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Method of Serious Traffic Incidents Analysis with the Use of Stochastic Timed Petri Nets

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ABSTRACT: One of the primary sources of information and inspiration in the creation of new, more secure solutions in traffic organization are the occurrences with most serious consequences called accidents (air), serious accidents (rail) or catastrophes (road, sea). Accidents investigation is usually conducted in terms of searching for the reasons of these events and to make preventive recommendations aimed at elimination of these causes. In this paper, it is proposed to draw more attention to the events of somewhat less severity of the consequences - serious incidents (air), traffic conflicts (road) and incidents (rail, maritime). A model of real serious traffic incident, created with the use of stochastic, timed Petri nets is presented. Simulation experiments were carried out, which allowed for determination of the probability of transformation of the incident into the accident. The proposed method of analyzing serious traffic incidents also allows to determine the effectiveness of the barriers that have prevented an accident in a real occurrence.

1 INTRODUCTION

Transport traffic safety is one of the most important goals of organization, management and supervision systems in different modes of transport. Proposals for new organizational and technical solutions are often the result of the analysis of the causes and circumstances of accidents, especially the most serious, which resulted in numerous fatalities. Examples of major transport accidents that resulted in key changes in safety perception were: an air traffic accident in Tenerife in 1977 (Netherlands Aviation Safety Board 1978), the Estonia ferry disaster in the Baltic Sea (Joint Accident Investigation Commission 1997), catastrophe of Senegalese ferry MV Le Joola off the coast of Gambia (Republique du Senegal 2002), the train disaster in Ufa near Chelyabinsk in Russia in 1989 (Surhone et al. 2010), aircraft collision over Überlingen (Brooker 2008). An example of a solution resulting from the last of these cases was systematic and comprehensive regulation of the use of traffic collision avoidance systems for aviation TCAS (Federal Aviation Administration 2011). A major change introduced into procedures was the rule of absolute subordination to the communicates of TCAS system, even in the case of different air traffic controller command.

Accidents investigation is usually conducted in terms of searching for the reasons and circumstances favourable to these events. These studies are carried out within the existing organizational structures that make use of well-established and legally sanctioned methods and procedures. They are directed at determining the causes of accidents and to make preventive recommendations aimed to eliminate these causes, and indirectly prevent the formation of analogous events in the future.

In transport, there are numerous safety barriers established - technical, procedural, organizational, management - in order to prevent accidents with catastrophic consequences. In this paper a method of traffic incidents analysis is proposed. Of course, incidents (serious incidents) are also examined by the aforementioned institutions. This examination, however, as in the case of accidents is focused on searching for reasons. Analysis of the incidents, however, also allows for exploration of possible scenarios for the development of the incident and checking what other effects it could bring about. This approach allows evaluating and verifying whether in this particular case, no transformation of the incident into accident was the result of hedging activities, or whether it was a coincidence. In the latter case one should suggest preventive recommendations relating to these events that did not actually occurred. In other words, it comes to the belief that set up safety barriers will work forever. Also in slightly different circumstances, such as worse weather conditions, or worse technical condition of the vehicle, etc. The fact that safety barrier worked in a particular incident does not give us a guarantee that it will be in any case.

In this paper it is proposed to analyze serious incidents quantitatively. The proposed approach is illustrated in the example of air traffic. The term "serious air traffic incident" usually involves a very dangerous event in which almost all barriers to protect against accidents have failed (in most cases except one). This allows to attempt to quantify the likelihood of failure of each of the elements of the safety assurance system. Unfortunately, in most cases, we do not have enough data that allows for a statistical determination of the frequency of events that make up the accident scenarios. There are also no measurement methods that can achieve such data. This is due to two reasons. The first is the extraordinary rarity of these events, and, until recently, a lack of public awareness of the need to report events of less important safety consequences. The second reason is very frequent participation of the so called human factor in these events (Kobyliński 2009). Analysis of the probability of particular human action or the probability of human error is very uncertain and subjective. The only available method of obtaining real knowledge about such events is the use of experts' opinions. These, obviously, are characterized by a lack of precision and clarity not allowing the use of such methods in the probabilistic analysis (Berg 2013).

