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PRE-DEPARTURE SEQUENCING METHOD IN THE TERMS OF THE DYNAMIC GROWTH OF AIRPORTS

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Abstract

The increase in air traffic requires organizational changes at the airport and near the airport. To ensure appropriate airport operating efficiency, it is becoming necessary to provide unobstructed flow of information between all parties involved in the process. Common decision-making process regarding operations carried out at an airport, based on legible information, may contribute to faster and more precise prediction of sequence of events.

This article aims to present pre-departure sequencing method in the terms of the dynamic growth of airports. This method dynamically defines current sequencing of departing aircraft with consideration of time required to maintain minimum separation between subsequent take offs and evaluates runway occupancy regarding planned arrivals.

Developed method uses criteria of reduction maximum delay on one handling position, which is starting runway in use. It is carried out by sequencing tasks, in accordance with non-decreasing requested times of completion. Greedy algorithm has been used to define sequence of carrying out take off operations based on the earliest possible time of the departure.

Faced with dynamic growth of airports, this method may contribute to improvement of predictability of events, and thus facilitate proper decision making, which will allow managing airport traffic smoothly and without unnecessary downtimes.

Keywords: *air transport, simulation of air traffic, pre-departure sequencing of aircraft*

1. Introduction

Dynamic growth of airports that have been observed over the last years is connected with increased interest in air transport. Currently air transport is the fastest growing sector of services, and predictions on air traffic intensity show that growth dynamic will not change until 2030. One condition for increase of air traffic is implementation of programmes for increase of airports throughput and providing proper level of air traffic process management. Traffic should be run in a way that allows reconciling mutually contradictory goals relating to maintaining traffic efficiency and smoothness, as well as proper level of safety.

Constant growth of air traffic, especially in airport area, puts great pressure on all ATC system components and all traffic participants. To ensure appropriate airport operating efficiency, it is becoming necessary to provide unobstructed flow of information between all parties involved in the process. Common decision-making process regarding operations carried out at an airport, based on legible information, may contribute to faster and more precise prediction of sequence of events. Better punctuality of operation executions achieved in the process may greatly contribute to reduction of delays.

One of the elements that are based on efficient flow of precise information about up to date advancement of flight plan is the pre-departure sequencing. Sequencing relates to setting up sequence of aircraft push back out of ground handling positions. The set up allows to reduce waiting time directly before the runway threshold and reduce traffic on taxiways by efficiently operated take offs.

In most cases, sequence of aircraft push back from their handling positions is carried out in accordance with FIFS rule (First In, First Served). This method may be compared to FIFO queue regime (First In, First Out) known in mass service theory. Aircraft reporting readiness for push back is serviced in accordance with request sequence. It does not guarantee optimal sequence of aircraft push back in the current traffic situation; moreover, it does not include aircraft users' preferences in case of heavy traffic. Reporting readiness for take-off by many aircraft at the same time may create queue before runway threshold. Thus, aircraft operators bear resulting financial losses, which come from delays, burning large amounts of fuel, which happens during waiting time before runway threshold.

This article presents evaluated method of pre-departure sequencing, which can determine estimated departure time and appropriate off block time on the basis of exchange information on expected moment of ground handling completion, taxi time before take-off, expected landings and given type of aircraft.

Pre-departure sequencing will allow ATC for efficient use of TOBT (Target off-Block Time), so the flight is optimally checked out of its position. Bearing in mind the flight advance, based on TOBT and considering situation on the apron, taxiways and around runways, ATC can provide value for TSAT (Target Start-up Approval Time). Knowing this time allows to set up aircraft in efficient pre-departure sequence, as a result ordered and smooth air traffic flow on runway is obtained, contrary to operation based on „First In, First Served” regime.

Pre-departure sequencing method sets the following goals:

- improvement of sequencing clarity,
- improvement of event predictability by defining TSAT and TTOT,
- improvement of punctuality (e.g. assignment of slots, plans of air operators),
- use optimisation of resources other than runways (e.g. gates, apron positions, vehicles, taxi ways, etc.).

