Chapter 4

Analysis of Accident Risk Related Events and the Roles of Agents in Conflict Recognition and Resolution during a Runway Incursion Scenario

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Analysis of Accident Risk Related Events and the Roles of Agents in Conflict Recognition and Resolution during a Runway Incursion Scenario

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Abstract. This paper extends a safety analysis based on a multi-agent dynamic risk model (DRM) of a future mix mode taxiing into position and hold (TIPH) operation. The TIPH operation aims at placing an aircraft on the mixed mode runway, ready for immediate takeoff as soon as takeoff clearance has been issued by the air traffic controller. In the previous safety analysis, accident risk results were obtained by Monte Carlo simulations of a multi-agent DRM for a particular scenario describing the conflict between an aircraft landing and an aircraft lining up while it should not. These risk assessment simulations and results obtained earlier do not provide insight into the underlying conflict detection and conflict recognition events that occur during the simulations. Therefore relevant events were defined and recorded in additional Monte Carlo simulations of the multi-agent DRM in different visibility conditions. An additional aim of the present research is an examination of the capabilities of agents to reduce the accident risk in the operation. This is studied in the DRM by placing agents out of monitoring or control loops in different visibility conditions. The results of the study make clear the extent to which each agent is able to reduce the accident risk and the complementarities between the agents' roles in controlling the accident risk.

Nomenclature:

DRM = dynamic risk model
TIPH = taxiing into position and hold

1. Introduction

The next generation Air Traffic Management in Europe has the ambitions to enable a 3-fold increase in air traffic services and capacity, with a reduction of delays on the ground and in the air, along with an improvement of the safety performance by a factor ten[7]. In support of improvement of aerodrome operations, a future taxi into position and hold (TIPH) operation was proposed in the RESET project of the European Commission 6th Framework Program. The phraseology standard of the International Civil Aviation Organization (ICAO) for this operation is "line up and wait". The TIPH operation aims at placing an aircraft on the mixed mode runway, ready for immediate departure as soon as no restrictions apply and the takeoff clearance can be issued by the air traffic controller[11]. As part of a safety assessment of the TIPH operation, a multi-agent Dynamic Risk Model (DRM) was developed for a runway incursion scenario involving an aircraft landing and an aircraft lining up while it should not.[10,11] This multi-agent DRM model was developed in the context of the TOPAZ (Traffic Organization and Perturbation AnalyZer) safety assessment methodology, which was first introduced by National Aerospace Laboratory NLR in 2001[1] and extended later with several aspects.[2,5,6,9] The methodology is aimed at the analysis of the safety risk of air traffic operations with the help of Monte Carlo simulations and risk uncertainty evaluations. The risk results obtained by the multi-agent DRM based safety assessment[10,11] include point estimates of collision probabilities given particular visibility conditions, risk decomposition results for various conditions, collision risk variation results for changes in a number of key parameters of the geometry and agents' performance, and risk sensitivity and risk uncertainty results obtained by a bias and uncertainty assessment of the accident risk. These results provide a considerable insight in the safety risk of the runway incursion scenario and the main risk contributors. Nevertheless, due to the complexity of the causal factors and the interactions between agents in the runway incursion scenario, it is not clear in detail from the earlier obtained results what the effect of the roles of the different agents on the accident risk is and how conflict detection and resolution events by the agents relate to the accident risk. Methods to obtain more insight in the behavior and the roles of agents in conflict detection and conflict resolution aspects for multi-agent DRM were provided in Ref. 8 and applied to a runway incursion scenario for an aircraft taking off and an aircraft crossing the runway while it should not.

The objective of the present study is to obtain more insight into the multi-agent DRM of the TIPH operation by using the methods of Ref. 8. Thus, the safety analysis presented in this paper aims at better understanding the relations between conflict recognition and conflict resolution events that may occur in the TIPH scenario and their relation to accident risk. Examples of such events are detection of the conflict by the pilots of landing or taxiing aircraft, activation of the runway incursion alert and resolution actions of the pilots. Therefore relevant events will be defined and recorded in additional Monte Carlo simulations in different visibility conditions. Based on the data obtained, the probability of each event and the probability of the event given a collision will be evaluated. An additional aim of the present research is an examination of the capabilities of agents to reduce the accident risk in the operation.This is studied in the DRM by placing agents out of monitoring or control loops in different visibility conditions. Accident risk results for a variety of combinations of agents being in or out of the monitoring role or control loop will be described and discussed. These results make clear the extent to which each agent is able

to reduce the accident risk and the complementarity between the agents' roles in controlling the accident risk.
The paper is structured as follows. Section II describes the TIPH operation, the runway incursion scenario and the multi-agent DRM. Section III describes the measurement and analysis of conflict detection and resolution events by agents in Monte Carlo simulations of the multi-agent DRM. Section IV describes the analysis of placing agents out of the monitoring role or control loop. Section V presents the conclusions of this paper.

