Analysis of the Relation between Serious Incident and Accident in Air Traffic

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International aviation organizations require Poland to define the so-called acceptable level of safety for traffic accidents. To calculate this, one requires statistical data on accidents. These, however, in recent years did not occur, or the size of the sample is insufficient. In the paper a method for predicting the number of accidents on the basis of information on air incidents is mentioned. This method can be efficient and effective if any regular relation between the air traffic accident and serious incident exists. In the paper a way to find this relation is proposed, by analyzing the relevant simulation models of serious incidents and accidents. For this purpose Petri nets were used.

Keywords: traffic safety, air traffic management, risk analysis.

1. INTRODUCTION

Air transport is a complex system combining advanced technical systems, operators (air traffic controllers, pilots) and procedures. All these elements work in a large spatial dispersion, but are closely interrelated. They interact, and the time horizon of these interactions is very short. In aviation, the risk is traditionally identified with the air accident, which typically produce a high number of deaths and huge financial losses. Severity of the consequences is the reason why the safety was always a key value in this mode of transport.

Polish aviation regulations define three categories of air events [1]:

- accident - as an event associated with the operation of the aircraft, which occurred in the presence of people on board, during which any person has suffered at least of serious injuries or aircraft was damaged,
- serious incident - as an incident whose circumstances indicate that there was almost an accident (such as a significant violation of the separation between aircraft, without the control of the situation both by the pilot of the aircraft and the controller)
- incident - as an event associated with the operation of an aircraft other than an accident, which would adversely affect the safety of operation (e.g. a violation of separation, but with the control of the situation).

The European Organization for the Safety of Air Navigation Eurocontrol issued six documents relating to safety standards, called the ESARR requirements. In air transport the last few years resulted in attempts to standardize the methods and tools of risk management, particularly in determining the acceptable (tolerable, target) level of safety [9]. Currently, European aviation authorities use safety minimums set by the ECAC (European Civil Aviation Conference) which were adopted by Eurocontrol in ESARR-4 regulations. Since 2005 they have been obligatory in Poland as well. The ESARR-4 regulations divide the events with the participation of ATM (Air Traffic Management) into 5 categories denoting an acceptable level of safety only for the category of "accidents". TLS (Target Level of Safety) defines the maximum value of probability of an accident, for the commercial aircraft, to be equal $1{,}55 \cdot 10^{-8}$

accident on a flight hour, or $2{,}31 \cdot 10^{-8}$ accident on a flight [5].

All ECAC member states are obliged to designate the so called CLS (Current Level of Safety) and compare it to TLS. It is also necessary to make a forecast of changes in the level of safety in future years and to propose possible remedies (in case of excess of acceptable standards).

This task is substantially difficult because the TLS concept is based on the number of accidents with regard to the volume of traffic. In many countries, however, there have been no air accidents in recent years. That is also a situation in Poland. In this case, a reliable determination of the required CLS value is impossible.

One method of solving this problem is to use data on air incidents, which are obviously more frequent than air accidents. If the value of the CLS determined based on incidents is within the limits specified for the accident, it is assumed that this is a satisfactory result, not requiring further research or action [4]. Such an approach, although it seems to be reasonable, can be subjected to criticism. It may in fact result in conviction of the high level of safety, when in fact situation is different. With not so big number of flights (not so many flight hours), which takes into account, one may find that the existence of only one case of air accident will result in a safety level worse than the required TLS. Such a situation occurs also in Poland. According to statistics from the Civil Aviation Authority [3], in 2009 there were 165.000 flight hours in whole Polish civil aviation. If only one accident of commercial aircraft had occurred, the CLS could be estimated at $6{,}05 \cdot 10^{-6}$, which is much more than recommended by Eurocontrol value of $1{,}55 \cdot 10^{-8}$.

In this paper a different approach is proposed. Serious air traffic incidents should be analyzed and used to determine the probability of transforming them into accidents. If there is any regular statistical relationship between incidents and accidents, then on the basis of serious incidents statistics, one can make a forecast of the number of accidents and thus determine the value of the CLS. In this article an attempt to find such a relationship is presented. For air traffic events modeling, Petri nets are used.

2. RISK IN AIR TRAFFIC

The risk in air traffic can be divided into conscious and unconscious. The first case (conscious risk) is when, despite the possibility of avoiding it, we decide to undertake the risky action. The unintentional (passive, unconscious) risk exists independently of our will or decision. For example, the decision to travel by air transport is associated with additional exposure to loss of life or health (conscious risk), while living near the airport, where there is a risk of loss of life due to airplane crash, represents a unconscious risk.

