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Airport operations safety assessment with the use of colored Petri nets

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ABSTRACT: Numerous operations connected with beginning and ending of air transportation process are executed at the airport. Each of these may be important for the safety of air traffic. However, due to the severity, the most important are taking off and landing operations carried out on runways. In many airports, there exists a system of two intersecting runways. In this case, usually one of the runways is used for takeoffs while the other one for landings. This allows increasing the capacity of the airport. Existing procedures are designed to ensure the safety of this process. However, the presence of traffic disturbances (for instance weather-related) and mistakes made by air traffic controllers and pilots could lead to a collision at the intersection of runways. The aim of this study is to estimate the probability of a collision at the intersection of runways with regard to disturbances in the procedures carried out. For this purpose there has been created a model of air traffic on intersecting runways, which are used alternately for takeoffs and landings. This model was developed as a hierarchical colored Petri net. Defined and included in the model are several groups of potential disturbances as well as the dynamics of the movement of aircraft in landing and take-off phases. Using this model, numerous simulation experiments were conducted thank to which the safety of traffic on intersecting runways has been assessed. The developed software tool allowed for determining the effectiveness of protective measures, such as, for instance, the use of additional technical means that allow for detecting the aircraft passing the runways intersection. The model and the tool has been implemented for Warsaw Chopin Airport, having the discussed structure of runways.

1 INTRODUCTION

In many European airports, there exists a configuration of two intersecting runways. This system is used mainly when there is no domination of wind direction in the airport area. Most preferred is performing the takeoff and landing operations into the wind. A collision-free system of two parallel runways has the disadvantage that the airport cannot be used if the surface crosswind is too strong. The system of intersecting runways is much more flexible. It increases the so-called airport usability, because it is possible to use the other runway (Malarski et al. 2007). Also in the case of windless weather which allows executing takeoff and landing operations at any of the runways, intersecting system makes it possible to increase the capacity of the airport. In such a situation one runway is usually used for takeoffs while the other one for landings. The next takeoff may be held if the aircraft landing on the other runway has passed the intersection point. Similarly, the next landing may be held if the aircraft taking off has passed the intersection. The time to reaching the intersection is less than the time required to perform a complete procedure, which is necessary when using only one runway (Stelmach et al. 2006).

The configuration of two intersecting runways, however, has a serious drawback. It is the existence of common point of different air traffic streams. In the case of a human error this can lead to simultaneous execution of the takeoff and landing operations and as a result—a collision with catastrophic consequences. It is worth noting that the biggest disaster in the history of civil aviation, which took place on the island of Tenerife in 1977 happened at the airport, which has just such a structure. And that fact was not without a significance for the accident causes (Netherlands Aviation Safety Board 1978). The error referred to may be, for instance, the Air Traffic Controller (ATC) clearance which will permit simultaneous takeoff and landing. It can also be committed by the aircraft crew, which can misread the permission obtained from the controller and as a result perform the procedure for which in fact did not have a permission.

The facts discussed here provoke the question that is the research subject of this work. To what extent the applicable procedures and technical safety barriers make the airport resistant to aircraft collision in the case, when there are two intersecting runways in simultaneous use? This question is particularly relevant against potential human errors, adverse weather conditions and traffic disturbances.

1.1 *Literature review*

The problem studied in this paper belongs to the class of so-called Runway Incursions (RIs). The International Civil Aviation Organization (ICAO) defines these as "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 take-off of aircraft" (ICAO 2007).

Many attempts have been undertaken to develop effective models of airport elements which would enable an analysis of the impact of various organizational activities on the safety and security of airport traffic. These use various methods of mathematical modeling, which include, among others, dynamical programming, fuzzy sets, queuing models, and hierarchical Bayesian models (Dell'Olmo & Lulli 2003, Horowitz & Santos 2009, Netjasov 2004, Skorupski 2014, Skorupski & Uchroński 2015, Ayres et al. 2013, Lower et al. 2013).