2. TIPH Scenario and Dynamic Risk Model

In the TIPH scenario under consideration an aircraft that has been cleared to taxi into position and hold can enter the runway after the aircraft currently using runway (either landing or taking off) has passed the waiting aircraft's position. The operation is supported by a level 3 advanced surface movement guidance and control system, which includes the uplink of air traffic control (ATC) surveillance data such as aircraft position data and runway incursion alert data. The TIPH procedure is applied during all 4 visibility conditions:[11]

1. Condition1: Visibility sufficient for the pilot to taxi and to avoid collision with other traffic on taxiways and at intersections by visual reference, and for personnel of control units to exercise control over all traffic on the basis of visual surveillance;
2. Condition 2: Visibility sufficient for the pilot to taxi and to avoid collision with other traffic on taxiways and at intersections by visual reference, but insufficient for personnel of control units to exercise control over all traffic on the basis of visual surveillance;
3. Condition 3: Visibility sufficient for the pilot to taxi but insufficient for the pilot to avoid collision with other traffic on taxiways and at intersections by visual reference with other traffic, and insufficient for personnel of control units to exercise control over all traffic on the basis of visual surveillance.
4. Condition 4: Visibility insufficient for the pilot to taxi by visual guidance only.

Three visibility conditions are considered in the model: visibility condition 1 (VC1), visibility condition 2 (VC2) and a combination of visibility condition 3 and visibility condition 4 (VC3/4).
The developed model for this scenario consists of eight agents that represent human operators and technical systems involved in the scenario[10,11] (Fig. 1): landing aircraft (AC_L), taxiing aircraft (AC_T), pilots of the landing aircraft (Pilots_L), pilots of the taxiing aircraft (Pilots_T), avionics of the landing aircraft (Avionics_L), avionics of the taxiing aircraft (Avionics_T), ATC system, and Airport and Environment (A&E).

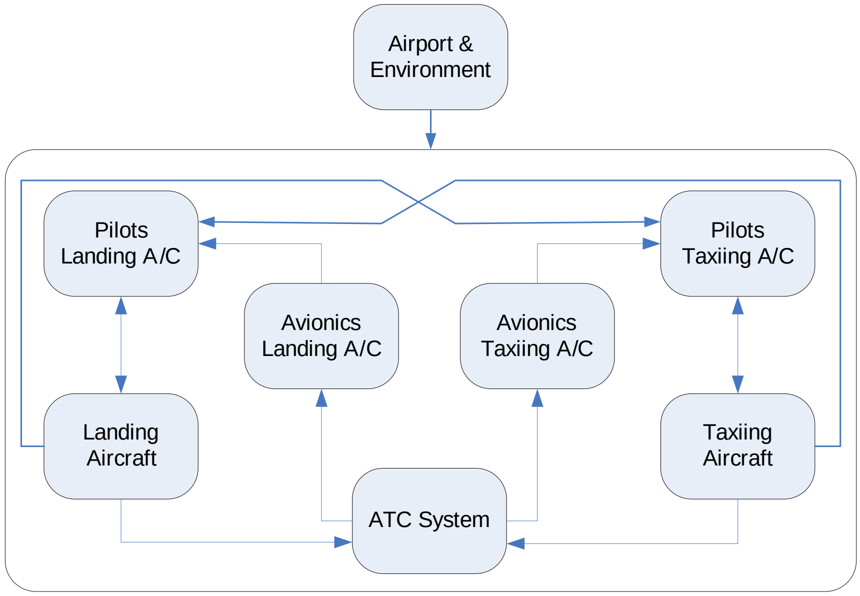

Figure 1. Relations between agents in the multi-agent DRM of the TIPH runway incursion scenario.

Mathematical models developed for each agent are based on a compositional specification approach using a stochastic dynamic extension of the Petri net formalism.[6,12] Within this Petri net formalism a hierarchically structured representation of the agents in the air traffic scenario is developed. Within each agent one or more key aspects are defined that are represented by Local Petri Nets (LPNs). The key aspects may include, for instance, situation awareness, task performance, of a human operator, flight phases, performance modes of aircraft, status of an alert system. Within the key aspects particular modes can be defined, e.g. within task performance of a controller such modes as monitoring, clearance specification and alert reaction are differentiated. This representation includes the dynamics within the modes as well, e.g. the dynamics of the time needed for the task performance, acceleration profile during take-off or the duration of an alert. The detailed specification of the TIPH model per agent can be found in Ref. 10 and Ref.11.

3. Events in the MC Simulations

In this section the safety assessment of the TIPH scenario by means of events related to the performance of the agents will be presented. The following subsections describe the defined events and present the Monte Carlo simulation results of the DRM.

