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Modelling of Traffic Incidents in Transport

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ABSTRACT: Safety is one of the most important criteria for assessing the transport process. The traffic process in available traffic space are partly organized and planned. However, these plans are subject to numerous disturbances of probabilistic nature. These disturbances, contribute to the commission of errors by the operators of vehicles and traffic managers. They lead to traffic incidents, which under certain circumstances may transform into accidents.
In the paper the method of modelling traffic incidents, using different types of Petri nets is presented. Example of the serious air traffic incident shows the opportunities offered by the application of this modelling technique. In addition, the possibility of its use in maritime transport, for example, modelling of traffic at the waterways intersection is presented.

1 INTRODUCTION

Transport is a complex system combining advanced technical systems, operators 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 sea, air or railway transport, the risk is traditionally identified with the accidents, 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 transport.

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

- 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).

In this paper, traffic incidents in transport are subject of interest. A method for modelling these incidents with use of Petri nets theory is presented. This method allows the analysis of the causes of incidents as well as assessing the probability of transformation of incidents into accidents. The method uses coloured, stochastic, timed Petri nets, with the time assigned to markers.

The first part of the paper presents basic information about Petri nets. The next discusses the specificity of the analyzed transport systems and a method of modelling those using coloured, timed Petri nets. The next two chapters contain examples of analysis using the proposed method. The first example comes from the air traffic and presents the calculation of the possibility of transforming a serious incident into an accident (Skorupski 2010). The second example concerns the maritime traffic and demonstrates the applicability of the method for modelling conflict at the intersection of the waterways.

2 THE BASICS OF PETRI NETS

Petri nets provide a convenient way to describe many types of systems. Especially a lot of applications they found in software engineering, where they are used particularly to describe and analyze concurrent systems. There is a rich literature in this subject, e.g. (Jensen, 1997, Szpyrka, 2008), which also contains an extensive bibliography of the topic. In this paper it was shown that Petri nets can also be used for modelling transport systems, particularly the traffic processes. The examples concern the analysis of traffic safety problems in air and maritime transport, but a similar approach can be applied to other modes of transport.

2.1 *Types of Petri Nets*

Depending on the needs, one can define different Petri nets with certain properties. However, there is a set of characteristics that are common to such networks. The basis for building a Petri net is a bipartite graph containing two disjoint sets of vertices called places and transitions. Arcs in this graph are directed and single, and therefore it is a Berge graph. A characteristic feature of the graph used in Petri nets is that the arcs have to combine different types of vertices. Below are presented brief definitions of basic types of Petri nets: first low, then a high level (Marsan et al. 1999). Detailed analysis of the properties of various types of nets is included in the literature and will not be discussed here.

2.2 *Generalised Petri net*

Generalised Petri net (GPN) is described as:

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

where:

P - set of places,

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

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

I, O, H: $T \rightarrow B(P)$

where $B(P)$ is the superset over the set P.

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

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

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

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

GPN is characterized by the fact that the functions described on arcs: $I(t,p)$, $O(t,p)$ and $H(t,p)$, can take values greater than 1, which is equivalent to the presence of multiple arcs between nodes.

2.3 *Marked Petri net*

Marked Petri net (MPN) is described as:

$$S_M = \{P, T, I, O, H, M_0\} \tag{2}$$

where: $N = \{P, T, I, O, H\}$ - generalised Petri net,

$M_0: P \rightarrow \mathbb{Z}_+$ is the initial marking, i.e. a function assigning an integer to each place.

We also say that the marking specifies the number of markers assigned to each of the places.

Initial marking, along with the rules governing the dynamics of the net, that is rules of marking changes, determine all possible reachable markings. The same network but with different initial markings will describe different systems.

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

$$\forall p \in t^+, M(p) \geq I(t,p) \wedge \forall p \in t^o, M(p) < H(t,p) \tag{3}$$

Firing of transition t, active in marking M removes from any place p belonging to the set t^+, as many markers as function $I(t,p)$ determines. At the same time it adds to any place p from the set t^-, as many markers as determined by the $O(t,p)$ function. This means firing of transition t will change actual marking to M' such that

$$M' = M + O(t) - I(t) \tag{4}$$

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

2.4 *Place-transition Petri net*

Place-transition net (PTN) is a generalized, marked Petri net, supplemented by the characteristics of places interpreted as their capacity, i.e. the maximum number of markers that can accommodate any of the places. Thus, a place-transition net can be written as

$$S_{PT} = \{P, T, I, O, H, K, M_0\} \tag{5}$$

where: $N = \{P, T, I, O, H\}$ - generalised Petri net,

$K: P \rightarrow \mathbb{N} \cup \{\infty\}$ – capacity of places, and the symbol ∞ means that a place has unlimited capacity,

$M_0: P \to \mathbb{Z}_+ \wedge \forall p \in P: M_0(p) \leq K(p)$ – initial marking.