Convenient tools for analysis of traffic processes in transport are Petri nets. Some examples in airport safety analysis include (Davidrajuh & Lin 2001, Oberheid & Söffker 2008, Werther et al. 2007). The general approach to using Colored Petri Nets (CPN) in modeling aircraft operations can be found in (Everdij & Blom 2004). In (Oberheid & Söffker 2008) a model of forward-looking planning of the arrival process at the airport is presented. It is implemented in 'CPN Tools' software package (as in the current study). A similar issue has been discussed in (Blom et al. 2001). Stroeve et al. (2013) used Petri net modeling for risk assessment of runway incursion scenarios. A similar approach was implemented in (Fota et al. 2015). Petri nets were also used to represent human factors problems during accident analysis (Johnson 1995) and to analyze various aspects of traffic problems in other modes of transport. In (Skorupski 2011), the general concept of modeling traffic processes in transport was described. Similarly, for instance (Gudelj et al. 2012) dealt with maritime traffic, and (Ishak et al. 2010) with rail traffic.

1.2 *Concept of the study*

Research problem undertaken in this paper is to find the probability of collision at the airport with two intersecting runways. It is particularly important to seek for the change of this probability when using a different operational procedure, in the case of a traffic interference or just an error. Such an analysis can identify those factors that have the greatest impact on the initiation of the accident. Acting proactively it will then be possible to eliminate these particularly significant hazards.

The paper is structured as follows. Section 1 presents the essence of the problem, a review of the literature and the research problem. Section 2 presents the issue of airport operations. Particular attention is paid to the problem of airport capacity and the impact of the efforts to increase it on air traffic safety. Especially in view of possible disruptions. Section 3 presents the object of modeling, that is the airport with two intersecting runways. As an example Warsaw Chopin Airport has been selected. Section 4 presents the model of airport traffic in the form of a hierarchical colored Petri net and also the computer software implemented in CPN Tools 4.0 environment. Section 5 presents the simulation experiments with safety evaluation under standard operations, disturbed operations and also in the case when additional preventive procedures are implemented. Section 6 contains a summary and conclusions.

2 AIRPORT OPERATIONS

Airport operations consist of landing, taking off, and taxiing. In each of them we deal with moving aircraft, and their routes may intersect many times with routes of other aircraft or airport service vehicles.

2.1 *Airport capacity*

The airport is a complex system which consists of many subsystems having different objectives and different operational characteristics. One of the main criteria for evaluation of the airport system is its capacity, i.e. the number of aircraft that can safely perform a takeoff or landing operation.

Due to the complexity of this system there are many factors that affect its capacity (Skorupski 2009). The most important parameter in determining the capacity is the Runway Occupancy Time (ROT). This time is the basis for determining the theoretical maximum throughput of the runway

$$C_{max} = \frac{3600}{\overline{ROT}} \qquad (1)$$

where:

C_{max}—maximum runway capacity at constant takeoff and landing operations, expressed in number of operations per hour,

$\overline{ROT}$—the average runway occupancy time in seconds. It depends on many factors: aircraft type, touchdown speed, the taxiway selected to leave the runway, runway surface conditions and many others.

As one can see from the formula (1) reduction of the ROT for every single takeoff and landing tends to increase the runway throughput. In practice, we use the concept of practical runway capacity which takes into account the random factors affecting airport operations carried out on the runway and resulting delays. Regardless of the definition the general relationship between the capacity and runway occupancy time is the same.

2.2 *Airport traffic safety*

In contrast to other phases of flight airport traffic is carried out in two dimensions. It would seem then that it is simpler and more secure. Unfortunately, it is not. This is mainly due to the short distance between the aircraft and a big number of them. Even in the case of relatively static procedures such as towing or taxiing it is possible that they may lead to accidents with casualties.

However, the most dangerous are the events involving aircraft performing landing or takeoff procedures. These procedures are complex, are held at high speeds and the potential consequences are usually very serious. These events typically include the category of Runway Incursion. Among them, the most dangerous are collisions in which both participating aircraft perform takeoff or landing.

2.3 *Disturbances in airport traffic*

Airport traffic is organized and supervised by the Air Traffic Control (ATC) services. Mainly by TWR (Tower) controller responsible for the runways and GND (Ground) controller responsible for the taxiways. They care about the safety of moving aircraft, mainly by ensuring the correct order to occupy the conflict points and providing guidance as to the use of runway or taxiway or in general the choice of the taxi route.