The risk may relate to objectively or subjectively known exposure to hazards, with a probability dependent on time, place, person, etc. There may be the risk of a global (e.g. climate change) or local (e.g. aircraft noise) nature. Certain groups of people are more vulnerable to the same type of risk than others, for example, aircraft pilots and passengers.

Depending on the duration of the threat we have to deal with continuous, single or cumulative risk [6]. And social risk can be divided into four types [8]:

- real risk, which can be determined based on the analysis of sequence of faults leading to adverse event,
- statistical risk, calculated on the basis of available data about previous events,
- anticipated risk, which can be predicted analytically based on models,
- perceived risk, which is felt intuitively.

Aviation, in particular air traffic management, is the human activity, which includes all four types of social risk. Insurance companies will look for air transport in terms of statistical risk, the passengers - the perceived risk, which for most people is greater than the statistical risk. Air traffic management will be mostly focused on the anticipated risk, determined by modeling the effects of introducing new organizational and technical systems.

Accidents in air traffic, characterized with respect to the risk, have several distinctive features:

- passengers and crew members are the people who are mostly vulnerable to risk, but there are also people on earth who are exposed to the same effect, but with significantly less probability,

- accidents are extremely rare events (in absolute sense), but with very serious consequences,
- risk is always present (with respect to time of flight), so we have to deal with non-cumulative risk.

Practical problem in air traffic is managing the risk and safety. It is usually resolved by examining the causes of incidents and accidents, determining risks associated with them and then determining (setting) standards, corresponding to the socially acceptable values. Determining the risk of accidents is an essential task, which can be implemented in various ways, ranging from very intuitive to a strictly formal (analytical), but is usually divided into several sub-tasks:

- identification of risk: the emergence of new risks or changes in traffic parameters, which change the current risk assessment,
- risk assessment: determination of the degree of risk aversion and the degree of acceptance of risk,
- dimensioning of risk: usually as the number of accidents per unit time (or distance or number of flights).

As far as now a lot of methods and models on different aspects of risk management in air traffic have been developed. The models to study the causes of actual, real incidents and accidents seem to be the most advanced. These are usually the methods used for other types of risky human activities, and only implemented for air traffic.

The second group consists of methods and models to assess the theoretical risk of possible collisions in air traffic. Although such collisions are rare, but their implications are very serious, so the development of such methods seems necessary. Since they concern the possibility of an accident, so it's kind of proactive thinking, aimed at preventing incidents in air traffic before they happen.

The third group are the methods of human errors analysis. Aviation accidents statistics indicates that the most common reasons for their occurrence are the errors of air traffic controllers and pilots. Finding the causes of these errors is difficult and an interdisciplinary task. However they need examination and risk assessment, especially since the man is just one element of a more complex man-machine system as air traffic management system.

The last group of risk analysis methods, are the third-party risk methods. While the statistical risk of losing life on the earth by an aircraft accident is much less than in the case of passengers, but socially perceived risk appears to be high. Those methods should be taken into consideration when choosing the location of the planned or upgraded airports.

3. METHOD OF ANALYSIS OF THE RELATION BETWEEN SERIOUS AIR TRAFFIC INCIDENT AND ACCIDENT

As it is widely known, the air traffic incidents are almost always a result of a combination of many different factors. During the development of a dangerous situation in time, there are also inhibitory factors that hinder or prevent this process.

Preliminary analysis of the various events in air traffic indicates that for the events classified as serious incidents, there would be sufficient occurrence of only one additional conducive factor, or the termination of only one inhibiting factor, to a serious incident turned into an accident. This observation is the basis for proposing the following method of analysis.

3.1. PURPOSE AND SCOPE OF THE ANALYSIS

While analyzing risk of serious incidents, with the use of event tree or fault tree, there are many elements which probabilities we do not know. In addition, events are dependent (in the probabilistic sense), what makes analysis more difficult. The method presented in this paper is based on analyzing only those additional factors that determine the creation of the accident. This definitely reduces the scope of analysis and also reduces the uncertainty of risk estimation. At the same time, this approach is adequate to achieve the goals of analysis - to determine the statistical dependencies between a serious incident and the air accident. As a result of finding such a relationship, it would be possible to estimate the number of accidents just on the basis of knowledge of the number of incidents.