A. Definition of Events

To gain more insight in the performance of the agents in the DRM, the following events were defined:

- E1: the landing aircraft starts the final approach;
- E2: the pilots of the landing aircraft detect the conflict and decide to initiate a missed approach;

- E2’: the pilots of the landing aircraft detect the conflict by own observation (rather than via the up-linked ATC alert) and decide for a missed approach;
- E3: the landing aircraft starts a missed approach maneuver;
- E4: the taxiing aircraft starts taxiing to line up on the runway;
- E5: the pilots of the taxiing aircraft detect the conflict and decide to taxi off the runway (such a decision is made if the aircraft is already on the runway);
- E5’: the pilots of the taxiing aircraft detect the conflict by own observation (rather than via the up-linked ATC alert) and decide to taxi off the runway;
- E6: the pilots of the taxiing aircraft detect the conflict and decide to stop taxiing (such a decision is made if the aircraft can stop in front of the runway);
- E6’: the pilots of the taxiing aircraft detect the conflict by own observation (rather than via the up-linked ATC alert) and decide to stop taxiing;
- E7: the taxiing aircraft comes to stance;
- E7’: the taxiing aircraft comes to stance following conflict detection by the pilots (the other reason of coming to stance is the end of the normal line-up operation);
- E8: the runway incursion alert of the ATC system becomes active;
- E9: the taxiing aircraft has taxied off the runway successfully;
- E10: the taxiing aircraft and the landing aircraft collide.

Figure 2 provides an overview of the relations between these events based on the DRM. For instance, Fig. 2 indicates that the runway incursion alert of the ATC (event E8) may result in conflict detection by the pilots of the landing aircraft (E2) or by the pilots of the taxiing aircraft Pilots_T, resulting in a decision either to stop (event E6) or to taxi off the runway (event E5). These events, in their turn, may result in the execution of these decisions by the pilots (event E3, E7’ and E9). The times of the first occurrence of the events were recorded in the MC simulations of the TIPH DRM and the occurrence of events E2’, E5’, E6’ and E7’ was inferred from the occurrence of related events.

B. Monte Carlo Simulation Results for Events in the DRM

A total of 10 million Monte Carlo simulation runs were performed for the condition that the pilots of the taxiing aircraft have the intent to line-up on the runway used by the landing aircraft in three visibility conditions. Table 1 shows the probabilities of the defined events and the conditional probabilities of these events given a collision event per three visibility conditions. Key observations from the results in Table 1 are explained next for each of the agents.

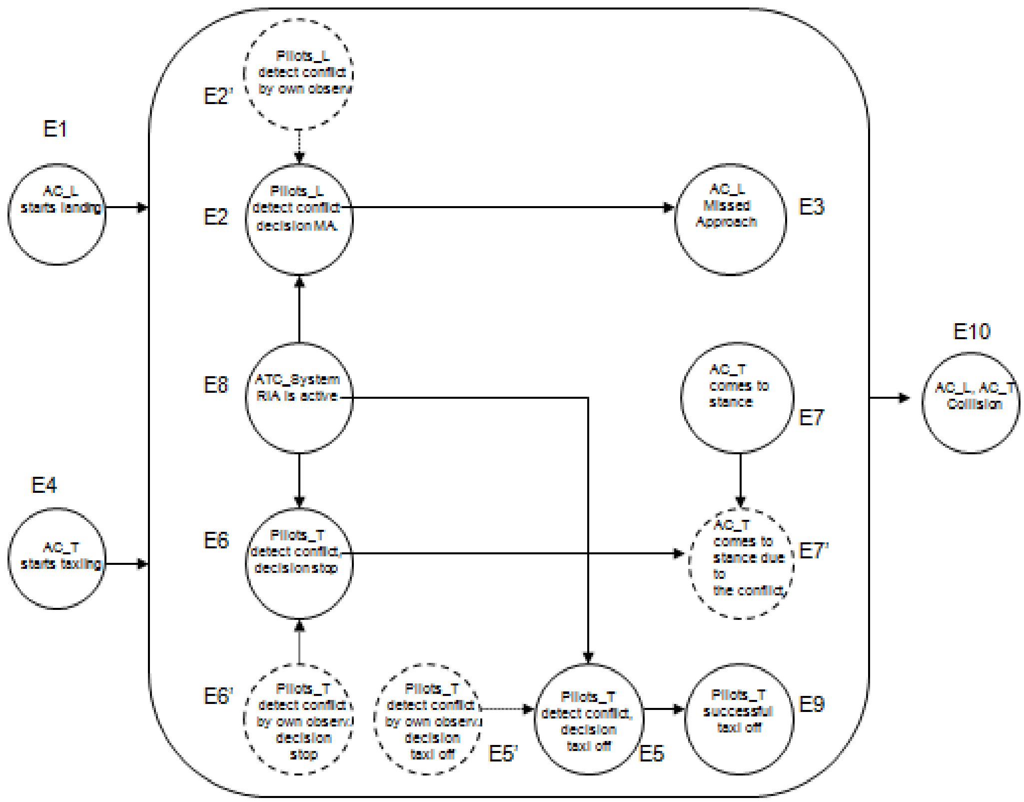

Figure 2. Relations between events in the MC simulations of the multi-agent DRM. Events in the solid circles are recorded in the MC simulations, events in the dashed circles are inferred from the relative timing of recorded events.