2.5 *Timed Petri net*

With timed Petri net (TPN) we have to do, when firing a transition is not immediate, but it takes a certain time. This means that definition of such net would take into account the timed characteristics described on the transitions

$$S_T = \{P, T, I, O, H, M_0, \tau\} \tag{6}$$

where $S_M = \{P, T, I, O, H, M_0\}$ – marked Petri net,

$\tau: T \to \mathbb{R}_+$ – delay function, specifying static delay $\tau(t)$ of transition t.

Characteristics on transitions may determine time associated with firing of the transition in different ways. In particular, this value may be described by a deterministic or a random variable with a given probability distribution. In the latter case, we may talk about the stochastic network. In addition to static delay it is sometimes convenient to use dynamic delay $\delta(t)$, defined as the rest of the time remaining until the firing of the transition t.

In timed Petri nets, the problem of verifying the conditions required for activation of transitions is closely related to treatment of transitions that have not been fired due to the expiration of the time less than $\tau(t)$, and which had lost activity. Depending on the specific system being modelled, there are three approaches possible:

- lack of memory – after firing of any transition, dynamic delays for all transitions are set back to the initial value, i.e. $\forall t \in T, \delta(t) = \tau(t)$,
- active memory – in case of firing any transition t, all other transitions, which lost activity as a result, shall take the value of dynamic delay equal to the initial value (as in the lack of memory case), and the transitions that remain active - will retain their existing value of $\delta(t)$,
- absolute memory – no matter which transition fires, all other transitions retain their dynamic delay value, and at next activation, countdown of the time remaining for firing continues.

2.6 *Coloured Petri net*

The main difference between generalised and coloured nets is the ability to define markers of different types. This is possible in coloured Petri nets (CPN). Marker type is called a colour. Each place in the coloured net is assigned a set of colours that it can store. Expressions are assigned to arcs and transitions that allow manipulating various types of markers. Coloured Petri net can be written as

$$S_C = \{\Gamma, P, T, I, O, H, C, G, E, M_0\} \tag{7}$$

where $S_M = \{P, T, I, O, H, M_0\}$ – marked Petri net,

Γ – nonempty, finite set of colours,

C – function determining what colour markers 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.

2.7 *Coloured, timed Petri net*

It is possible to combine the idea of CPN and TPN. In this case the following structure of coloured, timed Petri net (CTPN) is formed

$$S_{CT} = \{\Gamma, P, T, I, O, H, C, G, E, M_0, R, r_0\} \tag{8}$$

where: $S_M = \{P, T, I, O, H, M_0\}$ – marked Petri net,

Γ – nonempty, finite set of colours, each of which can be timed, that means whose elements are pairs consisting of colour and a timestamp,

C, G, E – have the same meaning as in the case of CPN, but taking into account the fact that certain sets of colours can be timed,

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

r_0 – initial time, $r \in R$.

In the TPN it is necessary to implement a model clock, which defines the local time flow. This is achieved usually by using timestamps, which are generally associated with the markers. This clock is used to determine which of the transitions can be activated. The condition for activation is the existence, for all input places of the transition, markings, in which all timestamps are smaller than local time.

The timed coloured Petri net changes the meaning of the marking M, in relation to the timed colours. In this case, the marking consists of a number of markers together with their timestamps, which may be different for each of the markers.

State of the system modelled by coloured, timed Petri net is called the pair (M,r), where M is the marking and $r \in R$ is a timestamp.

2.8 *Petri nets properties*

For each Petri net we can determine among others: the reachability graph, reachability set, evaluate the reversibility, the presence of deadlock, liveness, and boundedness. In the presented method of analysis, the most important property of the net (modelling a traffic incident) is the reachability of selected states (markings) from initial marking M_0. It allows assessing the probability and time of transition to those selected markings. Particularly important are the dead markings, because they illustrate the situations in which we can assess whether the traffic process results in an incident or in an accident.