3.2. PETRI NETS

Petri net is described as [7]:

$$N=\{P,T,I,O,H\} \tag{1}$$

where:

P - set of places

T - set of transitions, $T \cap P = \varnothing$

I, O, H, are functions respectively of input, output and inhibitors:

$I, O, H: T \rightarrow Bag\ (P)$
where $Bag\ (P)$ is the superset over the set P.

Given a transition $t \in$ it can be defined:

$t^{\bullet} = \{p \in P : I(t,p) > 0\}$ - input set of transition t

$t^{\bullet} = \{p \in P : O(t,p) > 0\}$ - output set of transition t

${}^{\circ}t = \{p \in P : H(t,p) > 0\}$ - inhibition set of transition t

Petri nets system is described as:

$$S=\{P,T,I,O,H,M_o\} \tag{2}$$

where

P - set of places

T - set of transitions, $T \cap P = \varnothing$

I, O, H, are functions respectively of input, output and inhibitors:

$I, O, H: T \rightarrow Bag\ (P)$
where $Bag\ (P)$ is the set of all possible supersets over the set P.

M_0: $P \rightarrow N$ is the initial marking, i.e. a function assigning an integer to each place.

Petri network model is described as:

$$M=\{P,T,I,O,H,PAR,PRED,MP\} \tag{3}$$

where:

P - set of places

T - set of transitions,

I, O, H, are functions respectively of input, output and inhibitors:

$I, O, H: T \rightarrow Bag\ (P)$
where $Bag\ (P)$ is the superset over the set P,

PAR - a set of parameters,

$PRED$ - a set of predicates limiting the range of parameters,

$MP: P \rightarrow N \cup PAR$ - a function that assigns to each of places the natural number or the parameter value from the set of natural numbers.

Transition t is called active in marking M if and only if:

$$\forall p \in {}^{\bullet}t, M(p) \geq O(t,p) \quad \wedge \quad \forall p \in {}^{\circ}t, M(p) < H(t,p) \tag{4}$$

Firing of transition t, active in marking M will change actual marking to M' such that

$$M' = M + O(t) - I(t) \tag{5}$$

This relationship is written briefly $M[t>M'$. We then say that M' is reachable directly from M. If the transition requires firing a sequence of sub-transitions σ, then we say that M' is reachable from M and denote $M\lfloor\sigma\rangle M'$.

For each Petri net we can determine: the reachability graph, evaluate the reversibility, the presence of deadlock, liveness, and boundedness. In the presented method of analysis, the most important property of the network (modeling an air incident) is the reachability of selected states (markings) from initial marking M_0. It allows to assess the probability and transition time for those selected markings.

3.3. OUTLINE OF PROPOSED METHOD

In the method presented in this paper the following interpretation was adopted:

- The set P corresponds to traffic situations. These situations are referred to both the location of a plane in the airspace, as well as issue of specific permits (clearances). The set P may include, for example, situations such as: aircraft ready for take-off, occupied runway, the plane at the intersection of the runways, taxiing started, etc. Additional elements of this set are situations describing the state of the environment, such as: the occurrence of more than 1000 meters of visibility, ATC controller busy, the pilot of another aircraft watches the situation on the maneuvering area etc.
- The set T corresponds to the set of events (actions) that change the traffic situation, particularly affecting the safety of maneuvers. These are events such as: ATC controller allows the start, the plane taxiing

at a certain taxiway, the plane does not stop the actual maneuver. These events can be characterized by two values: the time of their duration (including the important role played by the zero-time events, the so-called immediate events) and a priority, defined by the probability of realization of events that can occur simultaneously.

- The input function *I* defines the traffic situations that determine occurrence of certain events, output function *O* defines what event (action) must occur to change the status of the analyzed system, and the inhibitor function *H* specifies the traffic situations that must not exist to certain events can occur.
- The initial marking M_0 defines the traffic situation in which we begin the analysis, and the current marking *M* describes the current state of the system (process).