Pilots of Landing Aircraft (Pilots_L)

In VC1, Agent Pilots_L detects the conflict and makes a decision to undertake a missed approach (event E2) in 76% of all simulated conflict scenarios. Only in 0.9% of all cases, Pilots_L detects the conflict by own observation (event E2') and in the remaining 75% Pilots _L detects the conflict via the ATC system. Contributing to this difference is the model assumption that Pilots _L recognize the taxiing aircraft as conflicting if it is within a critical distance of 62 m from the runway center-line, whereas the alert threshold of the ATC system is 124 m. In the simulation runs ending in a collision in VC1, Pilots_L detects the conflict (event E2) in 99% cases. Pilots_L detects the conflict by own observation in 95% of these cases (event E2') and via the runway incursion alert (RIA) of the ATC system in 42%. Thus for the conditional case given a collision it is found that the probability of conflict detection by Pilots_L is higher than for the unconditional case and the contribution of the ATC system to conflict detection is significantly lower than in the unconditional case.

In VC2, agent Pilots_L detects the conflict and makes a decision to undertake a missed approach in 90% of all simulated conflict scenarios. In 1% of all cases Pilots_L detects the conflict by own observation (event E2') and in 89% Pilots_L detects the conflict via the ATC system. In the simulation runs ending in a collision in VC2, Pilots_L detects the conflict (event E2) in 100% cases.

Table 1. MC simulation results for the defined events: event probability P(Eq) and conditional event probability given a collision P(Eq|E10) in three visibility conditions.

Agent	***Event***		***VC1***		***VC2***		***VC34***	
	ID	***Description***	*P(Eq)*	*P(Eq|E10)*	*P(Eq)*	*P(Eq|E10)*	*P(Eq)*	*P(Eq|E10)*
AC_L	E1	Final Approach	100%	100%	100%	100%	100%	100%
Pilots_L	E2	Detect conflict and make a decision of missed approach	76%	99%	90%	100%	93%	85%
Pilots_L	E2'	Detect conflict by own observation	0.9%	95%	1%	82%	0.4%	37%
AC_L	E3	Initiates missed approach	70%	46%	84%	45%	85%	10%
AC_T	E4	Starts taxiing	100%	100%	100%	100%	100%	100%
Pilots_T	E5	Detect conflict and make a decision to taxi off the runway	19%	34%	20%	54%	20%	52%
Pilots_T	E5'	Detect conflict by own observation and make a decision to taxi off the runway	3%	12%	0.2%	17%	0.03%	6%
Pilots_T	E6	Detect conflict and make a decision to stop taxiing	77%	23%	75%	13%	74%	7%
Pilots_T	E6'	Detect conflict by own observation and make a decision to stop taxiing	32%	78%	8%	4%	2%	0.4%
AC_T	E7	Comes to stance	85%	16%	85%	38%	83%	46%
AC_T	E7'	Comes to stance as a result of a conflict detection of the Pilots of Taxiing Aircraft	77%	23%	75%	13%	74%	7%
ATC System	E8	Runway incursion alert is active	76%	42%	90%	54%	93%	56%
AC_T	E9	Performs taxi off runway successfully	18%	0%	19%	0%	20%	0%
AC_T, AC_L	E10	Collision	0.06%	100%	0.2%	100%	0.5%	100%

Pilots_L detects the conflict by own observation in 82% of these cases (event E2') and via the runway incursion alert (RIA) of the ATC system in 18%. Thus for the conditional case given a collision it is found that the probability of conflict detection by Pilots_L is also higher than for the unconditional case and the contribution of the ATC system to conflict detection is significantly lower in the conditional case than in the unconditional case. It is similar to the findings in VC1.

In VC3/4, agent Pilots_L detects the conflict and makes a decision to undertake a missed approach (event E2) in 93% of all simulated conflict scenarios. Only in 0.4% of all cases Pilots_L detects the conflict by own observation (event E2'). In the simulation runs ending in a collision in VC3/4, Pilots_L detects the conflict (event E2) in 85% cases. Pilots_L detects the conflict by own observation in 36.5% of these cases (event E2') and via the runway incursion alert (RIA) of the ATC system in 48.5%. Thus for the conditional case given a collision it is found that, contrary to the findings in VC1 and VC2, the probability of conflict detection by Pilots_L is lower than for the unconditional case. This suggests that the low visibility has diminished the detection probability, which leads to an increase in the accident probability. The contribution of the ATC system to conflict detection in VC3/4 is significantly lower in the conditional case than in the unconditional case, similar to the results in VC1 and VC2.

Pilots of Taxiing Aircraft (Pilots_T)

In VC1, Pilots_T agent detects the conflict and makes a decision to taxi off the runway (event E5) in 18.5% of all simulated conflict scenarios. Here Pilots_T detects the conflict by own observation in 2.5 % of cases (event E5'). Pilots_T agent detects the conflict and makes a decision to stop taxiing (event E6) in 77% of all simulated conflict scenarios. Here Pilots_T detects the conflict by own observation (event E6') in 32% of cases. The distance in front of the runway threshold within which the landing aircraft is recognized as conflicting by Pilots_T is 3 NM. In order to resolve the conflict, Pilots_T can initiate stopping if their taxiing aircraft AC_T is beyond the distance of 35 m from the runway center-line; if the taxiing aircraft is at the distance smaller than 35 m from the runway center-line, Pilots_T agent initiates taxiing off the runway. Totally for all simulation runs, Pilots_T detects the conflict in 95.5% cases (events E5 and E6), of which 34.5% cases by own observation (events E5' and E6'). It is much higher in comparison to the results obtained for Pilots_L agent, which detects the conflict by own observation only in 0.9% of all cases. In most of the conflict situation Pilots_T makes a decision to stop taxiing rather than to taxi off the runway, it means that in most cases the conflict is detected if the taxiing aircraft AC_T is further than 35 m from the runway center-line.