In many cases, the reachability graph is very complex and difficult to study, especially with the analytical methods. In those cases, methods to reduce the graph will be extremely useful (Sistla A.P & Godefroid P., 2004). The transport applications will use mostly the reduction related to stable sets of transitions. Reduction using symmetry will be used much less frequently.

3 MODELLING OF TRAFFIC INCIDENTS WITH THE USE OF PETRI NETS

As it is widely known, the traffic incidents in transport systems 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.

Transport system includes:

- passive components, namely infrastructure, including its characteristics,
- active elements, namely transport vehicles, performing tasks and creating a traffic flow,
- organisation, i.e. the relations between the elements of the transport system, aimed at realisation of transport tasks.

In this paper active elements of the transport system are studied, dealt dynamically, during the realisation of their task - that is, the traffic processes. Infrastructure and organisation are limitations to this process and must be, to some extent considered during its modelling.

The traffic process is ordered and designed to reach a specific destination of vehicles using the road (suitably organised in various branches of transport), including the organisational rules, regulations and standards to ensure the safety of all traffic participants. In this process, there are time periods in which vehicles move in a planned manner, in accordance with standard procedures. These fragments of the traffic process are characterized by its duration. The process is dynamic, because there is a change of position of vehicles in time, but from the point of view of the purpose of analysis, which is posed in this paper, it can be regarded as static. It is possible because in those time periods there are no events influencing the level of safety, and procedures such as changing speed or direction are planned, in accordance with the constraints resulting from characteristics of infrastructure components and tailored to the exploitation characteristics of vehicles.

Between these fragments there are traffic events which are extracted whereas the scope of the analysis. In the case of an analysis designed to assess the safety of the traffic process, these events are defined as having an impact on safety of traffic. For such events, one can include:

- occupation of conflicting point of the road (streets junction, runway, waterways crossing) characterised by the fact that there may be only one vehicle on it, or they may be few, but it is necessary to specify the order of passing this point by vehicles, as movement continued by each of them independently can lead to collisions,
- decision by the vehicle operator to continue the movement, or to change its parameters (direction, speed), in particular the decision to stop, or to realise an emergency manoeuvre to avoid collision,
- decision by the traffic dispatcher (air traffic controller, the railway station dispatcher, coordinator of traffic in seaport) of a similar nature,
- decision by the vehicle operator to take action that is inconsistent with the decisions (recommendations) of traffic dispatcher,
- occurrence of dynamic and intensive meteorological phenomena (storm, heavy fog), or other phenomena of an environmental nature that may affect the traffic process,
- occurrence of events (failures) associated with the vehicle or traffic control system, which cause hazard to vehicles.

The above mentioned events may have the nature of conditions, which logical value can be evaluated. In this case they are represented by a Boolean *true* or *false*. They may also have a nature of a certain process, mostly short-term. In this case, the event will be represented by its type, but also by duration.

Such an approach to the traffic process allows the use of Petri nets for modelling it. Stable traffic situations correspond to places in the net, traffic events – to transitions. Markers in places can be identified as traffic participants or states of environment. Participants may have different traffic characteristics. For example, we may consider several types of vehicles of varying size and performance. We may also consider objects constituting the disturbances, affecting the traffic process, such as pedestrians on the road, ground service cars on taxiways at the airport. Similar interpretation can be applied to states of environment or external events. Typically, these are logical conditions, and therefore existence of a marker in corresponding place represents the occurrence of the event.

As one can see the markers are of different types, which suggest the need to use coloured Petri nets. This is obviously a universal solution, but in simpler cases, the model of traffic incident can use a simpler place-transition net. This is possible if parts of the net using different types of markers are mostly disjoint. In cases where the same places are used by different types of markers CPN must be used.

Unlike other typical applications of Petri nets, in modelling traffic processes in transport, in most cases, it is necessary to use the timed Petri net. This results from the fact that time and the associated dynamic phenomena are often crucial in the analysis in this area. For example, while modelling traffic incidents, it is usually necessary to examine the time sequence of individual traffic situations, resulting in specific sequence of occupation of conflicting points. This sequence may decide about the occurrence of the accident or its avoidance. In specific cases, sometimes it is preferable to use timed characteristics associated with transitions, and sometimes associated with markers.

