Airport Traffic Simulation Using Petri Nets

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Abstract. Airport traffic consists of aircraft performing landing, takeoff and taxi procedures. It is controlled by air traffic controller (ATC). To safely perform this task he/she uses traffic surveillance equipment and voice communication systems to issue control clearances. One of the most important indicators of this process efficiency is practical airport capacity, which refers to the number of aircraft handled and delays which occurred at the same time. This paper presents the concept of airport traffic modelling using coloured, timed, stochastic Petri nets. By the example of the airport with one runway and simultaneous takeoff and landing operations, the applicability of such models in analysis of air traffic processes is shown. Simulation experiments, in which CPN Tools package was used, showed the impact of the initial formation of landing aircraft stream on airside capacity of the airport. They also showed the possibility of its increase by changes in the organisation of takeoff and landing processes.

Keywords: air traffic control, traffic processes modelling, Petri nets, airport capacity.

1 Introduction

The efficient interaction of all elements of airport is necessary to achieve a high level of safety, which in addition to the speed of movement is one of the fundamental factors of competitiveness of air transport. Particularly important processes in this complex system are traffic processes, including takeoffs and landings on runways, taxiing after landing and taxiing before takeoff which are held on taxiways. Numerous attempts are taken to develop effective models of airport elements. They use various methods of mathematical modelling. These include, among others: dynamical programming, fuzzy sets, queuing models, hierarchical Bayesian models.

A new concept of airport traffic modelling using coloured, timed, stochastic Petri nets is presented in the following sections. Petri nets are a convenient tool for analysis of traffic processes in transport. However, they are rarely used in airport capacity analysis. The few examples include [1,4]. The general approach to the use of coloured Petri nets in modelling of aircraft operations can be found in [2].

In this paper it was assumed that the planes report for take-off and landing according to the flight plan previously submitted, but disturbed by random factors. Such disruptions can occur at any stage (taxi, takeoff, approach, final approach, landing). In addition, this study examines the approach procedure with many details. For instance

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the procedural separations at fourth and at the second mile before the runway threshold is taken into account. Also the go-around procedure is included in the model.

The paper is completed with the example of utilisation of the model for determination of average operational delay, at given traffic procedures, and dependent on the traffic volume. Two cases were examined. In one of them traffic flow was characterised by a random time distance between consecutive aircraft inputs to the system. The other case provides initial, partial arrangement of landing aircraft flow.

The results were obtained using the CPN Tools 3.4 package [5,10]. A single simulation run corresponds to 30 takeoff operations and 30 landing operations, which is adequate to study traffic activities in real airport of assumed size and configuration. To determine the airside capacity of the airport - in different simulation runs the aircraft input rate was iteratively changed, so that it was possible to observe the dependence of traffic volume and mean operational delay. The whole study consisted of 100 individual simulation runs, for which the input intensity covered entire relevant area.

2 Airport Traffic Model

In this paper active elements of the transport system are studied, dealt dynamically, during the realization of their task - that is, the traffic processes. Infrastructure and organization are limitations to this process and must be, to some extent considered during its modelling. It is assumed that the purpose of the modelling is the airport's airside capacity. The search for opportunities to increase capacity, as well as its precise estimation is one of the most important elements of the Single European Sky concept [9].

2.1 Methodology

The air traffic process includes the organizational rules, regulations and standards, to ensure the safety of all traffic participants. In this process, there are time periods in which aircraft 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, but 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 this case these events are defined as having an impact on safety of traffic.

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.

This approach to the traffic process allows the use of Petri nets for modelling it [7]. Stable traffic situations correspond to places in the net, traffic events – to transitions. Tokens in places can be identified as traffic participants or states of environment.

The following methodology of air traffic processes analysis in terms of Petri net elements was adopted:

(a) The set of places *P* corresponds to traffic situations, in which a plane can be found during normal traffic.
(b) The set of transitions *T* corresponds to the set of events (actions) that change the traffic situation, particularly affecting the safety of manoeuvres.
(c) 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.
(d) 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.