Of the simulation runs ending in a collision in VC1, Pilots_T agent detects the conflict and makes a decision to taxi off the runway in 34% of cases (event E5), Pilots_T detects the conflict himself in 12% of these cases (event E5'), and in 22% Pilots_T detects the conflict via an up-linked ATC alert. Pilots_T agent detects the conflict and makes a decision to stop taxiing in 23% of cases (event E6), Pilots_T detects the conflict himself in 8% of these cases (event E6'), and in 15% the agent detects the conflict via an up-linked ATC alert. Here in most cases Pilots_T makes a decision to taxi off the runway, which indicates that AC_T is within a distance of 35 m from the runway center-line at the moment of the conflict detection for most cases ending in the collision. Totally for the condition when the collision occurs, Pilots_T detects the conflict in 57% cases (events E5 and E6), of which 20% are the cases when the conflict was detected by own observation. Thus for the conditional cases given a collision it is found that the probability of conflict detection by

Pilots_T is lower in the conditional case in comparison to the unconditional case and the contribution of the ATC system to conflict detection is significantly lower in the conditional case than in the unconditional case.

In VC2, Pilots_T agent detects the conflict and makes a decision to taxi off the runway (event E5) in 20% of all simulated conflict scenarios. Here Pilots_T detects the conflict by own observation in 0.2% of cases (event E5’). Pilots_T agent detects the conflict and makes a decision to stop taxiing (event E6) in 75% of all simulated conflict scenarios. Here Pilots_T detects the conflict by own observation (event E6’) in 8% of cases. Totally for all simulation runs, Pilots_T detects the conflict in 95% cases (events E5 and E6), of which approximately 8% by own observation (events E5’ and E6’). It is higher in comparison to the results obtained for Pilots_L agent, which detects the conflict by own observation only in 1% of all cases. In most of the conflict situations, Pilots_T makes a decision to stop taxiing rather than to taxi off the runway, which means that in most cases the conflict is detected if the taxiing aircraft AC_T is beyond the distance of 35 m from the runway center-line.

Of the simulation runs ending in a collision in VC2, Pilots_T agent detects the conflict and makes a decision to taxi off the runway in 54% of cases (event E5), Pilots_T detects the conflict himself in 17% of these cases (event E5’), and in 37% Pilots_T detects the conflict via an up-linked ATC alert. Pilots_T agent detects the conflict and makes a decision to stop taxiing in 13% of cases (event E6), Pilots_T detects the conflict himself in 4% of these cases (event E6’), and in 9% the agent detects the conflict via an up-linked ATC alert. Here in most cases Pilots_T makes a decision to taxi off the runway, which suggests that AC_T is within the distance of 35 m from the runway center-line at the moment of the conflict detection in most cases that ended with a collision. Totally for the condition when the collision occurs, Pilots_T detects the conflict in 67% cases (events E5 and E6), of which 21% are the cases when the conflict was detected by own observation. Thus for the conditional cases given a collision it is found that the probability of conflict detection by Pilots_T is lower in the conditional case in comparison to the unconditional case and the contribution of the ATC system to conflict detection is significantly lower in the conditional case than in the unconditional case.

In VC3/4, Pilots_T agent detects the conflict and makes a decision to taxi off the runway (event E5) in 20% of all simulated conflict scenarios. Here Pilots_T detects the conflict by own observation in 0.03 % of cases (event E5’). Pilots_T agent detects the conflict and makes a decision to stop taxiing (event E6) in 74% of all simulated conflict scenarios. Here Pilots_T detects the conflict by own observation (event E6’) in 2% of cases. It is 4 times lower than the results in VC2 and 16 times lower than the results in VC1. Totally for all simulation runs, Pilots_T detects the conflict in 94% cases (events E5 and E6), of which approximately 2% cases by own observation (events E5’ and E6’). It is higher in comparison to the results obtained for Pilots_L agent, which detects the conflict by own observation only in 0.4% of all cases. In most of the conflict situation Pilots_T makes a decision to stop taxiing rather than to taxi off the runway, which means that in most cases the conflict is detected if the taxiing aircraft AC_T is beyond the distance of 35 m from the runway center-line.