There is also a class of applications of Petri nets for modelling the traffic processes in transport, where it is sufficient to use non-timed nets. This is possible when considering only the sequence of events leading up to the situation of interest, or sequence of events as a consequence of certain initiating event. This is in fact a study of an event tree analysis, fault tree analysis, or bow-tie analysis. Analytical techniques derived from the theory of Petri nets, applied in this case, can produce very interesting results; in particular, can accelerate obtaining satisfactory results with high accuracy.

This paper describes two examples traffic incidents examination. First one is air traffic incident, with particular emphasis on modelling the process of transformation from the incident to an accident. Stochastic TPN with time associated with transitions was used. The second one is a model of waterway intersection, where two conflicting traffic flows occur. In this case stochastic CTPN was used. Term “stochastic” means that the time delays occurring in the net are partially random values of given probability distributions. Network structure itself, however, is deterministic.

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, and its cause was classified as a "human factor" and the causal group H4 - "procedural errors" (Civil Aviation Authority 2009).

4.1 *Circumstances of the serious incident*

In the incident on 13th of August 2007 participated two aircraft – Boeing 737 (B737) and the 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 the first to obtain permission to take-off. A moment after confirmation of permission to take-off, both aircraft began start 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. 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, 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 operate 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 are:

- lack of situational awareness at the B737 crew,
- inadequate monitoring of 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, include:

– 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.

TPN model representing this serious incident is shown in Figure 1.

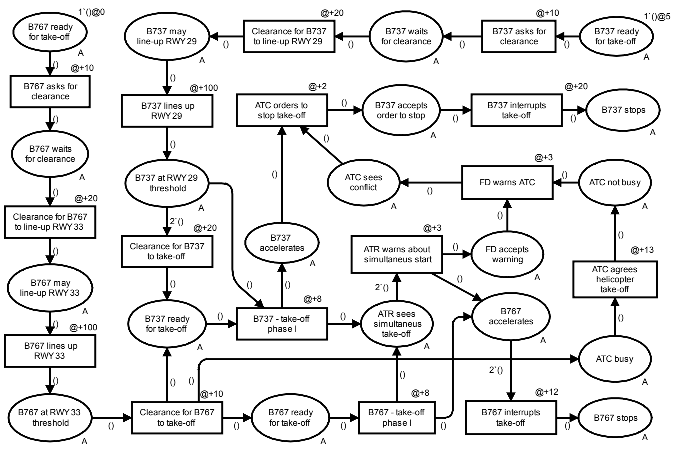

Figure 1. The basic model of a serious air traffic incident 344/07

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. For example, one may check how the situation would change if it was B767 the first aircraft to obtain permission to line up the runway.

In the presented example, 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.
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 can 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. 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 taxiing and lining up the runway. For example, change the set of places is determined as follows.

$$P_w = (P - P_r) \cup P_d \qquad (9)$$

where: P_w - a set of places in the modelled 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 (Figure 1) P_r = {"B767 awaiting permission to start", "B767 can line up RWY 33", "B767 on the RWY 33 threshold", "B767 ready for take-off", "B737 awaiting permission to start", "B737 can line up RWY 29", "B737 on the RWY 29 threshold", "B737 ready for take-off", "ATC not busy", "ATC busy", "ATR observes a simultaneous start"}.

On the other hand P_d = {„ATR warns?", "B737 continues to start", "B737 at the crossing", "B767 hears the warning?", "B767 continues to start", "B767 at the crossing", "B767 interrupts start?", "B767 begins deceleration", "weather?", "good visibility}.

A similar modification was made in regard to transitions, input, output and inhibition functions. An additional issue to consider is change of transition type – from timed to immediate or vice versa.

Petri net to model the transformation of the incident into accident, after reduction is shown in Figure 2.