2.2 The Object of Modelling

In this study the modelled system is an airport with one runway. There is one taxiway leading to runway threshold that is used by all aircraft. If it is impossible to perform the takeoff procedure immediately after finishing taxiing – aircraft wait at the end of taxiway before entering the runway. The takeoff sequence results from the order of reaching the waiting point on the FIFO rule.

In the case of a landing procedure, the scope of analysis includes final approach, starting from the fourth mile from runway threshold, up to aircraft exit into the taxiway. Runway occupancy time is dependent on the type of aircraft. It was assumed that in the modelled system there are three categories of aircraft. For each of them runway is equipped with a dedicated rapid exit taxiway. Should it be impossible to maintain the necessary separation at the second mile from the runway threshold, model provides the execution of missed landing procedure.

2.3 Petri Net for Airport Traffic Modelling

The model presented in this paper, was developed based on the Petri net, satisfying a number of conditions, which are necessary for the proper mapping of the essential elements of the system. Such a net must be: coloured, timed, stochastic and with priorities. Airport traffic model can therefore be written as [8]:

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

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 multiset over the set P, and functions I, O, H 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,

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

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

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

$X: T \times P \rightarrow \mathbb{R}_{+}$ –random time of realisation of traffic event (transition) t,

Γ – nonempty, finite set of colours,

C – function determining tokens that can be stored in a given place: $C: P \rightarrow \Gamma$,

G – function defining the conditions that must be satisfied for the transition, before it can be fired,

E – function describing the so-called weight of arcs,

R – set of timestamps (also called time points) $R \subseteq \mathbb{R}$,

r_0 – initial time, $r \in R$.

$B: T \rightarrow \mathbb{R}_{+}$ – function determining the priority of transition t.

3 The Model of Takeoff and Landing

The structure of Petri net modelling takeoff process and preceding it taxiing for takeoff process is shown in Figure 1. We can distinguish 13 places and 10 transitions here. We will accept the following designations of places:

$$P = \{p_1, p_2, \dots, p_{13}\} \qquad (2)$$

where: p_1 – „generator", p_2 – „ac after loading", p_3 – „ac may taxi to RWY", p_4 – „ac ready for takeoff", p_5 – „ac may line-up the RWY", p_6 – „ac at RWY threshold", p_7 – „begin of takeoff", p_8 – „end of phase I", p_9 – „airborne", p_{10} – „out", p_{11} – „RWY occupied", p_{12} – „RWY free", p_{13} – „may line-up".

The following designations of transitions were adopted in the model:

$$T = \{t_1, t_2, \dots, t_{10}\} \qquad (3)$$

where: t_1 – „takeoff input", t_2 – „clearance for taxiing", t_3 – „taxiing", t_4 – „clearance for RWY line-up", t_5 – „runway line-up", t_6 – „clearance for takeoff", t_7 – „takeoff phase I", t_8 – „detachment", t_9 – „procedural turn", t_{10} – „destination".

The structure of Petri net which is modelling the landing process from the fourth mile from the runway threshold to exit into one of the taxiways is shown in Figure 2.

In this model one can distinguish 11 places and 10 transitions. We will adopt the following designations of places:

$$P = \{p_{11}, p_{12}, \dots, p_{21}\} \qquad (4)$$

where: p_{11} – „RWY occupied", p_{12} – „RWY free", p_{13} – „may line-up", p_{14} – „generator init", p_{15} – „initialise", p_{16} – „4th mile", p_{17} – „4th mile - separation", p_{18} – „2nd mile", p_{19} – „2nd mile - separation", p_{20} – „touchdown", p_{21} – „exit in TX".

In addition, the following transitions designations were adopted in the model:

$$T = \{t_{11}, t_{12}, \ldots, t_{17}\} \tag{5}$$

where: t_{11} – „generator”, t_{12} – „landing input”, t_{13} – „approach”, t_{14} – „overshoot”, t_{15} – „final landing”, t_{16} – „braking”, t_{17} – „destination”.

