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Strengthening air traffic safety management by moving from outcome-based towards risk-based evaluation of runway incursions

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Strengthening air traffic safety management by moving from outcome-based towards risk-based evaluation of runway incursions

Problem area

Current safety management of aerodrome operations uses judgements of severity categories (A, B, C, D, E) to evaluate runway incursions. This severity categorization 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 a main driver of the severity determination. This closest distance attained depends to a considerable extent on uncontrolled random circumstances, such as another aircraft being nearby at the time of the initiation of the runway incursion. In incursions that are judged as being less severe (C, D) typically the same types of errors or misunderstandings by pilots or controllers lead to initiation of runway incursions and the distinction with more severe (A, B) cases is primarily due to some uncontrolled circumstances. The consequence is that current safety management is driven largely by random outcomes, wherein lessons from incursions with less severe (C, D) outcomes may be undervalued and there may be an overreaction to severe (A, B) outcomes.

Description of work

In this paper, we present a new framework for the analysis of runway incursions, which does not use an outcome-based severity category, but which is strictly based on the risk of scenarios associated with runway incursions. Such a scenario describes the state at the initiation of the runway incursion, e.g., a small aircraft enters a runway near the runway start while its pilots are lost and it comes into conflict with a large aircraft landing in good visibility conditions. A main step in the framework 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. This is effectively achieved for large sets of scenarios by agent-based dynamic risk modelling.

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Results and conclusions

Yearly about a thousand runway incursions were reported in the USA in fiscal years 2008 to 2013, where 0.6% were judged as severity A, 0.6% as B, 40% as C, and 59% as D. Data analysis shows that the closest horizontal distance in a runway incursion event was always more than 1280 meters for D events, it was mostly between about 300 and 2500 m for C events, and it was mostly within 40 meters for A and B events. Analysis of combined closest horizontal and vertical distances shows that B events were often fly overs, whereas A events included close stops on the grounds, as well as fly overs with predominantly smaller vertical distances than B events.

The basis of the risk-based framework is an inventory of runway incursion scenarios. Such inventory was developed using 13 scenario descriptors with 2 to 5 options each, resulting in 169 main scenarios with up to 243 subcases. It was shown for a set of more than 200 severity A, B and C incursions that almost 99% could be described by the scenario inventory. The developed risk-based framework for assessment of runway incursions consists of the following five steps:

1. Mapping of runway incursions to scenarios. This step sets the basis and it is done for every runway incursion, using only information up to its initiation.
2. Assessment of the probabilities of scenarios, expressed as rates per airport movement, using statistics of series of associated runway incursions.
3. Assessment of the conditional probabilities of a collision given scenarios. These probabilities are assessed by risk modelling, primarily using agent-based dynamic risk models.
4. Assessment of the conditional probabilities of the human and material collision impact categories given a collision in a scenario. These probabilities are assessed using risk modelling.
5. Evaluation of runway incursion risk by combining the results of Steps 2, 3 and 4, and comparison with safety criteria

Applicability

The proposed risk-based framework for runway incursions supports effective safety management of aerodrome operations. Such a risk-based methodology may also be effectively used for evaluation of other types of air traffic incidents.

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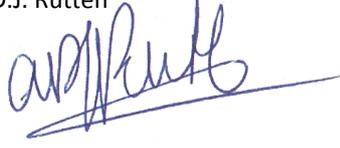
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Summary

Current safety management of aerodrome operations uses judgements of severity categories to evaluate runway incursions. Incident data show a small minority of severe incursions and a large majority of less severe incursions. We show that these severity judgements are mainly based upon the outcomes of runway incursions, in particular on the closest distances attained. As such, the severity-based evaluation leads to coincidental safety management feedback, wherein causes and risk implications of runway incursions are not well considered. In this paper we present a new framework for the evaluation of runway incursions, which effectively uses all runway incursions, which judges same types of causes similarly, and which structures causes and risk implications. The framework is based on risks of scenarios associated with the initiation of runway incursions. As a basis an inventory of scenarios is provided, which can represent almost all runway incursions 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.

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1 Introduction

The safety of runway operations is one of the key focus points of Air Traffic Management (ATM). 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. Major accidents such as at Tenerife in 1977 (583 casualties) [2], Omsk in 1984 (178 casualties) [3], and Linate Airport in 2001 (118 casualties) [4] are sad reminders of the deadly consequences that runway incursions may have.

Safety programs such as [5, 6] 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 [7, 8] and on the development of runway incursion prevention systems in the aircraft, air traffic control (ATC) tower, ground vehicles and aerodrome [9]. 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 [10]. For safety management of runway operations, runway incursions need to be reported and analysed [1, 11].

As part of such analysis of runway incursions, the International Civil Aviation Organization (ICAO) recommends to classify their severity 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 incursions. FAA does not apply category E for insufficient information, since a decision about the severity is always made. Statistics on runway incursions and the associated severities are regularly published in runway safety reports and runway safety plans [5, 12]. In addition to such reports, FAA publishes the details of runway incursions, including their severity categories, in a publicly accessible on-line database system, called FAA Aviation Safety Information Analysis and Sharing (ASIAS) [13]. In Europe, the European Aviation Safety Agency (EASA) provides statistics of safety occurrences, including runway incursions, in its annual safety review [14]. 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 from the ASIAs database.

The current severity categorization of runway incursions (A, B, C, D, E) 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 a main driver of the severity determination. This closest distance attained depends to a considerable extent on uncontrolled random circumstances, such as another aircraft being nearby at the time of the initiation of the runway incursion. In incursions that are judged as being less severe (C, D) typically the same types of errors or misunderstandings by pilots or controllers lead to initiation of runway incursions and the distinction with more severe (A, B) cases is primarily due to some uncontrolled circumstances. The consequence is that current safety management is driven largely by random outcomes, wherein lessons from incursions 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 incursions, which does not use an outcome-based severity category, but which is strictly based on the risk of scenarios associated with runway incursions. Such a scenario describes the state at the initiation of the runway incursion, e.g., a small aircraft enters a runway near the runway start while its pilots are lost and it comes into conflict with a large aircraft landing in good visibility conditions. A main step in the framework 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. The results provide detailed feedback on risks of runway incursion scenarios, wherein similar kinds of errors or misunderstandings leading to runway incursions in similar conditions give similar risk values. This provides a basis for risk-informed rather than coincidental safety management.

The paper is structured as follows. Section 2 sets the stage by introducing states and events in the evolution of runway incursions and by providing a number of illustrative examples of runway incursions. Section 3 describes and discusses the current severity-based approach for assessment of runway incursions, including an analysis of the relation between shortest distances and severity categories. Section 4 presents the development of an inventory of runway incursion scenarios, which forms the basis of the new framework. Section 5 presents the steps in the new risk-based framework and provides illustrative results. Section 6 discusses the framework and describes future research opportunities.

Parts of this research were also presented in a conference paper [15].

2 Many ways for evolution of runway incursions

There are many ways in which a runway incursion can arise and given its initiation there are many ways in which it can develop next, up to an accident as the most severe consequence. In line with the argumentation on accident precursors of [16], Figure 1 illustrates relations between states X_t (circles) and events E_t (arrows) before and after the initiation of runway incursions. The states describe sets of variables that are relevant for taxiing and runway operations, such as the type of operation (e.g. takeoff, land, taxi), the position of an aircraft, and the situation awareness (SA) of pilots. The events are occurrences during taxiing and runway operations, such as acts of observation or communication by pilots/controllers, and aircraft manoeuvring. Following a particular state, there is a multitude of possible events, which is indicated by the dashed arrows in Figure 1. These events may occur in various orderings and in a continuum of times.

In Figure 1 we consider, as a leading example, potential runway incursions between an aircraft A_1 , which taxis from a gate for departure, and an aircraft A_2 , which approaches a runway for landing. An initial state X_{t_a} describes the states of the aircraft before (ante) any precursor of a runway incursion occurred. For instance, this state may include the sizes of aircraft A_1 and A_2 and their positions at the gate or along the approach path.

We denote the time of the initiation of a runway incursion as t_0 . For times $t_a < t < t_0$ there can be various events that are precursors of a runway incursion, e.g. the pilots of aircraft A_1 make a wrong turn such that they have a wrong SA about their own position, or the pilots of aircraft A_1 forget an ATC instruction such that they have a wrong SA about the ATC instruction. Such inflicted states may lead to a runway incursion event $E_{t_0}^{RI}$ wherein aircraft A_1 passes the hold-short line of the runway and comes into conflict with aircraft A_2 that is about to land. Often, however, these kinds of inflicted states do not lead to a runway incursion, as there are various events that can prevent the progression to a runway incursion event, such as the pilots recognizing that they are at a wrong position, or being warned by ATC. In the scheme of Figure 1, the state X_{t_0} that is attained at the start of the runway incursion depends on the initial state X_{t_a} and the events that occurred for $t_a < t \leq t_0$.

Following the initiation of a runway incursion there may be a variety of events occurring for $t > t_0$, e.g., pilots recognize the conflict with the other aircraft, ATC warns pilots, aircraft A_2 initiates a go-around, or aircraft A_1 stops. All these types of events, their orderings, and timing have impact on the kind of final state in the evolution of the runway incursion at time t_f , when the entities involved are closest. For instance, final states may be aircraft A_2 flies over aircraft A_1 at 100 ft, aircraft A_2 goes around at 1 mile, aircraft A_1 stops at 10 ft before the runway edge while aircraft A_2 passes, or the aircraft are collided.