Air traffic controllers use the appropriate procedures to ensure collision-free traffic. An important test for these procedures are all kinds of interference or minor errors that may arise in the aerodrome traffic. It is important that despite the disturbances, these procedures continue to provide safety (Hollnagel et al. 2006).

Disturbances and errors in the aerodrome traffic may include, among others:

- difficult weather conditions, especially limited visibility resulting from the fog, smoke, etc.
- delays due to the non-nominal taxiing speed,
- poor runway surface condition manifested mainly by reduced friction coefficient, for instance due to snow or rainfall,
- use of the runway exit different than planned because of the different characteristics of the landing roll,
- notification of a Foreign Object Debris (FOD) on the airport maneuvering area, which needs to be removed by the relevant airport services,
- taxiing with the use of wrong taxiway, other than specified in the air traffic controller clearance (Skorupski 2015),
- interference to radio communications between controllers and aircraft crews,
- improper acceptance of the ATC clearance issued to another aircraft.

Proactive approach to the airport traffic safety requires analyzing how the existing procedures and applied technical solutions protect against the adverse effects of such interference. Such analysis should be carried out even in a situation where the probability of interference seems to be vanishingly small.

3 THE OBJECT OF ANALYSIS—AIRPORT WITH TWO INTERSECTING RUNWAYS

The mathematical model of airport traffic presented in Section 4 has been developed in the form of Petri net with a view to its universality and applicability for each airport with two intersecting runways. However, due to the paper's volume the generic model will not be described. Instead its implementation for Warsaw Chopin Airport (ICAO code: EPWA) will be presented. General structure of this airport is shown in Figure 1.

Due to the airport capacity, if the weather conditions permit, the following control strategy is

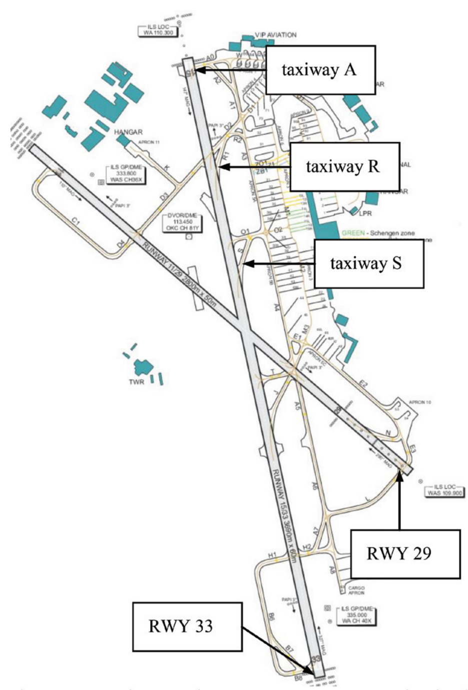

Figure 1. Two intersecting runways at Warsaw Chopin airport.

usually used: taking off aircraft use RWY 29 runway and landing aircraft use the RWY 33 runway. The same strategy has been implemented in the airport traffic model. This strategy is advantageous with regard to minimizing the time and distance covered during taxiing. It also does not require crossing the runways during taxiing. The most important safety threat in this case is the runways crossing point, where the collision is possible.

4 AIRPORT TRAFFIC MODEL

The model of air traffic on intersecting runways has been implemented as a hierarchical, colored, timed Petri net. The network hierarchy is represented in the form of so-called "pages" responsible for different parts of the model: *TakeOff-29*, *Landing-33*, *Braking*, *Landing roll*, *Takeoff roll*, *Turn*.

4.1 *General characteristics of Petri nets*

Petri nets are a convenient tool for the description of concurrent systems. They have an increasing number of applications in the area of modeling traffic processes, including air transportation.

The basis for building a Petri net is a bipartite graph containing two disjoint sets of vertices called places (designated by ellipses) and transitions (rectangles). A characteristic feature of the graph used in Petri nets is that the arcs have to combine different types of vertices.

The set of places P corresponds to traffic situations in which a plane can be found during normal traffic. These situations refer both to the location of the plane in the airspace as well as to the issue of specific permits (clearances).

The set of transitions T corresponds events (actions) that change the traffic situation, particularly affecting the safety of maneuvers.

The set of arcs defines traffic situations that determine the occurrence of certain events and the results of those events.

