



Method for identification of conflict points in the intelligent system of an aircraft taxi route choice

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ABSTRACT

axiing belongs to airport operations, which are characterized by a large number of aviation safety events, including even accidents. Currently telematic solutions are introduced, which are intended to assist in coordination of the taxiing, such as A-SMGCS system. One of the advanced features of this system is the automatic selection of the taxi route. The paper presents the concept of intelligent taxi route choice system that could be implemented on the fourth level of A-SMGCS system at the airport. The module for identification of conflict points, which is the main subject of this study, is a very important part of the taxi route choice system. A mathematical model and a computer tool CP-DET that can detect conflict points in the structure of taxiways are presented in the paper. These points change dynamically, along with changes in the structure of airport traffic. Identification of conflict points allows the intelligent management of the taxiing process, for example, by selecting an alternative taxi route.

Keywords: air traffic, airport surface management system, Petri nets, traffic safety, intelligent taxi route choice system, conflict points identification

1. Introduction

Airport ground traffic is characterised by high intensity and high complexity, especially in large European hub airports. At the same time incidents, serious incidents or even accidents with losses in equipment or even casualties occur in this traffic. This is due to the complex structure of taxiways and small distances between taxiing aircraft (Geng et al. 2012).

Taxiing usually takes place at pre-defined routes. This is not a good solution because it does not take into account the current traffic situation, weather conditions, and the current state of airport infrastructure. In this paper, we propose to create automated intelligent system which is based on the analysis of the above factors and on simulation of further development of the traffic situation. This system will suggest an alternative taxi route, also to the aircraft which have already started a taxi procedure. The main factor that suggests that the route should be changed is the existence of conflict points, which

means points that cannot be passed without having to wait and giving way to another aircraft. These points may be changing dynamically depending on the operating conditions and environmental factors.

In this paper we present the concept of the mathematical model and computer tool CP-DET (Conflict Point DETection) to determine the points of conflict. This solution indicates these points, but also shows the level of interference that they introduce. It is represented by the average delay time at a given point.

2. The aircraft taxiing process

Taxiing is an operation in which the aircraft moves on the airport manoeuvring area, using its own engines. Taxiing process is organized and controlled by a specialized airport tower (TWR) control service, in particular by a Ground Controller (GND) (ICAO 2007a). Taxi clearance should include appropriate instructions to the aircraft crew that help them to find the right taxiway, to

avoid collisions with other aircraft or obstacles and to minimize the potential unintended aircraft incursion on the runway in use (Schönefeld & Möller 2012).

The process of taxiing for the take-off begins when the pilot obtains a taxi clearance (ICAO 2007a). Then the GND controller specifies which taxiways should be used to reach the target runway. Other supporting information may also be transmitted to the taxiing aircraft, for example which aircraft to follow or to give a way. Taxiing after landing process is similar.

Standard taxiways at the airport are identified by the corresponding signs on the ground and should be published in the Aeronautical Information by the appropriate aviation authority.

2.1. The problem of taxiing aircraft safety

As statistics show, in the taxiing process numerous air occurrences take place (EUROCONTROL 2012, Federal Aviation Administration 2009). These are usually incidents or serious incidents, but sometimes also accidents occur. 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.

Safety problems of taxiing aircraft may have several reasons. A large number of aircraft on the airport manoeuvring area is one of the most important. Another problem is the large area of the airport and its complex structure. Yet another important safety factor is the weather conditions. Equally important are: errors in the labelling, errors in the controller-pilot communication, lack of knowledge of the airport topography, etc.

All these factors cause that we are looking for alternative systems of organisation and support of taxiing aircraft control systems. They have the nature of intelligent telematic systems. On the one hand, they automatically acquire information about the current aircraft positions and transmit it to the Air Traffic Control (ATC) position where it can be displayed on the special imaging devices. On the other hand, they transmit information and traffic clearances from the controller to the aircraft crew. The third very important aspect of such systems is to assist the controller in choosing the taxi route for each aircraft. This is particularly important in the case of large airports, with a dense taxiways network. Taxiing aircraft routing is a dynamic problem, since the decision depends not only on the aircraft route start and end points, but also on the current traffic on the airport manoeuvring area. And that is changing over time.