2. Sequencing tasks problem

Most task sequencing problems belong in the group of combinatorial problems. Two main combinatorial problems can be distinguished:

- decision problem – those are problems with a question that can be answered with „yes” or „no”;
- optimization problems – those are problems that require finding extremes of certain objective function.

Each optimization problem cannot be easier than equivalent decision problem. Combinatorial problems can also be distinguished based on their membership in certain groups, called computational complexity classes in decision problems. Above all, the following classes can be distinguished:

- *NP* class that comprise all decision problems, whose complexity is at most exponential;
- *P* class comprises all decision problems, whose complexity is at most polynomial, where it seems that $P \neq NP$ and *P* is a true subclass of *NP*, but it is still an open issue;
- *NP*-complete are the class that contains classically difficult combinatorial decision problems with not known algorithm of polynomial complexity, therefore it can be presumed, that problems in this class are of exponential complexity.

Complexity order of the best exact algorithm that solves the given problem may be defined on the basis of whether the problem under consideration belongs to specific class. Therefore, if $P \neq NP$, then problems of the *NP*-complete class cannot be solved with any algorithm with polynomial complexity, which means, that complexity of the best exact algorithm for this problem is exponential.

Examined problem belongs to the group of optimizing tasks related to sequencing of tasks on one handling position. It can be said that the problem is computationally difficult. Analysed problem is also *NP*-hard. It concerns a situation, where tasks are assigned to one position, and sequence of tasks execution is the optimizing criterion. Therefore, the chosen algorithm in its subprocedure considers a hard problem, so it must be computationally hard itself. This article focuses on creating method that dynamically defines the best pre-departure sequence within current set of aircraft. Algorithm used from the group belongs to group of heuristic algorithms, more precisely to domain of greedy algorithms and is adjusted for the problem needs; and precision of its operation can be verified by induction.

Task sequencing problem *л* is an ordered sequence of parameters that describe given problem with criterion of sequencing. Not all parameters must have their values assigned. When setting values of all parameters for a given sequencing problem л, the outcome is a specific sequencing problem *I*, whereas set of all specific sequencing problems for the problem л is denoted with $D_л$.

Given task $Z_j \in \mathcal{Z}$ is described with the following data:

- Vector of execution times – $\tau_j = [\ \tau_{1j}, \tau_{2j}, \ldots, \tau_{mj}]^T$, where τ_{ij} is the time, when position Pi executes task Z_j. Time of Z_j task execution on P_i position equals to $\tau_{ij} = \tau_j/b_i$, $i = 1, 2, \ldots, m$, where τ_j is the time of Z_j task execution on specified standard position (e.g. the slowest one), while b_j is the coefficient of the Pi position speed and standard position speed ratio.
- Time of arrival (readiness for execution) – r_j. If all tasks from the $\mathcal{Z}$ set have these times equal, then it is assumed, that $r_j = 0, j=1, 2, \ldots, n$.
- Time of execution completion – d_j. If the Z_j task execution must be completed before time d_j, then d_j is called critical line.
- Weight – w_j, which can be interpreted as cost of staying in the system for the time unit. Therefore, cost of staying in the system for Z_j task, completed at time t is equal to $w_j t$.

Each task in the $\mathcal{Z}$ set is an indivisible task, because breaks in execution of any task are impossible.

Each of the tasks $Z_j \in \mathcal{Z}$ is a dependent task with defined sequence restrictions: $Z_i < Z_j$ means that execution of Z_i task must be completed before starting of Z_j task execution.

3. Problems of deterministic sequencing of tasks

Problem of tasks sequencing relates to assignment of tasks to resources, e.g. to handling positions, in order to execute the tasks in compliance with additional restrictions. Depending on the given problem, task assignment to processors aims to:

- optimize given criteria function, that defines quality of sequencing – this may be e.g. maximizing profit or minimizing total sequencing time;
- answer to the question: is sequencing compliant with all restrictions possible to construct at all?