Tokens (located in places) can be identified as traffic participants (aircraft), air traffic control states or real numbers (value of speed, distance).

The main feature of Colored Petri Nets (CPN) is the ability to define markers of different types. Marker type is called a color. Each place in the colored net is assigned a set of colors that it can store. Expressions are assigned to arcs and transitions that allow manipulating various types of markers. Using colored Petri nets allows one to simplify the structure of the model, and at the same time to observe each individually modeled aircraft. This is possible because of the ability of CPN to distinguish between markers.

4.2 *Petri net for modeling airport operations*

The general idea of the model consists in mapping mixed take-off and landing operations on intersecting runways together with simultaneous observation of aircraft positions on runways and in the airspace around the airport. The ability to continue operations and to occupy individual places (waypoints) depends on the fulfillment of provisions, which must be confirmed by the Air Traffic Control (ATC) clearances. ATC actions are also reproduced in the model.

The airport traffic S_{AT} model presented in this paper can therefore be written as

$$S_{AT} = \{P, T, I, O, H, M_0, \tau, X, \Gamma, C, G, E, R, r_0, B\} \tag{2}$$

where:

P—set of places, T—set of transitions, $T \cap P = \varnothing$,

I, O, H, are functions, respectively, of input, output and inhibitors: $I, O, H: T \to B(P)$, where $B(P)$ is the superset over the set P,

$M_0 : P \to \mathbb{Z}_+ \times R$—initial marking,

$\tau : T \times P \to \mathbb{R}_+$—delay function, specifying the static delay $\tau(t)$ of transition t moving tokens to place p,

$X : T \times P \to \mathbb{R}_+$—random variable describing the time of carrying out transition t leading to place p,

Γ—nonempty, finite set of colors,

C—function determining what color of tokens can be stored in a given place: $C : P \to \Gamma$,

G—function defining the conditions that must be satisfied for the transition before it can be fired; these are the expressions containing variables belonging to Γ, for which the evaluation can be made, giving as a result a Boolean value,

E—function describing the so-called weights of arcs, i.e. expressions containing variables of types belonging to Γ for which the evaluation can be made, giving as a result a multiset over the type of color assigned to a place that is at the beginning or the end of the arc,

R—set of timestamps (also called time points) closed under the operation of addition, $R \subseteq \mathbb{R}$,

r_0—initial time, $r \in R$.

$B : T \to \mathbb{R}_+$—function determining the priority of transition t; this function applies only for transitions that are simultaneously active; in this situation a free choice of transition to be fired is possible.

The output of the model consists of time-dependent functions determining the location of tokens in places:

- tokens of AC color, representing aircraft movement parameters (position, speed, etc.)
- tokens of ATC color, representing the air traffic control services clearances.

4.3 *Mapping the aircraft dynamics in the model*

The model of airport traffic represents the aircraft dynamics through the use of the so-called timed Petri nets. It consists in that the tokens located in places which determine the possibility of occurrence of the events are active at specific time points. This allows one to easily represent the time flow in the model.

As for the aircraft movement, all phenomena associated with the acceleration or deceleration of the aircraft are taken into account. The construction of the model allows us to cope with different accelerations (delays) resulting from the type of the aircraft or the runway friction coefficient.

For example, in Figure 2 a fragment of the model responsible for mapping the take-off run is presented.

Transition *Distance calculation* is responsible for determining the distance which the taking off aircraft covered depending on the elapsed time. The determined value is kept out in the place *Distance* and is used to check whether the taking off plane has passed the runways intersection (transition *Crossing check*). If so, then the appropriate token is placed in the place *AC at crossing*, which is the signal for the commencement of landing procedure on the other runway. A little earlier the "line-up and wait" procedure may be performed on the same runway by another aircraft planning to take off. This is checked by a transition *Line-up check*. If so, then appropriate token is placed in the place *RWY29 clear for line-up*. The place *Time* is the counter showing the duration of the takeoff roll procedure.

Analogously to the presented takeoff operation the landing process model has been implemented. It takes into account the different methods of braking: aerodynamically, by using the wheels brakes and the thrust reverser. The last two devices can be activated at any time during the braking after landing. And it is possible to represent this fact in the model.