The analysis, which aims to determine the relationship between serious incident and accident in air traffic, consists in carrying out the simulation of the process modeled by a suitable Petri net, together with recording the time and the probability of staying in each state. General algorithm of the method is as follows:

- Development of a model of a serious air traffic incident as a Petri net. It is necessary to take into account all the events (leading to or inhibiting the incident) and time relations between them.
- Reduction of the network, which consists in elimination of places and transitions that do not affect the transformation of the incident into accident.
- Development of the scenarios of transforming an incident into accident. These scenarios must take into account both the appearance of additional events and absence of inhibiting events.
- Development of a model of an accident, taking into account reduction of the network and all the possible scenarios as defined in previous section.
- Simulation of the process, with registration of system states, time spent in specific states, the average number of markers in each place.
- Isolation of system states representing the transformation of the incident into accident, determination of the joint probability of those states.

4. EXAMPLE ANALYSIS – SERIOUS AIR TRAFFIC INCIDENT 344/07

As an example illustrating the method a serious air traffic incident which occurred in August 2007 at Warsaw airport will be presented. Its participants were Boeing 767 and Boeing 737 aircraft, ant its cause was classified as a "human factor" and the causal group H4 - "procedural errors" [2].

4.1. CIRCUMSTANCES OF THE SERIOUS INCIDENT

In the incident on 13 August 2007 two aircraft participated – Boeing 737 (B737) and Boeing 767 (B767), which more or less at the same time were scheduled for take-off from the Warsaw-Okęcie airport. As the first, clearance for line-up and wait on runway RWY 29 was issued to B737. As a second, clearance for line-up and wait on runway RWY 33 was given to B767 crew. The latter aircraft was also the first to obtain permission to take-off. A moment after confirmation of permission to take-off, both aircraft began starting procedure at the same time. B737 crew assumed that the start permission was addressed to them. They probably thought, that since they first received permission to line up the runway, they are also the first to be permitted to start. In addition, the categories of wake turbulence caused, that it would be better to start B737 before B767, from the traffic point of view. Decision of the controller, however, was different. An air traffic controller (ATC) did not watch planes take-off, because at this time he was busy agreeing helicopter take-off. The situation of simultaneous start was observed by the pilot of ATR 72, which was standing in queue for departure. He reacted on the radio. After this message, B767 pilot looked right and saw B737 taking-off. Then, on his own initiative, he broke off and began a rapid deceleration, which led to stopping the plane 200 meters from the intersection of the runways. Assistant controller heard the ATR 72 pilot radio message and informed the controller that B737 operated without authorization. A controller, who originally did not hear the information by radio, after 16 seconds from the start, recognized the situation and strongly ordered B737 to discontinue take-off procedure. B737 crew performed braking and stopped 200 m from the intersection of the runways.

4.2. MODEL OF SERIOUS INCIDENT

This air traffic incident almost led to collision between the two aircraft, it means to accident. As in most such situations, there were many factors contributing to the creation of this dangerous situation. The most important were:

- lack of situational awareness at the B737 crew,
- inadequate monitoring at radio communications and, consequently, wrong acceptance of permission for the start, in fact directed to another plane,
- lack of the crew cooperation in the B737 cockpit,
- lack of proper monitoring of the take-off by the controller,
- controller's lack of response to the information from the pilot of ATR 72 transmitted by radio.

The factors impeding the development of the accident, which resulted in preventing it, included:

- good assessment of dangerous situation by the crew of B767 and decision to immediately discontinue take-off,
- good recognition of the hazard by the crew of the ATR 72 and immediate sending a message by radio,
- good weather conditions for visual observation of the runways,
- proper response of assistant controller.

Petri net model representing this serious incident is shown in Figure 1.

