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Quality assessment of the traffic flow management process in the vicinity of the airport

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ABSTRACT: The organization of traffic in the vicinity of transportation network nodes is a major challenge for traffic management services. It is essential to ensure the safety of moving vehicles, in air transport achieved through the use of appropriate separation between aircraft. In recent years, however, growing emphasis is on providing high throughput, which is particularly important due to the ever increasing traffic. Existing methods for supporting traffic management are evolving in the direction of increasing the planning horizon and the early formation of traffic streams. In air transport, it takes the form of Arrivals Management (AMAN), which is one of the key objectives for the SESAR project—technological part of the concept of the Single European Sky program. The result of the process of arrivals management is the sequence of aircraft, taking into account not only their order but also the time of appearance in the relevant navigation waypoints. In this paper we analyze the problem of reliability assessment of the traffic flow management process. In the case of sequence of aircraft separated by a small time interval we may expect the high capacity of the airport, but it is likely that, because of the need to maintain the safety, the sequence will be distorted and will not be possible to realize. Introduction of an additional time buffer between aircraft has the opposite effect. Our paper presents a mathematical model and a computer tool allowing for the evaluation of the traffic flow management process in case of random disturbances, which may be subject to aircraft. Particular attention is paid to disturbances that can be partially predicted. The algorithm for compensation of this type of interference in the aircraft arrivals planning process is proposed.

1 INTRODUCTION

Air traffic volume has been increasing at a rapid rate for years. This, in turn causes increasing problems with the punctuality of air operations. Delays are closely connected with the airport capacity and the capacity of the airspace surrounding an airport. Landing operations have a high impact on the airport capacity. Their number depends, among others, on the organization of the stream of aircraft approaching for landing. The distance between succeeding aircraft is the main factor determining the airport capacity. It depends mainly on the separations, that is on the minimum distances defined in applicable international regulations. Surveillance-based horizontal radar separation of 5 Nautical Miles (NM) has been widely adopted (PANSA, 2013). However, whenever circumstances so require, a controller should designate larger separations, taking into account, among other things, also the wake vortex turbulence and the weather conditions.

Some of these elements are deterministic and can be taken into account during pre-tactical traffic planning. Others are stochastic and require ongoing adjustments of the organization of the landing aircraft stream. In both cases the air traffic controller has to cope with the decision-making problem of determining the required distance between the landing aircraft. The schedule obtained as a result of solving this decision-making problem can be assessed using various criteria, and even be the subject of multi-criteria group assessment (Skorupski 2014b). In this paper we undertake the problem of schedule assessment based on the average time per landing.

There is a number of papers related to the development of methods and algorithms for the scheduling process. An overview can be found in the study of Kwasiborska & Skorupski (2014). Sölveling & Clarke (2014) developed an algorithm for the determination of an optimal (or close to optimal) solution of the stochastic operation sequencing problem. It works for one or more runways while minimizing the difference between the begin and the end time of the task sequence.

There are many algorithms that can achieve optimal solutions with different objective functions. However, they are usually NP-hard. So very much attention is paid to the development of simplified and heuristic methods that give close to optimal solutions. An interesting solution was presented by Caprì & Ignacio (2004). They used genetic algorithms to obtain a solution for the formulated dynamic programming problem, which also takes into account aircraft departure scheduling. Similar methods are used by Hansen (2004).

In most papers the uncertainty concerning the time necessary for realization of each aircraft operation is dealt with probabilistic methods. However, Tavakkoli-Moghaddam et al. (2012) proposed a different approach based on the application of the fuzzy set theory. The problems of air traffic organization, its assessment, support of the scheduling process with the Mode S data, as well as modern air traffic and airspace planning concepts are discussed in more detail in (Skorupski 2014).

A number of studies proved the necessity of planning much earlier merging of aircraft streams that arrive from different directions. This problem, known as arrival management has been discussed for instance in (Boursier et al. 2007) and (Zhu et al. 2012). The problem of scheduling departures of aircraft is much less popular in the literature. It has ben formulated in (van Leeuwen et al. 2002). A comprehensive research in this area is presented in (Weigang et al. 2008). Development of the concept and implementation of the AMAN (arrival management) and DMAN (departure management) systems is also one of the principal tasks of the SESAR program, which is the technological part of the Single European Sky (SES) initiative. As a part of the ongoing work, preliminary tests of the developed solutions have been performed at the Paris CDG airport as well as in the areas of TMA (Terminal Area) London, Rome, Amsterdam, and Malmoe (SESAR 2013).

All the aforementioned studies primarily focus on the issue of establishing of proper scheduling. Of course, on this occasion different optimization criteria are defined as well as different optimization constraints. In this paper a slightly different approach is considered. We assume that the landing aircraft queue is planned and organized in advance. The research problem is to assess this queue taking into account both the airport capacity and the possibility to reliably realize this landing sequence. However, in fact, we want to assess the quality of the air traffic flow management process that resulted in a given landing aircraft queue.

