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Model of the Hierarchical Process of Managing the Approaching Air Traffic in the Terminal Area

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Abstract. Air traffic in the airport controlled area is carried out according to standard procedures. However, they are disturbed by random factors, so the traffic is stochastic in nature and requires ongoing monitoring by the air traffic controller that operates in the approach control sector (TMA). One of his/her goals is to form the landing aircraft queue so as to maximize the airport capacity. The task is difficult because there are multiple entry points to the TMA and many points at which the individual aircraft streams merge. The paper presents the model of the process of forming landing aircraft queue. The model has been implemented as a coloured Petri net. It has a hierarchical structure corresponding to the actual multi-level structure of the merging aircraft streams process. The study shows an example of modelling of the approaching air traffic consisting of aircraft landing at the Warsaw Chopin airport on the RWY 11 runway. The developed software system SECRAN can be used to support the approach controller in the planning process and in the current control of approaching air traffic in TMA area.

Keywords: Air traffic · Airport arrival management · Hierarchical sequencing · Petri nets · Air traffic controller support

1 Introduction

Air traffic within a Terminal Area (TMA) is planned and controlled by the approach control service (APP). Traffic volume is especially high around the airport - the nodal point in air transportation network. Many aircraft perform complicated manoeuvres: the approach and landing and also climbing after the takeoff. Therefore, typical APP controller tasks are extremely difficult [9]. In recent years, another task - to prepare the aircraft sequence for landing is becoming increasingly important. This sequence should allow a smooth and timely landing of any aircraft in such a way as to maximize the available capacity of the airport, which in most cases is the bottleneck of the air transport system. The aircraft scheduling task is a hierarchical one, with respect to each aircraft it consists of a number of decisions over the time.

An air traffic controller is assisted in his/her tasks by the appropriate intelligent systems that allow one to remotely obtain information about the aircraft positions. Then, they work out control decisions using the available flight plans and control algorithms in use [5]. At the end, they transmit control clearances to the aircraft to

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execute [1]. Works towards the establishment of efficient algorithms for controller support in the process of forming a queue of landing aircraft is conducted in many research centres (e.g. in Europe as a SESAR programme) (SESAR 2013).

Arriving aircraft traffic management support is the subject of this paper. The outline of the mathematical model in the form of Petri net, its implementation in the form of a computer system SECRAN (SEquence CReator and ANalyser), and some examples of simulation experiments that show the applicability of the proposed solution are presented. Creating a schedule of landings in accordance with a predetermined landing control algorithm and evaluation of the control algorithm in terms of different parameters (e.g. the capacity or punctuality) can be assigned to the main areas of application. In this paper both of these areas will be presented.

2 Landing Aircraft Scheduling as a Part of the Air Traffic Management in the Airport Area

2.1 General Principles of Planning the Traffic Incoming to the Airport

Incoming air traffic is organized according to the runway in use. The decision on its choice shall be taken with taking into account the meteorological conditions (especially the strength and direction of the wind), navigational equipment, traffic situation, etc. [6]. For airports with multiple runways many variations are possible, especially when we assume the configuration in which one runway is used for the take-off and another for the landing. The choice of the runway in use determines the end point of the arriving aircraft trajectory.

The starting point of the arrival trajectory is dependent on the direction of the approaching aircraft and air route used previously. Arrival procedures, the so-called STARs, are predefined between the starting and the end points. Their names are derived from the names of the starting points of the procedure [7]. They are designated by a list of waypoints, for which also recommended cruising altitude and speed limit can be determined. The APP controller can modify STAR procedures. Most often the modification consists in bypassing some waypoints and flying directly between any two navigational waypoints [2]. The so-called *direct* may lead even from the starting point to the end point without changing direction.

2.2 Airport Capacity and Air Operations Safety

A problem of landing aircraft scheduling is in fact the problem with two conflicting objectives. On the one hand, we seek to maximize the airport capacity [16]. This can be achieved by organizing the queue for landing in such a way that the aircraft are densely packed (the distance between them is small). This makes it possible to realize a lot of landings per unit time. Dense packing is obtained when the aircraft sequence is suitable with respect to the weight categories and the APP controller uses the minimum separation allowed by the regulations [4].