This paper is divided into five sections. The first contains the introduction to the research problem. The second part deals with the principles and practice of investigating the causes of aviation accidents. The third section shows the process of formation of a serious incident and the essence of traffic incident analysis focused on searching for the quantitative assessment of the effectiveness of the safety barriers. The fourth presents a simple example of a serious incident analysis, explaining the method of analysis of the effectiveness of safety barriers. The fifth section contains summary and presentation of the findings of the research.

This paper is an updated and revised version of (Skorupski 2013). The update takes into account recent activities and insights regarding possibilities to use stochastic, timed Petri nets in serious traffic incidents analysis. Moreover, it reflects questions which arise at the TransNav 2013 Conference in Gdynia in June this year.

2 AIR TRAFFIC ACCIDENTS AND INCIDENTS INVESTIGATION

Polish aviation regulations define three categories of events (Aviation Law 2002):

- accident - 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 - 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 - 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).

Air traffic events investigation is regulated both by international and national regulations: Annex 13 to the Chicago Convention (ICAO 2001) and EU Regulation 996/2010 on the investigation and prevention of accidents in civil aviation (European Union 2010). These documents define the basic principles of accidents and incidents investigations, which include:

- key role of EASA,
- cooperation between committees investigating accidents in different countries,
- the absolute need for reporting incidents,
- recommendations for accident prevention.

The basic legal act of national importance "Aviation Law" in Part VI "Air Navigation" in Chapter 3, "Managing the flight safety and investigating accidents and incidents" regulates the operation of accident investigation committee (Aviation Law 2002). Detailed rules of proceeding are defined in Regulation of the Minister of Transport on accidents and incidents (Minister of Transport 2007).

In recent years, much emphasis is put on a proactive approach to ensuring the safety of air traffic. It is based on preventive reporting of damages and failures, which is obligatory to those who have the ability to detect them before they cause dangerous traffic event.

However, for many years the most important and the most seriously considered are the recommendations issued by the State Commission for Aircraft Accident Investigation (PKBWL) as a result of the study of the reasons for air events. The PKBWL consist of: chairman, two deputy, secretary and members - experts in the field of aviation law, flight training, air traffic, aviation technology maintenance, aircraft construction, and aviation medicine. In some cases additional assistance of experts is necessary, both from the above mentioned areas and from the field of navigation, rescue, meteorology and aeronautical communications.

Generally an air traffic event examination procedure begins with the notification to the accident investigation committee. Then the chairman of the committee shall qualify the event by severity of its effects. Accidents and serious incidents are investigated by PKBWL. Incidents and other events (such as damages or defects detected) examination may be provided by the user of aircraft, air navigation services provider, airport management.

The basic principle of PKBWL operation is to improve the safety of air transport, rather than find and punish the guilty. For this reason, the regulations specify the purpose of the Commission, stating that it does not adjudicate the guilt and responsibility. At the same time law guarantees full security and freedom of testimony for all people co-operating with the Commission (including the participants of the event), by introducing a clause that the release of the results of Commission's investigation can be made only with the consent of the court. And the court while deciding whether to release the results should take into account whether such making information public is more important than the negative consequences that may result for the air transport safety. Additional protection is granted to members of the Commission, which must not be questioned as a witness as to the facts which might reveal the results of investigation.

All these factors make the study of the causes of air events, carried out in accordance with the rigors of this legislation, an extremely effective way to discover the mechanisms that lead to accidents. Preventive recommendations lead to the elimination of these mechanisms and thereby reduce the number of events.

However, analysis of Commission's reports shows that these recommendations are focused on the causes and circumstances leading to the event. In the case of incidents and serious incidents it is implicitly assumed that organizational, technical and human barriers which worked properly and prevented the development of incident into accident, will work properly in other similar situations. This assumption may not be true. One can identify many cases of similar incidents in which a barrier in one of them worked, and in another did not. Analysis of the effectiveness of these key barriers in air traffic incidents enables the quantitative assessment, which is very difficult using other methods.

