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Aircraft Taxi Route Choice in Case of Conflict Points Existence

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Abstract. Aerodrome ground traffic management consists of many processes. Their complexity causes that telematic solutions intended to assist both the air traffic controller who coordinates taxiing and the pilot who executes them are introduced. An example of such a solution is A-SMGCS system. At the moment, intensive research on advanced system functions are carried out. They include smart taxi route choice taking into account the current traffic situation. The paper presents the model and the computer software tool implementing the dynamic taxi route choice module. It can be used in case of congestion in the aerodrome traffic described by the so-called conflict points. Presented taxi route choice system is integrated with the developed before system to identify conflict points. This allows intelligent traffic process management through the selection of an alternate taxi route. Such a solution could be implemented on the third level of A-SMGCS system.

AQ1

AQ2

Keywords: Aerodrome traffic management · A-SMGCS system · Aircraft taxi route choice

1 Introduction

Aircraft taxing before takeoff and after landing are standard procedures in aerodrome traffic. Their goal is to displace an aircraft between the runway in use and the designated parking place. In opposite to air traffic in airspace, taxing may seem to be quite simple. It takes place only in two dimensions and is much less dynamic at the same time. Unfortunately, this process is not so easy to organise and to supervise. At big airports a network of taxiways is usually complicated, many aircraft are taxing at the same time and their taxi routes intersect in many places. This is favourable for pilots mistakes. At the same time, the same factors, as well as air traffic services work technology based on visual observation of airfield, favour mistakes committed by an air traffic controller. All of that causes, that many incidents occur in aerodrome traffic, including serious incidents or even accidents with disastrous consequences [14, 15]. Common issues include: collisions with other aircraft, collisions with fixed elements of airport equipment, collisions with other motor vehicles, such as baggage trolleys, snow removal equipment, etc. The most serious incidents take place when it comes to accidental take-off from a taxiway or unauthorized runway crossing (Runway Incursion), or even taxiing on the runway. In these cases an accident with a large number of fatalities may even occur.

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This paper is a continuation of [1], which presented the method of determination of conflicts points in taxiways structure. Conflict points characterize areas of traffic congestion and more precisely the points where delays appear. Waiting to pass the conflict point takes place in sections adjacent to it. In case when these sections are short or many aircraft are waiting, this may cause creation of new conflict points. The method presented in the previous paper is based on a model developed by using Petri nets. In this paper we present the next step aiming at building the module of intelligent system which will support taxiing process. It allows finding an alternative taxi route, taking into account dynamic changes of time necessary for passing a conflict point. Therefore, algorithm for finding a dendrite of shortest routes was used [4]. Subsequently, it was computer implemented in CPN Tools environment as coloured, time Petri net.

2 Systems Supporting Aerodrome Traffic Control

Aerodrome traffic is supervised by air traffic control services, namely by the so-called ground controllers (GND). They must constantly observe traffic situation, not only aircraft but also movement of all technical service vehicles and people staying at the airfield. Ground controllers can use various supporting systems, especially in busier airports. One of the most advanced supporting system is A-SMGCS (Advanced Surface Movement Guidance and Control System). It provides control and guidance in manoeuvring area. It allows to improve safety of aerodrome operations, especially in low visibility conditions [5, 16]. An A-SMGCS should support following primary functions [2]: surveillance, routing, guidance and control.

Surveillance function provides pilots and controllers information about actual traffic situation. Each aircraft and ground service vehicle is identified and marked. Data about objects' positions are constantly updated for guidance and control requests.

Routing function is responsible for determining taxi route for every aircraft and vehicle in manoeuvring area. This function is crucial for aerodrome traffic safety and efficiency, because it helps to optimize routes to prevent conflict situations. Moreover, aircraft or vehicle moving correctly on planned route is easier to follow. Furthermore, routing function should allow to change designated route in case of occurrence of movement obstruction or as a result of changing the destination point. This may happen, for instance, when parking place assignment changes dynamically according to operational reasons. It is expected that routing should be implemented in an intelligent way, which means that system should anticipate difficulties caused by air traffic congestion. An algorithm presented in this paper, together with its implementation, will be an element of the module responsible for A-SMGCS system routing function. It will allow designation of the fastest taxi route for aircraft. Data continuously provided to this module will let it to determine alternative taxi routes and also dynamically change the route of already taxiing aircraft.