Many evaluation criteria of solutions in the taxi route selection process can be defined (Kondroška & Stankunas 2012). In this paper we propose the use of the safety criterion which is expressed by the use of strategy to avoid potentially conflicting points. The identification of such points is still a problem. The model and the CP-DET software tool presented in the following sections allow one to dynamically assess the traffic situation and to find those points. This could be the basis for the selection of an alternative taxi route. Details of the use of such tools in A-SMGCS systems are described in section 3.1.

2.2. Support systems for taxiing process control

In the broadest sense Surface Movement Guidance and Control (SMGC) system consist in organizing and control of the traffic of all aircraft, service vehicles and personnel in the airport area (ICAO 2007b, Pestana et al. 2011). To allow the safe operation of the airport in difficult weather conditions is the main reason why SMGC system is introduced.

SMGC system should implement several groups of requirements:

1. The requirements of a general nature: providing a communication between the air traffic control services and the aircraft and ground handling vehicles, a small workload when using the system, the use of navigational aids and procedures specified in ICAO regulatory documents, compatibility between the different elements of the system supporting and directing traffic, providing information about the current and forecasted weather conditions.
2. Pilots requirements: assisting from landing to taking a parking place, and also from the release of the parking place to obtaining the takeoff clearance, providing information about the taxi route, providing information about the location at the airport during taxiing, assisting with parking, warning of the need to change the direction, to stop, to limit the speed, identification of areas to be avoided, providing information about the movement of other aircraft or ground handling vehicles.
3. ATC services requirements: identification of aircraft and ground handling vehicles, providing information about their positions and movements, identification of the occurrence of temporary obstacles, providing information on the operational status of system components, enabling training and exercises.
4. Another requirement for all systems or applications used in air traffic management is mandatory certification and testing.

3. Automatic taxi route selection in A-SMGCS

Advanced Surface Movement Guidance and Control System (A-SMGCS) is an example of a commercial system for the airport surface movement management support (ICAO 2004). It uses multiple sources of information about the location of objects (Siergiejczyk & Krzykowska 2013). Thanks to this, A-SMGCS can effectively perform a surveillance function. It involves identification (assigning labels) of objects on the airport manoeuvring area and also the update of information on all their movements. Finally, the A-SMGCS systems have to meet three further levels of functions:

- the allocation of routes; consisting in determining the routes for all vehicles, along with the ability to change them if necessary,
- directing; manifested by providing the guidance for the next manoeuvre, along with automatic adjustment for the change in the assigned route,
- control; consisting in traffic supervision taking into account taxiways throughput, detecting and resolving potential conflicts, detecting over-concentrated areas, together with changing the

assigned route to avoid these areas, ensuring the separation between aircraft, alerting about runway incursions.

While the supervision and allocation of routes functions are widely implemented in commercial solutions, the higher functional levels are still the subject of research and development (Borkowicz et al. 2006, Zhu et al. 2012, Zhu & Lu 2014). In this paper we deal with the problem of dynamic detection of places with conflict risk and significant due to the high traffic density. This is a part of the fourth, the highest functional level of A-SMGCS systems.

3.1. The concept of intelligent taxi route choice system

In this paper, we present the model and software tool CP-DET that allow for the dynamic identification of conflict points in the structure of the taxiways network. These solutions represent a stage in the ongoing work towards the development of an intelligent system for supporting the air traffic controller and the aircraft crew in choosing the best taxi route. The idea is to analyze the current and planned traffic, to determine the conflict points by means of simulation and finally to identify alternative routes in case of a high probability of encountering such a point of conflict.

A very important element of this concept is the correct location of the conflict points. Under this term we mean points at which it is not possible to continue the movement, and it is necessary to wait and give way to the aircraft moving on other taxiways. Such an analysis can be carried out for the static case with other methods. However, we are talking about the air traffic, which is dynamic and randomly changing. In addition, the planning horizon is very short - no more than a few minutes. In such a situation, it is necessary to use simulation methods in which taxiing aircraft will have a planned route, but its execution time will be random. The result of the simulation can be a decision to change the taxi route so as to avoid the current conflict points.