The second goal of the Scheduling process is to ensure punctuality of landings and also safety and high reliability of a planned sequence execution. When the aircraft are densely packed, even a small distortion of their movement (for example due to wind or inaccuracies in the navigation) could lead to an infringement of the separation. This must not happen. Therefore, in such a situation, it is necessary to perform the special procedure by which one or more aircraft move to the end of the queue. In this case, the execution time of a series of landings increases. Such unexpected manoeuvres may also be relevant for the traffic safety [14].

It is easy to see that the APP controller should use a scheduling algorithm in which both criteria are taken into account. The task is difficult, multi-criteria, therefore it is necessary to support him/her with a kind of an intelligent system [13]. The importance of both criteria may vary over time. Therefore, one cannot provide the optimal solution, and should seek a solution appropriate for the current traffic situation and the status of the environment.

2.3 Multi-level Process of Forming the Landing Aircraft Queue

Forming a landing aircraft queue is usually performed in the TMA region directly related to the aerodrome where the landing is to take place. However, traffic streams overlap in the areas with a big number of airports. Therefore, solutions are sought in which the planning horizon is greater [8]. In such a situation one can propose a solution in which the individual streams are partly coordinated and merged in earlier stages of flight. This concept results from the analysis of STAR procedures. It is also advantageous from the safety point of view. Uncertainty about the punctuality of arrivals would be very large if all aircraft are directed to one merging point. In the case of disturbances we would have to deal with the situation of many aircraft performing complex manoeuvres in a limited airspace. Therefore it is more convenient to merge streams of aircraft arriving from similar direction earlier. On the one hand this makes the decomposition of the scheduling process; on the other hand the uncertainty as to the punctual arrival is lower.

3 The Model of Hierarchical Process of Landing Aircraft Scheduling

The structure of the model of approaching aircraft queue creation process adopted in this paper is somewhat similar to the concept presented [3]. In their paper an attempt to apply a so-called “list algorithm” for APP controller decision support was undertaken. The model in the form of Petri net proposed here extends the capabilities of that approach. The flight time is treated here as dynamic and random variable. Additionally flight time measurements and shortcuts (*directs*) that are actually used by air traffic controllers have been taken into account.

3.1 Subject of Modelling - the Area of Analysis and Assumptions

The paper analyzes the hierarchical process of creating the arriving aircraft schedule for STAR procedures leading to a landing on the RWY 11 runway at the Frederic Chopin Airport in Warsaw. STAR routes are presented in Fig. 1, and Table 1 presents a brief description of all procedures available in this case

In the basic version of the model we assume that *directs* are not used and all aircraft perform the full STAR procedure. This assumption has been adopted to better take into account the multi-level hierarchy of landing queue creation process. In most cases, the *directs* are routed to the end point of the STAR procedure or in its immediate vicinity. This causes that many intermediate merging points are omitted. This may bring the multi-dimensional problem to a one-dimensional problem. Because of the practice, the effect of using *directs* will be examined in the experimental part of this work.

The nature of the scheduling algorithm used by the APP controller is the second major assumption of this model. Based on the considerations in Sect. 2 it is assumed that aircraft are sequenced according to the scheduled time of their appearance at the TMA border, without changing their order (FIFO principle). In addition, it is assumed that the controller does not apply redundant space between aircraft, and they are scheduled in such a way as to keep the separation required by international regulations, in particular related to the turbulence behind the aircraft [2].