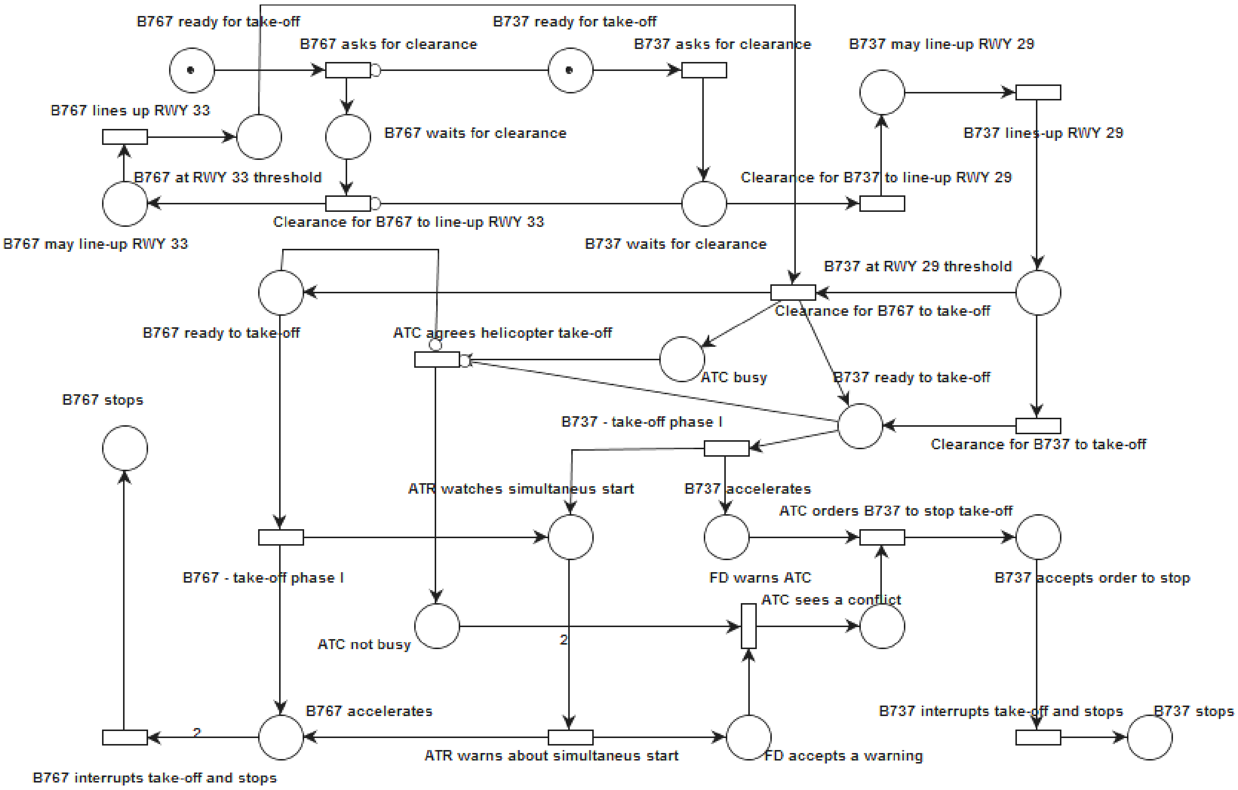

Figure 1. The basic model of a serious air traffic incident 344/07

4.3. MODEL OF AIR TRAFFIC ACCIDENT

Analysis of the factors leading to the incident may give an answer to the question what is the probability of such incident. In this case, such an analysis can be very interesting. It is, for example, to check how the situation would change if it was B767 the first aircraft to obtain permission to line up the runway. In this case the crew of the B737 would not have a reason to accept a permission issued for the B767.

In the presented method, however, a goal is to find a probabilistic dependence between the serious incident and an accident that could result from it. In this case, it is necessary to notice that it is sufficient that there exists only one additional factor, and incident would in fact be an accident. There are several scenarios that lead to an accident.

1. B767 crew, busy with their own take-off procedure does not pay attention to the message transmitted by radio by the ATR 72 pilot.
2. B767 crew takes a wrong decision to continue the take-off, despite noting B737 aircraft. Such a decision could arise, for example, with this reasoning: "there is no possibility to stop before the intersection, let B737 stop - after all, we have a permission to start, maybe we can pass the intersection before the B737, etc.".
3. ATR 72 pilot does not watch the situation on the runways, just waiting for permission to line-up the runway.
4. ATR 72 pilot observes a dangerous situation, but does not immediately inform about it on the radio, instead discusses it with other members of his own crew.
5. Assistant controller does not pay attention to the information given by radio by the ATR 72 pilot, or does not respond to it properly - does not inform the controller.
6. Weather conditions (visibility) are so bad that it is impossible to see the actual traffic situation. This applies to B767, ATR 72 crews, and the air traffic controller.

All these scenarios will lead with certainty (or with great probability) to transformation of the incident into an accident, and will be analyzed using Petri net model. In this analysis one should take into account the possibility of occurrence of each scenario separately, as well as several of them at once.

4.4. Probability of incident-accident transformation

Analysis of the probability of transformation of incident into an accident must take into account the probability of each scenario mentioned above. Designation of some of these probabilities is very difficult or even impossible, because of the lack of statistical data, or it is even not possible to measure some values. In the case of scenario 6 we can use statistical data on meteorological conditions (visibility) in the airport. But in other scenarios, it is necessary to refer to experts' evaluation.