4.4 *Computer tool in CPN Tools environment*

The presented model has been implemented as a computer software using CPN Tools 4.0 environment (Jensen et al. 2007). It is a very convenient tool because it allows at the same time creating a model, simulating at different input parameters and simultaneously analyze the results in the state space.

The model of air traffic at the Warsaw Chopin airport is implemented as the hierarchical Petri net in which different parts of the model are created independently and during the simulation are synchronized by means of special mechanisms. These include so-called fused places and substitution transitions.

Figure 3 shows the page *TakeOff-29* responsible in the model hierarchy for the process of aircraft takeoff from runway RWY 29.

The part of the net shown in Figure 3 allows one to observe three important elements of the model:

1. Substitution transitions. They are marked with rectangles with a double line—*Takeoff roll* and *Turn*. Their role is to implement the hierarchical structure of the model. For example, a transition *Takeoff roll* is a single element on *TakeOff-29* page, but its internal structure is more complex. It is an equivalent of the previously discussed page *Takeoff roll* (Fig. 2).
2. Fused places. These are the places labeled in the bottom left corner. All fused places marked with the same label are identical, regardless of which part of the model they are placed in. Examples are places labeled "29 L/U" in Figures 2 and 3. In both cases it is the same place used for judging whether an aircraft can line up the RWY 29 runway. The mechanism of fused places also gives the ability to synchronize the hierarchy-specific elements of the model.
3. Places that store the tokens of ATC color (*33 to Cp occupied*, *29 to CP occupied*, *RWY29 clear for line-up*, *RWY29 clear for take-off*). They contain the information necessary for air traffic control services on the basis of which they issue ATC clearances. These are key elements of procedures analyzed in this paper. Occupation or release of individual points by aircraft results in the appearance or removal of the relevant tokens in these places. Thus places with tokens

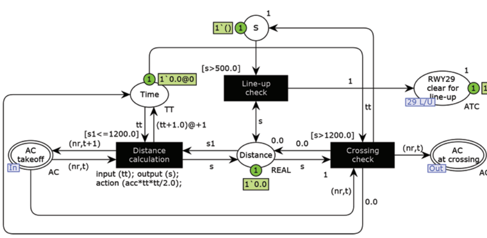

Figure 2. Page *Takeoff roll* of the airport traffic model at EPWA airport.

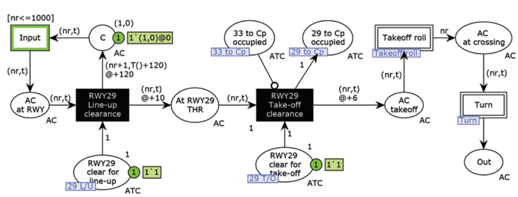

Figure 3. Petri net for modeling the process of taking off from RWY 29 (page *TakeOff-29* of the model of airport traffic at EPWA).

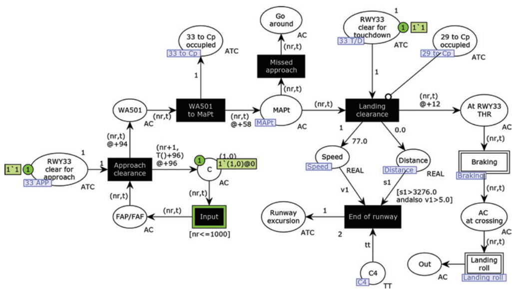

Figure 4. Petri net for modeling the process of landing on RWY 33 (page *Landing-33* of the model of airport traffic at EPWA).

of ATC color provide the basis to permit (or prohibit) the operation.

Figure 4 shows the *Landing-33* page which is responsible for modeling the process of landing on a RWY 33 runway.

The landing aircraft input to the model is performed at the FAP/FAF (Final Approach Point/ Final Approach Fix) navigational waypoint which is the starting point of approach using ILS (Instrumental Landing System). If it is possible to continue the approach (indicated by the presence of the token in place *RWY33 clear for approach*), then the aircraft moves to the next waypoint (WA501). From this moment in time the runway RWY 33 is treated as occupied (place *33 to Cp occupied*) and other operations are not allowed on this runway. Then the aircraft moves to the MAPt waypoint where the possibility of landing is checked (transition *Landing clearance*). If the landing is possible the aircraft performs a touchdown (place *At RWY33 THR*). If not—a go-around procedure is performed (transition *Missed approach*). In the case of unhindered landing the braking procedure occurs (substitution transition *Braking*). After passing the intersection of runways (place *AC at crossing*), the final phase of the roll (substitution transition *Landing roll*) followed by exit to the taxiway (place *Out*) takes place.