Task sequencing problem can be defined by distinguishing set of *n* tasks $\mathcal{Z}=\{Z_1, Z_2, \ldots, Z_n\}$, *s* set of handling positions $\mathcal{S} = \{S_1, S_2, \ldots, S_s\}$ and *m* set of additional resource types $\mathcal{P}=\{P_1, P_2, \ldots, P_m\}$. Sequencing of tasks is the process of $\mathcal{Z}$ set tasks assignment to positions from the $\mathcal{S}$ set, with consideration of additional resources from the $\mathcal{P}$ set. Obtained sequencing describes way of operation execution with consideration of all additional restrictions.

Tasks sequencing problems can be divided primarily by nature of handling positions that carry out the set of tasks. This division can be expressed by defining positions as parallel or dedicated. In case of parallel positions, each task can be carried out by any handling position. Parallel positions carry out tasks in the same way (which does not exclude possibility of different work speeds). Dedicated positions feature task processing in a defined way. Each task $Z_j \in \mathcal{Z}$ for dedicated positions is divided into operations $O_{1j}, O_{2j}, \ldots, O_{kjj}$, and each of them may require different handling position.

Aspect fundamental to definition of task sequencing problem is determination of objective function. It affects quality of proposed sequencing. It is determinant for evaluation of given algorithm efficiency at solving given problem. Functions can be distinguished to maximize given parameter (e.g. profit of execution of specific tasks) or to minimize the parameter (e.g. total time of sequencing).

Z_j task is available at time t, if $r_j \leq t$ and all its preceding tasks were executed until time t.

Sequencing is such time assignment of positions in $\mathcal{S}$ set to tasks from the $\mathcal{Z}$ set, which meets the following conditions:

- at any moment, any single position carries out one task at most;
- Z_j task is carried out in time interval $[r_j, \infty)$;
- all tasks will be carried out;
- for each pair of tasks Z_i, $Z_j \in Z$, such that $Z_i < Z_j$, execution of Z_j task starts after Z_i is completed;
- in case of indivisible tasks, execution of no task from Z set can be interrupted.
- In a given sequencing, it is possible to define for task Z_j, $j=1, 2, \ldots, n$:
- time of completion C_j;
- flow time (staying in the system) F_j, which is the sum of waiting time and execution time: $F_j = C_j - r_j$;
- delay L_j: $L_j = C_j - d_j$;
- final delay T_j: $T_j = max\{C_j - d_j, 0\}$.

In task sequencing theory, classification system is widely used to quickly classify problems. The system is commonly called three-field notation, which is presented in the following form: $\alpha \mid \beta \mid \gamma$. Field α defines set of handling positions, field β describes set of tasks, and field γ defines objective functions. Field α can take the following values:

- P – identical, parallel positions,
- Q – uniform, parallel positions,
- R – arbitrary, parallel positions,
- O – open handling system (dedicated positions),
- F – flow handling system (dedicated positions),
- J – general handling system (dedicated positions),
- Field γ defines objective functions that may take the form:
- sequencing length (or execution time for set of tasks),

$$C_{\max} = \max\{C_j\}, \tag{1}$$

- average flow time (or average time of task staying in the system),

$$\overline{F} = \frac{1}{n}\sum_{j=1}^{n} F_j, \tag{2}$$

- maximum delay (difference between required and actual time of processing completion for the given task),

$$L_{\max} = \max\{L_j\}, \tag{3}$$

- profit from task sequencing,

$$Q = \sum_{j=1}^{n} Q_j, \tag{4}$$

where Q_j is the current profit from execution of the given task.

Objective function (criterion) allows evaluating obtained sequencing. Procedure, called sequencing algorithm for the problem л, finds sequencing for specific problem $I \in \mathcal{D}_л$, if only such sequencing exists. Optimal sequencing algorithm for the problem л is the name for sequencing algorithm, which ensures minimizing of accepted criterion for any specific problem $I \in \mathcal{D}_л$. Sequencing algorithm for the problem л, which is not optimal, is called heuristic.