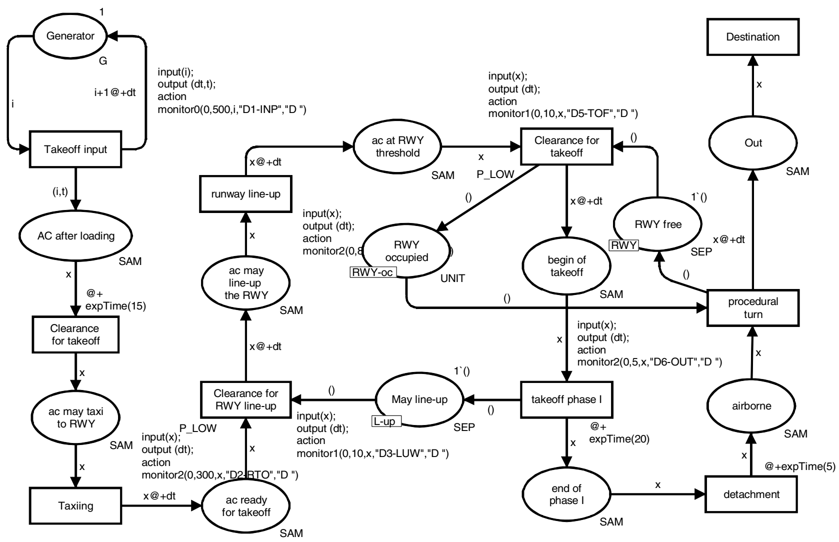

Fig. 1. Model of takeoff process at the airport with one runway

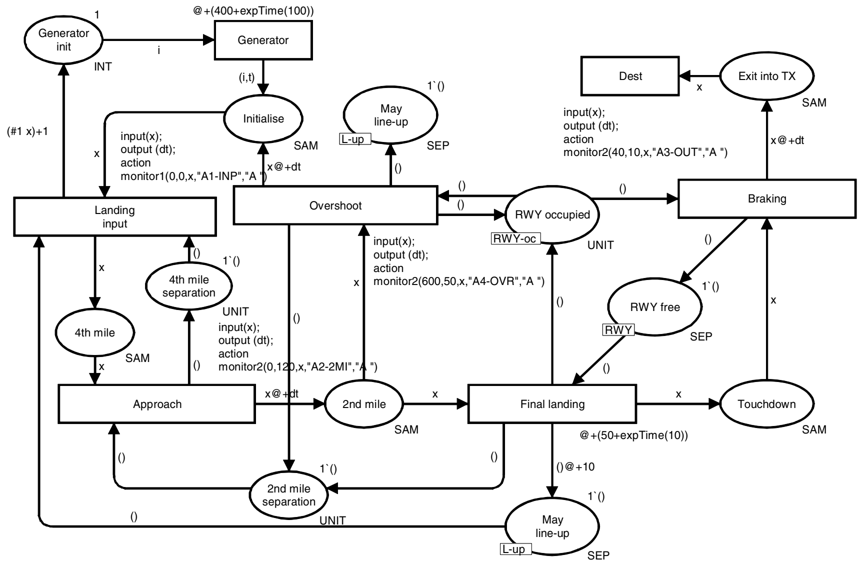

Fig. 2. Model of landing process at the airport with one runway

4 Simulation Analysis of Airport Traffic

The presented model can be used to analyse various issues related to airport operations. These are among others:

- research of the efficiency of use of existing infrastructure at the existing traffic volume and structure,
- analysis of the possibility of increasing traffic at the airport, with simultaneous control of quality indicators,
- study of the effects of the planned modernisation, such as changes in equipment, extension of runways, taxiways and fast runway exits,
- airport's airside capacity analysis, both in existing traffic and equipment as well as in case of changes (failure or upgrade).

4.1 Simulation Experiments

Simulation experiments were performed iteratively. In each iteration the input stream intensity was increased until the saturated traffic was achieved. The study began with input stream mean intensity of:

- in experiment 1 – 12 aircraft per hour, both arriving and departing,
- in experiment 2 – 20 arriving aircraft per hour and 12 departing aircraft per hour.

Simulation with the use of CPN Tools package was provided by the successive events method, with the rhythm of event changes determined by the timestamps $r \in R$ (see formula (1)). This package performs the simulation in step-by-step mode, which allows observation of the progress of traffic process, and if necessary change the parameters characterising the system. Thanks to available automatic replication, it is possible to perform many simulation runs for different initial markings or different input parameters. This latter feature was used in this study to repeat the simulation process with different characteristics of aircraft input stream.