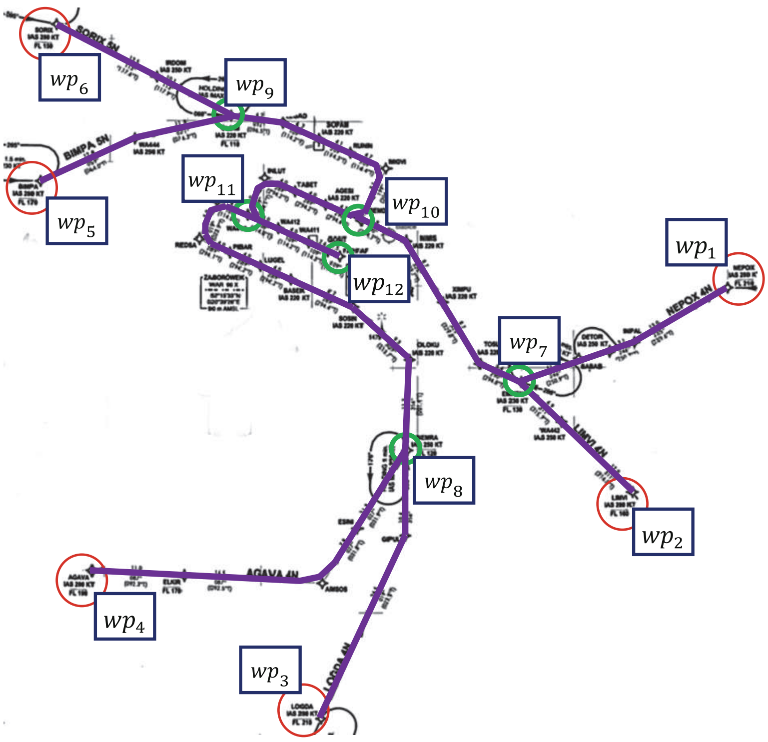

Fig. 1. Arrival trajectories for Warsaw Chopin airport RWY 11 [own study]

Table 1. STAR procedures for RWY 11 [own study]

Procedure	NEPOX	LIMVI	LOGDA	AGAVA	BIMPA	SORIX
Length [km]	158.9	143.3	179.1	200.8	149.6	148.5
Sequencing stages	3	3	2	2	3	3
Waypoints number	16	15	15	17	15	17

3.2 Model of Hierarchical Scheduling Process

The analysis of the structure of all RWY 11 STAR procedures shows that in the scheduling process one can distinguish 12 important waypoints. These are: TMA input points, which are also starting points of the scheduling process, first, second and third level merging points, and one end point. We denote

$$WP = \{wp_i\}, i = 1, 2, \ldots, w \tag{1}$$

the set of important waypoints, $w = 12$.

The set of entry points we define as

$$EP = \{wp_i\}, i = 1, \ldots 6 \tag{2}$$

where $wp_1 =$ NEPOX, $wp_2 =$ LIMVI, $wp_3 =$ LOGDA, $wp_4 =$ AGAVA, $wp_5 =$ BIMPA, $wp_6 =$ SORIX.

The set of merging points we define as

$$MP = \{wp_i\}, i = 7, \ldots 11 \tag{3}$$

where $wp_7 =$ EMKEN, $wp_8 =$ BEMRA, $wp_9 =$ OLDIM, $wp_{10} =$ REMDI, $wp_{11} =$ WA413.

The set of scheduling end points we denote

$$LP = \{wp_i\}, i = 12 \tag{4}$$

where $wp_{12} =$ FAP/FAF.

The structure of the aircraft flow is shown schematically in Fig. 2.

The compliance with minimum separation between aircraft in accordance with the rules shown in Table 2 is checked in each important waypoint.

Separation is dependent on the aircraft weight category, depending on their maximum take-off weight:

- heavy (H) – aircraft with a take-off weight of more than 136,000 kg,
- medium (M) - aircraft with a take-off weight of 7,000 to 136,000 kg,
- light (L) – aircraft with a take-off weight of less than 7,000 kg.

In cases not included in Table 2 it is assumed that the minimum separation is one minute.

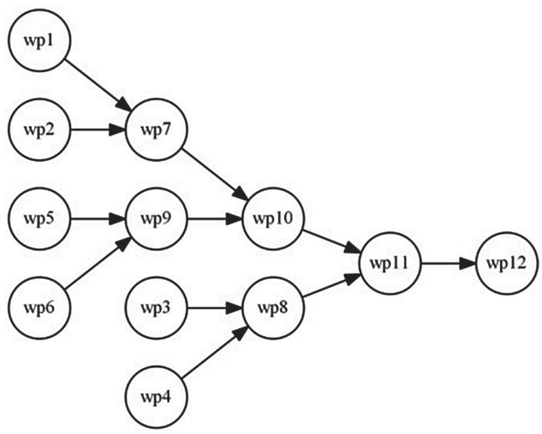

Fig. 2. A scheme of the aircraft flow in the model [own study]

Table 2. Minimum separation between arriving aircraft [own study]

Lead aircraft	Follower aircraft	Minimum separation
heavy (H)	light (L)	3 min.
heavy (H)	medium (M)	2 min.
medium (M)	light (L)	3 min.