4. Formulation of task sequencing problem

Formulated problem is aimed to find such sequencing of departing aircraft on one runway between two consecutive landings that would minimize maximum delay L_{max} with consideration of minimum separations. Nature of the problem is the sequencing process of tasks from Z set on one handling position (machine).

$\mathcal{Z}$ set represents departing aircraft, while handling position is the runway in use. Each task in the $\mathcal{Z}$ set is an indivisible task, because breaks in execution of any task are impossible.

Each of the tasks $Z_j \in \mathcal{Z}$ is a dependent task with defined sequence restrictions: $Z_i < Z_j$ means that execution of Z_i task must be completed before starting of Z_j task execution.

Criterion of maximum delay is used to evaluate sequencing:

$$Lmax = max\ \{L_j\}, \tag{5}$$

where Lj is the completion time of j task execution.

Analysed task sequencing problem is defined as problem $1||Lmax$. To solve it in accordance with maximum delay L_{max} criterion, method of neighbouring pair's inversion has been used. Thanks to iterative modifications of a given sequencing by local task shifting, this method finds optimal solution.

Sequencing algorithm used to develop pre-departure sequencing method can be qualified to greedy algorithms. Group of these algorithms belongs to group of heuristic algorithms with polynomial complexity.

List algorithms present form of greedy approach to the solved problem. It means that choice of each subsequent task for sequencing, as well as choice of target handling position, is chosen only on the basis of information about current sequencing and set of tasks that have not yet been sequenced. Every time the procedure defines next task for sequencing into the first handling position from the set of handling positions.

It can be stated for pre-departure sequencing, that the most important is the current situation to be solved, because it is the situation that the optimal solution is being constructed for. That is why when choosing algorithm that would define appropriate pre-departure sequence, greedy algorithm has been used, which allows to obtain globally optimal solution based on accepted criterion, using locally optimal (greedy) choices.

5. Method of pre-departure sequencing

This method is based on greedy algorithm, which makes a choice that currently seems to be the best one in each step, bringing to globally optimal solution. In accordance with this principle, in each minute of the program operation, the algorithm calculates take off times TTOT for all aircraft that are included on the take-off list. Subsequently calculated values are compared to make sequencing. In the developed method it is assumed, that departures are carried out in straight direction, in one direction of the runway.

These operations result in sequencing the aircraft set by the most optimal moment of TSAT push back and evaluation of starting time for each aircraft TTOT. Based on push back time evaluation, the application defines locally optimal pre-departure sequence, which is the sequence that allows the soonest start at current conditions for the current set of aircraft waiting for start-up clearance. In starting sequence definition, the following factors were considered:

- estimated time of aircraft ground handling completion – TOBT (Target off-Block Time);
- estimated aircraft taxiing time before take-off, from defined standing position on the apron – EXOT (Estimated Taxi-out Time);
- aircraft size;

– minimums of longitudinal separation at turbulences in aerodynamic wake – vortex;
– estimated arrival time of aircraft waiting for landing approach – TLDT (Target Landing Time).