The model and the computer tool have been validated with the use of real data by comparing the data obtained from measurements with the times obtained from the model. Due to the volume of the paper, details of the validation are not shown.

5 SIMULATION EXPERIMENTS

The model in the form of hierarchical Petri net allowed for conducting simulation experiments. The following sections present experiments in which the collision probability has been studied for the nominal conditions, then for the scenarios describing possible disturbances. At the end some preventive measures were suggested and it was examined how they are able to bring the probability of a collision in the case of disturbances to the initial value.

5.1 *Results for nominal conditions analysis*

As a reference the situation in which there are no traffic disturbances, no pilots or air traffic controllers errors was adopted. In addition, it was assumed that the duration of each operation is always equal to the nominal value or the average value from measurements. For instance, with respect to the dynamic characteristics of aircraft it was assumed that all landing aircraft have the same touchdown speed (77 m/s) and brake following the same pattern: for 17 seconds only aerodynamic brakes, then thrust reverser at low pressure rotor speed equal to 0.7 of a maximum value, then the wheels brakes at 0.6 of the maximum value. This is the braking profile, which allows the minimal time to reach the rapid exit taxiway S, the most frequently used at Warsaw Chopin airport (Fig. 1). Similarly, it was assumed that all taking off aircraft have the same acceleration characteristics.

For these conditions a simulation of mixed landing and taking off operations was carried out. The total number of aircraft serviced was $2 \cdot 10^4$. Operating procedures at the airport with intersecting runways are designed for safety, to ensure that there will be no conflict situation. This was confirmed in a simulation study. There were no cases of potentially dangerous situation. The planned takeoff and landing operations were realized during $1.65 \cdot 10^6$ seconds. This gives a throughput equal to 43.6 operations per hour.

5.2 *Disturbances scenarios*

In the real air traffic there are many disturbances from the nominal situation as defined in Section 5.1. The most common are: different touchdown point, different durations of each operation performed (resulting in different runway occupancy times), different braking profiles, etc. All of them are typical stochastic deviations. For this kind of disturbances one can also include the emergency and error situations: failure to perform a command, too long reaction time, use of exit taxiway other than specified in the ATC clearance, etc.

The developed model and software tool allow one to analyze safety in cases of disturbed traffic. The overall structure of the model remains unchanged, it is only necessary to introduce new parameters of the model. And so, in the following sections three scenarios will be considered:

1. The touchdown speed is random, with all values in the range from 70 m/s to 84 m/s equally probable. It was assumed also that there are no human errors.
2. In addition to the variable touchdown speed aircraft can land at some distance from the runway threshold. It was assumed that this distance can vary from 0 to 300 m.
3. This scenario includes an analysis of the small error by the air traffic controller. Its essence is to permit the aircraft lining up RWY 29 runway to take off not at the moment when landing aircraft passes the runways intersection, but rather after 34 seconds from its touchdown, which is the time usually necessary to cover the distance touchdown point-runways intersection at nominal conditions and an assumed deceleration profile.

5.3 *Results of safety analysis for disturbed traffic*

In scenario 1 there is a number of cases in which the landing aircraft are forced to perform a go-around procedure followed by a repeated approach for landing. This is due to the fact that the variable touchdown speed may extend the ROT. The main reason is the inability to use the runway exit taxiway S due to the excessive speed. In this case runway exit taxiways R (or even A) are used (Fig. 1). Given the dense packing of the aircraft landing queue (in order to achieve high throughput) this may cause the inability to continue the landing because of the occupied runway. A simulation experiment conducted indicates that the probability of such an event is about $9 \cdot 10^{-3}$.

Go-around procedure itself is not dangerous. But it constitutes a certain risk as the controller does not plan the air traffic and also his/her activities, taking into account the occurrence of such event. So this situation is for him/her a kind of surprise, and as such may be an initiating event for mistakes.