3 ANALYSIS OF AIR TRAFFIC INCIDENTS

As mentioned in previous sections, this paper proposes an analysis of serious incidents not only in terms of reasons of their occurrence, but rather the probability of their transformation into an accident with consequences of loss of life or serious damage to equipment. In (Skorupski 2012a) a model (in the form of Petri net (Jensen 1997)) of conversion of incident into accident was presented. The actual incident occurred at Chopin Airport in Warsaw, where a simultaneous takeoff of two aircraft on two intersecting runways occurred. Fault tree of this incident is shown in Figure 1.

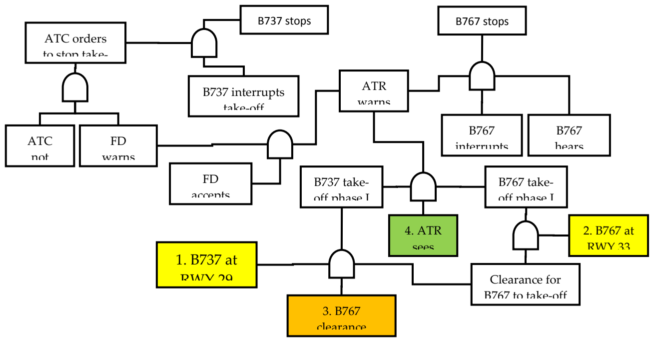

Figure 1. Fault tree of serious incident 344/07.

In this tree, we can distinguish the events that make up the incident. The most important are: occupying at the same time two intersecting runways (events 1 and 2 in Figure 1) and the key event for the creation of an incident - acceptation by the B737 crew, clearance for takeoff issued to other aircraft (event 3). Qualitative analysis of this event was performed by PKBWL. It should be noted it is not involved in quantitative analysis, which means that it does not consider how the proposed preventive recommendations reduce the likelihood of an accident. They are looking for such events (actions, omissions, organizational errors etc.), which elimination would break the causal sequence leading to the incident.

From the point of view of the method of serious incidents analysis, as proposed in this paper, the most important event is marked by number 4 in Figure 1. It represents the most important safety barrier, which protected before the accident (Lower et al. 2013b). It turns out that preventive action aimed at the elimination of the possibility of breaking this barrier moves the evaluation of probability of accidents into the area of *very rare* values. According to probability scale used in this paper it means reduction of incident-accident transformation probability to about 10^{-7}. This means a significant increase in the level of safety. Elimination (or reduction of the likelihood) of the barrier breaking is practically possible. Pilot training should be carried out to increase the conviction of the need to monitor the airfield during the taxiing procedure and while waiting for permission to take-off. One can also consider the introduction of recommendation to carefully observe other traffic into the operating instructions. Usually, there are several scenarios that lead to the failure of all barriers. These scenarios can be analyzed using event tree method (ETA). An example of the analysis is presented in (Lower et al. 2013a). This analysis allows to determine the probability of conversion of the incident in the accident, but also to quantify the effectiveness of the barrier. In the case of high risk of breaking the barrier, propose of preventive measures in relation to the events that have played a positive role in preventing the accident should be also considered. In this case, those measures should be based on strengthening the effectiveness of the barrier. This is a novel approach, but it seems appropriate and effective. It may give better results in prevention than the standard prophylactic recommendation for reasons of incidents. Especially as one can learn the quantitative characteristics (probability) characterizing such events.

Speaking about the risk of breaking the safety barrier one should understood the combination of probability of breaking it and possible consequences. We can determine the probability by event tree analysis. Determining the consequences may require further analysis of aircraft movements dynamics or use of other methods to estimate the effects of an accident, for example evaluation by experts (Hanninen et al. 2012).

4 EXAMPLE OF TRAFFIC INCIDENT ANALYSIS

In this section serious air traffic incident will be presented and analyzed with the use of Petri nets. The incident happened at Chopin airport in Warsaw. A method described in (Skorupski 2012b) was used during analysis.