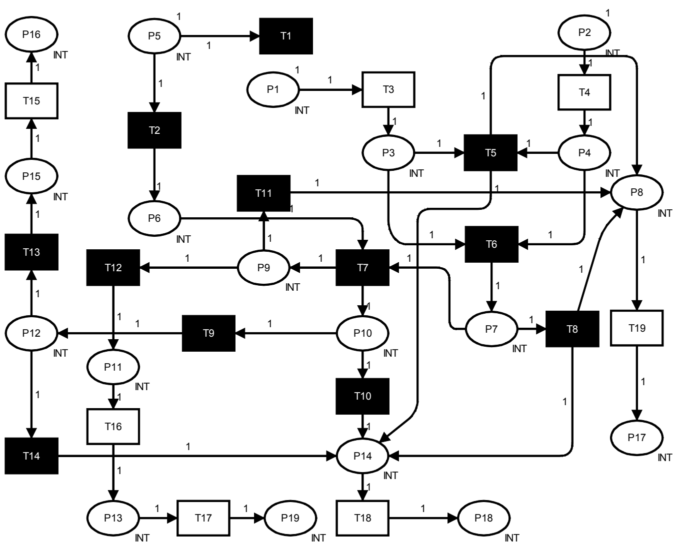

Figure 2. Model of serious incident 344/07 transformation into air traffic accident (after reduction of the states).

This network may be treated as a stochastic timed Petri net. Its analysis allows observing some interesting relationships between a serious incident and the air traffic accident. It also allows determining some quantitative dependencies.

Assume the following places designations: p_1 – „B767 ready for take-off", p_2 – „B737 ready for take-off", p_3 – „B767 accelerates", p_4 – „B737 accelerates", p_5 – „weather?", p_6 – „good visibility", p_7 – „ATR warns?", p_8 – „B737 continues take-off", p_9 – „FD accepts warning?", p_{10} – „B767 hears warning?", p_{11} – „ATC sees conflict", p_{12} – „B767 interrupts take-off?", p_{13} – „B737 accepts order to interrupt take-off", p_{14} – „B767 continues take-off", p_{15} – „B767 begins braking", p_{16} – „B767 stops", p_{17} – „B737 at crossing", p_{18} – „B767 at crossing", p_{19} – „B737 stops".

The set of all states, called a reachability set, for model of accident is presented in Table 1.

The most important markings, from the perspective of the analysis presented in this article, are given in Table 2. Other states as well irrelevant places – were omitted.

Table 1. The reachability set for the model of accident arising from incident 344/07

M_0	$p_1+p_2+p_5$	M_1	p_1+p_2	M_2	$p_1+p_2+p_6$
M_3	p_2+p_3	M_4	p_1+p_4	M_5	$p_2+p_3+p_6$
M_6	p_4+p_6	M_7	p_3+p_4	M_8	$p_3+p_4+p_6$
M_9	p_8+p_{14}	M_{10}	p_7	M_{11}	$p_6+p_8+p_{14}$
M_{12}	p_6+p_7	M_{13}	p_8+p_{18}	M_{14}	$p_{14}+p_{17}$
M_{15}	p_8+p_{18}	M_{16}	$p_6+p_{14}+p_{17}$	M_{17}	p_9+p_{10}
M_{18}	$p_{17}+p_{18}$	M_{19}	$p_6+p_{17}+p_{18}$	M_{20}	$p_{10}+p_{11}$
M_{21}	p_8+p_{10}	M_{22}	p_9+p_{12}	M_{23}	p_9+p_{14}
M_{24}	$p_{11}+p_{12}$	M_{25}	$p_{11}+p_{14}$	M_{26}	p_8+p_{12}
M_{27}	p_9+p_{15}	M_{28}	$p_{11}+p_{15}$	M_{29}	$p_{11}+p_{18}$
M_{30}	$p_{13}+p_{14}$	M_{31}	p_8+p_{15}	M_{32}	$p_{11}+p_{16}$
M_{33}	$p_{13}+p_{15}$	M_{34}	$p_{13}+p_{18}$	M_{35}	$p_{14}+p_{19}$
M_{36}	p_8+p_{16}	M_{37}	$p_{15}+p_{17}$	M_{38}	$p_{13}+p_{16}$
M_{39}	$p_{15}+p_{19}$	M_{40}	$p_{18}+p_{19}$	M_{41}	$p_{16}+p_{17}$
M_{42}	$p_{16}+p_{19}$				

Table 2. Selected states of the system (model of accident)

	M_{18}	M_{19}	M_{40}	M_{41}	M_{42}
p_6 – good visibility	0	1	0	0	0
p_{16} - B767 stops	0	0	0	1	1
p_{17} - B737 at crossing	1	1	0	1	0
p_{18} - B767 at crossing	1	1	1	0	0
p_{19} - B737 stops	0	0	1	0	1

States M_{40}, M_{41}, M_{42} (called safe states) illustrate situations in which there is no accident. States M_{18} and M_{19} represent the situation that analysed serious incident transforms into accident. The joint probability of finding system in one of these states is the searched probability of incident-accident transformation. It can be determined both analytically and by simulation using a suitable software tool. Analytical method for determining the sought probabilities will be presented on the example of the final state M_{19}. Partial subgraph of the reachability graph, for reaching M_{19} from initial state M_0 is shown in Figure 3.