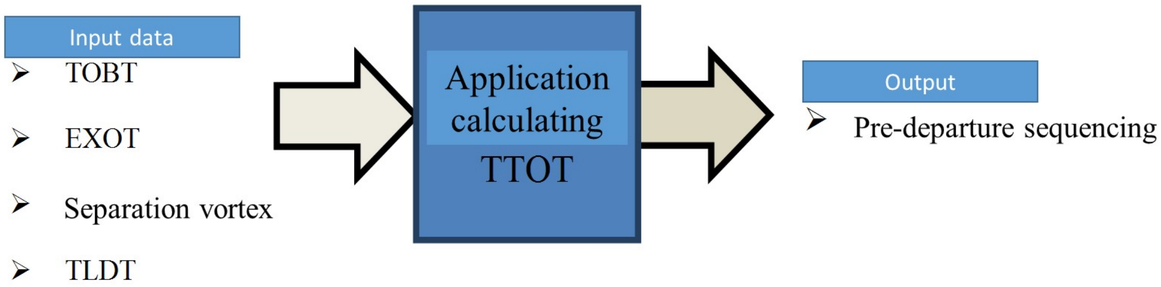

Fig. 1. Diagram shows developed method for pre-departure sequencing

TOBT is chosen from the time range 15 to 30 minutes. The value from this range is generated randomly with equal probability for all types of aircraft. Aircraft target landing time TLDT is created in such a way, that each TLDT must differ from preceding TLDT by not less than 2 minutes. Frequency of landings appearance varies and it depends on time in day-night cycle.

Aircraft types have been divided into three categories by maximum take-off weight. The program can generate aircraft of the types LIGHT, MEDIUM and HEAVY. Probability of HEAVY type aircraft appearance was defined as 0.2, for MEDIUM the probability is 0.4 and for LIGHT it is also 0.4.

Aircraft generation is random. Each generated object takes the assigned initial parameters:
– type of aircraft: LIGHT, MEDIUM, HEAVY;
– apron position;
– taxi time from the apron position to runway in use EXOT;
– time of ground handling completion EOBT (Estimated off Block Time).

During program operation, incoming aircraft data is generated in parallel. Each position in the field „Planned landings" has TLDT value assigned, which defines target-landing time, and appropriate status that informs, whether the flight started approach operation or is still flying. When TLDT becomes equal to current simulation time, and then given flight gets status „Landing". In the opposite case its status is „Flying". Arrivals after landing are removed from the list in each simulation step. TLDT value is generated randomly with different probability, depending on time of day. This results in sequence of subsequent TLDT values with minimal 3-minute intervals.

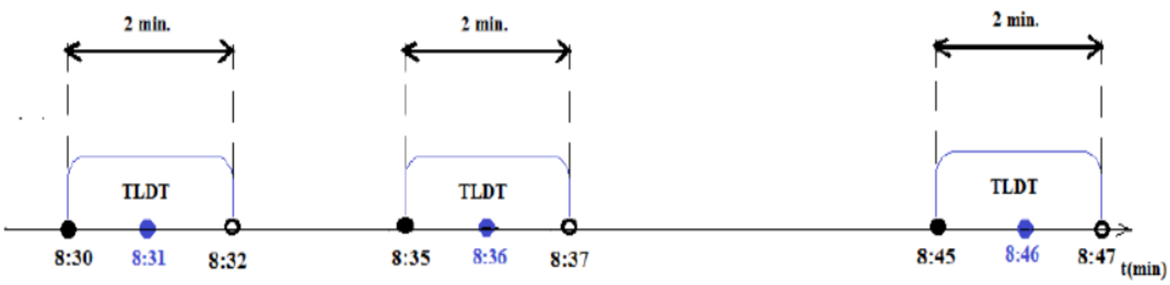

Fig. 2. Exemplary sequence of Target Landing Times TLDT

In accordance with the program assumptions, each flight appearing in the system can be one of the three aircraft types: HEAVY (H), MEDIUM (M) or LIGHT (L). Therefore, minimum separation value for each flight may take value of 3 minutes, 2 minutes or 1 minute. Developed method of pre-departure sequencing defines expected take off time TTOT for each flight in the current set of departures.

Sequence of aircraft push back is defined by sequencing values from the TTOT set, sorted from the smallest to the greatest. Sequencing is done each time new flight appears in the system.