4.1 *The course and the circumstances of the incident*

An example concerns the incident No. 291/05, which took place in winter conditions, on 31 December 2005 (Civil Aviation Authority, 2008). There was only one aircraft involved - Boeing 757-200 (B757). During the take-off operation, in acceleration phase, the crew felt a sudden shudder to the left and immediately performed a rejected take-off procedure. The maximum velocity of the aircraft was 70 knots. The crew of another aircraft, waiting for permission to take-off, reported by the radio that they can see flames in the left engine of B757.

After discontinuation of the take-off, the plane has been surveyed. No damages were found. Engine test has also been performed. Its operating parameters were consistent with the standard, resulting in the crew found that the engine is working properly. The crew reported to be ready to take-off again. Due to the large number of operations on that day, expected waiting time for permission to taxi was 45 minutes. In this situation, captain made a consultation with an experienced mechanic, after which he decided to cancel the flight. As a result of this decision, the plane was suspended in operation and two days later a detailed borescope study of left engine was made. Borescopes are commonly used in the visual inspection of aircraft engines, aeroderivative industrial gas turbines, steam turbines, diesel engines and generally in cases where the area to be inspected is inaccessible by other means. The inspection showed serious damage to the compressor blades, which excluded further use of this engine.

The period of suspension in operation of the aircraft was used to carry out the survey of the right engine, which did not show any irregularities so far. During the survey serious damages to the right engine compressor blades were also found. They were of the same nature as in the left engine. This precluded also the right engine from further operation.

4.2 *The causes of the event*

PKBWL investigated this event and determined that the most likely cause of the incident was a collision with a foreign object of a soft nature, pulled into both engines during the take-off operation. As a result, there was a density shock, local air density increase, causing overload and breakage of the rotor blades in both engines. Contributing factors to the creation of such a situation were: winter weather and release of the parking brake while switching aircraft's thrust automaton, which increases the likelihood of snow and ice to be sucked into the engine.

4.3 *Analysis of the causes of the event and activities of the Commission*

As always in such cases, PKBWL was focused on the causes of the incident. The Commission's report shows that its actions were in full effect. The cause was aspiration of snow during take-off. Commission adopted, as always in such situations, preventive recommendations. They consisted of:

- recommendation to use the information about the circumstances of this event for pilots and technical crew training, as well as the personnel responsible for the winter maintenance at the airport,
- consideration of the possibility to change internal procedures and equipment to improve winter maintenance of the airport,
- consideration to improve procedures of reporting technical problems, and their removal by the technical staff of the carrier.

As one can see, preventive recommendations are focused mainly on the elimination of events that led to the incident. In this case, to eliminate the possibility of aspiration of snow into the engine. It should be noted, however, that events affecting the safety of the travelling passengers, took place also in the cockpit of the B757 and during technical inspection. An analysis of the incident, along with the model of transforming it into an accident, using Petri nets is presented below.

4.4 *Model of incident*

The process of transformation of analyzed incident into accident can be modelled with Petri net:

$$S_{INC} = \{P, T, I, O, M_0, \tau, X, \Gamma, C, G, E, R, r_0\} \quad (1)$$

where:

P – set of places,

T – set of transitions, $T \cap P = \emptyset$,

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

I, O: T → B(P), where B(P) is the multiset over the set P, and functions I, O are determined for transition $t \in T$ as:

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

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

$M_0: P \to \Sigma_+ \times R$ – initial marking,

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

$X: T \times P \to \mathbb{R}_+$ – random variable, describing random time of realization of traffic event (transition) t leading to traffic situation (place) p,

Γ – nonempty, finite set of colours,

C – function determining what colour 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 weight 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 colour 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 $R \subseteq \mathrm{R}$,

r0 – initial time, $r \in R$.

Petri net model of this incident is shown in Fig. 2.