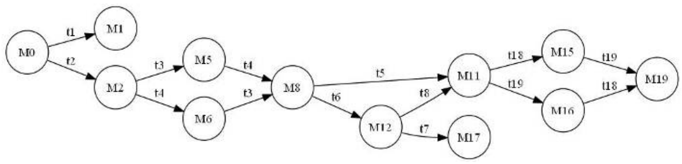

Figure 3. Partial subgraph of reachability of final state M_{19}.

Let's assume the following transitions designations: t_1 – „bad weather", t_2 – „good weather", t_3 – „B767 take-off phase I", t_4 – „B737 take-off phase I", t_5 – „ATR not watches", t_6 – „ATR watches", t_7 – „ATR warns", t_8 – „ATR not warns", t_9 – „B767 hears", t_{10} – „B767 not hears", t_{11} – „FD not accepts", t_{12} – „FD accepts", t_{13} – „B767 interrupts", t_{14} – „B767 not interrupts", t_{15} – „B767 decelerates", t_{16} – „ATC orders B737 to interrupt", t_{17} – „B737 interrupts take-off and stops", t_{18} – „B767 take-off phase II", t_{19} – „B737 take-off phase II".

Immediate transitions t_1, t_2, t_5, t_6, t_7, t_8, t_9, t_{10}, t_{11}, t_{12}, t_{13}, t_{14} are assigned weights, respectively: α_1, α_2, α_5, α_6, α_7, α_8, α_9, α_{10}, α_{11}, α_{12}, α_{13}, α_{14}. These weights are used to determine the probability of firing transitions in a situation of a conflict. Timed transitions t_3, t_4, t_{15}, t_{16}, t_{17}, t_{18}, t_{19} are assigned the intensities of realisation, respectively: μ_3, μ_4, μ_{15}, μ_{16}, μ_{17}, μ_{18}, μ_{19}. Also for this type of transitions in the event of a conflict, it is necessary to determine the probability of firing one of the conflicting transitions.

Because of the purpose of analysis, it is possible to reduce the reachability graph. Reduction consists of the removal of states that do not affect the probability of finding the system in the state M_{19}. Reachability graph after reduction is shown in Figure 4.

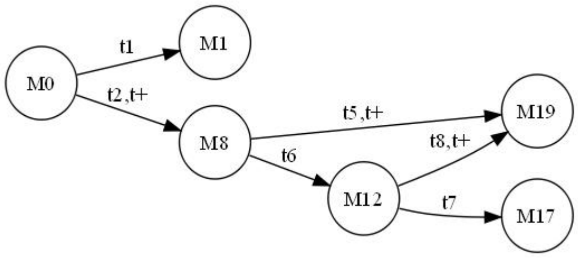

Figure 4. Reduced reachability graph for state M_{19}.

In this case, the probability that the system will move from the state M_0 to M_{19} depends on the probabilities of firing of immediate transitions t_2, t_5, t_6 and t_8, and is described by the two sequences σ_1 and σ_2, and after reduction of intermediate states is as follows:

$$\sigma_1 = M_0[t_2, t_+\rangle M_8[t_5, t_+\rangle M_{19} \quad (10)$$

$$\sigma_2 = M_0[t_2, t_+\rangle M_8[t_6\rangle M_{12}[t_8, t_+\rangle M_{19} \quad (11)$$

$$P(M_0[\sigma_{1-2}\rangle M_{19}) = \frac{\alpha_2}{\alpha_1+\alpha_2}\cdot\left(\frac{\alpha_5}{\alpha_5+\alpha_6}+\frac{\alpha_6}{\alpha_5+\alpha_6}\cdot\frac{\alpha_8}{\alpha_7+\alpha_8}\right) \quad (12)$$

It is worth noting that in this case the probability of transforming incident into accident is not affected by intensities of timed transitions, and only the weights of immediate transitions.