Of the simulation runs ending in a collision in VC3/4, Pilots_T agent detects the conflict and makes a decision to taxi off the runway in 52% of cases (event E5), Pilots_T detects the conflict himself in 6% of these cases (event E5’), and in 46% Pilots_T detects the conflict via an up-linked ATC alert. Pilots_T agent detects the conflict and makes a decision to stop taxiing in 7% of cases (event E6), Pilots_T detects the conflict himself in 0.4% of these cases (event E6'). Thus, Pilots_T detects the conflict almost totally via the alerts generated by the ATC and decides to stop taxiing. These results are not surprising taking into account the bad visibility condition. In most cases Pilots_T makes a decision to taxi off the runway, which suggests that AC_T is within the distance of 35 m from the runway center-line at the moment of the conflict detection in most cases ended with the collision. Totally for the condition when the collision occurs, Pilots_T detects the conflict in 59% cases (events E5 and E6), of which 6% are the cases when the conflict was detected by own observation. Thus for the conditional cases given a collision, it is found that the probability of conflict detection by Pilots_T is lower in the conditional case in comparison to the unconditional case and the contribution of the ATC system to conflict detection does not differ much from the unconditional case as the conflict detection occurs primarily via the alert system in both conditions due to the bad visibility.

Landing Aircraft (AC_L)

The behavior of agent AC_L reflects the conflict resolution actions initiated by Pilots_L. In VC1, Pilots_L makes a decision of Missed Approach in 76% of all cases (event E2) and in 70% of the simulation runs agent AC_L initiates Missed Approach (event E3). In the remaining 6%, the execution of Missed Approach might be not possible since the landing already commenced. For the cases ending in a collision, the Missed Approach is executed in 46% of cases (event E3). The probability of the execution of the missed approach (event E3) is significantly lower for the conditional cases ending in a collision in comparison to the unconditional cases.

In VC2, Pilots_L makes a decision of Missed Approach in 90% of all cases (event E2) and in 84% of the simulation scenarios Pilots_L agent initiates Missed Approach (event E3). For the cases ending in a collision, the Missed Approach is executed in 45% of cases (event E3).The probability of the execution of the missed approach (event E3) is significantly lower for the conditional cases ending in a collision in comparison to the unconditional cases.

In VC3/4, Pilots_L makes a decision of Missed Approach in 92% of all cases (event E2) and in 85% of the simulation scenarios Pilots_L agent initiates Missed Approach (event E3). For the cases ending in a collision, the Missed Approach is executed in 10% of cases (event E3). The probability of the execution of the missed approach (event E3) is significantly lower for the conditional cases ending in a collision in comparison to the unconditional cases. This finding can be observed across all visibility conditions; it indicates that the execution of Missed Approach in most cases was not followed by a collision.

Taxiing Aircraft (AC_T)

The behavior of agent AC_T reflects the conflict resolution actions initiated by Pilots_T. In VC1, AC_T comes to stance in 85% of cases (event A7), and comes to stance as a result of conflict detection in 77% of cases (event E7'). In 18% of the simulation runs AC_T agent performs taxiing off the runway successfully (event E9). Pilots_T makes a decision to taxi off in 19% of cases, so only in 1% the pilots do not succeed in their conflict resolution action. For the cases ending in a collision, AC_T comes to stance as a result of conflict detection in 23% of cases (event E7'). This probability is significantly lower for the conditional cases ending in a collision (event E7') in comparison to the unconditional cases. In VC2, AC_T comes to stance in 85% of cases (event A7), and comes to stance as a result of conflict detection in 75% of cases (event E7'). In 19% of the simulation scenarios AC_T agent performs taxiing off the runway successfully (event E9). Pilots_T makes a decision to taxi off in 20% of cases, so only in 1% the pilots do not succeed in their conflict resolution action. For the cases ending in a collision, AC_T comes to stance as a result of conflict detection in 13% of cases (event E7'). This probability is significantly lower for the conditional cases ending in a collision (event E7') in comparison to the unconditional cases. In VC3/4, AC_T comes to stance in 83% of cases (event A7), and comes to stance as a result of conflict detection in 74% of cases (event E7'). In 20% of the simulation scenarios AC_T agent performs taxiing off the runway successfully (event E9). Pilots_T makes a decision to taxi off in 20% of cases, thus the pilots almost always succeed in their conflict resolution action. It is similar to the results found in VC1 and in VC2. For the cases ending in a collision, AC_T comes to stance as a result of conflict detection in 7% of cases (event E7'). This probability is significantly lower for the conditional cases ending in a collision (event E7') in comparison to the unconditional cases across all visibility conditions; it suggests that in most cases stopping taxiing was not followed by a collision in all visibility conditions.

ATC System
In the model a runway incursion alert is provided by the ATC system when the landing aircraft is within 5556 m (3NM) of the runway threshold and the taxiing aircraft is within 124 m from the runway center-line. In VC1, the runway incursion alert (RIA) is active in 76% of all cases (event E8) and in 42% cases ending in a collision. In VC2, RIA is active in 90% of all cases and in 54% cases ending in a collision. This percentage is much higher in comparison to the results obtained in VC1. It can be explained by the fact that in a good visibility condition the conflict had been detected and resolved before the alert became active. In VC3/4, RIA is active in 93% of all cases and in 56% cases ending in a collision. This percentage is approximately similar to the results obtained in VC2.

4. Simulations with changed roles of agents in the control loop

In the following subsections the conditions of placing agents out of the monitoring role or control loop are described and the simulation results of these changes in the operation are discussed.