Guidance function provides tips for aircraft pilots and car drivers that allow them to move on designated track. Additionally, it allows them keeping awareness about traffic situation and monitoring operational status.

Control function, most of all, detects conflicts and provides problem solution. System alarms the controller about potential conflicts on runways and in manoeuvring area of the airport.

A-SMGCS has 4 functional levels of realisation [2]. Levels of traffic situation visualisation and monitoring, and warning about movement conflict as well as intrusion to the reserved area are already defined. However, levels of planning (routing) and automatic guidance are still tested. Algorithm described in this paper can support the research efforts on planning level regarding to aircraft movement.

The crucial problem is to supply the data to the A-SMGCS system. They will allow to locate aircraft and others vehicles. The most important sources of information are:

1. SMR (Surface Movement Radar). This radar allows detection of moving objects and showing the actual traffic situation in manoeuvring area via the suitable interface. Variable information is presented on the background of permanent elements, like runways, taxiways, buildings. SMR is especially useful in low visibility conditions. Thanks to the connection with ASDE (Airport Surface Detection Equipment), it is possible to correlate information included in flight plan with the actual position of an aircraft.
2. ADS-B (Automatic Dependant Surveilance - Broadcast). It is a system supplying data about positions of aircraft through the use of transponders (Mode-S).
3. MLAT (Multilateration). It is a technology of hyperbolic positioning, used to locate the aircraft. It is independent surveillance system, based on broadcasting ground stations, remote receiving ground stations and central ground station, calculating an aircraft position. The signal sent reaches several receivers and basing on difference in arrival time, the system is able to designate three-dimensional position of an aircraft [7].
4. Data Fusion. It is not a data acquisition system but rather a module which allows integration of data from different sources.

3 Method of Finding the Conflict Points

For the purpose of this study a model of the aircraft taxi process was developed in the form of coloured, hierarchical Petri net. It is presented in details in [1]. Petri nets are a powerful formalism for describing and modelling the dynamics of concurrent systems. In this section the concept and the basic elements of the model will be presented briefly. Also its implementation with the use of the CPN Tools 4.0 package will be discussed in brief.

3.1 Petri Net Model for Determining Conflict Points

The first phase of the model creation is the analysis of the structure of examined airport manoeuvring area. It aims at recognition of starting and ending points of aircraft movement (runways and terminal gates) and possible taxiways. The analysis of taxiways structure allows one to present them schematically in the form of a graph. The edges represent taxiways sections, and the nodes are the points of taxiways crossings. They are also the potential conflict points mentioned in this study.

Hierarchical, coloured, timed Petri net was used for mapping the dynamic taxiing processes occurring in the analyzed area. Processes were modelled in accordance with the actual rules applicable in air traffic. The Petri net was constructed using the general principles defined in [8, 9]. The following structure of the Petri net was adopted

$$S_{TX} = \{P, T, A, M_0, \tau, \mathrm{X}, \Gamma, C, G, E, R, r_0, B\} \quad (1)$$

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.

3.2 Software Tool CP-DET for Determining Taxiing Conflict Points

Calculation module CP-DET for determining conflict points was built based on the developed mathematical model. It was implemented with the use of CPN Tools 4.0 package [13], which allows to implement the hierarchical Petri nets and to divide the model by using the so-called page mechanism.

The main page of the model (*Main*) is shown in Fig. 1. It implements the general structure of the model together with the dynamics of the aircraft movement on individual taxiway sections in accordance with the rules adopted by airport traffic management. On this page there are two substitution transitions (marked as rectangles with double frame): *Permissions to use TWY* and *Permission to begin*. They model operations carried out by GND air traffic controller which is responsible for ensuring the safe taxi operation.