The second scenario makes even more problems with timely and collision-free landing procedure. In this case the probability of the necessity to perform a go-around procedure is about $2.45 \cdot 10^{-2}$. Taking off aircraft in both of these scenarios are at most forced to wait longer to begin the takeoff. But this is not very common since the disturbances described by scenarios 1 and 2 lead to a faster release of the runway section from the touchdown point to the intersection of the runways, which is beneficial to the possibility of initiating the takeoff. Possible longer RWY 33 runway occupation takes place just beyond the intersection of runways.

The third scenario, paradoxically, is beneficial to the runway capacity. In this case the takeoff operation may begin not later than 34 seconds after the touchdown of the preceding landing aircraft. This results in a greater concurrency of operations. Unfortunately, this is against the rules and causes a significant reduction in the air traffic safety. In the simulation experiment there was no collision observed in scenario 3. Also there was no situation when the difference in time of occupation of the conflict point by taking off and landing aircraft was so small that it could be identified as the collision. However, with the probability of $3.6 \cdot 10^{-3}$ there was a situation when the landing aircraft and taking off aircraft performed their operations simultaneously. This should be considered as a serious air traffic incident and preventive measures should be implemented to avoid such a situation.

A summary of the results of the experiments is shown in Table 1.

The results show that defined disturbances scenarios do not lead to a collision at the intersection. This does not mean that it is impossible. Further work is needed to show under which conditions the estimate of the collision probability is different from zero. It should be noted, however, that the incident, which may be the result of an error modeled by scenario 3 is extremely dangerous and can result in an accident with fatalities. In fact, it should be treated as an event inadmissible in air traffic. Therefore, in Section 5.4, a proactive proposal to eliminate this kind of event will be presented.

5.4 *Analysis of the preventive measures effectiveness*

As a preventive measure it is proposed to replace the visual observation of the airfield by the use of technical means which allow detecting the aircraft passing the runways intersection. The proposed solution is to install suitable detectors placed at a certain distance from this point. The role of the sensors is to detect an aircraft and provide information to the air traffic controller. The controller on the basis of this information can issue an ATC clearance for the takeoff.

The simulation experiment modeling the use of the proposed solution shows that it eliminates hazardous situations relating to the scenario 3. It

Table 1. Results of experiments.

	Probability of go-around	Probability of an incident
No disturbances	$<10^{-4}$	$<10^{-4}$
Experiment 1	$9 \cdot 10^{-3}$	$<10^{-4}$
Experiment 2	$2.45 \cdot 10^{-2}$	$<10^{-4}$
Experiment 3	$<10^{-4}$	$3.6 \cdot 10^{-3}$

also causes a slight reduction in capacity (about 7%) resulting from the fact that in this case take-offs begin with a slight delay compared to the basic situation. In this organizational variant the capacity is equal to 40.4 aircraft per hour.

6 SUMMARY AND FINAL CONCLUSIONS

The paper presents a model of aerodrome traffic at the airport where there are two intersecting runways. The model was created as a hierarchical colored Petri net. The model was implemented in the CPN Tools 4.0 environment on the example of Warsaw Chopin airport.

The model allows for easy analysis of various types of traffic events such as a typical delay in the execution of an operation, adverse weather conditions, inaccurate touchdown point, etc. In addition, the model also allows the analysis of errors and emergency situations.

The paper presents a brief analysis of three traffic situations. It shows that random traffic disturbances in the case of densely packed queues of taking off and landing aircraft result in adverse traffic effects. In particular there is often the need for a go-around procedure after a missed approach. It also shows that the lack of accuracy in observation of traffic situation can lead to dangerous situations that can be qualified as serious air traffic incidents. Preventive measures were proposed that use automatic aircraft detectors, which eliminate the possibility of this kind of dangerous situation. Unfortunately, this results in a slight worsening of the airport capacity.

Further work is planned to expand the research to include other disturbances scenarios, in particular related to possible human errors and technical failures. This will allow for finding proactive solutions to prevent adverse effects. In addition, various options of using intersecting runways for takeoffs and landings will be examined. The variant considered in the presented model (take-offs on RWY 29 and landings on RWY 33) is the most commonly used and best known to ATC controllers. Analysis of other possible configurations can produce some interesting conclusions.

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