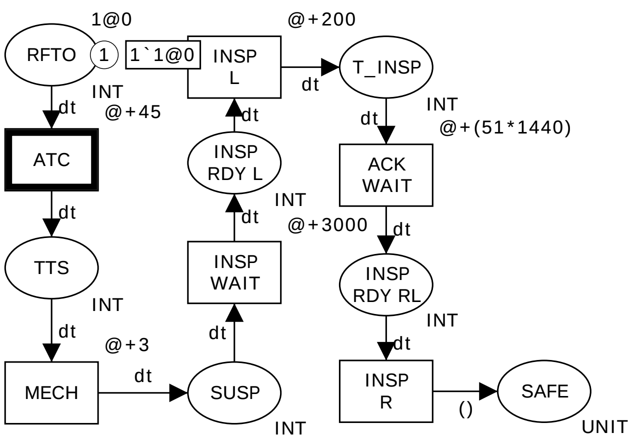

Figure 2. Basic model of air traffic incident 291/05

This model allows tracing the course of the actual incident, without taking into account other events that could change it. Parameters of the model presented in Figure 2 reflect of both the static and dynamic phenomena occurring in the analysed incident.

Designation of places is as follows:
– *RFTO* - aircraft ready for takeoff (p_1),
– *TTS* - aircraft crew knows the time to beginning of taxiing process (p_2),
– *SUSP* - aircraft use is suspended until left engine borescopes inspection (p_3),
– *INSP RDY L* - aircraft is ready for left engine borescopes inspection (p_4),
– *T_INSP* - aircraft starts waiting for admission to flight (p_5),
– *INSP RDY R* - aircraft is ready for right engine inspection (p_6),
– *SAFE* - there is no takeoff before detection of failures in both engines (p_7).
– Designations of transitions are as follows:
– ATC - controller’s decision to wait for taxiing (t_1),
– MECH - consultation with an experienced mechanic (t_2),
– INSP WAIT - waiting for the borescopes inspection of the left engine (t_3),
– INSP L - left engine borescope examination (t_4),
– ACK WAIT - waiting for authorization to use the aircraft (t_5),
– INSP R - right engine inspection (t_6).

4.5 *Simulation experiments*

By using CPN-Tools software package - a tool for creation and simulation of models using Petri nets, a number of simulation experiments were conducted. Their goal was to:
– find the probability of transformation of the incident into accident, where many elements of the model were treated as random values, but with expected values equal to those actually observed in the incident,
– seek the barrier, which appropriate functioning has prevented the creation of an air accident, and which caused that in fact only a serious incident occurred.

The plan of experiments assumed modification of the model resulting from scenarios of conversion of the incident into an accident. The following scenarios were considered:

1 There is a small traffic at the airport - in this case the time necessary to begin taxiing at the second attempt to take-off would be small and the captain would have decided to begin the take-off procedure instead of consulting the situation with the mechanic.
2 The captain does not choose to consult the problem with an experienced mechanic - being sure that the positive results of left engine inspection ensure safety.
3 Right engine survey is not performed - in case of quick repair of the left engine.

To perform analysis of the above scenarios, it was necessary to modify the basic model in such a way as to take into account the probability of each event, and to reproduce a random durations of events. Both groups of values have the large impact on the probability of conversion from the incident into an accident. Petri net for examination of scenarios 1 to 3 is shown in Figure 3.

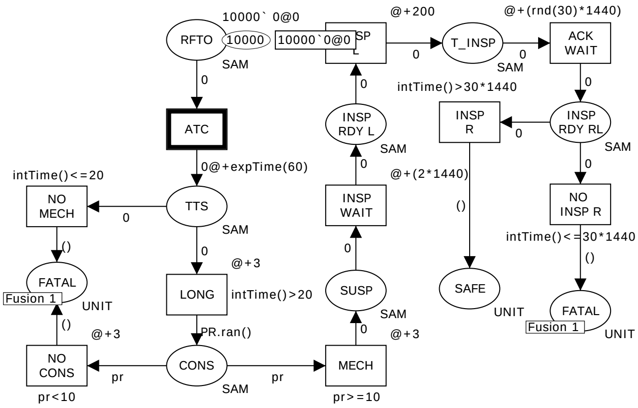

Figure 3. Model of air traffic incident 291/05 for analysis of transformation of incident into accident.

