two helicopters. The evaluation was not yet done for D events, as the inventory development was focused on conflicts in the current research. Nevertheless, it is expected that several of the scenario descriptors, like type and size of the physical entity, and intent of the pilot or vehicle driver can be effectively used to describe scenarios associated with D events. Future research should enhance the scenario inventory by inclusion of events without a direct conflict.

The extent to which the different scenarios have different collision risk results depends on the risk models used for the evaluation of the various scenarios. The scenario inventory presented in this paper was developed by the authors on the basis of known key factors influencing the collision risk and it was restricted by the scope chosen. For instance, runway incursion alerting systems were excluded from the scope of this study, but in future enhancements of the scenario inventory it may be decided to include the availability of such systems as a scenario indicator. Doing so would enable safety management to account for the risk reduction that may be achieved by such advanced system. In general, there are many factors that may have an effect on the risk of a collision due to a runway incursion, such as the use of particular procedures (e.g., larger spacing in poor visibility), technical systems (e.g., runway status lights, runway incursion alerting systems), or aerodrome infrastructure (e.g. position of hold-short lines, crossing runways). Future research should enhance the scenario inventory by coordination with runway safety management teams about the needed range of scenario indicators.

In applying the current inventory to a runway incursion event, a user has to specify values for 13 scenario descriptors with discrete values, representing 2, 3, 4 or 5 options per descriptor. In our application to runway incursion events we found that most scenario descriptors can be easily set. However, the descriptor for the intent of the pilot or driver intruding the runway could in many cases not be extracted from the narratives, since often the reason of the incursion was not specified. Although the proposed framework can associate multiple scenarios to a runway incursion event, from a safety management perspective it is preferred to know the intent of the human operator at the time of the initiation of the runway incursion. As such it is recommended to include such information in narratives of runway incursion events. This would require to systematically include feedback of pilots / drivers on their perspective. In addition, future research should evaluate the practical feasibility of setting scenario descriptors by runway safety management teams.

In the proposed risk-based framework, collision risk results have to be attained for each scenario, i.e. for each subcase per main scenario. Building on collision risk models in [15-17] agent-based dynamic risk modelling can well account for dependencies between runway incursion scenario descriptors and it can systematically achieve collision probabilities for large sets of runway incursion scenarios. In addition, the use of expert judgment or probabilistic graphical models as fault/event trees or Bayesian belief networks may be considered if safety barriers are independent or the overall risk of a scenario can be argued to be negligible. Future research should enhance the completeness of the risk results for scenarios in the inventory.

The proposed risk-based framework for the evaluation of runway incursion events has several commonalities with risk assessment of current or new designs of aerodrome operations. In particular, results of the core of the framework, being the collision risks of runway incursion scenarios, can be effectively used as a basis for risk assessment of aerodrome operations and operation designs. In this way the new risk-based framework supports integral safety management from design to operations. In such integral safety management, runway incursion events are safety indicators that are used to update probability estimates of runway incursion scenarios made in the design phase. The uptake of the new risk-based framework for the evaluation of runway incursion events in integral safety management stands in contrast with the current severity-based evaluation of events, which focuses on event outcomes and has no risk assessment component.

The proposed risk-based evaluation of runway incursion events uses information up to the initiation of an incursion as a basis for an assessment of the risk of potential consequences of such incursion. This strict usage of information prior to a runway incursion event does not mean that information on the actual outcome of an event should be discarded in the risk-based framework. Information about the ways that runway incursion events evolve and end provides valuable information that should be used in safety management. In our risk-based framework this information serves as a source for validation of the collision risk models. In particular, information on types and timing of conflict recognition by pilots and controllers, their subsequent actions, the manoeuvres of aircraft and the evolution of the distance during the conflict serves to validate the performance of agents and the interactions between agents in an agent-based dynamic risk model. In such validation, potential biases and uncertainties in the agent models can be evaluated and the combined effect on the collision risk can be assessed by the approach of [18]. These validation results serve to update the collision risk results in the evaluation of runway incursion events. Future research should define what specific data should be gathered on the evolution of runway incursion events and how these can be used to validate the collision risk models.

Current severity-based evaluation of incidents is not only done for runway incursion events, but also for other types of air traffic incidents, such as inadequate separation, separation minima infringement, deviation of ATC clearance, and unauthorized penetration of airspace [11]. Evaluation of the severity of a wide range of air traffic incidents is an important part of the Eurocontrol Risk Analysis Tool [19]. In the light of the identified limitations of the severity-based evaluation of runway incursion events and the advantages of the proposed risk-based framework, we advise future research on the potential limitations of severity-based evaluation of other air traffic incidents and the possibilities for risk-based assessment for a range of air traffic scenarios.

In conclusion, we have identified limitations of current severity-based evaluation of runway incursion events, which hinder effective safety management of aerodrome operations. We have proposed a new risk-based evaluation framework, which assesses collision risks of scenarios associated with runway incursion events. We have presented several methods in support of this framework, as well as recommendations for future research and development.

Acknowledgement

We thank Joseph Teixeira (FAA) for his support of the research.

Disclaimer

The opinions expressed are those of the authors and do not necessarily reflect the views of FAA or NLR.