A. Definition of changing the role of agents in the control loop

To better understand the potential of agents to restrict the risk increase in cases where the performance of other agents is affected, additional Monte Carlo simulations were performed, where the agents are placed out of the monitoring role or out of the control loop. This was done for the following agents: Pilots Landing Aircraft (Pilots_L), Pilots Taxiing Aircraft (Pilots_T) and ATC System. The conditions for changing the role of these agents are:

• Pilots_L does not perform active monitoring of the traffic situation, neither visually nor via the Cockpit Display of Traffic Information (CDTI); however, it may detect a conflict via up-linked alerts generated by the ATC system.
• Pilots_T does not perform active monitoring of the traffic situation, neither visually nor via the Cockpit Display of Traffic Information (CDTI); however, it may detect a conflict via up-linked alerts generated by the ATC system.
• ATC system does not specify alerts, since the Runway Incursion Alert (RIA) component of the ATC system does not work.

B. Simulation Results

For all combinations of these conditions, the conditional collision risk of the runway incursion scenario given the visibility condition has been determined by Monte Carlo simulations, using 1 million simulations per scenario. Table 2 shows the accident risk and the risk increase factor with respect to the risk for the nominal case A1 (with all agents monitoring / alerting).

Table 2. Conditional collision risk results and risk increase factors for various conditions with agents in ('yes') and out ('no') of the monitoring/alerting role in three visibility conditions.

Case	Pilots_L	Pilots_T	ATC: RIA	VC1		VC2		VC34	
				Accident Risk	Risk increase factor	Accident Risk	Risk increase factor	Accident Risk	Risk increase factor
A1	yes	yes	yes	1.48e-08	1.00	4.80e-08	1.00	1.41e-07	1.00
A2	yes	yes	no	2.56e-07	17.3	5.07e-06	106	2.21e-05	157
A3	yes	no	yes	4.69e-08	3.17	6.83e-08	1.42	1.49e-07	1.06
A4	yes	no	no	8.89e-07	60.1	5.77e-06	120	2.18e-05	155
A5	no	yes	yes	3.89e-08	2.63	9.46e-08	1.97	1.44e-07	1.02
A6	no	yes	no	1.72e-06	116	1.38e-05	286	2.13e-05	151
A7	no	no	yes	1.45e-07	9.79	1.44e-07	3.01	1.40e-07	0.99
A8	no	no	no	2.11e-05	1425	2.18e-05	455	2.14e-05	152

Table 2 shows that the collision risk of the runway incursion scenario increases by a factor 1426 in Visibility Condition 1 (VC1), by factor 455 in Visibility Condition 2 (VC2) and by factor 152 in Visibility Condition 3/4 (VC 3/4) if none of the agents would be actively monitoring the traffic situation (case A8). In this case an accident is thus only prevented by chance. The accident risk of case A8 thus forms an upper bound for this particular runway incursion scenario.
The collision risk of the runway incursion scenario increases only by factor 9.8 in VC1 if none of the human agents would be actively monitoring the traffic situation while the ATC alert system is working nominally (case A7). The collision risk increases only by factor of 3 in VC2 for the same case A7. It is three times lower in comparison to the findings in VC1. These results are quite predictable as they are related to the case where none of the human agents is actively monitoring the traffic situation and thus the worse visibility condition does not play a crucial role here. The collision

risk of the runway incursion scenario is about constant in VC 3/4 if none of the human agents would be actively monitoring the traffic situation while the ATC system is working nominally. It does not differ from case A1, which forms the lower bound for this particular model. In other words, it demonstrates that the RIA of the ATC system plays a dominant role in conflict detection and resolution.

If only the alert system of ATC is out-of-the-loop (case A2), the collision risk is increased by factor 17 in VC1, which is almost two times higher than the risk increase of case A7, where both pilots are out of the monitoring role. For case A2 in VC2, the collision risk increases by factor 106. It is 6 times higher than the risk increase factor found for this case in VC1. This finding indicates the increasing role of the ATC system in the condition where the visibility is diminished. In VC2, the risk increase factor of case A2 is 35 times higher in comparison to case A7. Compared to VC1, where the difference between cases A2 and A7 was much lower, it indicates the significant contribution of the ATC system to conflict detection and resolution in this visibility condition. In VC3/4, if only the alert system of ATC is out-of-the-loop (case A2), the collision risk is increased by factor 157. It is 9 times higher than the risk increase factor found for this scenario in VC1 and 1.5 times higher than the risk increase factor for this scenario in VC2. The risk increase factor for this scenario (A2) in VC3/4 is 157 times higher than for case A7. In fact, human agents do not play any role in this visibility condition and all collision risk is determined by the alerts of the ATC system.

Almost equal risk increase factor can be observed in all cases in VC3/4 where the RIA of the ATC system does not work. These are cases A2, A4, A6 and A8. In all other cases, where the ATC system is working properly and one or more human agents are not actively monitoring the traffic situation, the risk increase factor approximates the value of 1.

In general, the highest risk increase in all visibility conditions is observed for cases when the ATC system is out of the loop. These are scenarios A2, A4, A6 and A8.