Compared to Figure 2 there are new places in this model:

– CONS - pilot is considering the consultation with a mechanic (p_8),
– FATAL - take-off with inoperative engine was performed, which would be likely to result in an accident (p_9),
– There are also additional transitions:
– NO MECH - pilot decides to begin the second take-off without consulting the situation with a mechanic, because of short waiting time to begin taxing (t_7)
– LONG - recognition of the taxi waiting time to be long, that makes the pilot to consider the decision to undertake consultations with the mechanic (t_8),
– NO CONS - captain decides not to take the consultation with the mechanic (t_9),
– NO INSP R - decision not to examine the right engine due to the short waiting time for decision allowing the use of an aircraft (t_{10}).

Analysis of a simple event tree aimed at determination of probabilities of the above scenarios indicates that the total probability of taking off with a damaged engine can be described by the equation:

$$P_k = P_a + (1 - P_a) \cdot P_b + (1 - P_a)(1 - P_b) \cdot P_c \quad (2)$$

where

P_a, P_b and P_c are the probabilities of the scenarios, respectively 1, 2 and 3.

After transformation we obtain

$$P_k = P_a + P_b + P_c - P_a \cdot P_b - P_a \cdot P_c - P_b \cdot P_c + P_a \cdot P_b \cdot P_c \quad (3)$$

Assuming that the second attempt of take-off with severely damaged one or two engines would cause an accident, formula (3) is also a formula for determining the likelihood that analyzed incident becomes an accident.

Simulation experiments required modification of the model shown in Figure 3 in the following way

1 Modification of function $e \in S$ describing an arc between transition t1 (ATC), and the place p2 (TTS). The parameter of function expTime appearing in this expression, determines the expected time, after which the beginning of taxiing for take-off is possible. In the case of very low traffic, this time will be close to 0; otherwise it can reach values greater than 60 minutes.
2 Probability of consulting the decision with a mechanic is modelled using PR.ran function that generates a random value uniformly distributed in the range [0..100]; it can be identified with the values of probability. Depending on the value of generated random variable pr, which is the label of the output arcs from place p8 (CONS), the values of function G for arguments t2 (MECH) and t9 (NO_CONS) determine the probability of consultation with a mechanic (transition t2 MECH) or no consultation (transitions t9 NO_CONS).
3 Time of suspension in service of the aircraft is represented by the value of function X(ACK_WAIT, INSP_RDY_R). Function rnd appearing in this expression determines the random duration of the aircraft remaining in the suspension, expressed in number of days. This random variable is described with a Poisson distribution with a parameter which is also the rnd function parameter.

The results of the 10,000 simulation runs show that at accepted values of probability and time constants of the dynamic analysis, the likelihood of continuation of airplane operation with at least one of the engines being defective is 0.62. It should be assumed that such an event would end in the destruction of the engine during the next take-off, and this would result in the inevitable accident with catastrophic consequences. It is therefore the probability of converting the incident into accident determined by simulation, at random values characterizing the events in the formation of the incident. It was adopted that the expected values of random variables characterizing the dynamic events (in time domain) are equal to the values observed during the actual incident.

Sensitivity analysis of the likelihood of conversion of the incident into accident, according to the application of additional measures (in an ad hoc or systemic manner) to eliminate specific threats (scenarios) was also conducted. For example, the relationship between probability P_k and traffic volume with corresponding to this time of waiting to begin taxiing (scenario 1) is shown in Figure 4. Probability of conversion of the incident into accident, depending on the likelihood of resignation from the consultation with the mechanic, which corresponds to a probability of the scenario 2 is shown in Figure 5. Dependence of P_k on the waiting time for authorization for the plane to operate (scenario 3) is shown in Figure 6.