While performing the assessment it is necessary to take into account all the constraints associated with the separations between aircraft and the possible random deviations from the planned time of arrival. Such an approach is not focused on a search for the optimal solution, but it can easily support the achievement of such a goal. Indeed, a comparison of results for different scheduling algorithms, taking into account different external conditions, may make it possible to find the best solution among them. However, in our paper we only propose the queue assessment method.

2 DISTURBANCES AND THEIR IMPACT ON THE AIR TRAFFIC

The evaluation of the landing aircraft scheduling process will be performed solely by taking into account stochastic disturbances due to the fact that they affect the largest number of delayed landings. The most common disturbances that occur during the final phase of a flight include: disturbances caused by weather conditions, aircraft failures (Tomaszek et al. 2011), pilot and controller errors (Żurek et al. 2010, Skorupski & Wiktorowski 2015), unauthorized runway incursions (Lower et al. 2013), and also birds appearing in the final approach area of the airport. The subsequent part of the paper presents an assessment of the scheduling process disturbed by one of these factors. In order to perform the assessment, a mathematical model and a computer software tool have been created that enable modeling the actual sequences carried out in the airport, but also simulate disturbances and the applied ATC actions. These actions are expressed by the variable distances between the subsequent landing aircraft in the queue rather than by a change of the order of landings.

Disturbances which appear in the traffic process can change the landing procedure time. By this we mean the time period of flight from the initial point of scheduling to the moment when aircraft leaves the runway. Only some or all aircraft included in the schedule may be affected by the disturbances. However, when assessing the scheduling, it is necessary to determine this in advance.

2.1 *Measurements of air traffic*

To make an assessment of the arrivals management process in TMA Warsaw, in June 2012 measurements of an actual air traffic were performed. The data that was collected included, among others:

- the aircraft identification marks,
- the time and location of the aircraft appearance at the boundary of the TMA region,
- the runway in use which, together with the input point, unambiguously describes the standard arrival procedure (STAR) used,
- the time and place where the aircraft was merged with the landing aircraft stream that was being formed,

– the time to reach the initial point of the assessment process; in this research it was assumed to be a point 8 NM away from the runway threshold,
– the time to reach the end point of the assessment process; it was assumed to be the point where the aircraft leaves the runway after landing.

The end point of the assessment process was assumed due to the existing air traffic regulations, according to which the following aircraft may land when the preceding aircraft has left the runway. An example of the real aircraft landing sequence is presented in Table 1.

An analysis of the gathered measurement data indicates that merging aircraft streams flowing from different input points is realized in various places.

The sequence presented in Table 1 was formed on the distance between 21 and 11 NM from the runway threshold. This means that there is no clearly specified point that can be considered as the initial point of the scheduling. It was chosen arbitrarily. When analyzing all the sequences, it was found that the shortest distance where forming the landing aircraft stream was completed was 8 NM from the runway threshold. Thus, for the sake of comparability of the assessments of each sequence, a point 8 NM away from the threshold was assumed as the initial point of scheduling.

2.2 *Scenarios of traffic disruptions*

As was mentioned before, a few typical scenarios of traffic disruptions will be presented in the following sections, together with simulation results of one of the scenarios.

1. The scenario analyzes a disturbance caused by the horizontal movement of air masses at the speed of 10 m/s, moving from 80°E at a 30º angle in relation to the axis of landing aircraft. The disturbance makes two aircraft (the second and the third in the sequence) to appear about 2 minutes earlier, causing the need for corrective action by the air traffic control services.
2. The second scenario refers to difficulties caused by poor visibility (not exceeding 600 m) due to a very dense fog located up to 9 NM from the runway threshold. The disturbance impedes the landing operation of all aircraft in the sequence, causing a random change of flight time within +/–2 min.
3. The scenario involves an unauthorized intrusion of a general aviation aircraft which, due to the pilot's lack of attention, unexpectedly appears in the area of increased air traffic at 3 NM from the runway threshold, disrupting the operation of the approaching aircraft. In this situation, the pilot of the landing aircraft has two possibilities: to go-around or, if possible, to delay the landing of the aircraft, so that the disturbing aircraft can safely leave the approach area. The go-around means that the aircraft has to move to the end of the sequence. In the Warsaw Chopin Airport area this means the average flight delay of about 14 minutes.
4. The scenario describes a disruption caused by a flock of birds that constitute a serious threat for engines of landing aircraft. We assume that birds have been located at the runway threshold. The time necessary for the airport services to get rid of the birds is about 5 minutes. This will result, analogously to the scenario 3, in a delay of the first landing aircraft from the queue or in a go-around procedure.
5. The scenario involves Foreign Object Debris (FOD) found on the runway. FOD is a small object that endangers the safety of takeoff and landing operations. This scenario will be analyzed using the model described in the following part of the article. Any possibility of a FOD presence on the runway requires appropriate preventive actions, especially an inspection of the runway and possible FOD's removal. Due to the purpose of this scenario it was assumed that the object does not require an intervention by additional services and can be immediately neutralized by the runway inspector. However, during the inspection take-off or landing operations cannot be performed. It was assumed that the moment in time when the FOD was noticed is random and can occur at any time. Depending on the distance between the aircraft and the runway threshold, a decision will be made between two alternatives: a delay or a go-around.
6. The scenario describes a situation when an error of navigation equipment occurs combined with poor pilot skills that lead to a situation where an aircraft shortens its planned duration of a flight by about 2 minutes.