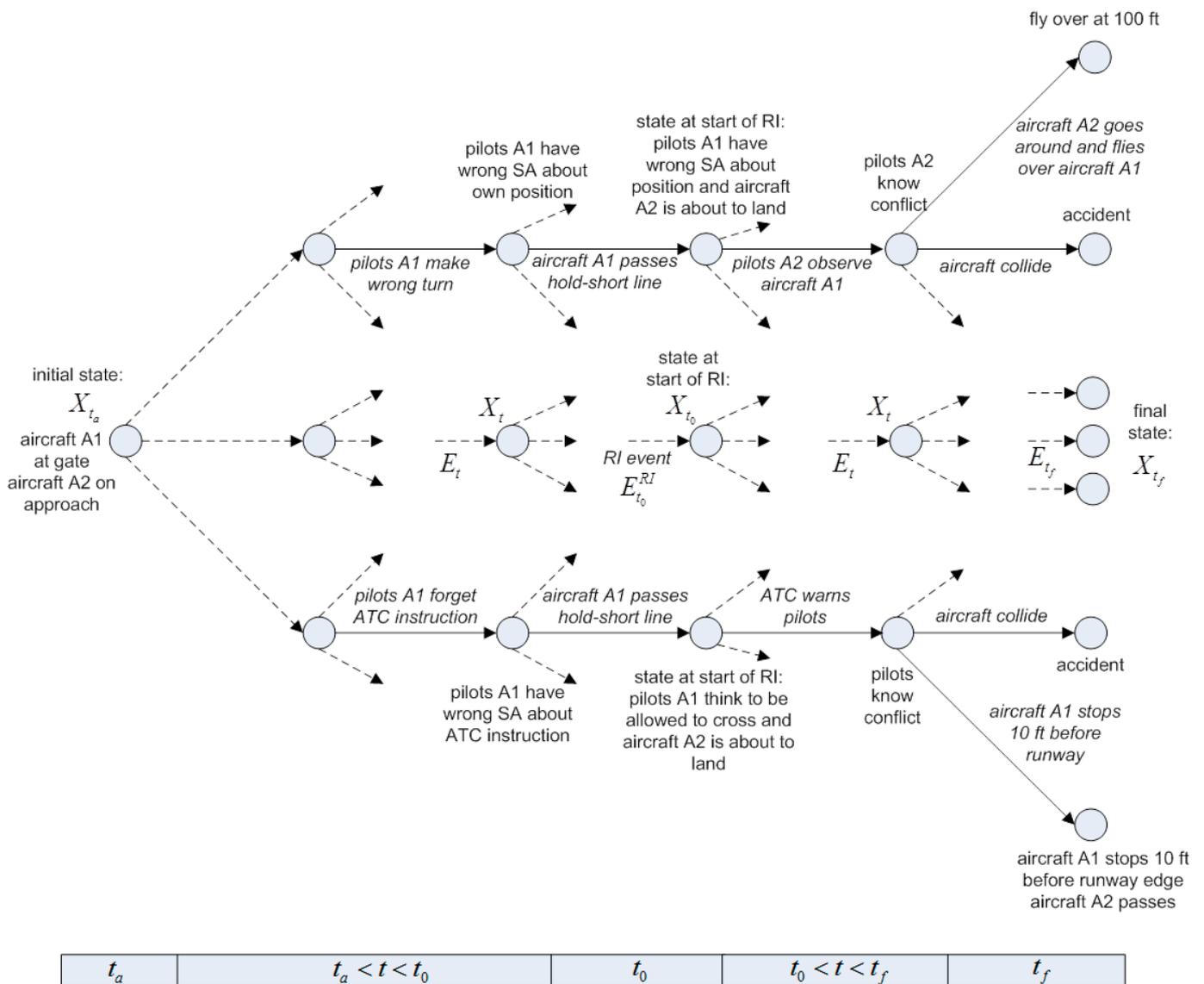


Figure 1. Illustrative diagram for development of runway incursions, representing states (circles) and events (arrows). Runway incursions start at time t_0 and they are dependent on states and events for $t_a \leq t < t_0$. For $t > t_0$ a runway incursion develops towards a final state at time t_f .

As an illustration of the ways that actual runway incursions evolved, Table 1 shows descriptions of some runway incursions in the FAA ASIAs RWS database [13]. For each of these incursions we added key features of the states X_{t_0} and X_{t_f} . Cases 1 to 5 all consider conflicts between an aircraft that is about to land and an aircraft taxiing on the runway without permission. In cases 1, 3 and 5 the taxiing aircraft lined up on the runway erroneously, either because the pilots seem to have thought to be allowed to do so (cases 1 and 3), or the pilot took a wrong turn and was lost (case 5). In cases 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 case 6 an aircraft lined up and took off without clearance, thus creating two types of runway incursions, wherein it (luckily) did not come into conflict with other traffic. The final states achieved in these incursions are varied, ranging from a fly over with 15 m vertical separation to a go-around at 1 mile from the runway. It can be observed in Table 1 that also the severity evaluations for these incursions are varied, ranging from A to D. Such severity evaluations will be discussed in depth next in Section 3.

Table 1. Descriptions of selected runway incursions in the FAA ASIAs RWS database [13], and the severity as evaluated by FAA. For each incursion we noted the states X_{t_0} and X_{t_f} as explained in Figure 1 RI ID refers to numbering used in this paper, RWS ID is the numbering in the FAA ASIAs RWS database, the severity is the evaluation done by FAA.

RI ID	1	RWS ID	7842	Severity	A
<p><i>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.</i></p>				<p>X_{t_0} :</p> <ul style="list-style-type: none"> – aircraft A_1 lines up at runway – pilot A_1 erroneously thinks line-up is allowed – aircraft A_2 on final approach <p>X_{t_f} :</p> <ul style="list-style-type: none"> – A_2 flies over A_1 at 15 m 	
RI ID	2	RWS ID	6596	Severity	B
<p><i>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.</i></p>				<p>X_{t_0} :</p> <ul style="list-style-type: none"> – aircraft A_1 crosses runway – reason for error pilot A_1 unclear – aircraft A_2 on final approach <p>X_{t_f} :</p> <ul style="list-style-type: none"> – A_2 flies over A_1 at 60 m 	
RI ID	3	RWS ID	8098	Severity	C
<p><i>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</i></p>				<p>X_{t_0} :</p> <ul style="list-style-type: none"> – aircraft A_1 lines up at runway – pilot A_1 erroneously thinks line-up is allowed – aircraft A_2 on final approach 	

<i>go-around at one quarter (.25) mile final. Distance from approach end runway 27R to Romeo is more than 2,000 feet.</i>				X_{t_f} :	
				– A ₂ goes around at 400 m	
RI ID	4	RWS ID	8343	Severity	C
<i>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.</i>				X_{t_0} :	
				– aircraft A ₁ crosses runway	
				– reason for error pilot A ₁ unclear	
				– aircraft A ₂ on final approach	
				X_{t_f} :	
				– A ₂ goes around at 400 m	
RI ID	5	RWS ID	7980	Severity	D
<i>A Cessna C182 was instructed to taxi via Bravo, cross Runway 15 on Bravo and proceed to Runway 6, which pilot read back. The C182 turned onto Taxiway Alpha instead of continuing on Bravo, entered Runway 6 without clearance and conflicted with a Piper PA28A on final same runway. The PA28A was issued a go around at one (1) mile final to avoid loss of separation.</i>				X_{t_0} :	
				– aircraft A ₁ crosses runway	
				– pilot A ₁ is lost after making a wrong turn	
				– aircraft A ₂ on final approach	
				X_{t_f} :	
				– A ₂ goes around at 1600 m	
RI ID	6	RWS ID	7985	Severity	D
<i>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.</i>				X_{t_0} (1):	
				– aircraft A ₁ lines up at runway	
				– pilot A ₁ thinks line-up is allowed	
				X_{t_f} (1):	
				– A ₁ lines up without conflict	
				X_{t_0} (2):	
				– aircraft A ₁ takes off	
				– pilot A ₁ thinks takeoff is allowed	
				X_{t_f} (2):	
				– A ₁ takes off without conflict	

3 Severity-based assessment of runway incursions

This section provides an overview of the severity-based assessment of runway incursions, such as is being applied in current safety management. Section 3.1 describes the factors considered in runway incursion severity judgements by assessment teams. Section 3.2 provides statistical data of runway incursion rates for the various severity categories and some literature human factors in runway incursions. Section 3.3 provides an analysis of the relation between the closest distance attained in runway incursions and the severity class. Building on these results, Section 3.4 discusses the limitations of the current severity-based approach for safety management of runway operations.

3.1 Judgements of runway incursion severity categories

The severity of a runway incursion is typically assessed by a team made up of air traffic controllers, airline pilots, airport operation/design experts, and a team leader. A severity assessment depends on the information available for the occurrence as well as on the composition and the judgements of the team. ICAO advises to use information on the following aspects to classify the severity of a runway incursion [1]:

1. *Proximity of the aircraft and/or vehicle.* This is the closest horizontal distance between entities involved when they are both on the ground, the closest vertical distance when an aircraft flies over another entity, or the proximity that best represents the probability of a collision when the entities are separated in both vertical and horizontal planes.
2. *Geometry of the encounter.* For instance, encounters between two aircraft on the same runway are more severe than incidents with one aircraft on the runway and another aircraft approaching the runway.
3. *Evasive or corrective action.* When the pilot of an aircraft takes evasive action to avoid a collision (e.g. hard braking, swerving, rejected takeoff, go-around), the magnitude of the manoeuvre is an important consideration in classifying the severity. Stronger evasive actions contribute to higher severity ratings.
4. *Available reaction time.* Encounters that allow the pilot little time to react to avoid a collision are more severe than encounters in which the pilot has ample time to respond.
5. *Environmental conditions, weather, visibility and surface conditions.* Conditions that degrade the quality of visual monitoring or degrade the stopping performance of aircraft may increase the severity of the incursion.
6. *Factors that affect system performance.* Factors such as communication system failures or communication errors contribute to the severity of an incident.

Some of these aspects consider the state at time t_0 of the start of a runway incursion, whereas others reflect the evolution and outcome of the runway incursion for $t > t_0$. In particular, the

encounter geometry, available reaction time and environmental conditions are already known at t_0 , whereas the proximity and evasive action can only be known for $t > t_0$. For factors affecting system performance, some may be known at the start, such as a communication error leading to the incursion, whereas others may also arise after the start of the incursion, such as a communication error during conflict resolution or a sudden communication system failure.

There are no strict rules on how to evaluate above aspects and how to combine them into an overall evaluation of the severity of a runway incursion. As such, the severity label attached to a runway incursion clearly depends on the judgements of the particular assessment team.

3.2 Statistics and human factors of runway incursions

Figure 2 shows an overview of the rate of runway incursions reported in the USA for each of the severity categories that occurred in fiscal years 2008 to 2013 (fiscal years are from 1 October to 30 September). The rate is expressed per airport operation, i.e. per aircraft departure or arrival. The rates for severity A and B incursions are based upon 2 to 13 events per year, and these small numbers contribute to the fluctuations in the yearly rates. There is no trend manifest in the development of the rate for severity A and B incursions and the average rates over these years are $1.2\text{E-}7$ and $1.3\text{E-}7$ for A and B cases, respectively, which contributes about 0.6% to the total runway incursion rate for each of A and B categories. The large majority of runway incursions are classified as severities C (40%, about 400 per year) and D (59%, about 600 per year). An increasing trend in the rates of severity C and D incursions can be observed in fiscal years 2008-2013, leading to an increase in the overall rate of reported runway incursions from $1.7\text{E-}5$ in 2008 to $2.5\text{E-}5$ in 2013 (mean $2.0\text{E-}5$). This increasing trend does not necessarily imply that the rate of occurrences has increased in these years, since the increase may also be due to a better reporting culture, triggered by awareness campaigns.