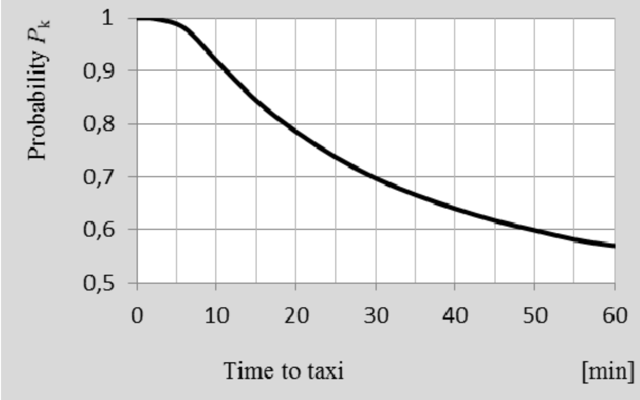

Figure 4. Relation between P_k and estimated time to begin of taxi procedure.

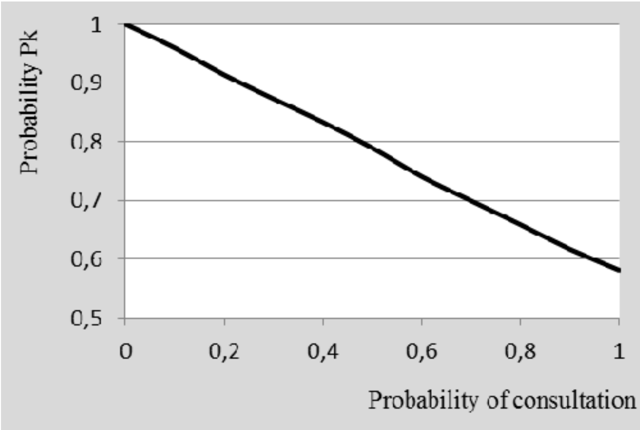

Figure 5. Relation between P_k and probability of consultation with the experienced mechanic.

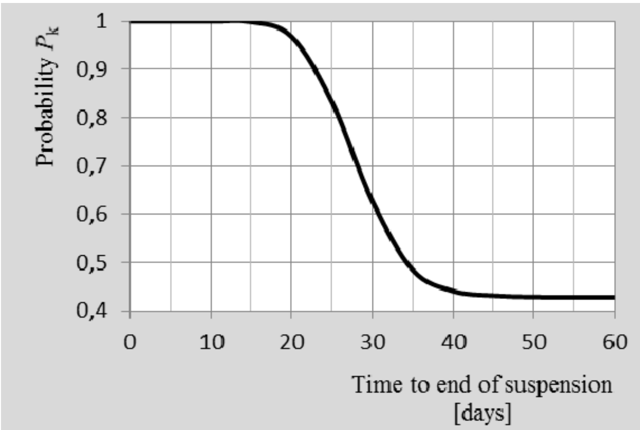

Figure 6. Relation between P_k and time to end of suspention.

5 SUMMARY AND CONCLUSIONS

The analysis of scenarios, transforming the incident into accident clearly shows the potential of analyzing incidents that can be used to improve transport safety. Cited in Section 3, the analysis of incident 344/07 shows the dependence of the possibility of an accident on the actions of ATR 72 aircraft waiting in line for take-off. Its activity in the observation of the neighbourhood area was crucial to avoid an accident. However, this barrier is not permanent. The pilot of this aircraft could be busy with his own take-off procedure and could not observe the situation on the runways. One might then consider the introduction of such a procedural requirement. The analysis of only the reasons for such an incident does not result in this kind of safety recommendations.

These findings are confirmed by the analysis of the incident 291/05, which uses different analytical methods and different types of modelling. According to the author, this suggests that in many similar situations of traffic incidents, also in other modes of transport, it is possible to receive interesting and important results. The essential common element may be a demonstration of effectiveness of the various barriers aimed at preventing accidents with catastrophic consequences. Sample analysis results for the case in question are presented in Section 4.

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