4.2 Results of Simulation Experiments

The result of a single simulation run is a pair of values that specify the traffic volume and operational delay. In the first experiment the average input intensity of landing and takeoff aircraft was the same. Results of this experiment for 100 completed simulation runs are given in Figure 3a. Each point is the result of simulation using CPN Tools of 30 landing and 30 taking off planes.

As an airside capacity of the airport, the traffic volume for which the probability that the average delay is greater than the accepted value (10 minutes) is bigger than 0,5 was adopted [6]. In this example it reached 18 takeoff and landing operations per hour.

For the second simulation experiment it was assumed that landing aircraft are initially formed into a stream, in which spacing between aircraft is practically constant and close to the value of separation on approach to landing, which is equal two minutes. Additionally, in a study it was assumed that the flow of taking off aircraft starts about 40 minutes after the beginning of the series of landings. The results are presented in Figure 3b. They show a significant increase in capacity of the airport, despite the continued unfavourable composition of the traffic (50% of landings and 50% of takeoffs, which report randomly with high intensity).

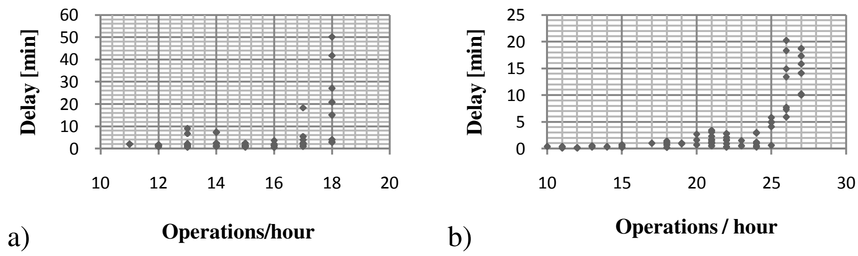

Fig. 3. Results of experiments: a) without initial forming of traffic streams, b) landing traffic spacing – 2 minutes, takeoff traffic postponed by 40 minutes

The increase in capacity is significant – about 50%. Traffic volume at which saturation occurs and also rapid increase in the average delay is 27 operations per hour. The initial arrangement of arriving aircraft stream is very beneficial, as it allows increasing the number of landing operations performed per unit of time. But on the other hand the close packing of landing aircraft makes taking off planes to wait for completion of the entire series of 30 simulated landings. In this case there is no practical ability to perform any takeoffs in the gaps between landings. The waiting time of departing aircraft is larger in this case than in experiment 1. However increase in capacity is possible, thanks to changes in the departing aircraft stream. The highest value of capacity occurs when departing aircraft stream begins reporting readiness to taxi after completion of a little over half of the landings. Figure 3b shows the results for that particular situation – the series of takeoffs begins 40 minutes after the beginning of a series of landings. If they begin simultaneously resulting airport capacity is lower. The same occurs when it begins later. In these cases, the increase in capacity is about 20%.

5 Conclusion

This paper presents an integrated model of taking off and landing processes built using coloured, timed, stochastic Petri nets. As shown by simulation experiments conducted using CPN Tools package, this model allows for easy and efficient obtaining reliable results. As the toolbox permits to study the occurrence graph of model execution, verification of the formal correctness of developed models was also performed.

The results of simulation experiments lead to some interesting conclusions. Air traffic control services in approach area tend to implement the controller support systems that allow the formation of landing stream in order to increase its internal density, of course in accordance to the separation rules. This allows for greater number of operations per unit time, thereby increasing the capacity of the airport. It is the reasonable attitude, but as shown by simulation experiments, only when the number of taking off aircraft is small. Otherwise, the necessity of waiting for finishing the series of landings causes significant delays in departures, and capacity decreases. The most preferred solution is to control the flow of taking off aircraft in such a way, that initial moment of their reporting to ATC is planned after completing about half of the landings. Obtained in this way increase in total capacity reaches 50% of the value calculated for the landing stream without forming. Any larger displacement of taking off stream reduces the delay, but also reduces the total number of operations per unit time. Similarly smaller displacement increases the waiting time without increasing the number of operations. In both cases, no increase in capacity is achieved.

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