An extensive analysis of about 8800 runway incursions that occurred in the USA in the years 2001-2010 is presented in [17]. A variety of statistical techniques was used to examine relations between factors in the runway incursions and the determined severities. This statistical analysis revealed that, amongst others, runway incursions due to controller errors tend to be more severe, commercial carriers tend to be involved in less severe incidents, incursions during takeoff tend to be more severe than incursions during landing, the presence of more runway intersections is associated with a higher probability of more severe runway incursions, and having more runways at a particular airport is associated with a lower probability of more severe runway incursions. It is advised in [17] to perform more research regarding effects of pilots variables, weather variables, and controllers variables on severity of runway incursions, as well as to develop models for the frequency of runway incursions.

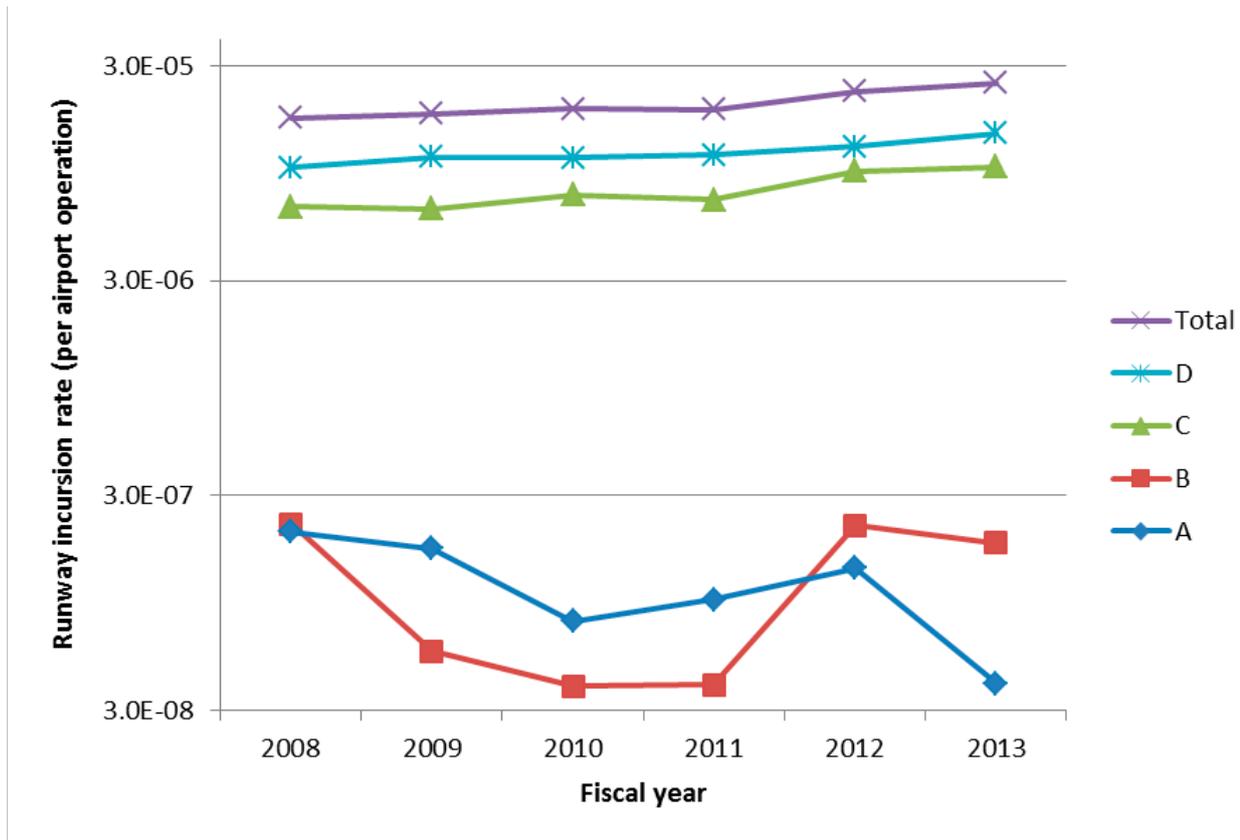


Figure 2. Rate of reported runway incursions per departure or arrival (log-scale) in the national airspace system of the USA in fiscal years 2008-2013, based on data in [12].

A series of studies on human factors in runway incursions has been published by Cardosi and colleagues [7, 8, 18]. Human factors in runway incursions from a pilot perspective were studied in [7] by analysis of 300 pilot reports in the Aviation Safety Reporting System (ASRS) for incursions in 2001 and 2002. Most incursions concerned taxiing aircraft: in 35% of the incursions the aircraft crossed the hold-short line without passing the runway edge, in 10% of the incursions the aircraft entered the runway without lining up or crossing, in 15% of the incursions the aircraft lined up on the runway, and in 27% of the incursions the aircraft crossed the runway. Pilot factors that contributed to the runway incursions include

- loss of position awareness, e.g. due to performing head-down tasks or due to a wrong turn during taxiing;
- communication problems, e.g. interpreting a “taxi to” instruction as a clearance to cross a runway or accepting another aircraft’s clearance; and
- expectation biases, e.g. expectations about holding positions along routes.

Controllers errors that contributed to runway incursions include forgetting about an aircraft or a closed runway, inadequate coordination between controllers (e.g. between runway and ground controllers), and readback/hearback errors [8].

3.3 Closest distance in runway incursion events

The closest proximity attained between the entities in a runway incursion is the first-mentioned determinant of the severity categorization approach [1]. To obtain more insight in the relation between the closest distance and severity, we performed an analysis using the narratives of a set of runway incursions. The closest proximity reported in the narratives are mostly estimates from controllers or sometimes pilots made by visual observation. The closest proximity is decomposed in horizontal and vertical components; a collision would occur if both components are zero.

For our analysis we used FAA runway incursion data [13] for a six years period (fiscal years 2008 to 2013) to characterize the relatively rare severity A and B incursions. For the more frequently occurring severity C and D incursions we used a single year (FY2010), which is in the middle of this six years period. FY2010 contains sufficient data for the purpose of our analysis and the characteristics of severity C and D incursions are not expected to differ from those obtained in other years. Next we specify some details about the incursions in our data set.

- Severity A incursions from FY2008 – FY2013. A total of 39 incursions are in the database. For 37 of them both the horizontal and vertical distance for the closest proximity could be extracted from the narratives. One of these runway incursions resulted in a collision between an aircraft and a vehicle. Since inclusion of an accident in the incident severity categorization is not in line with the ICAO guidelines [1], we excluded it from the analysis. As such, 36 severity A incursions were retained for the analysis.
- Severity B incursions from FY2008 – FY2013. A total of 40 incursions are in the database. For all these, both the horizontal and vertical distance for the closest proximity could be extracted from the narratives, and they were all retained for the analysis.
- Severity C incursions from FY2010. A total of 386 incursions are in the database. For 382 incursions the closest horizontal distance could be extracted from the narratives, but for most incursions the closest vertical distance was not reported. In the analysis of severity C incursions we therefore focussed on closest horizontal distance only.
- Severity D incursions from FY2010. A total of 574 incursions are in the database. In 492 incursions (86%) there was only one entity, with no other traffic mentioned. In 15 incursions (2.6%) two entities were involved, but they did not include a conflict with an aircraft taking off or landing. Often these were cases where an aircraft erroneously took the line-up and/or takeoff clearance of a second aircraft, while the second aircraft stayed behind the hold-short line. In 67 incursions (12%) an aircraft that was about to land was involved. In these cases a closest horizontal distance was reported and these were included in the analysis. There were no severity D incursions in the data sample involving an aircraft taking off.

In many of the narratives of these incursions the closest distances are explicitly mentioned and we used those values for the analysis. In cases where a lower or upper bound is specified, e.g. “closest horizontal distance was more than 1000 feet” or “vertical distance was less than 100 ft”, the bound was used in the analysis, i.e. 1000 ft and 100 ft in the examples provided. In cases where a range is provided, e.g. “vertical distance was estimated to be 50-100 feet”, the minimum value of the range was used, i.e. 50 ft in the example. We noticed that the determination of the closest

horizontal distance was not always done consistently in the narratives. Especially in part of the narratives of severity C incursions we observed some cases where the distance when both entities were still on the ground was used, rather than the distance in the horizontal plane when both aircraft were closest. Lacking a complete overview of these incursions we did not attempt to correct such inconsistencies. In narratives without explicitly indicated closest distances we estimated them on the basis of related distances provided in the narratives. In cases of conflicts involving a landing aircraft, often a distance to the runway where a go-around instruction was given is provided, e.g. “a go-around was issued at 1 mile”. In these cases, such distance was used as the shortest distance in the analysis, although the actual closest horizontal distance during the go-around manoeuvre may well have been smaller.

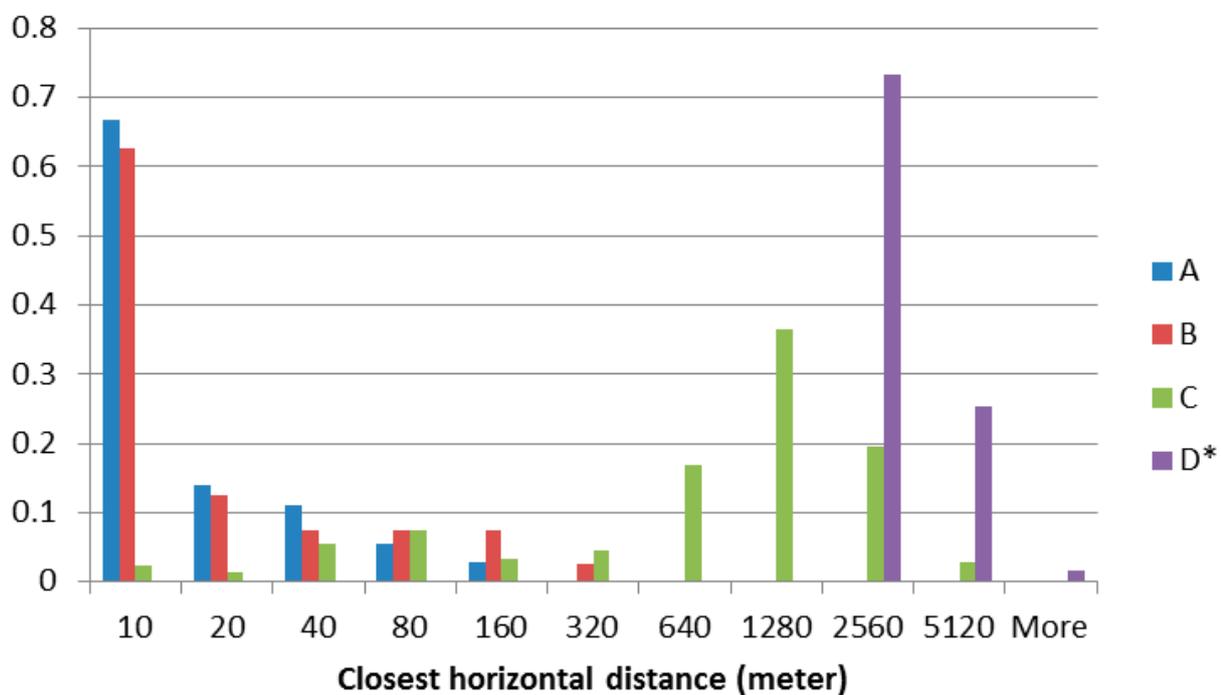


Figure 3. Empirical probability density functions of the closest horizontal distance (2-log scale) in a runway incursion event given severity category A, B, C or D*. The set D* includes the D events with a conflict involving an aircraft on final approach (12% of all D events). The distance associated to a bin is its upper bound, e.g. the bin for 10 meter includes distances from 0 to 10 meter.