3.2. The model of the process of identifying conflict points

For the purpose of this study the model of the aircraft taxi process was developed in the form of coloured, hierarchical Petri net. It is a recognized tool for the analysis of such issues (Davidrajuh & Lin 2011, Skorupski 2013c). In this section the concept and the basic elements of the model, which reflects an aircraft taxiing for the take-off from RWY 29 runway at Frederic Chopin Airport in Warsaw will be presented briefly. And parts of its implementation with the use of the CPN Tools 4.0 package will be discussed in Section 3.3.

Part of the airport along with marked RWY 29 runway and taxiways A, D, E, F, U and Z analyzed in this study are shown in Figure 1.

The analysis of taxiways structure allows one to present them schematically in the form of a graph. For the analyzed part of the airport this scheme is shown in Figure 2. The edges represent taxiways sections, and the nodes are the points of taxiways crossings. They are also the potential conflict points sought in this study.

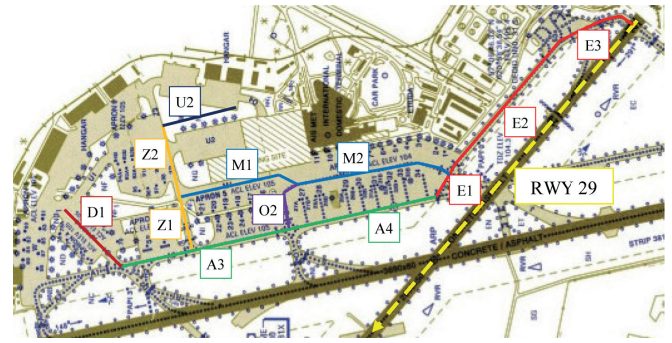


Fig. 1. Taxiways at the Warsaw Frederic Chopin Airport (excerpt) [own study]

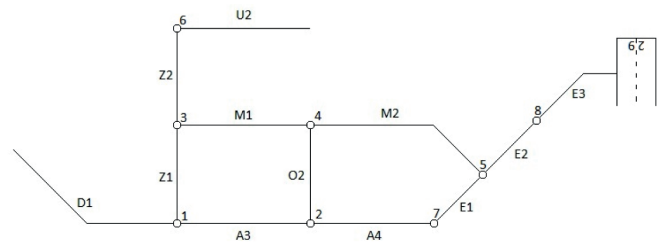


Fig. 2. Model of taxiways leading to RWY 29 runway at Warsaw Frederic Chopin Airport [own study]

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 (Skorupski 2011, 2013a, b). The following structure of the Petri net was adopted

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

where:

P – set of places,

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

$A \subseteq (TxP) \cup (PxT)$ – set of arcs,

$M_0: P \rightarrow \mathbb{Z}_+ \times R$ – marking which defines the initial state of the system that is being modeled,

$\tau: TxP \rightarrow R_+$ – function determining the static delay that is connected with carrying out activity (event) t ,

$X: TxP \rightarrow R_+$ – 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) $R \subseteq R$,

r_0 – initial time, $r_0 \in R$.

$B: T \rightarrow R_+$ – function determining the priority of a given event, i.e. controlling the net’s dynamics when there are several events that can occur simultaneously.

3.3. Software tool CP-DET for determining taxiing conflict points

Calculation module CP-DET for determining the conflict points was built based on the developed mathematical model. It was implemented with the use of CPN Tools 4.0 package (Westergaard & Kristensen 2009). This software has been increasingly recognized among researchers working on the modelling of dynamic processes in recent years. This is due to the possibility of using extensive graphic editor to create a model in the form of coloured Petri net, and also its simulation and analysis in the state space. It is also possible 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 Figure 3. 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.

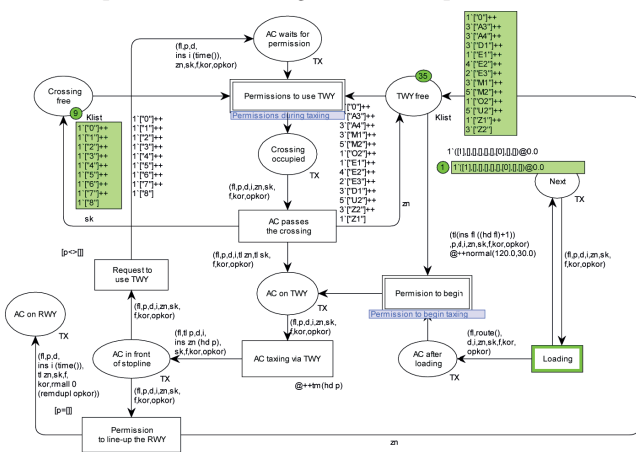


Fig. 3. Main page of the model (*Main*) [own study]

The set consists of two colours in this model: Tokens belonging to the colour represent taxiing aircraft and have the following structure

$$t_x = 1' (fl, p, d, i, zn, sk, f, kor, opkor) @ timestamp \quad (2)$$

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 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 Warsaw Chopin Airport.