5 EXAMPLE ANALYSIS – VESSEL TRAFFIC AT WATERWAYS INTERSECTION

Majzner & Piszczek (2010) formulated the interesting problem of analysis of traffic safety at the intersection of the waterways. This problem can be modelled using the presented method.

Two streams of traffic are studied: longitudinal moving along the fairway with the speed v_w and crossing stream moving with the speed v_p. It was assumed that the ships moving in the longitudinal stream have the right of way to the ships in the crossing stream. The study analyses the average waiting time for ships of crossing stream and the probability of avoiding a premise for a collision, as a function of intensity of longitudinal stream. Example of Petri net for modelling this kind of problem is presented in Figure 5. The net is the coloured, stochastic, timed Petri net with priorities.

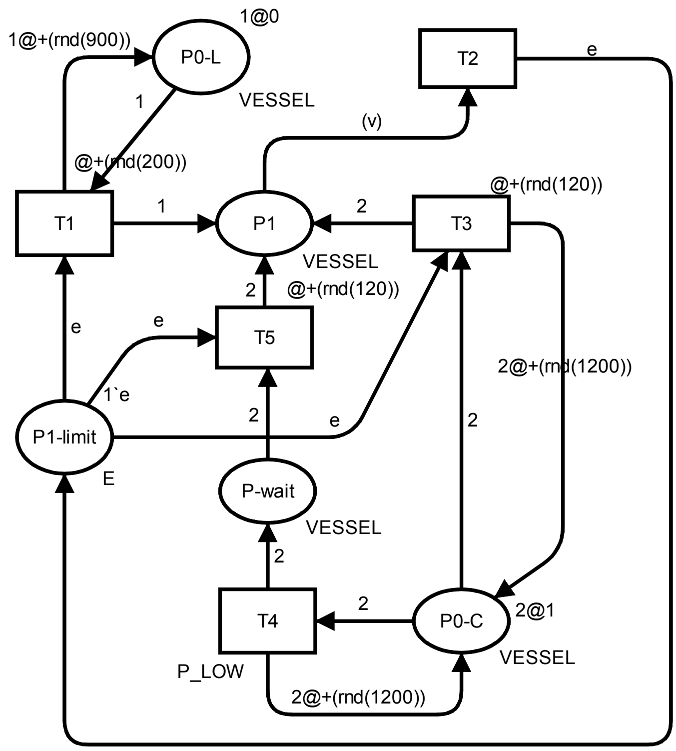

Figure 5. CPN modelling incidents at waterway intersection.

Places designations are: p_{0L} – "unit from longitudinal stream arrives at intersection", p_{0C} – "unit from crossing stream arrives at intersection", p_1 – "vessel occupies intersection", $p_{1\text{-limit}}$ – "anti-place for limiting the number of vessels at intersection to 1", p_{wait} – "vessel waits in the queue".

Transitions designations are: t_1 – "unit from longitudinal stream enters the intersection", t_2 – "unit leaves the intersection", t_3 – "unit from crossing stream enters the intersection", t_4 – "unit from crossing stream enters the waiting area", t_5 – "unit from waiting area enters the intersection",

Assuming the figures from discussed example we obtain similar results. For example, for the parameters shown in Figure 5 (longitudinal traffic - 4 units per hour, crossing traffic - 3 units per hour) consistency of results from simulation experiments with the results of the sample model is above 90% for mean delay time.

This indicates the usefulness of the proposed modelling method to analyze safety and traffic capacity problems in the fairways. We may also expect good results while researching other problems in the field of maritime traffic engineering.

6 SUMMARY AND CONCLUSIONS

In the paper the method of modelling traffic incidents and accidents was presented.

Petri nets are used for modelling. Type of net used, depends on individual case and objective of analysis. Presented examples show the applicability of the proposed method for analysis of traffic processes in various modes of transport. The use of Petri nets allows to easily generating the reachability graph, which is the basic tool of analysis. This graph is often large and the effective application of the method depends on its reduction. The problem of effective reduction constitutes a different research problem.

Method can be used in practice for improvement of the transport safety. The case described as aviation example is a part of analysis that is necessary before any new equipment or procedure can be introduced. The simple model described as maritime example may be used as a part of more complex optimisation models for marine traffic engineering.

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