Figure 3 shows the empirical conditional probability density functions (PDFs) for the closest horizontal distance given the severity. For severity D incursions, which concern a conflict with a landing aircraft, the graph shows that the closest horizontal distance was always more than 1280 m. This mostly reflects cases where a go-around was issued at distances of more than a mile from the runway. The closest horizontal distance of severity C incursions covers a broad range of values between 0 and 5000 m. Values up to 160 m often reflect cases where an entity stopped behind the hold-short line and a landing or taking off aircraft passed by, either on the ground or in the air. For most severity C incursions the closest distance was between about 300 and 2500 m, reflecting distances where aircraft cancelled takeoff or initiated a go-around. The distributions for severity A

and B incursions both show a large peak for closest horizontal distances up to 10 m and overall they are quite similar, although larger distances are somewhat more prominent for severity B incursions.

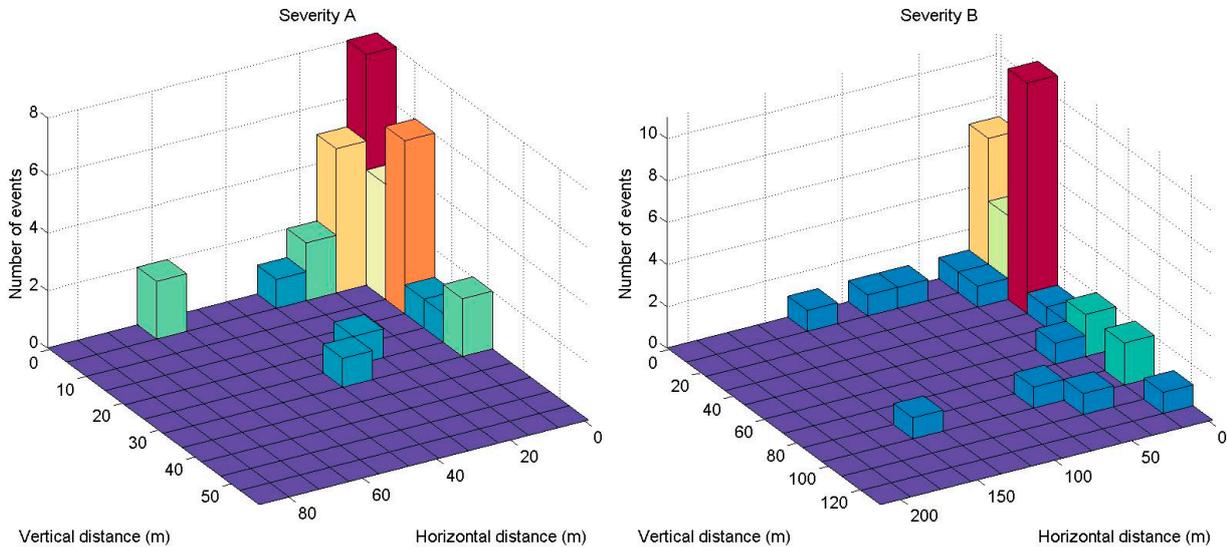


Figure 4. 2D Histograms of the closest horizontal and vertical distances in runway incursion events of severity A (left figure) and severity B (right figure). Note that the figures have different scales.

If we include the vertical dimension of the closest proximity, as shown in the 2D histograms in Figure 4, we can observe differences in the proximity distance distributions for severity A and B incursions. For almost all severity A incursions either the vertical distance was close to zero, i.e. both entities were on or very close to the ground (18 incursions), or the horizontal distance was close to zero (22 incursions). In 8 incursions both the horizontal and vertical distance were close to zero and a collision was narrowly avoided, e.g. two aircraft being on the ground and only 3 meter separation remaining. Overall, the closest horizontal and vertical distances of severity A incursions were mostly within 60 m and 40 m, respectively. Most severity B incursions are in the bins with the smallest horizontal distance, which mostly represent fly overs. The closest vertical distance in the severity B incursions was typically larger than in the severity A incursions with values up to 120 m and a peak in the distribution between 20 and 40 m.

3.4 Limitations of severity-based evaluation of runway incursions

The analysis in Section 3.3 shows that the severity label attached to a runway incursion is mainly based on the closest distance attained in the incursion, i.e. it is outcome-based. This is also illustrated by the examples in Table 1. In the context of Figure 1 it means that the severity label is mainly based on the final state X_{t_f} . The statistics in Section 3.2 reveal that the usage of the

current severity categorization has led to a large distinction between the frequency of severity A and B incursions (1.2%), on the one hand, and the frequency of severity C and D incursions (98.8%), on the other hand. As safety management tends to perceive A and B outcomes as more problematic than C and D outcomes, the large distinction in the statistics implies that lessons from the large majority of severity C and D incursions are undervalued in the safety management cycle and that there may be an overreaction to severe (A, B) outcomes .

A major limitation of the outcome-based assessment of runway incursions is that it considerably depends on uncontrolled random circumstances. For instance, in all incursions 1, 3, 5 and 6 of Table 1 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 incursions 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 incursion 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 incursion 6 was considered as least serious (D). As another example, an aircraft crossed the runway without permission in both incursions 2 and 4 of Table 1, 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.

Another main limitation of the severity-based evaluation of runway incursions is that it does not provide means to structure reasons of the runway incursions and to evaluate the risk implications of such reasons. For instance, in both incursions 2 and 4 of Table 1, the taxiing aircraft crossed the runway erroneously, and reasons for these errors were not reported. 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. 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.

In conclusion, there is a need for evaluation of runway incursions that provides informative feedback to safety management by effectively using all runway incursions, by judging same types of errors similarly, and by providing a structure for their reasons and risk implications.

4 Runway incursion scenarios as basis of the new framework

To overcome the limitations of the outcome-focused approach in the current assessment of runway incursions, we have developed a risk-based approach for potential consequences given the start of a runway incursion. This approach uses scenarios to characterize states at the start of runway incursions. Section 4.1 describes the concept of using scenarios for the risk assessment. Section 4.2 presents the development of an inventory of runway incursion scenarios. Section 4.3 provides a mapping of a data set of runway incursions to the scenario inventory.

4.1 Scenarios for risk evaluation of runway incursions

As a basis for risk-based evaluation of runway incursions we distinguish between what did happen until the initiation of a runway incursion and what may happen following the initiation of the runway incursion. Referring to Figure 1, we use knowledge about all conditions and events for $t \leq t_0$ to assess probabilities of adverse consequences of a runway incursion for $t > t_0$. Considering that the information for $t \leq t_0$ is reflected in the state X_{t_0} at the start of the runway incursion, this implies assessing the risk given the state X_{t_0} of a runway incursion event $E_{t_0}^{RI}$.

Every runway incursion event $E_{t_0}^{RI}$ is unique and it has a particular state X_{t_0} . As a way towards a practically feasible approach for risk assessment of runway incursion events, we associate each unique state X_{t_0} with a runway incursion scenario. A runway incursion scenario $S_{i,j}$ is a high-level description of a set of runway incursions with similar initial states X_{t_0} , where the indices i and j represent main scenarios and subcases, respectively. Examples of runway incursion scenarios are (1) small aircraft enters runway at the runway middle while its pilots are lost and it comes into conflict with a large aircraft taking off in good visibility, or (2) small aircraft crosses at the runway start without ATC clearance and comes into conflict with a small aircraft landing in reduced visibility. Given a particular runway incursion scenario, it can be argued what its consequences may be and what the probabilities of these consequences are, i.e. what the associated risk is.

4.2 Development of a scenario inventory

As a basis for the risk-based evaluation we use an inventory of runway incursion scenarios. On the one hand, this inventory should be sufficiently broad, such that differences in the probabilities of adverse consequences that may be due to conditions at the start of a runway incursion are accounted for by different scenarios. On the other hand, 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. The development of a

suitable scenario inventory requires an iterative process, which balances requirements from representation of incursions, 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 $S_{i,j}$ are described by a number of scenario descriptors β_r . Each scenario descriptor can take on a number of discrete values and we distinguish main scenario descriptors and subcase descriptors. A scenario is uniquely described by setting values for all descriptors, where one value is chosen for each descriptor. Table 2 shows the set of descriptors that has been developed in the current research. The main scenario descriptors (β_1 to β_{10}) consider the runway configuration, the types and operations of the involved physical entities (PE), the runway incursion initiating entity, the direction and relative position of the encounter, and the intent of the human operators of the physical entities. 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. The subcase descriptors (β_{11} to β_{16}) describe the sizes of the involved physical entities, the location on the runway(s), the runway hold position, and the visibility condition. The sets of possible values of some descriptors depend on the types of physical entities involved in the incursion.

Table 2. Overview of runway incursion scenario descriptors. A scenario is uniquely described by setting values for all descriptors, where one value is chosen for each descriptor. The sets of possible values of some descriptors depend on the types of physical entities involved in the incursion.