The moment when an aircraft performs the off-block procedure is the first important moment in which a potential collision with other moving aircraft may happen. Aircraft parking stands are arranged close to each other, and often there is a situation where a number of aircraft at the same time try to join the stream of already taxiing aircraft. *Permission to begin taxiing* page (Figure 4) shows a model of that decision-making situation. In the proposed module of intelligent system for supporting taxiing in A-SMGCS, the permission to begin taxiing procedure is based on the occupancy of the appropriate section represented by the *TWY free* place. Tokens that are present in this place determine the number of free places in each section. For example, in the situation shown in Figure 3, three aircraft more may taxi in section A3 and two aircraft more in section E3.

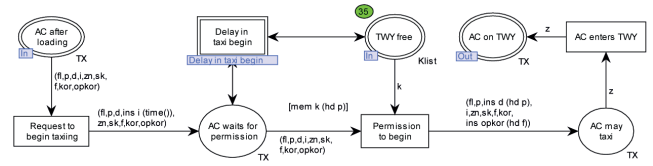


Fig. 4. Page *Permission to begin taxiing* [own study]

Another important place endangered by a collision is a taxiway intersection. 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 (Figure 5). Due to its size, only a small portion of this page is presented in Figure 5. It shows the analysis of only one taxiway section (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. In the following stages of the research the possibility of a collision on the individual section will also be taken into account. This will result in proposing alternative routes bypassing not only collision points, but also more busy sections.

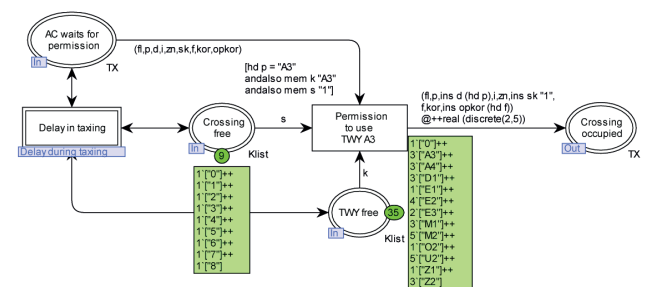


Fig. 5. Part of the page *Permissions during taxiing* [own study]

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 intersections numbering is consistent with Figure 2. 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.

The CP-DET calculation module contains additional pages *Delay in taxi begin* and *Delay during taxiing*, which allow one to record conflict situations and traffic delays occurring in these cases. This allows one to precisely identify the points that generate the most of such adverse situations. The results presented in the following sections were obtained with the use of the recording function of these pages. However, due to the paper size limitation these pages will not be further discussed.

3.4. Simulation experiments

In order to demonstrate applicability of this model and CP-DET computer tool in A-SMGCS systems, three simulation experiments were conducted. They led to determination of the conflict points together with an analysis of the degree of traffic disturbance introduced by these conflict situations.

These experiments were carried out for the process of aircraft taxiing for the takeoff on RWY 29 runway at Warsaw Frederic Chopin Airport. In the experiments, data on actual traffic were used; in particular aircraft taxi times on different sections. They were collected during the measurements in 2013. Taxi times mentioned above are random. The corresponding random variables characteristics were identified and used in the simulations. Table 1 presents calculated mean values and standard deviations of recorded data.