3.3 Coloured Petri Net for Evaluation of the Process of Managing the Approaching Air Traffic in the Terminal Area

The structure of the aircraft flow shown in Fig. 2 was the basis for the creation of a model in a form of hierarchical, coloured Petri net. This approach allows us to achieve several goals.

First, it is possible to determine (plan) the aircraft sequence according to the accepted scheduling algorithm. We can thus obtain a fully intelligent telematic solution. Aircraft positions (and therefore the time they appear in the waypoints from the *EP* set) can be obtained automatically from the air traffic surveillance systems [10]. The SECRAN system works out the solution of the scheduling problem. This solution and the expected distance between the aircraft can be transmitted from the APP controller on board the aircraft by means of voice communication or by using a digital air data link (e.g. CPDLC).

On the other hand, the use of this model and the computer tool SECRAN allows for simulation analysis of the air traffic in the TMA. One can analyse the traffic quality indicators (e.g. punctuality, reliability) of the obtained sequences in the absence of disturbances, but also in the presence of various non-nominal situations. Analysis of the results of such simulations allow for optimization of the scheduling algorithm.

To carry out research and experiments the hierarchical coloured Petri net with the following structure was used [11, 12, 14]

$$S_{AM} = \{P, T, A, M_0, \tau, X, \Gamma, C, G, E, R, r_0, B\} \quad (5)$$

where:

P – set of places,
T – set of transitions $T \cap P = \emptyset$,
$A \subseteq (T \times P) \cup (P \times T)$ – set of arcs,
$M_0 : P \rightarrow \mathbb{Z}_+ \times R$ – marking which defines the initial state of the system that is being modeled,
$\tau : T \times P \rightarrow \mathbb{R}_+$ – function determining the static delay that is connected with carrying out activity (event) t,
$X : T \times P \rightarrow \mathbb{R}_+$ – random time of carrying out an activity (event) t,
Γ – finite set of colors which correspond to the possible properties of tokens,
C – function determining what kinds of tokens can be stored in a given place: $C : P \rightarrow \Gamma$,
G – so-called "guard" function which determines the conditions that must be fulfilled for a given event to occur,
E – function describing so-called weights of arcs, i.e. the properties of tokens that are processed,
R – set of timestamps (also called time points) $R \subseteq \mathbb{R}$,
r_0 – initial time, $r_0 \in R$.
$B : T \rightarrow \mathbb{R}_+$ – function determining the priority of a given event, i.e. controlling the net's dynamics when there are several events that can occur simultaneously.

One of the most important components of this structure is the set of colours, which in the case of this model takes values $\{GI, AC, SEQ\}$. GI colour represents the consecutive numbers and times of appearance of aircraft in the system. Colour AC contains information on the parameters of moving aircraft, and the colour SEQ represents the sequence of aircraft appearing in the waypoint.

4 Simulation Analysis of the Hierarchical Process of Arrivals Management

The model of approaching aircraft scheduling, discussed briefly in Sect. 3, has been implemented in CPN Tools 4.0 package as SECRAN program. The developed Petri net is coloured and hierarchical. The net's hierarchy corresponds to the hierarchy of the scheduling process and is being implemented by the mechanism of pages that allows one to separate parts of the model. The synchronization of pages in this case is implemented by a mechanism of fused places. These places are marked with ellipses with a label in the lower left corner (Figs. 3, 4 and 5). In the basic version of the presented model six pages have been created. Due to the limitation of the paper's volume only some of them will be presented.

The first page presented is *Merge 1–2 to 7*. It has two important functions in the model:

- implements the input of the aircraft into the analysed TMA, including checking the separation on input waypoints wp_1 NEPOX and wp_2 LIMVI
- combines traffic streams approaching from wp_1 and wp_2 in the merging point wp_7 EMKEN, also with separation checking function.