Descriptor β_r	Value	Explanation	
Main scenario descriptors			
β_1	Runway configuration	<i>Single</i>	Runway incursion (RI) on a single active runway
		<i>Intersecting</i>	RI on intersecting active runways
β_2	Type of physical entity 1 (PE1)	<i>Aircraft</i>	PE1 is always an aircraft
β_3	Type of physical entity 2 (PE2)	<i>Aircraft</i>	RI between two aircraft
		<i>Vehicle</i>	RI between aircraft and vehicle
		<i>Person</i>	RI between aircraft and person
		<i>Helicopter</i>	RI between aircraft and helicopter
β_4	Operation of PE1	<i>Takeoff</i>	Aircraft is taking off or in initial climb
		<i>Land</i>	Aircraft is landing or in final approach
		<i>Taxi</i>	Aircraft is taxiing
β_5	Operation of PE2, if PE2 is aircraft	<i>Takeoff</i>	Aircraft is taking off or in initial climb
		<i>Land</i>	Aircraft is landing or in final approach
		<i>Taxi</i>	Aircraft is taxiing
	Operation of PE2, if	<i>Any</i>	No distinction is made for the operation of a

Descriptor β_r		Value	Explanation
	PE2 is vehicle, person, or helicopter		vehicle, person or helicopter
β_6	Runway incursion initiating entity	<i>PE1</i>	PE1 initiates the RI
		<i>PE2</i>	PE2 initiates the RI
β_7	Intent of pilots of PE1	<i>Takeoff</i>	Pilots think that takeoff is allowed and initiate the takeoff roll
		<i>Land</i>	Pilots think that landing is allowed and continue the final approach in preparation of landing
		<i>Lineup</i>	Pilots intend to line-up on the runway
β_8	Intent of human operator of PE2, being pilot of a taxiing aircraft	<i>Cross</i>	Pilots intend to cross an active runway
		<i>Lineup</i>	Pilots intend to line-up on the runway
		<i>AlongTw</i>	Pilots intend to taxi over a normal taxiway or an inactive runway
		<i>AlongRw</i>	Pilots intend to taxi along an active runway
		<i>Stop</i>	Pilots intend to stop and hold short of an active runway
	Intent of human operator of PE2, being a vehicle driver	<i>Cross</i>	Driver intends to cross an active runway
		<i>AlongTw</i>	Driver intends to taxi over a normal taxiway or an inactive runway
		<i>AlongRw</i>	Driver intends to taxi along an active runway
		<i>Stop</i>	Driver intends to stop and hold short of an active runway
	Intent of human operator of PE2, being person or helicopter pilot	<i>Any</i>	No conditions are distinguished for the intent of a helicopter pilot or of a person on the runway
β_9	Encounter direction	<i>Opposite</i>	RI where the physical entities move in the opposite direction
		<i>Same</i>	RI where the physical entities move in the same direction
		<i>Intersect</i>	RI where the movement vectors of physical entities intersect
β_{10}	Encounter relative position	<i>InFront</i>	PE2 is in front of PE1
		<i>Behind</i>	PE2 is behind PE1
Subcase descriptors			
β_{11}	Size of PE1	<i>Small</i>	Aircraft of 18,600 kg (40,000 pounds) or less maximum certificated takeoff weight (MCTW)
		<i>Large</i>	Aircraft between 18,600 and 136,100 kg (40,000 and 300,000 pounds) MCTW
		<i>Heavy</i>	Aircraft with 136,100 kg (400,000 pounds) or more MCTW
β_{12}	Size of PE2, if PE2 is	<i>Small</i>	Aircraft of 18,600 kg or less MCTW

Descriptor β_r		Value	Explanation
	aircraft	<i>Large</i>	Aircraft between 18,600 and 136,100 kg MCTW
		<i>Heavy</i>	Aircraft with 136,100 kg or more MCTW
	Size of PE2, if PE2 is vehicle	<i>Tow</i>	A vehicle towing an aircraft
		<i>Other</i>	Any other vehicle
Size of PE2, if PE2 is person or helicopter	<i>Any</i>	No distinction is made in sizes of persons or helicopters	
β_{13}	Location on runway 1	<i>Start</i>	RI is between 0 and 1000 m from the runway threshold
		<i>Middle</i>	RI is between 1000 and 2000 m from the runway threshold
		<i>End</i>	RI is more than 2000 m from the runway threshold
β_{14}	Location on runway 2	<i>Start</i>	RI is between 0 and 1000 m from the runway threshold
		<i>Middle</i>	RI is between 1000 and 2000 m from the runway threshold
		<i>End</i>	RI is more than 2000 m from the runway threshold
		<i>None</i>	There is no intersecting runway (single runway case)
β_{15}	Runway hold position	<i>Small</i>	Runway hold position is about 46 m (150 ft) from the runway centerline
		<i>Medium</i>	Runway hold position is about 76 m (250 ft) from the runway centerline
		<i>Large</i>	Runway hold position is about 122 m (400 ft) from the runway centerline
		<i>None</i>	There is no taxiway with a runway hold position
β_{16}	Visibility condition	<i>VC1</i>	Visibility condition 1 of [30], implying good visibility where both pilots and controllers can visually observe all traffic
		<i>VC2</i>	Visibility condition 2 of [30], implying reduced visibility where controllers cannot visually observe all traffic, but pilots still can see traffic on/near the runway
		<i>VC34</i>	Visibility condition 3 or 4 of [30], implying severely reduced visibility where controllers nor pilots can well see traffic on/near the runway

In combination, these scenario descriptors represent the runway incursion scenarios. Examples of main scenarios are:

- Main scenario S_5 : Single runway ($\beta_1 = \textit{Single}$), involving two aircraft ($\beta_2 = \textit{Aircraft}$, $\beta_3 = \textit{Aircraft}$), where PE1 is taking off ($\beta_4 = \textit{Takeoff}$) and PE2 is taxiing ($\beta_5 = \textit{Taxi}$), PE2 initiates the runway incursion ($\beta_6 = \textit{PE2}$), the pilots of PE1 intend to takeoff ($\beta_7 = \textit{Takeoff}$),

the pilots of PE2 intend to taxi over a normal taxiway ($\beta_8 = \textit{AlongTw}$), PE2 moves on a taxiway intersecting the runway ($\beta_9 = \textit{Intersect}$), in front of PE1 ($\beta_{10} = \textit{InFront}$).

- Main scenario S_9 : Single runway ($\beta_1 = \textit{Single}$), involving two aircraft ($\beta_2 = \textit{Aircraft}$, $\beta_3 = \textit{Aircraft}$), where PE1 is landing ($\beta_4 = \textit{Land}$) and PE2 is taxiing ($\beta_5 = \textit{Taxi}$), PE2 initiates the runway incursion ($\beta_6 = \textit{PE2}$), the pilots of PE1 intend to land ($\beta_7 = \textit{Land}$), the pilots of PE2 intend to cross the active runway ($\beta_8 = \textit{Cross}$), PE2 moves on a taxiway intersecting the runway ($\beta_9 = \textit{Intersect}$), in front of PE1 ($\beta_{10} = \textit{InFront}$).

Examples of subcases for these main scenarios are:

- Subcases $S_{5,1}$ and $S_{9,1}$: PE1 is a large aircraft ($\beta_{11} = \textit{Large}$), PE2 is a small aircraft ($\beta_{12} = \textit{Small}$), the taxiway used by PE2 is in the middle of the single runway ($\beta_{13} = \textit{Middle}$, $\beta_{14} = \textit{None}$), the runway hold position is at 250 ft from the runway centerline ($\beta_{15} = \textit{Medium}$), and the visibility is good ($\beta_{16} = \textit{VC1}$).
- Subcases $S_{5,2}$ and $S_{9,2}$: PE1 is a small aircraft ($\beta_{11} = \textit{Small}$), PE2 is a small aircraft ($\beta_{12} = \textit{Small}$), the taxiway used by PE2 is at the start of the single runway ($\beta_{13} = \textit{Middle}$, $\beta_{14} = \textit{None}$), the runway hold position is at 150 ft from the runway centerline ($\beta_{15} = \textit{Small}$), and the visibility is reduced ($\beta_{16} = \textit{VC2}$).

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, both above mentioned main scenarios S_5 and S_9 contain 243 subcases, being all combinations of 3 sizes of PE1, 3 sizes of PE2, 3 locations on a single runway, 3 runway hold positions, and 3 visibility conditions.

4.3 Mapping of runway incursions to the scenario inventory

To obtain insight in the completeness of the runway incursion scenario inventory, a mapping was made of runway incursions to the scenarios. This was done during an early part of the research and development, wherein we used a FY2004-2010 dataset of 232 runway incursions, including all severity A and B incursions in the US in fiscal years 2004 to 2010 and part of the severity C

incursions in fiscal year 2010. Using the narratives for each incursion the applicable descriptors of the scenario inventory were identified. On this basis we distinguished the following cases of the number of main scenarios that apply to an incursion:

- The runway incursion cannot be described by any of the main scenarios.
- The runway incursion can be described uniquely by one main scenario.
- The runway incursion 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 3: Overview of the number of main scenarios (none / one / multiple) that are associated with severities A, B and C runway incursions in the particular FY2004-2010 dataset.

Number of scenarios	A		B		C		Total	
	Count	Percentage	Count	Percentage	Count	Percentage	Count	Percentage
None	3	3.3%	0	0.0%	0	0.0%	3	1.3%
One	66	71.7%	45	71.4%	44	57.1%	158	68.1%
Multiple	23	25.0%	18	28.6%	33	42.9%	71	30.6%
Total	92	100.0%	63	100.0%	77	100.0%	232	100.0%

Table 3 provides an overview of the mapping of the runway incursions to the main scenarios. It follows that 98.7% of the 232 analyzed incursions could be mapped to one or several main scenarios of the inventory. The incursions 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 incursions is mapped to a single main scenario. It follows from the results for the severity categories in Table 3 that relatively larger fractions of severity A and B incursions are mapped to a single main scenario than the severity C incursions. This is explained by the typically more detailed narratives of more severe incursions, which provide a better basis for a unique scenario selection.

A considerable part (31%) of the incursions is mapped to multiple (up to 4) main scenarios. In these cases sufficient information was not available to uniquely select the scenario descriptors. Frequently missing information in the narratives of the runway incursions 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. Examples of such cases without an explanation of the viewpoint of pilots are incursions 2 and 4 of Table 1. What was the situation awareness of the pilots that led to the runway incursion? The pilots may have thought (mistakenly) that they were allowed to cross the runway, or maybe they thought still to be taxiing along a normal taxiway at the moment they were actually on the runway crossing. Using the runway incursion descriptors of Table 2, this means that

for these cases $\beta_8 = Cross$ and $\beta_8 = AlongTw$ are both possible values (while the other descriptors can be set uniquely), such that these runway incursion events are associated with two main scenarios.

Table 4: Top-5 of main scenarios associated with runway incursions in the particular FY2004-2010 dataset.