Table 1. Times of taxiing for takeoff on RWY 29 runway [own study]

Taxiway section	A3	A4	M1	M2	O2	E1	E2	E3	D1	U2	Z1	Z2
Mean taxiing time [s]	62	57	55	80	26	22	101	40	66	136	30	30
Standard deviation [s]	19	18	17	31	7	7	18	10	16	28	7	9

Experiment 1

The simulation experiment was performed for the data presented in Table 1. The process of taxiing to the RWY 29 runway was modelled. As a result, 439 aircraft completed the taxiing and reached the runway threshold. In 26 cases the conflict situation occurred and there was a need to wait for the opportunity to go through the taxiways intersection. This means that nearly 6% of the aircraft encountered a conflict situation. However, the delays were small. They ranged from a few to about twenty seconds. Figure 6 shows the taxiway sections where collision situations occurred, along with the number of these events.

As one can see, the conflict situations occurred mostly before entering the section E1 so the actual collision point was the point number 7 (Figure 2). This is mainly due to the fact that the section E1 capacity is limited as it is a very short section. In the case that the presented model was used to support routing in intelligent systems like an A-SMGCS it is easy to suggest that an alternative

taxi route should use taxiway M, bypassing both the conflict point 7 and the section E1.

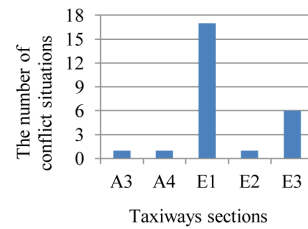


Fig. 6. The number of conflict situations (Experiment 1) [own study]

Experiment 2

Experiment 1 (for actual conditions) will be treated as a reference. In the second experiment we examined how the number and distribution of conflict points changes for the same part of the taxiways network but for the increased traffic. For this purpose the generator increased the intensity of aircraft ready for taxiing appearance. It is assumed that the aircraft appears exactly every 40 seconds. All other settings remain unchanged.

For such settings a simulation was performed resulting in 250 aircraft that completed taxiing and reached the RWY 29 runway threshold. As many as 117 of them have encountered a conflict situation. The average delay resulting from the need to wait at conflict points was 19.5 seconds. Distribution of conflict points is shown in Figure 7a.

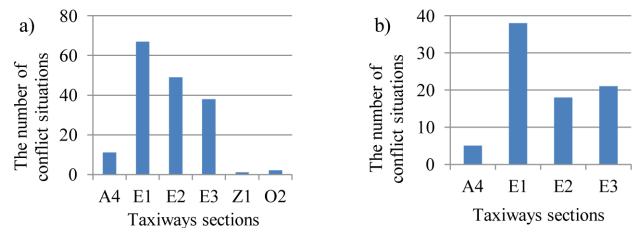


Fig. 7. The number of conflict situations: a) Experiment 2, b) Experiment 3 [own study]

Experiment 3

In the experiment 3 the study for the increased time of going through the runways intersection was conducted. These times were increased for all crossings. This test reflects the situation when the response time of a taxiing aircraft crew is greater than the nominal. This can happen when the aircraft crew does not know the airport topography well or they need more time due to the difficult weather conditions or the surrounding traffic is very complicated.

As a result of the simulation, 252 aircraft completed the taxiing and reached the runway threshold. In 66 cases the conflict situation occurred. The average delay per aircraft was in this case, as much as 33 seconds. It is therefore clearly higher than in the previous experiment. Distribution of conflict points is shown in Figure 7b.

In both experiments conducted for conditions worse than actual, the increase in the number of conflict situations, as well as their duration is clearly visible. For the part of the airport under consideration, always the biggest problem was the taxiway E, especially its section E1. However, the results show that in the case of increased traffic (Experiment 2) applying a strategy of using the

taxiway M is not effective. It requires the use of the E2 taxiway section. In the case of increased traffic it is also a bottleneck, and the preceding point number 5 (Figure 2) should be treated as a conflict point.

4. Conclusion

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 (and partially described) indicate full usefulness of such an approach for determining the conflict points of taxiway network. They also allow for the identification of additional characteristics such as the average delay of the taxiing process.

As indicated at the beginning of this paper, the work on the development of methods of supporting air traffic controllers and aircraft crews in the taxiing process is carried out at the moment. This is especially important for large airports with a complicated structure. However, as shown by the results presented in this paper, even for smaller airports the support of intelligent telematic advice systems will be necessary. They will be crucial in case of increased traffic volume or weaker visibility. The presented model and CP-DET software tool can be applied in the currently developed (for example in the European project SESAR 2020) solutions in this area, particularly in relation to the more advanced features such as dynamic control of taxi route selection.

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