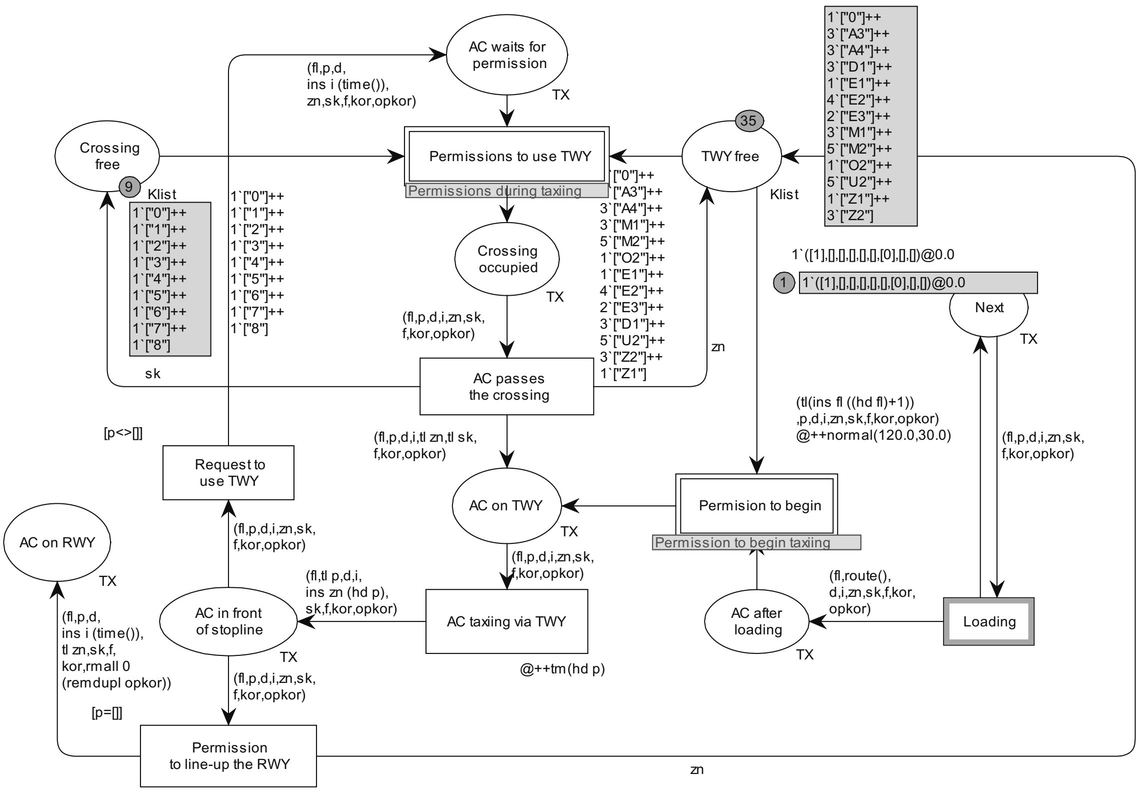

Fig. 1. Main page of the model (*Main*) [own study]

The set Γ consists of two colours in this model: $\Gamma = \{TX, Klist\}$. Tokens belonging to the *TX* colour represent taxiing aircraft and have the following structure

$$tx = 1'(fl, p, d, i, zn, sk, f, kor, opkor)@timestamp \tag{2}$$

where

fl – aircraft's number in the system,
p – planned taxi route (sequence of taxiway sections),
d – actual (realised) taxi route (sequence of taxiway sections),
i – moments in time when taxiing through individual taxiway sections finished,
zn – taxiway section currently occupied by the aircraft,
sk – taxiways crossing currently occupied by the aircraft,
f – total aircraft's delay [s],
kor – set of taxiway sections where the aircraft had to wait before entering,
opkor – times of waiting before entering the sections from the *kor* set,
timestamp – represents the moment in time when the token becomes active.

The planned taxi route is defined by a series of taxiway sections and is generated as a result of execution of the *route*() function by the *Loading* transition. The output of this function is one of the predefined routes used at the airport.

The most crucial places endangered by a collision are taxiway intersections. Analysis of the situation and working out a decision allowing the aircraft to go through the intersection are included in the model on *Permissions during taxiing* page (Fig. 2). Due to its size, only a small portion of this page is presented in Fig. 2. It shows the analysis of only one taxiway section (designated as A3). The model assumes that only intersections endangered by a collision are sought, while during taxiing on a single taxiway section collisions do not occur.