ID	Main scenario description	Count	
S_5	Aircraft takes off and taxiing aircraft enters runway erroneously, while its pilots have the intent to taxi over a normal taxiway or an inactive runway	31	13.4%
S_2	Aircraft takes off and taxiing aircraft enters runway erroneously, while its pilots have the intent to cross the active runway and think they are allowed to do so	27	11.6%
S_{10}	Aircraft lands and taxiing aircraft enters runway erroneously, while its pilots have the intent to taxi over a normal taxiway or an inactive runway	24	10.3%
S_9	Aircraft lands and other aircraft lines up on the runway erroneously, while its pilots think they are allowed to line-up	21	9.1%
S_7	Aircraft lands and taxiing aircraft enters runway erroneously, while its pilots have the intent to cross the active runway and think they are allowed to do so	20	8.6%

There is a considerable variety in frequency by which scenarios are associated with runway incursion events. Table 4 shows the top-5 of the mostly associated scenarios in the FY2004-2010 dataset. These are all incursions between aircraft landing or taking off with another aircraft taxiing on the runway erroneously, since its pilots think to be on a normal taxiway, or to be allowed to cross or line-up. There are also various scenarios without any associated runway incursions in the particular FY2004-2010 dataset. For instance, scenarios where an aircraft initiates takeoff erroneously and comes into conflict with an aircraft crossing or lining up were not encountered in the dataset. As another example, a scenario where two aircraft are taking off in opposite directions on the same runway was not in the dataset, whereas a scenario where two aircraft were landing in opposite directions on the same runway was encountered twice in the dataset. Clearly, the lack of observations in the dataset does not exclude a scenario, especially given the limited size of the dataset.

Overall, the inventory of runway incursion scenarios provides a broad set of incursions that may occur. Mapping of runway incursion events to scenarios provides the basis for assessing probabilities of runway incursion scenarios, as will be explained in detail next in Section 5.

5 Steps in the risk-based framework for assessment of runway incursions

Building on the scenario inventory developed in Section 4, the risk-based framework for assessment of runway incursions consists of the following five steps, such as shown in Figure 5.

1. Mapping of runway incursions to scenarios. This step sets the basis for the risk-based assessment and it needs to be done for every runway incursion, using only information up to its initiation.
2. Assessment of the probabilities of scenarios, expressed as rates per airport movement (takeoffs, landings), using statistics of series of associated runway incursions.
3. Assessment of the conditional probabilities of a collision given scenarios. These probabilities are assessed by risk modelling, primarily using agent-based dynamic risk models.
4. Assessment of the conditional probabilities of the human and material collision impact categories given a collision in a scenario. These probabilities are assessed using risk modelling.
5. Evaluation of runway incursion risk by combining the results of Steps 2, 3 and 4, and comparison with safety criteria

Next, Sections 5.1 to 5.5 provide details of each step and give some illustrative results.

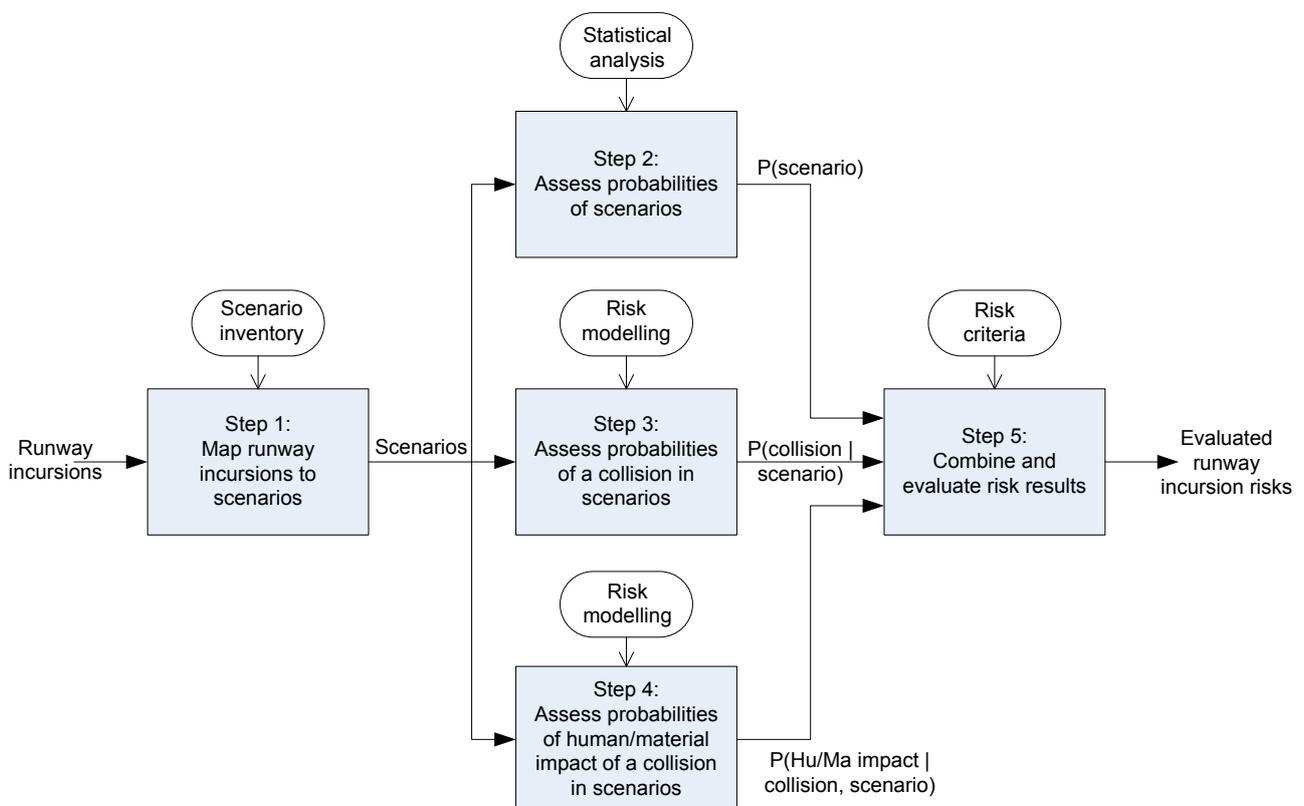


Figure 5. Diagram of the steps in the risk-based framework for assessment of runway incursions.

5.1 Step 1: Mapping of runway incursions to scenarios

Step 1 in the runway incursion risk modeling framework sets the basis by mapping of runway incursions to scenarios. A runway incursion is mapped to a single scenario if it is thus described uniquely. However, as explained in Section 4.3, there is not always sufficient information available to map an incursion to a single scenario. To associate multiple possible scenarios with an incursion, a probabilistic approach is followed. This implies that for a particular runway incursion event E_{q,t_0}^{RI} (with q a counting index) the conditional probabilities $P(S_{i,j} | X_{q,t_0})$ of all scenarios $S_{i,j}$ are assessed given the state X_{q,t_0} at the start of the runway incursion, with $\sum_{i,j} P(S_{i,j} | X_{q,t_0}) = 1$. If

the runway incursion 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.

Methods to assess the conditional probabilities $P(S_{i,j} | X_{q,t_0})$ include:

1. *All possible scenarios are assessed equally probable.* For instance, consider a runway incursion event caused by a taxiing aircraft, where all scenario indicators are clear except for the intent of the taxiing pilot. In particular, it not specified in the narrative why the pilots of a taxiing aircraft caused a runway incursion, and it is considered that it may either be due to (a) the pilots thinking they were allowed to cross the runway, or due to (b) the pilots thinking that they were taxiing on a normal taxiway (not crossing the runway). The conditional probabilities may be assessed as $P(S_{i,j} | X_{q,t_0}) = 0.5$ for both possible scenarios.
2. *The user assesses the conditional probabilities.* Taking into account all indications in the narrative and related information for operations on the airport considered, a user of the method assesses the conditional probabilities of the scenarios. For instance, in above example a user may consider it more likely that the pilots did not know to be heading towards the active runway, and assign a larger value to the conditional probability for the scenario associated to case (a).

For the results presented in this paper, we used the first method to assess the conditional probabilities $P(S_{i,j} | X_{q,t_0})$. In the mapping of events to scenarios in Section 4.3, we found that events with associated scenarios have 1, 2, 3, or 4 possible scenarios for a particular event, such that the values for $P(S_{i,j} | X_{q,t_0})$ are 1, 0.5, 0.333, and 0.25, respectively.

5.2 Step2: Assess probabilities of scenarios

The objective of Step 2 is to assess the probabilities of runway incursion scenarios, expressed as rate per airport operation (landing / takeoff). Such probabilities are assessed statistically, on the basis of runway incursion events that occurred in a particular time frame T_m , such as a year or a

series of years. An estimate of the overall probability of a runway incursion E^{RI} in general for a specific time frame T_m is provided by the empirical probability

$$P_{T_m}(E^{RI}) = \frac{N_{T_m}^{RI}}{N_{T_m}^{AO}}, \quad (1)$$

where $N_{T_m}^{RI}$ is the number of runway incursion events in time frame T_m and $N_{T_m}^{AO}$ is the number of airport operations. An estimate of the conditional probability of a particular runway incursion scenario given the occurrence of a runway incursion is

$$P_{T_m}(S_{i,j} | E^{RI}) = \frac{1}{N_{T_m}^{RI}} \sum_{q=1}^{N_{T_m}^{RI}} P(S_{i,j} | X_{q,t_0}), \quad (2)$$

where the probability estimates $P(S_{i,j} | X_{q,t_0}^{RI})$ stem from Step 1. As a scenario $S_{i,j}$ is by definition always coupled to a runway incursion E^{RI} , an estimate of the probability of a runway incursion scenario, expressed per airport operation, now is

$$P_{T_m}(S_{i,j}) = P_{T_m}(S_{i,j}, E^{RI}) = P_{T_m}(S_{i,j} | E^{RI}) \cdot P_{T_m}(E^{RI}) = \frac{1}{N_{T_m}^{AO}} \sum_{q=1}^{N_{T_m}^{RI}} P(S_{i,j} | X_{q,t_0}). \quad (3)$$

Although for a large organization as FAA there are about 1000 runway incursions per year, the number of incursions that can be associated with a specific scenario $S_{i,j}$ may be small, leading to significant uncertainty in the probability estimate. As a way forward, the probabilities for a main scenario S_i can be estimated with less uncertainty by aggregating over its subcases:

$$P_{T_m}(S_i | E^{RI}) = \frac{1}{N_{T_m}^{RI}} \sum_{q=1}^{N_{T_m}^{RI}} \sum_j P(S_{i,j} | X_{q,t_0}), \quad (4)$$

$$P_{T_m}(S_i) = \frac{1}{N_{T_m}^{AO}} \sum_{q=1}^{N_{T_m}^{RI}} \sum_j P(S_{i,j} | X_{q,t_0}). \quad (5)$$

In a similar way, probability estimates $P_{T_m}(\beta_r | E^{RI})$ and $P_{T_m}(\beta_r)$ can be achieved for the subcase descriptors β_r (Table 2), e.g. the conditional probability that a taxiing aircraft has size Small given a runway incursion, the conditional probability of visibility VC2 given a runway incursion, or the probability that a runway incursion occurs in the middle of the runway. Next, if we assume that the main scenarios are independent from the subcases and the subcases are independent from each other, then the conditional probability of a scenario given a runway incursion can be assessed by

$$P_{T_m}(S_{i,j} | E^{RI}) = P_{T_m}(S_i | E^{RI}) P_{T_m}(S_j | E^{RI}) = P_{T_m}(S_i | E^{RI}) \prod_{r \in D_j} P_{T_m}(\beta_r | E^{RI}), \quad (6)$$

where D_j denotes the set of descriptors associated with subcase j . If it follows from statistical data or expert reasoning that some of the components can clearly not be considered being independent, such dependencies should be included in the assessment. An example of such dependency is a scenario involving an aircraft lining up and an aircraft landing, wherein the location of a runway incursion can be expected to be predominantly near the start of the runway.