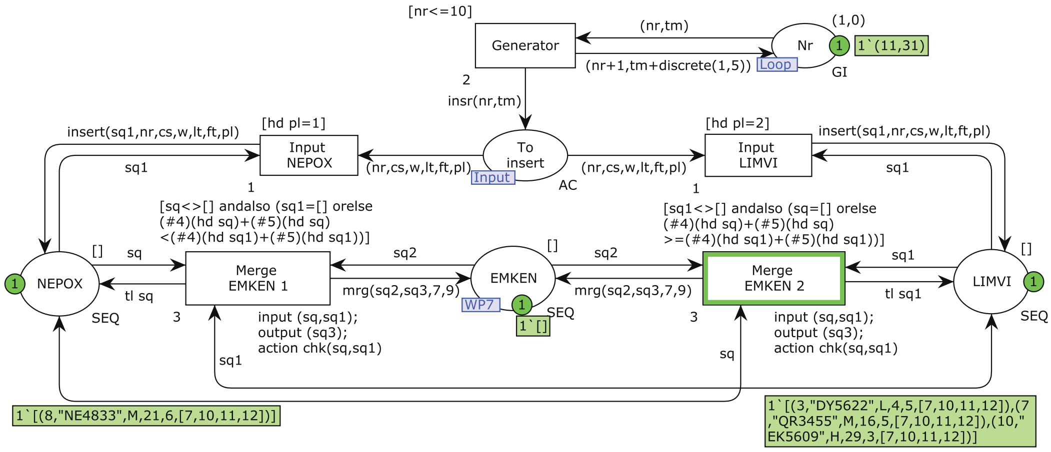

Fig. 3. Page *Merge 1–2 to 7* in the model of scheduling traffic approaching RWY 11 [own study]

Petri net implementing *Merge 1–2 to 7* page is shown in Fig. 3.

On Fig. 3 in places NEPOX and LIMVI we can notice a sequence of aircraft appearing in the navigation waypoint. The sequence is shown in the box below the place. Every single aircraft is described by the token having the following structure:

$$ac = 1`(nr, cs, w, lt, ft, pl) \tag{6}$$

where:

nr – aircraft's number in the system,
cs – identification mark of the aircraft, so-called call sign,
w – weight category of the aircraft,
lt – planned time of the aircraft's appearance in the merging point,
ft – random time of flight to the next merging point,
pl – further planned route, written as a series of numbers of important waypoints.

Examples of the generated data shown on Fig. 3 demonstrate that at the LIMVI waypoint three aircraft are going to appear: DY5622 at time 4, QR3455 at time 16 and EK5609 at time 29.

Figure 4 shows the page *Merge 7–9 to 10*. It contains the model of the flight, which begins in waypoints wp_7 EMKEN and wp_9 OLDIM, and ends with merging these two

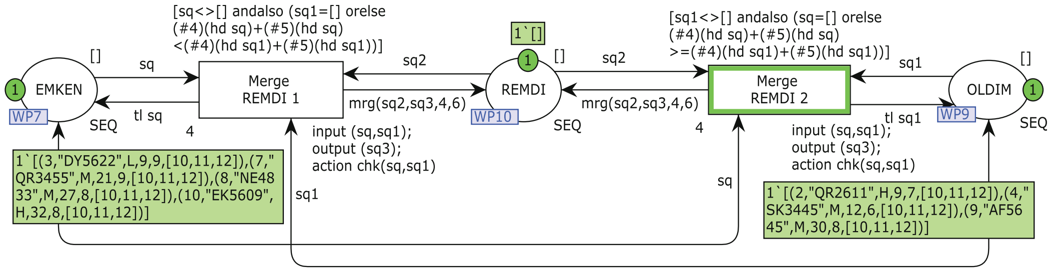

Fig. 4. Page *Merge 7–9 to 10* in the model of scheduling traffic approaching RWY 11 [own study]

streams at the point wp_{10} REMDI. All aircraft carry out the full STAR procedure. Tokens in the waypoint wp_7 EMKEN represent plan of flights over this waypoint, which is the result of merging streams starting in points wp_1 NEPOX and wp_2 LIMVI shown in Fig. 3.