Table 1. Comparison of developed sequencing method with the „First In, First Served" method

Method	*Flight*	*Sequencing*	*EOBT*	*TSAT*	*TTOT*	*L delay [min]*
First in, first served	H100	1	10:00	10:10	10:20	0
	L101	2	10:11	10:11	10:23	2
	H102	3	10:12	10:12	10:25	3
	Flight					
Developed method	H100	2	10:00	10:12	10:22	2
	L101	1	10:11	10:11	10:21	0
	H102	3	10:12	10:13	10:23	1

Table 1 presents comparison of two sequencing methods. Both methods assume fixed pre-departure taxi time from the handling position (EXOT), which is 10 minutes. Letters H and L in the „Flight" column denote aircraft type, HEAVY or LIGHT, respectively. Number in Sequence column shows push back sequence defined in accordance with the method. Time entered in EOBT column shows the moment of ground handling completion, when aircraft is ready for push back. TSAT defines actual time of push back clearance. TTOT is the aircraft take off time. Delay column shows difference between aircraft take off, and the sum of taxi out time (EXOT) and time of handling completion EOBT. Therefore, delay is time lost due to waiting.

First In, First Served shows sequencing method, where push back sequence is defined based on sequence of ground handling completion. Aircraft with completed handling immediately starts taxiing towards the runway. In this situation, there is no delay on apron position, and ASAT time equals to EOBT. Aircraft wait for take-off before runway threshold to keep minimum separations.

Developed method manipulates times intended to keep minimum separations to establish the most optimal push back sequence, which would reduce total delay of the take-off. In this method, amount of time needed to keep necessary minimum separation between subsequent take offs is predicted with advance. This causes to hold certain aircraft on apron positions, despite of completed handling. This allows maintaining smooth traffic and prevents from waiting on runway threshold.

Sum of delays for all flights shows, that developed method held two aircraft on handling positions for 1 minute and allowed for reduction of total take off delay by 2 minutes compared to First In, First Served method.

6. Summary

Developed method assumes, that problem of pre-departure sequencing is the problem of deterministic task sequencing on one handling position. Delay time is the criterion, that is represented by the difference between ground handling completion time (and clearance for push back), and requested time of ground handling completion. This method proposes solving the problem with greedy algorithm. The algorithm is heuristic, and in each step, it makes the best choice for a given moment (greedy) to sequence tasks for execution. Given the problem complexity, this algorithm is sufficient.

This method allowed obtaining clear sequencing of aircraft present on apron positions. This sequencing assigns numbers in queue in accordance with non-decreasing times of aircraft take offs. This allows to reduce total delay time and makes more frequent take offs possible.

This method can make the controller job easier by prompting sequence of push back clearances, which would include data of taxi out time, times of runway occupancy by arriving aircraft and changes in pre-departure sequence that can reduce time assigned to keep minimum separations required by turbulences in aerodynamic wakes.

Pre-departure sequencing method can be improved by more precise definition of varying aircraft taxi times. This however requires further studies and appropriate statistical analysis.

References

[1] EUROCONTROL, *Airport CDM Implementation Manual,* EUROCONTROL, 2012.

[2] Kleinberg, J., Tardos, E., *Algorithm design*, Cornell University, 2005.

[3] Kwasiborska, A., Markiewicz, K., *Metody listowego szeregowania samolotów lądujących jako narzędzie wspomagania kontrolera w podejmowaniu decyzji*, w: Prace Naukowe Politechniki Warszawskiej. Transport, Oficyna Wydawnicza Politechniki Warszawskiej, nr 104, 2014.

[4] Kwasiborska, A., *Multicriteria pre-departure sequencing of aircraft using the greedy scheduling algorithm* , [w:] CLC 2013: Carpathian Logistics Congress - Congress Proceedings / Feliks Jerzy (red.), 2015, TANGER Ltd., Ostrava.

[5] Kwasiborska, A., Skorupski, J., *Metody szeregowania zadań, jako narzędzie rozwiązywania problemu sekwencjonowania samolotów*, [w:] Prace Naukowe Politechniki Warszawskiej. Transport, Oficyna Wydawnicza Politechniki Warszawskiej, nr 101, 2014.

[6] Minimum technical specifications for Airport Collaborative Decision Making (Airport CDM) sytems, EUROCAE 2008.

[7] Sysło, M. M., Deo, N., Kowalik, J., *Algorytmy optymalizacji dyskretnej z programami w języku Pascal*, PWN, Warszawa 1999.