Taking into account the objectives of the analysis, it is possible to eliminate certain states without loss of accuracy, while simplifying the analyzed model. This applies, for example, to almost all the places and transitions associated with the process of taxing and lining up the runway. For example, change the set of places is determined as follows.

$$P_w = (P - P_r) \cup P_d \tag{6}$$

where

P_w - a set of places in the modeled accident,

P_r - a set of reduced places,

P_d - a set of places added to the model, to reflect the above-mentioned scenarios.

In this case (Fig. 1)

$$P_r=\{p_1, p_2, ..., p_{11}\} \tag{7}$$

where: p_1 - B767 awaiting permission to start, p_2 - B767 can line up RWY 33, p_3 - B767 on the RWY 33 threshold, p_4 - B767 ready for take-off, p_5 - B737 awaiting permission to start, p_6 - B737 can line up RWY 29 , p_7 - B737 on the RWY 29 threshold, p_8 - B737 ready for take-off, p_9 - ATC not busy, p_{10} - ATC busy, p_{11} - ATR observes a simultaneous start.

On the other hand

$$Pd=\{p_{12}, p_{13}, ..., p_{21}\} \tag{8}$$

where: p_{12} - ATR warns?, p_{13} - B737 continues to start, p_{14} – B737 at the crossing, p_{15} - B767 hears the warning?, p_{16} - B767 continues to start, p_{17} - B767 at the crossing, p_{18} - B767 interrupts start?, p_{19} - B767 begins deceleration, p_{20} - weather?, p_{21} - good visibility.

A similar modification was made in regard to transitions, input, output and inhibition functions. Petri net to model the transformation of the incident into accident, after reduction is shown in Figure 2.