Merging traffic streams in the waypoint wp_{10} REMDI required a change in the time of appearance of DY5622 aircraft in this waypoint. It was scheduled to report there at the time of 18 (at the time 9 in the waypoint EMKEN and 9 min of flight on the section EMKEN-REMDI). For the sake of separation as a result of the merging process, the planned flight time over the point REMDI was set to 21. The effect of merging traffic flows in the REMDI waypoint can be seen in Fig. 5 (a box on the right).

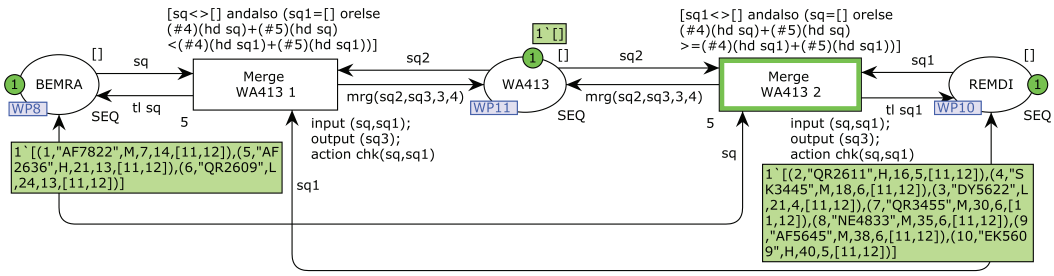

Fig. 5. Page *Merge 8–10 to 11* in the model of scheduling traffic approaching RWY 11 [own study]

4.1 The Module for Determination of the Landing Sequence

As was already indicated, by using the concept of hierarchical (distributed) aircraft scheduling we decompose this task. This makes the proper synchronization of aircraft arrival times easier for a single merging point. However, in return, to predict the situation in further merging points is more difficult. The mathematical model and the computer tool SECRAN, used in this work, allow for the determination of the final sequence, together with planned (expected) times of appearance over the subsequent waypoints. Developed solutions (decisions) can be transmitted remotely to the aircraft crew through the voice communication or data link. The crew, in turn, can programme their onboard flight management systems (FMS) to meet the expectations of air traffic control services.

Landing sequence for a sample set of 10 aircraft will now be presented. Aircraft arrivals to the entry points *EP* were generated according to the assumptions presented in Sect. 3.1. Table 3 shows the parameters of the entries in these points. These are respectively: the aircraft's number, weight category and time of arrival [min].

Taking into account: the nominal flight time corresponding to the length of the segment, the speed limit on the entry point, possible random deviations of flight time and the minimum required separation - sequences for merging points of the first level are shown in Table 4.

The aircraft sequence after merging traffic streams on the second level in the hierarchy (at REMDI point merging streams from EMKEN and OLDIM waypoints) is as follows (weight categories omitted):

Table 3. Aircraft arrivals to TMA [own study]

Entry point	NEPOX	LIMVI	LOGDA	AGAVA	BIMPA	SORIX
First aircraft	4, H, 7	5, H, 12	2, M, 3	1, L, 0	9, H, 26	
Second aircraft	8, L, 24		3, L, 6	6, L, 17	10, L, 30	
Third aircraft				7, L, 20		

Table 4. The results of the first-level merging [own study]

Merging point	EMKEN	BEMRA	OLDIM
First aircraft	4, H, 13	1, L, 10	9, H, 32
Second aircraft	5, H, 15	2, M, 11	10, L, 35
Third aircraft	8, L, 29	3, L, 14	
Fourth aircraft		6, L, 28	
Fifth aircraft		7, L, 29	

$$\langle (4,20),(5,22),(8,36),(9,38),(10,43) \rangle \tag{7}$$

The sequence on the third level of merging (in WA413 point merging streams from REMDI and BEMRA waypoints) is as follows:

$$\langle (1,24),(2,25),(4,26),(5,27),(3,30),(8,42),(9,43),(6,46),(7,47),(10,48) \rangle \tag{8}$$