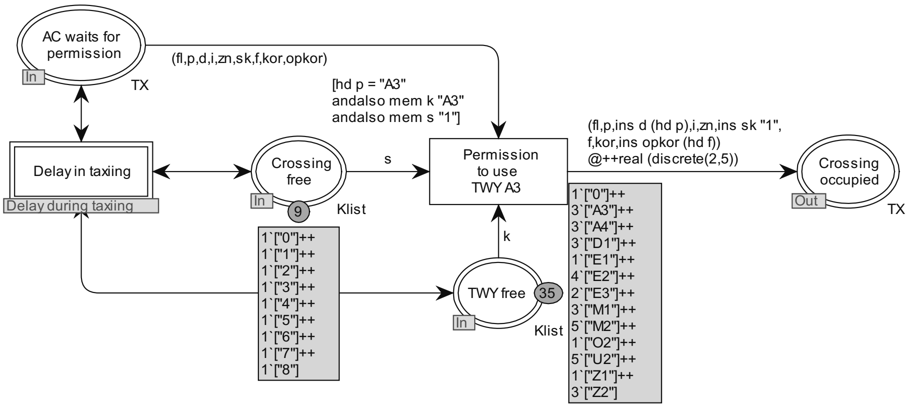

Fig. 2. Part of the page *Permissions during taxiing* [own study]

The decision allowing an aircraft to occupy the intersection is taken based on information in tokens stored in a place *Crossing free*. These tokens represent free intersections. Lack of token means that the intersection is currently occupied by an aircraft. The existence of free space on another part of the planned taxi route which permits an aircraft to easily leave the intersection is an additional condition required to occupy the intersection. Checking if this condition is met is based on the tokens contained in the *TWY free* place.

4 Supporting a Proccess of Finding a Taxi Route

Usually a taxi route between specified starting point and ending point (in case of taxing to takeoff - between parking place and runway in use) is statically predefined and used in most cases. On the one hand it is reasonable because it decreases the possibility of making mistakes in the taxi route designation or during the process of passing the taxiing instructions to the aircraft. On the other hand it is disadvantageous from a traffic management point of view, as it doesn't include actual (or expected) traffic situation.

The model, together with its implementation in form of CP-DET software presented in Sect. 3 allows designation of conflict points in the taxiways network. Conflict points may arise as result of traffic congestion, technical failures causing blockade of some taxiways sections, deterioration of weather conditions etc. The idea of the created system is to dynamically, intelligently designate the taxi route, taking into account the actual traffic situation represented by a set of conflict points. Thus, it will be possible to optimize a route with taxiing time taken as a criterion. Even better effects could be obtained if we use the forecasted traffic situation. An important element of the whole concept is a way of obtaining information about the actual taxiing time in particular sections. If we use the forecasted situation, there is a need for simulations, which include all future planned departure operations. If we use the current situation, the same information sources as for A-SMGCS system can be used. Installation of special sensors on the taxiways should be considered as well. This will make possible to track current traffic situation more efficiently and faster update all necessary taxiing times.

4.1 Model of Taxiways Network

Taxiways structure can be presented as a net, which is based on graph G

$$G = \langle V, B \rangle \tag{3}$$

where: V - set of graph vertices, representing taxiways intersections, and B – set of graph edges, representing a taxiway section. Typically, these sections have their own designations at the airport and are used to define the taxi route for the aircraft. Set B can be defined as:

$$B \subseteq V \times V = \{(u, v): u \neq v\} \tag{4}$$

Graph G is a digraph, as taxiways have specified direction of movement. Finding the route with the shortest taxiing time requires determination of time characteristics on edges

$$t\colon B \to \mathbb{R}_+ \tag{5}$$

where $t(u, v)$ defines the taxiing time on the section connecting vertex u with vertex v.

In Sect. 5 an example of taxiways structure at London Heathrow airport, together with graph model of it, will be presented.

4.2 Algorithms for Finding Extremal Routes

There are a lot of algorithms for finding the shortest route in the network. These include Dijkstra's, Bellman-Ford's, Floyd-Warshall's algorithms. Because of the size of the paper, the comparative analysis of these algorithms will not be presented. As a result of this analysis the well known algorithm called maximum dendrite of shortest routes has been chosen to use [4]. In the literature also some specific algorithms suitable for tackling the ground movement problem can be found. One of the solutions is Taxi Route Planner (XRP) tool that aims at minimizing the holding time of aircraft that are maneuvering on airport taxiways, for both arriving and departing aircraft [11]. This is done in two consecutive steps, that is, a standalone, shortest path solution from runway to apron (or vice versa), neglecting the presence of other aircraft on the airport surface, followed by a conflict detection and resolution task that attempts to reduce and possibly nullify the number of conflicts generated in the first phase. Another interesting approach can be found in [6]. A sequential graph based algorithm to address the ground movement problem was introduced there. This algorithm aims to absorb as much waiting time for delay as possible at the stand (with engines off) rather than out on the taxiways (with engines running). The impact of successfully achieving this aim is to reduce the environmental pollution. Similar approach can be found in [3]. It presents Spot And Runway

Departure Advisor (SARDA) - an individual aircraft-based advisory concept for surface management. It utilizes the concept of the collaborative decision making with gate-holding as a measure to decrease aircraft fuel consumption.