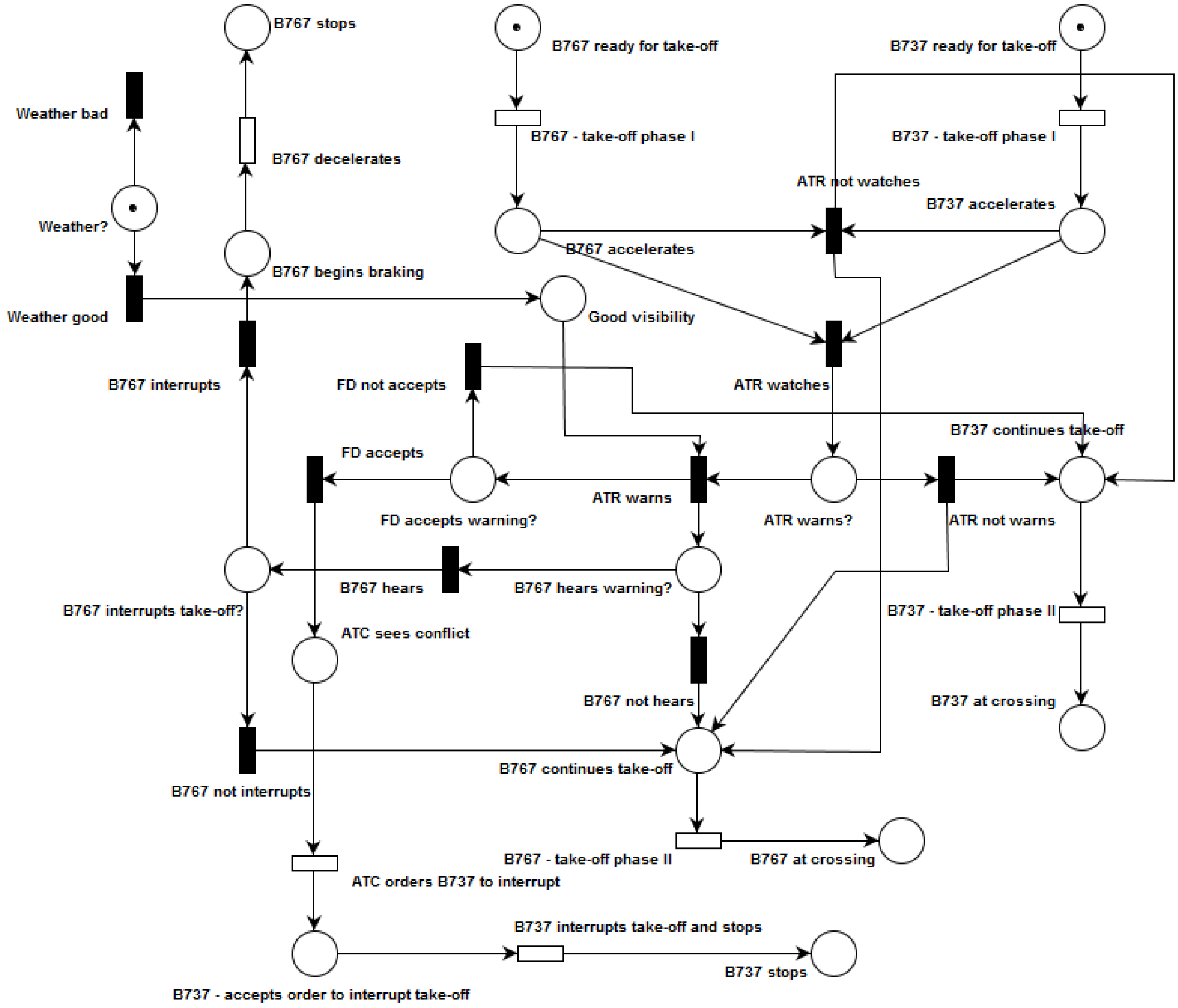

Figure 2. Model of serious incident 344/07 transformation into air traffic accident (after reduction of the states).

This network may be treated as a generalized stochastic Petri net (GSPN). Its simulation analysis allows to observe some interesting relationships between a serious incident and the air traffic accident. It also allows to determine some quantitative dependencies. For example, in the given network one can distinguish 25 stable states and 17 vanishing states. The most important, from the perspective of the analysis presented in this article, are given in Table 1. Other states as well irrelevant places – were omitted. States M_{15}, M_{19}, M_{22}, M_{23}, M_{24} (called safe states) illustrate situations in which there is no accident. For example, in safe state M_{24} there is one marker in place p_{19} - B767 begins braking and one marker in place p_{22} - B737 stops. The transition to this state is possible by firing the immediate transition "B767 interrupts” and the timed transition “B737 interrupts take-off and stops" (Fig. 2). The joint probability of firing of these two transitions, and the time at which this occurs can be easily determined both analytically and by simulation using a suitable software tool. In the present study a PIPE (Platform Independent Petri Net Editor) package was used.

Table 1 shows also the mean residence times of the system in each state. They are the result of the assumed function of intensity of timed transitions and the probabilities of immediate transitions. For each of the stable states, the probability that the system reaches them was determined. The final joint probability that system reaches any of those safe states in this example equals 0.4. Of course this is only an estimate, the more accurate determination requires collecting relevant statistical data derived from measurements or expert assessments.

Table 1. Selected states of the system
(in the model of an accident)

	B737 on the crossing	**B737 stops**	**B767 on the crossing**	**B767 stops**	**Time [s]**
M_{11}	0	0	1	0	6,7
M_{12}	1	0	0	0	6,7
M_{13}	0	0	1	0	5
M_{15}	0	0	0	1	5
M_{17}	0	0	1	0	6,7
M_{18}	1	0	0	0	6,7
M_{19}	0	0	0	1	6,7
M_{20}	1	0	0	0	10
M_{21}	0	0	1	0	10
M_{22}	0	1	0	0	6,7
M_{23}	0	0	0	1	10
M_{24}	0	1	0	0	10

Source: simulation results

5. SUMMARY AND CONCLUSIONS

In the paper the method of simulation analysis of the relationship between the air traffic serious incident and accident was presented. The starting point for this analysis was the assumption that a serious incident describes a situation in air traffic, in which only one additional adverse event is sufficient to cause an accident. In the analyzed example (real air traffic incident), there are six scenarios, which lead to the transformation of an incident into accident. Simulation analysis, using generalized stochastic Petri nets, allowed to determine the probability of incident-accident conversion, which in this example is 0.6.

This kind of analysis creates a general method for forecasting the number of accidents on the basis of the number of incidents (serious incidents) in air traffic. Development of such a method would be an important step towards the use of TLS concept in a practice of air traffic management. However, this is dependent on the repeatability of results for other aviation incidents. Verification of such relation is planned in the future. If it turns out, that for other air traffic events, the relationship between the incident an accident is of a similar nature, it would seem justified to try to formulate a general theorem in this regard.

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