The final sequence in FAP/FAF merging point is as follows:

$$\langle (1,28),(2,29),(4,30),(5,31),(3,34),(8,45),(9,46),(6,49),(7,50),(10,52) \rangle \tag{9}$$

4.2 Scheduling Algorithm Evaluation - Simulation Experiments

The second possible application of the solution presented in this paper is the evaluation of the scheduling algorithm used by the APP controller. A good indicator for this assessment is the average interval between landings. This indicator assesses both scheduling objectives, which were mentioned in Sect. 2.2 - capacity and punctuality. In this section, two scheduling strategies will be compared. First, the reference one, was described in Sect. 3.1. It consists in: aircraft perform full STAR procedure, and FIFO rule is used. The second strategy will be modified in a way that *directs* will be used in selected waypoints.

Average interval between landings is a random value. Among other things, it is very dependent on the arrival traffic stream characteristics. To eliminate individual variability, a simulation experiment was conducted in which 10^4 sequences were tested. Average interval between landings for the strategy without the use of *directs* and for the strategy with *directs* used in three waypoints AGAVA, NEPOX and BIMPA are presented in Table 5.

Table 5. Scheduling strategies comparison [own study]

Strategy	Average interval between landings [min]
No *directs*	5.14
Direct: AGAVA-REDSA	4.93
Directs:AGAVA-REDSA and NEPOX-NIMIS	4.89
Directs: AGAVA-REDSA, NEPOX-NIMIS and BIMPA-REDSA	4.82

The structure of the aircraft flow in the experiment is shown in Fig. 6. In this experiment, a set of important waypoints consists of $w = 14$ elements. Additional waypoints, which are targets of *directs* will be denoted as

$$ADP = \{wp_i\}, i = 13, 14 \quad (10)$$

where wp_{13} = REDSA, and wp_{14} = NIMIS.

As one can see, the use of *directs* improves the assessment that can be attributed to the analyzed scheduling strategies. The average distance between landings translates directly into airport capacity. The observed difference of more than 6% between strategy without *directs* and strategy with three *directs*, in relation to the airport capacity can be considered significant.

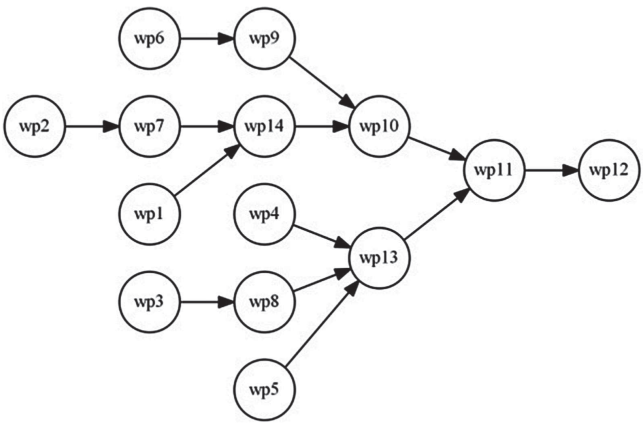

Fig. 6. A scheme of the aircraft flow in the simulation experiment No 3. [own study]

5 Conclusion

In the paper a model in the form of coloured Petri net, together with a computer tool SECRAN created with the use of CPN Tools 4.0 package is presented. They allow for the analysis of the problem of multi-stage, hierarchical scheduling of aircraft approaching for landing. This issue is very important from a practical point of view, and the necessity of its solution is strongly emphasized recently in European research projects.

The model and software presented in this paper allows one to determine the detailed sequence of aircraft, in accordance with adopted scheduling strategy, over all merging points. The schedule contains both the sequence and the aircraft flight times on particular waypoints. Even for simple scheduling algorithm, as presented in this paper, this question is difficult, especially since the flight times are random variables.

The second important application area of the presented SECRAN system is the evaluation of scheduling algorithms used in practice. Through their comparison we can search for better solutions. The paper proposes and presents the evaluation in terms of the average interval between landings, which is inversely proportional to the airport capacity. The results of experiments show that even at very simple scheduling algorithms it is possible to significantly increase the capacity of the airport area.

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