References

[1] ICAO. Manual on the prevention of runway incursions. International Civil Aviation Organization; Doc 9870; 2007.
[2] FAA. The strategic runway safety plan. Federal Aviation Administration; 2012.
[3] Eurocontrol. European action plan for the prevention of runway incursions. 2011.
[4] DiFiore A, Cardosi K. Human factors in airport surface incidents: An analysis of pilot reports submitted to the Aviation Safety Reporting System (ASRS). Cambridge, MA, USA: Volpe National Transportation Systems Center; DOT-VNTSC-FAA-06-14; 2006.
[5] Cardosi K, Chase S, Eon D. Runway safety. Air Traffic Control Quarterly. 2010;18:303-28.
[6] Schönefeld J, Möller DPF. Runway incursion prevention systems: A review of runway incursion avoidance and alerting system approaches. Progress in Aerospace Sciences. 2012;51:31-49.
[7] ICAO. Safety Management Manual (SMM). Montreal, Canada: International Civil Aviation Organization; Doc 9859; 2013.
[8] Eurocontrol. ESARR 2: Reporting and assessment of safety occurrences in ATM, edition 3.0. Brussels, Belgium: Eurocontrol; 2009.
[9] FAA. Runway safety - Publications. http://www.faa.gov/airports/runway_safety/publications/
[10] FAA. FAA Aviation Safety Information Analysis and Sharing (ASIAS). www.asias.faa.gov
[11] EASA. Annual Safety Review 2013. European Aviation Safety Agency; 2014.
[12] ICAO. Advanced surface movement guidance and control systems (A-SMGCS) manual. International Civil Aviation Organization; Doc 9830 AN/452; 2004.
[13] Blom HAP, Bakker GJ, Blanker PJG, Daams J, Everdij MHC, Klompstra MB. Accident risk assessment for advanced air traffic management. In: Donohue GL, Zellweger AG, editors. Air Transport Systems Engineering: AIAA; 2001. p. 463-80.
[14] Everdij MHC, Blom HAP, Stroeve SH, Kirwan B. Agent-based dynamic risk modelling for ATM: A white paper. Eurocontrol; 2014.
[15] Stroeve SH, Blom HAP, Bakker GJ. Systemic accident risk assessment in air traffic by Monte Carlo simulation. Safety Science. 2009;47:238-49.
[16] Stroeve SH, Blom HAP, Bakker GJ. Contrasting safety assessments of a runway incursion scenario: Event sequence analysis versus multi-agent dynamic risk modelling. Reliability Engineering & System Safety. 2013;109:133-49.
[17] Stroeve SH, Van Doorn BA, Bakker GJ. Safety assessment of a future taxi into position and hold operation by agent-based dynamic risk modelling. Journal of Aerospace Operations. 2012;1:107-27.
[18] Everdij MHC, Blom HAP, Stroeve SH. Structured assessment of bias and uncertainty in Monte Carlo simulated accident risk. Proceedings 8th International Conference on Probabilistic Safety Assessment and Management, New Orleans, USA, 2006.
[19] Eurocontrol. Risk Analysis Tool. Brussels, Belgium: Eurocontrol; ESP/2009-81; 2009.

Author Biographies

Sybert Stroeve has a M.Sc. degree in Electrical Engineering of Twente University (1991) and a Ph.D. degree in Mechanical Engineering of Delft University of Technology (1998). He is Senior Scientist at NLR with key interests in human performance modelling and agent-based dynamic risk modelling for air transport safety management.

Pradip Som is the R&D Manager for the FAA Office of Safety – Air Traffic Organization, and leads the research and development efforts in the areas of Aviation Safety Management Systems, Safety Operational Improvement, New Technology Introduction, NextGen, Data Analytics, and International ATM Harmonization by interaction with Eurocontrol and ICAO. Dr. Som is responsible for the design and development of mathematical, statistical, and econometric techniques to analyze processes and systems and to make recommendations regarding potential system safety and efficiencies within FAA operations and the National Airspace System (NAS). Dr. Som Co-Chairs the Action Plan 26 – Airport Operations Harmonization Group, and Action Plan 15 – Safety R&D Group with Eurocontrol and is an active contributor to several ICAO Panels on aviation collision risk. Dr. Som is also a contributing member to CANSO (Civil Air Navigation Services Organization) – a global ATM Organization – and leads aviation safety and performance researches. Before joining FAA, Dr. Som worked for American Airlines and US Airways for several years and was involved in the development of airlines decision support systems including Revenue Management, Demand Forecasting, and Overbooking. Dr. Som possesses a B.Sc. degree in Mechanical Engineering, M.Sc degree in Industrial Engineering and Ph.D degree in Operations Research.

Bas van Doorn has a M.Sc. degree in Applied Mathematics of Twente University (1988). He is a R&D engineer at NLR and has performed many safety assessments of new or changed operations in air transport using techniques such as agent-based dynamic risk modelling, air safety data analysis and expert judgement.

Bert (G.J.) Bakker has a M.Sc. degree in Applied Mathematics of Twente University (1989). He is research engineer at NLR with key interest in stochastic systems and rare event simulation. He has developed and implemented a wide range of stochastic dynamic models for probabilistic safety assessments of air transport operations (existing as well as advanced design improvements).