Based on the Monte Carlo simulation results of the modified TIPH model, three main conclusions can be drawn about the performance of the agents of the given DRM across three visibility conditions:

1. The up-linked ATC alerts support reducing the collision risk far more than active monitoring by the pilots of both aircraft.
2. Active monitoring by the pilots of the landing aircraft supports collision risk reduction more than active monitoring by pilots of the taxiing aircraft in VC1 and VC2.
3. Pilots of both aircraft play barely any role in a collision risk reduction in VC3/4.

5. Conclusion

In the present study the additional risk analysis based on the TIPH DRM was performed. First, several events were defined and recorded in the MC simulations of the DRM. Second, additional simulations of changes in the operations were performed by means of excluding of agents capable of conflict detection and/or resolution out of monitoring or control loop. It was done for three agents of the DRM: pilots of the landing aircraft, pilots of the taxiing aircraft and the Runway Incursion Alert (RIA) component of the ATC.

In previous work[8] it was found that for a runway incursion scenario in VC1 between an aircraft taking off and an aircraft crossing while it should not, the accident risk reducing capability of ATC runway incursion alerts is very small and the roles of the pilots quite important. This can be explained by the operation assessed in Ref. 8, where the alerts are communicated to the pilots of both aircraft via the air traffic controller, which leads to an additional delay with respect to the direct up-linked ATC alert in the TIPH operation.

The main finding of the present study is that, in contrast to the findings in Ref. 8, for this particular TIPH scenario the RIA component of the ATC system plays a crucial role in conflict detection, and the pilots of the landing aircraft play a somewhat larger role in conflict detection and resolution in comparison to the pilots of the taxiing aircraft. The additional value of the present research is improving transparency of the given multi-agent DRM. In general, the results of this study provide more insight in the role of agents and their behavior in the TIPH DRM. As such, the obtained results provide useful feedback to operational designers.

In future research, the results of the present study will be taken into consideration for establishing interlevel relations between the multi-agent DRM of the TIPH operation and other agent-based models in ATM at different abstraction levels according to the framework presented in Ref. 3 in the context of the ComplexWorld project[4].

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References

[1]Blom, H.A.P., Bakker, G.J., Blanker, P.J.G., Daams, J, Everdij, M.H.C., Klompstra, M.B. "Accident risk Assessment for Advanced Air Traffic Management", Eds: G.Donohue et al., *Air Transportation Systems Engineering*, AIAA, 2001.

[2]Blom, H.A.P., Stroeve, S.H., Jong, H.H. de. "Safety Risk Assessment by Monte Carlo Simulation of Complex Safety Critical Operations", Eds: F. Redmill and F. Anderson, *Proc. 14th Safety Critical Systems Symposium*, Bristol, UK, 2006.

[3]Bosse, T., Hoogendoorn, M., Klein, M.C.A., and Treur, J. (2010). "A Three-Dimensional Abstraction Framework to Compare Multi-Agent System Models". In: Pan, J.-S., Chen, S.-M., and Nguyen, N.T. (eds.), *Computational Collective Intelligence: Technologies and Applications, Proceedings of the Second International Conference on Computational Collective Intelligence, ICCCI'10, Part I. Lecture Notes in Artificial Intelligence*, vol. 6421, Springer Verlag, 2010, pp. 306-319.

[4]Complex World. "Complex ATM White Paper". Technical Report, October 2010.

[5]Everdij, M.H.C., Blom, H.A.P., Stroeve, S.H. "Structured assessment of Bias and Uncertainty in Monte Carlo Simulated Accident Risk", *PSAM8*, 2006.

[6]Everdij, M.H.C., Klompstra, M.B., Blom, H.A.P., Obbink, B. K. "Compositional specification of a multi-agent system by stochastically and dynamically coloured Petri nets". H.A.P. Blom, J. Lygeros (eds.), *Stochastic hybrid systems: Theory and safety critical applications*, Springer, 2006.

[7]SESAR. “European Traffic Management Master Plan”. Edition 1, 2009.
[8]Stroeve, S.H., Blom, H. A.P., Bakker, G.J. “Contrasting Safety Assessment of a Runway Incursion Scenario by Event Sequence Analysis versus Multi-Agent Dynamic Risk Modelling”, *ATM 2011*, 2011.
[9]Stroeve, S.H., Blom, H. A.P., Park, M.N.J van der. “Multi-Agent Situation awareness error evolution in accident risk modelling”. *Proceedings of the 5th USA/Europe ATM R&D Seminar*, 2003.
[10]Stroeve, S.H., Doorn, van B.A., Bakker, G.J. “Safety Assessment of a Future Taxi into Position and Hold Operation by Agent-Based Dynamic Risk Modelling”. *Journal of Aerospace Operations*, Vol. 1, 2012, pp. 107-127.
[11]Stroeve, S.H., Doorn, van B.A., Bakker, G.J., Nieto, J.I. “RESET. D7.4: Preliminary safety Case. Part 1: Taxi Into Position and Hold”, 2010.
[12]Dynamically Coloured Petri Net, “Appendix. RESET. D7.4: Preliminary safety Case. Part 1: Taxi Into Position and Hold”, 2010.