4.3 Petri Net to Designate Alternative Taxi Route

Taxiway network defined by formulas (3)–(5) can be modelled as Petri net. This approach allows easy implementation of the algorithm for finding alternative taxi route, defined in Sect. 4.2. In general, the way of coloured timed Petri net creation proceeds according to the following scheme:

1. Graph G nodes become places in Petri net. They keep tokens of the colour T, which represents features of algorithms for finding the shortest routes dendrite. Colour T is defined as

   ```
   colset T = product INT*LP
   ```

   where INT represents an integer and LP is a list of integers.
   The token $md = 1'(t, lp)$ stored in the place modelling vertex v represents a route from the parking position (vertex 0) to the vertex v, where t is a total taxi time and lp is a list vertices in the shortest route.
2. Time characteristics $t(u, v)$ also become places in Petri net. However, they keep tokens of the colour which can be considered as integer numbers. They represent taxiing time on the section determined by (u, v) pair.
3. Edges (u, v) of graph G become transitions. The transition input places are: place representing vertex u and place representing characteristic on arc $t(u, v)$. Output place of the transition representing section (u, v) is the place modelling the vertex v.
4. Functions E, describing weights of arcs in Petri net (formula 1), realize steps of the algorithm for finding the shortest routes dendrite. They modify the special data structure containing the list of vertices in the shortest route and also the minimum taxiing time.

5 Example of Method Application

A part of taxiways system at London Heathrow airport is presented in Fig. 3. To make presentation clear, only few taxiways intersections were considered. They are marked by circles with figures. The taxiways not included, were marked by short lines crossing the taxiways.

The net representing part of taxiways system presented in Fig. 3 is shown in Fig. 4. In this case:

$$\begin{aligned} G = &\langle \{0, 1, 2, 3, 4, 5, 6\}, \\ &\{(0, 1), (1, 2), (1, 3), (3, 2), (2, 6), (5, 6), (3, 4), (4, 5), (4, 6)\}\rangle \end{aligned} \tag{6}$$

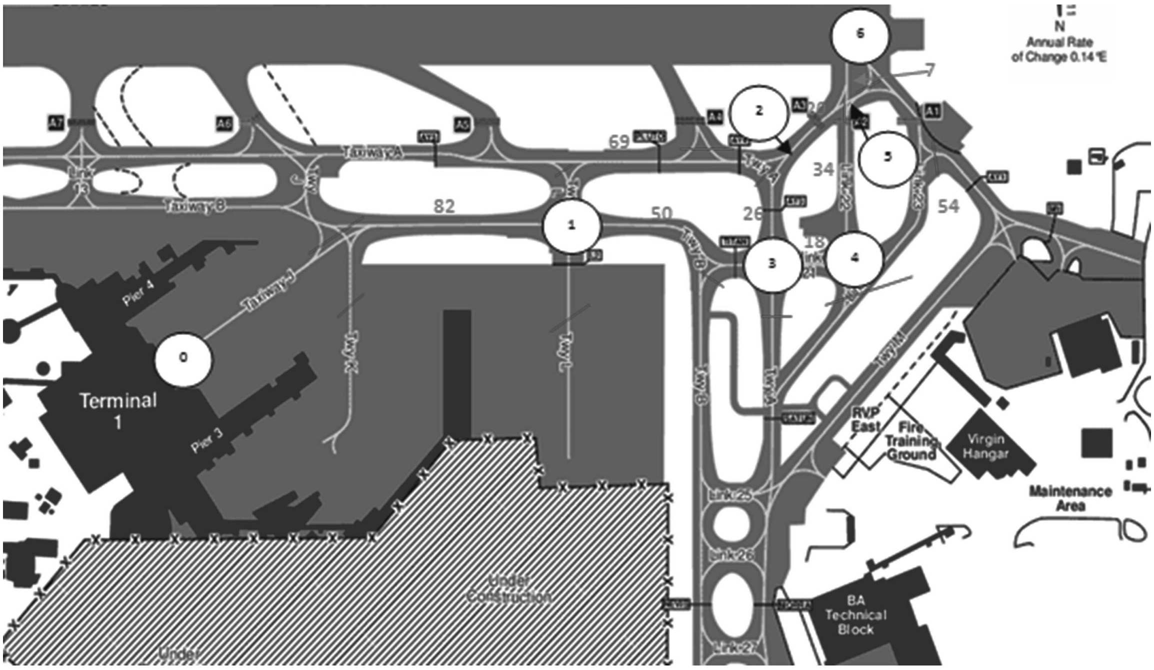

Fig. 3. London Heathrow airport with vertices and taxi times [own study]