Given a dataset of runway incursions for a particular time frame, there may be scenarios without any associated runway incursion, as explained in Section 4.3. Assuming zero-valued probabilities for such scenarios would imply a too optimistic view on the risk. For such scenarios expert-based lower bounds for the scenario probabilities can be used. An expert can base such lower bounds for instance on probabilities observed in other relevant datasets, or an expert can use reasoning on the relative likelihood of scenarios without data versus scenarios with data.

In conclusion, Step 2 of the framework primarily uses runway incursions data and airport operations data to assess probabilities of scenarios. As a secondary means it uses expert judgment to decide on dependencies between scenarios and subcases, and to provide lower bounds for probabilities of scenarios without associated incursions. Some illustrative results of this step are provided in Section 5.5.2.

5.3 Step 3: Assess probabilities of a collision in scenarios

Step 3 in the runway incursion risk modeling framework concerns the assessment of the conditional probability of a collision event E^{coll} given a runway incursion scenario $P(E^{\text{coll}} | S_{i,j})$ for each main scenario i and subcase j . These probabilities may depend on the time frame considered (denoted by $P_{T_m}(E^{\text{coll}} | S_{i,j})$), if there have been introduced changes that influence the collision probabilities, e.g. new ways of working or new alerting systems. Often though, these probabilities can be considered as being time independent.

There are several ways, in principle, to assess the conditional probabilities of a collision given a scenario, including

1. statistical evaluation of runway incursion-related accidents,
2. expert judgment,
3. development of a probabilistic graphical model such as a fault/event tree or Bayesian belief network, or
4. agent-based dynamic risk modelling (DRM).

Next, we will discuss the feasibility of these methods for assessing the conditional collision probabilities.

Re 1. Statistical evaluation of runway incursion-related accidents. To assess the conditional probability of a collision given a particular runway incursion scenario on the basis of statistical data, there should be a sufficient number of collisions that can be associated with each runway incursion scenario. The number of accidents due to runway incursions is small. For instance, according to data in the NLR Air Safety Database there were 8 such accidents in the USA in the years 1998-2011. Given such small number of accidents, statistical evaluation of individual scenarios is not a feasible approach for this step.

Re 2. Expert judgment. In spite of known limitations, expert judgment of probabilities is often used in risk assessment studies [19, 20]. For our application, direct expert judgment would require experts to assess in a consistent way the conditional probabilities of large numbers of runway incursion scenarios (main scenarios and subcases). Such direct expert judgment is not considered practically feasible for a complete set of runway incursion scenarios, but it may be useful for assessment of a limited set of runway incursion scenarios for which no other models are available.

Re 3. Probabilistic graphical models: fault/event tree, Bayesian belief network. Fault and event trees are being used predominantly in risk assessments, including air traffic safety studies. Bayesian belief networks are more generic probabilistic graphical models, which include the representation capabilities of fault/event trees, and their use in risk assessment is growing [21, 22]. Such probabilistic graphical models can represent safety barriers between the occurrence of a collision and a runway incursion scenario, such as “timely interaction by ATC”, “collision avoidance by pilots”, “proficiency”. In such approach, the conditional probability of a collision given a runway incursion scenario can, e.g., be evaluated as

$$P(E^{\text{coll}} | S_{i,j}) = \prod_k P(\bar{E}_k^{\text{sb}} | S_{i,j}) = \prod_k P(\bar{E}_k^{\text{sb}} | \beta_{r \in D_{i,j}}), \quad (7)$$

where \bar{E}_k^{sb} denotes the event that the k -th safety barrier is not effective and $\beta_{r \in D_{i,j}}$ denotes the set of descriptors associated with scenario $S_{i,j}$. As is customary in a safety barrier model, it is assumed in Eq. (7) that the various safety barriers are independent. Since the effectiveness of a safety barrier needs to be assessed for each scenario in Eq. (7), further simplifying assumptions would have to be adopted to make it practically feasible. For instance, it could be assumed that particular safety barriers only depend on a limited set of runway incursion descriptors β_r or it could be assumed that effects of relevant descriptors are independent from each other. In essence, to make inference by a probabilistic graphical model practically feasible, assumptions about independencies need to be adopted such that the number of conditional probabilities that need to be evaluated is reduced. The primary means to assess these conditional probabilities is expert judgment, since other data sources are often lacking for such detailed conditional probabilities. However, obtaining sufficiently accurate risk results for runway incursion scenarios is often difficult, as argued in [23]. In conclusion, given the range of interdependencies that need to be assumed to make probabilistic graphical models practically feasible and the difficulty in quantifying the conditional probabilities herein, these models are not considered feasible to well assess a considerable range of runway incursion scenarios. Only runway incursion scenarios where assumptions about independencies between the involved entities can be argued to not lead to significant uncertainty in the collision risk, and where no other more suitable models are available, may be reasonably evaluated by probabilistic graphical models such as fault/event trees and Bayesian belief networks.

Re 4. Agent-based dynamic risk modelling. Agent-based DRM uses an agent-based perspective on air traffic scenarios, stochastic dynamic modelling, and rare event Monte Carlo simulation, to arrive at collision risk for the scenarios [24, 25]. 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 [23, 26, 27]. Where the other three methods discussed above only use and

combine data on event probabilities to arrive at conditional collision probabilities, 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 [27] 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 runway incursion scenario $P(E^{\text{coll}} | S_{i,j})$ in Step 3, specific parameter values can be set in the agent-based DRM for each of the descriptors β_r associated with scenario $S_{i,j}$. Next, conditional collision probabilities can be attained for each of the scenarios by rare event Monte Carlo simulation. In conclusion, agent-based DRM provides a suitable approach for the assessment of the conditional collision probabilities in Step 3, as it can well represent the dependencies between entities in runway incursion scenarios and it can efficiently evaluate large numbers of runway incursion scenarios.

To illustrate the capabilities of agent-based DRM for Step 3, models of [23, 26, 27] were adapted and extended to achieve risk results for a variety of runway incursion scenarios between aircraft taxiing and landing, and between aircraft taxiing and taking off. Examples of conditional collision risk results for two main scenarios are shown in Table 5. The main scenarios consider 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 (S_9), and the situation that an aircraft lands and a taxiing aircraft enters the runway erroneously, while its pilots have the intent to taxi over a normal taxiway or an inactive runway (S_{10}). The difference between these two main scenarios lies only in the intent of the pilot of the taxiing aircraft. The subcases of these main scenarios 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. As an illustration, Table 5 shows the conditional collision probability for 8 subcases of each main scenario. For almost all subcases, the probabilities of a collision in main scenario S_{10} exceed those in S_9 , since the monitoring performance of the pilots of the taxiing aircraft is assumed to be better in scenario S_9 . The results for subcases 1, 2, and 3 show that the risk decreases if the hold short position is further from the runway and that this decrease is strongest for S_9 . 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 5 illustrate that there are considerable differences in factors relating conditional collision probabilities of the various subcases for the main scenarios. For instance, the risk is increased by a factor 36 for

subcase 1 versus subcase 2 in S_9 , whereas it is only increased by a factor 1.7 for the same subcases in S_{10} .

Table 5. Examples of conditional collision risk results given scenarios (main + subcase), as achieved by rare event Monte Carlo simulation. Only results for some subcases and two main scenarios are shown.

Sub-case	Size landing aircraft	Size taxiing aircraft	Taxiway location	Visibility condition	Runway hold distance	Conditional collision probability
<i>Main scenario S_9: Aircraft lands and other aircraft lines up on the runway erroneously, while its pilots think they are allowed to line-up</i>						
1	Large	Small	Start	VC1	Small	3.0E-3
2	Large	Small	Start	VC1	Medium	8.3E-5
3	Large	Small	Start	VC1	Large	1.0E-6
4	Large	Large	Start	VC1	Medium	1.5E-4
5	Heavy	Small	Start	VC1	Medium	4.6E-4
6	Large	Small	Middle	VC1	Medium	3.8E-5
7	Large	Small	Start	VC2	Medium	4.3E-3
8	Large	Small	Start	VC3/4	Medium	5.7E-2
...
243 subcases in total						
<i>Main scenario S_{10}: Aircraft lands and taxiing aircraft enters runway erroneously, while its pilots have the intent to taxi over a normal taxiway or an inactive runway</i>						
1	Large	Small	Start	VC1	Small	3.1E-2
2	Large	Small	Start	VC1	Medium	1.8E-2
3	Large	Small	Start	VC1	Large	6.0E-3
4	Large	Large	Start	VC1	Medium	2.8E-2
5	Heavy	Small	Start	VC1	Medium	3.0E-2
6	Large	Small	Middle	VC1	Medium	8.6E-3
7	Large	Small	Start	VC2	Medium	2.0E-2
8	Large	Small	Start	VC3/4	Medium	3.7E-2
...
243 subcases in total						

In conclusion, agent-based DRM is chosen as the primary method for Step 3 of the runway incursion risk modelling framework. Only for those runway incursion scenarios where the development costs for agent-based DRM would largely exceed the value of the expected increase

in accuracy of the risk results, it can be considered to use direct expert judgment or a probabilistic graphical model as fault/event trees or Bayesian belief networks.

5.4 Step 4: Assess probabilities of human / material impact of a collision in runway incursion scenarios

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, would 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 in Table 6 a number of severity categories for human impact C_k^{Hu} and material impact C_k^{Ma} , with k a category index. 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 the 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.