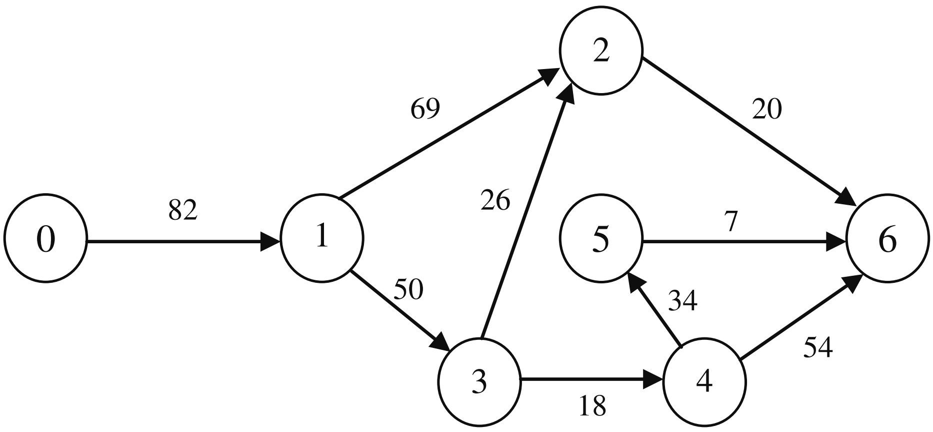

Fig. 4. Taxiways represented by a net [own study]

Values of function *t* were defined, based on distance between vertices and standard taxing speed, which includes aircraft movement on straight section and arcs. The taxiing speed was measured during real operation. It is usually about 10 knots, which means about 5 m/s. However, sometimes the taxiing speed at particular airport locations is a safety bottleneck, so it may be decided to implement speed restrictions [10].

Petri Net for this example, constructed according to principles described in Sect. 4.3 is presented in Fig. 5. Places named “0”, “1”, “2” etc. represent the nodes *G* of the graph shown in Fig. 4. Time characteristics $t(u, v)$ are stored in places named: “0–1”, “1–2”, “1–3” etc. Transitions are responsible for updating the total time necessary to taxi via a section (u, v). The list of vertices in the shortest route is represented by the *lp* variable, which is of colour *LP* defined as list of integers. An important part of this Petri net are the functions *ch2* and *ch3*, which choose the minimum taxi time. The final solution is stored in place named “D”.

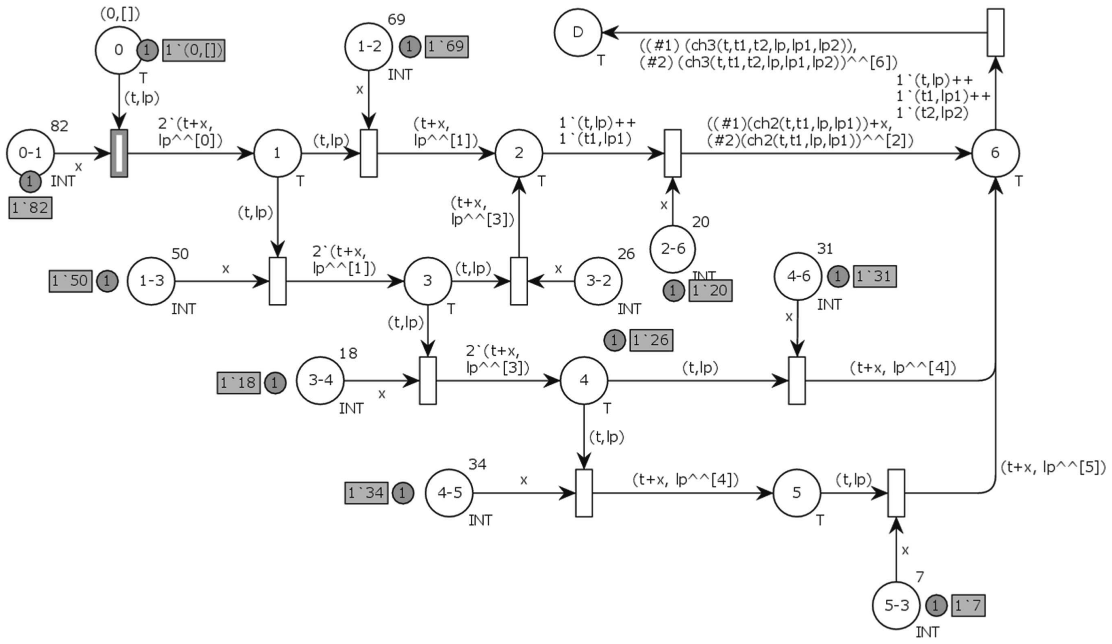

Fig. 5. Petri net for finding the fastest taxi route [own study]

Using the simulator which is a part of CPN Tools package allows finding the fastest taxi route. The sequence of vertices in this route is: $\langle 0, 1, 2, 6 \rangle$. The shortest taxi time which corresponds to it equals $t(0,1) + t(1,2) + t(2,6) = 171$ s.

The algorithm for determining conflict points which was discussed in Sect. 3 allows modification of transit times represented by the places keeping the tokens of colour INT. Therefore the integration of both applications, which is the next step of research, will let automatic generation of an alternative taxi route in case of the occurrence of traffic interferences which are represented by conflict points. To illustrate applicability of this solution, two simulation experiments will be presented.

Experiment 1. In the first experiment the following scenario will be examined. The aircraft is still at parking position (vertex 0) when, because of increased traffic, also the taxi times increase. The new values are (in seconds): $t(0,1) = 100$, $t(1,2) = 83$, $t(2,6) = 40$, $t(1,3) = 55$, $t(3,4) = 25$, $t(3,2) = 35$, $t(4,6) = 40$, $t(4,5) = 45$, $t(5,6) = 20$. In this situation, there is a possibility to recalculate the taxi time again and look for alternate taxi route which is now more beneficial than route which was planned originally. After the simulation, it turns out that the alternative taxi route is described by a sequence of vertices $\langle 0, 1, 3, 4, 6 \rangle$ and the new shortest taxi time is 209 s.

Experiment 2. In the second experiment we assumed that the aircraft is already taxiing and it is approaching to the vertex 3. Taxi time to the vertex 3 was 132 s and the scenario assumes that in this moment, because of intensive precipitations, the taxi times in particular sections change in the following way (in seconds): $t(2,6) = 30$, $t(3,4) = 30$, $t(4,5) = 25$, $t(4,6) = 38$ and $t(5,6) = 20$. There is a possibility to recalculate the taxi route and change the taxi instructions appropriately. The fastest route for the new traffic situation is $\langle 0, 1, 3, 2, 6 \rangle$ and the new shortest taxi time is 188 s.

6 Conclusion

The concept of finding the fastest taxi route, which was presented in this paper, also allows finding an alternative route in case of receiving the information about a change of the traffic situation. The method of determination of the conflict points allows at the same time predicting a new situation based on the movement plans within the manoeuvring area of the airport. There is a possibility of integration of both solutions (which is planned in the next stage of research). This will allow determination (by simulation) of the new, alternative routes if the prediction of future traffic situation suggests that it is necessary.

The hierarchical structure of the coloured, timed Petri net, presented in this paper, allows for the simulation of the actual and projected air traffic. Experiments carried out indicate full usefulness and efficiency of such an approach for determining the alternative taxi route. However, it is necessary to check the concept on more complex taxiways network.

An important issue which needs to be verified, is whether the concept of finding the best route for each aircraft individually (which was assumed here) gives a globally optimal solution. Knowing the typical properties of this kind of dynamical systems, it can be expected that the solution obtained here is better than standard, but it isn't globally optimal. Therefore it is necessary to modify the approach, by applying network planning mechanisms and simultaneous optimisation of taxi routes of all aircraft at the same time. Such research will be undertaken and for that purpose we plan to use a Dynamic Programming method.

Recently, the research on airport ground movement has started to take into account a speed profile optimisation problem so that not only time efficiency but also fuel saving and decrease in airport emissions can be achieved at the same time [12]. This problem is difficult to solve due to its computational load. However, using different objective functions (not just the time) is very promising research direction, which we plan to undertake in the future.

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