Table 6. Provisional categories for human and material impact of collisions between aircraft in runway incursion scenarios.

k	Human impact C_k^{Hu}	Material impact C_k^{Ma}
1	Many fatalities	Hull loss
2	Some fatalities	Substantial damage
3	Serious injuries only	Minor damage
4	No serious injuries or fatalities	No or negligible damage

The objective of Step 4 is to estimate the probabilities of attaining these human and material impact categories given a collision and a scenario: $P(C_k^{\text{Hu}} | E^{\text{coll}}, S_{i,j})$ and $P(C_k^{\text{Ma}} | E^{\text{coll}}, S_{i,j})$. In principle, these probabilities may be dependent on a time frame, but typically they can be considered constant. For such collision consequences assessment a modelling approach has been developed for collisions between aircraft landing or taking-off with aircraft taxiing. Herein, the consequences of a collision are evaluated on the basis of overlap of aircraft surface zones in a collision and the change in kinetic energy due to a collision. The overlap of aircraft surface zones reflects, e.g., that wing-tail collisions are less severe than fuselage-fuselage collisions. The change in kinetic energy reflects, e.g., that the impact of a collision with a heavy aircraft that collides at a high speed is more severe than for a collision with a light aircraft that collides at a low speed.

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. Details of the collision consequences modelling are out of the scope of the current paper.

5.5 Step 5: Combine and evaluate 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 multiple runway incursion events in a dataset.

5.5.1 Single runway incursion events

The evaluation of single runway incursion events is based on results of Steps 1, 3 and 4. In particular, the conditional probabilities of scenarios given the initial state of a runway incursion $P(S_{i,j} | X_{q,t_0})$ from Step 1 and the conditional probabilities of a collision given scenarios $P(E^{\text{coll}} | S_{i,j})$ from Step 3 are used to determine the conditional probability of a collision given the state at the initiation of a runway incursion event:

$$P(E^{\text{coll}} | X_{q,t_0}) = \sum_{i,j} P(E^{\text{coll}} | S_{i,j}) \cdot P(S_{i,j} | X_{q,t_0}). \quad (8)$$

Herein it is assumed that the runway incursion scenarios provide a complete characterization of the collision probability, i.e. they include all collision risk relevant factors. 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:

$$P(C_k^{\text{Hu/Ma}}, E^{\text{coll}} | X_{q,t_0}) = \sum_{i,j} P(C_k^{\text{Hu/Ma}} | E^{\text{coll}}, S_{i,j}) \cdot P(E^{\text{coll}} | S_{i,j}) \cdot P(S_{i,j} | X_{q,t_0}), \quad (9)$$

where $C_k^{\text{Hu/Ma}}$ represents the human or material impact categories.

The conditional probabilities given a runway incursion event for a collision, or for the human/material impact categories can 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 safety management receives class feedback for risk levels.

An illustration of the conditional probabilities of a collision given the runway incursion events of Table 1 is provided in Table 7. For each of the events involving a conflict between two aircraft, 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 a quite different view than those of the severity outcomes. The largest collision risks are associated with incursions 2, 4, and 5 which had B, C, and D 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 incursion 1, having the most severe outcome, is considerably lower than those of incursions 2, 4, and 5. The lowest risk is attained for incursion 3, which is associated with a scenario similar to that for incursion 1, except here the aircraft lines up in the middle of the runway rather than at its start.

Table 7. Conditional collision probabilities given the initiation of runway incursions 1 to 5 of Table 1, and the severities of their particular outcomes.

RI ID	Associated runway incursion scenario(s)	Coll. risk given RI initiation	Severity of RI outcome
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
5	Aircraft (small) lands and taxiing aircraft (small) enters runway erroneously, 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 middle; visibility is VC1	2.4E-3	D

5.5.2 Aggregated risk results for multiple events in a dataset

The results for multiple runway incursion events from Steps 1, 2, 3 and 4 can be combined to achieve an overview of risk levels over a particular period T_m (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 $P_{T_m}(S_{i,j})$ obtained in Step 2 (using results of Step 1) and the conditional probabilities of a collision given the scenarios $P_{T_m}(E^{\text{coll}} | S_{i,j})$ obtained in Step 3:

$$P_{T_m}(E^{\text{coll}}) = \sum_{i,j} P_{T_m}(E^{\text{coll}}, S_{i,j}) = \sum_{i,j} P_{T_m}(E^{\text{coll}} | S_{i,j}) \cdot P_{T_m}(S_{i,j}). \quad (10)$$

Herein, often the conditional probability of a collision given a scenario does not depend on the time frame, such that it is simply $P(E^{\text{coll}} | S_{i,j})$. 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 runway 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:

$$P_{T_m}(C_k^{\text{Hu/Ma}}, E^{\text{coll}}) = \sum_{i,j} P_{T_m}(C_k^{\text{Hu/Ma}} | E^{\text{coll}}, S_{i,j}) \cdot P_{T_m}(E^{\text{coll}} | S_{i,j}) \cdot P_{T_m}(S_{i,j}). \quad (11)$$

Herein, the conditional probabilities of a collision and of the consequences of a collision typically are independent of the time frame.

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 well 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.

An illustration of aggregated risk results is shown in Figure 6. 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 and the overall (summed) rate for this set of scenarios is 2.3E-6. The conditional probabilities of a collision given a main scenario vary between 6E-4 and 3E-2. In combination these provide probability estimates for a collision due to a main scenario in the range from 2E-11 to 7E-9 per airport operation and 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 6, the

overall probability of a collision is mainly due to the two main scenarios S_5 and S_{10} . 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 S_5 and S_{10} . 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.

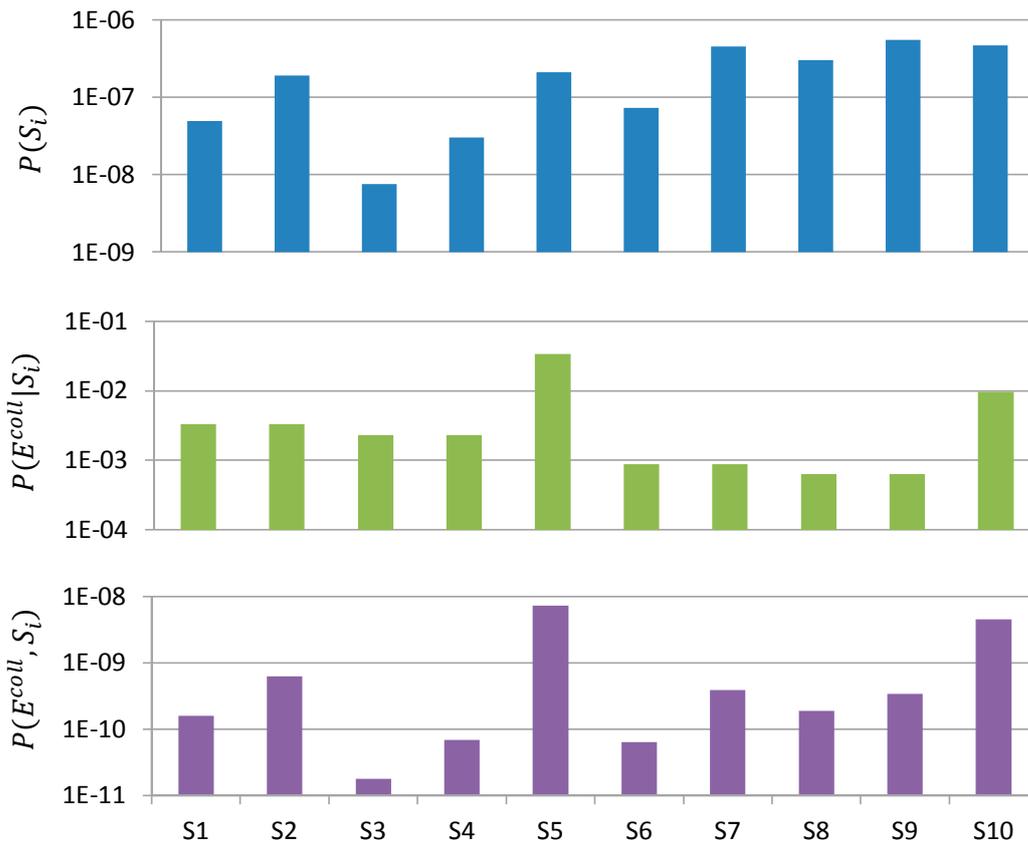


Figure 6. Illustration of aggregated tentative risk results (per airport operation) for a number of main scenarios: scenario probabilities (top figure), conditional probabilities of a collision given scenarios (middle figure), probabilities of collision for scenarios (bottom figure).

6 Discussion

In current safety management of airport operations, runway incursions are evaluated using severity categories, such as A to E [1], A to D [5], or Serious incident to Not determined [14]. We have presented data showing that such severity assessment is to a large extent based on the outcomes of the runway incursions, in particular on the closest distance attained. Limitations of such outcome-based evaluation are the potential neglect of the large majority of incursions that were judged as less severe, but which arose due to similar errors and misunderstandings as more severe incursions, and the lack of a structure for reasons and risk implications of the runway incursions.

In this paper we have presented a new framework for the analysis of runway incursions, which is strictly based on the risk of scenarios associated with the state at the start of a runway incursion. Two important ingredients in the framework are the inventory of runway incursions and the risk modelling used to evaluate their risk implications. Next, Section 6.1 discusses the inventory of runway incursion scenarios and its future research options. Section 6.2 discusses the risk modelling and its future research options. Finally, Section 6.3 discusses implications for evaluation of other types of air traffic incidents.

6.1 Inventory of runway incursion scenarios

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 initial states that may occur, most notably including those with significant differences in risk results. 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. It was shown for a set of more than 200 severity A, B and C incursions that almost 99% could be described by the scenario inventory. This indicates that it is able to describe the large majority of runway incursions 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 severity D incursions, as the inventory development was focused on conflicts in the current research. Future research should enhance the scenario inventory by inclusion of runway incursions without a direct conflict.

The scenario inventory presented in this paper was developed 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 not included, 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. 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 incursions. 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.

6.2 Risk modelling

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 [23, 26, 27] it was shown that 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 the scenarios in the inventory.

The proposed risk-based framework for the evaluation of runway incursions 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 risk results 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 in integral safety management stands in contrast with the current severity-based evaluation of runway incursions, which focuses on their outcomes and has no risk assessment component.

The proposed risk-based evaluation of runway incursions uses information up to the initiation of an incursion as a basis for 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 a runway incursion should be discarded in the risk-based framework. Information about the ways that runway incursions evolve and end provides valuable information, which can serve 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 [28]. Future research should define what specific data should be gathered on the evolution of runway incursions and how these can be used to validate the collision risk models.

6.3 Implications for other types of air traffic incidents

Current severity-based evaluation of incidents is not only done for runway incursions, 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 [14]. Evaluation of the severity of a wide range of air traffic incidents is an important part of the Eurocontrol Risk Analysis Tool [29]. In the light of the identified limitations of the severity-based evaluation of runway incursions 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.

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