Table 1. Example of measured sequence of aircraft landing at Warsaw Chopin Airport on runway RWY 11 (6 July 2012).

	Entering a sequence		Scheduling	
Call sign	Time	Distance	Beginning	End
LOT456	07:25:09	13	07:26:35	07:31:15
LOT270	07:27:30	13	07:28:58	07:33:01
LOT215	07:29:29	11	07:30:49	07:34:57
LOT3AW	07:31:40	17	07:33:14	07:37:11
LOT165	07:33:49	12	07:35:22	07:37:55
SAS751	07:34:16	21	07:38:05	07:41:18

3 ASSESSMENT OF THE SCHEDULING PROCESS

3.1 *The assumptions*

In the proposed method and the computer system for the scheduling process assessment the following assumptions have been adopted:

1. Landing at Warsaw Chopin Airport is considered. Aircraft approach from different directions but the landing is carried out with the use of the same runway RWY 11 according to established STAR procedures.
2. The disruption that is described by the scenario 5 is considered.
3. The scheduling assessment criterion is the average time necessary for one landing. The landing time for each aircraft is counted from the moment in time when and aircraft reaches the point 8 NM away from the RWY 11 runway threshold until it clears the runway for the next landing via one of available taxiways.
4. The actual sequence presented in Table 1 is assessed. However, the distances between subsequent aircraft are going to change. We assume that they express the applied scheduling strategy. The assessment will give the answer for the question about the best distance (separation) between the aircraft in the queue.
5. The minimum separation between landing aircraft is 5 NM.
6. The minimum time separation during landing is assumed according to the international regulations (ICAO 2007) and shown in Table 2. This separation minima are determined due to the wake vortex turbulence. They are based on the division of aircraft into three categories according to the maximum take-off weight:
   - Heavy (H)—aircraft with a take-off weight over 136 000 kg,
   - Medium (M)—aircraft with a take-off weight between 7000 kg and 136 000 kg,
   - Light (L)—aircraft with a take-off weight of less than 7000 kg.

   For the remaining cases (not included in Table 2) separation of one minute has been adopted.
7. The planned landing time is determined on the basis of the planned time of appearance in the initial point of the analysis and the average time of flight in this space which is assumed to be 6 minutes.
8. Aircraft appear at the initial point in the sequence and time specified by the schedule.
9. Redundant time distance between subsequent aircraft Z (reserve) is a decision variable, the choice of which is assessed.

Table 2. Minimum separations between arriving aircraft.

Lead aircraft	Follower aircraft	Minimum separation
Heavy (H)	Light (L)	3 min.
Heavy (H)	Medium (M)	2 min.
Medium (M)	Light (L)	3 min.

3.2 *Mathematical model and computer tool*

In the research Colored Stochastic Petri Nets (CSPNs) were used as a tool to describe the air traffic in the vicinity of the airport and to simulate different scheduling strategies used by air traffic controllers. CSPNs were also used for the modeling of air traffic in previous works of the authors (Skorupski 2011a, b, 2015), so the principles and details of the creation of such models will be omitted.

Practical implementation of the model that allows performing simulation experiments was developed as the computer software tool using CPN Tools 4.0 package. Two example parts of the model for quality assessment of the traffic flow management process in the vicinity of the airport are shown in Figures 1 and 2.

3.3 *Scheduling process assessment*

Quality assessment of the traffic flow management process in the vicinity of the airport will be made according to the formula

$$OS\,(Q_i) = \frac{lr_i - lt_1}{ls}\,[S] \tag{1}$$

where:

Q_i—*i*-th landing sequence,
OS—the function determining the scheduling assessment,

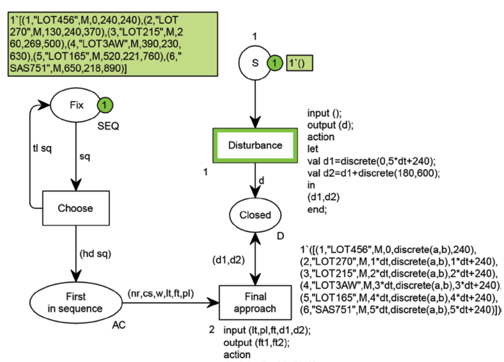

Figure 1. CSPN model for scheduling assessment—aircraft input and disturbance appearance.

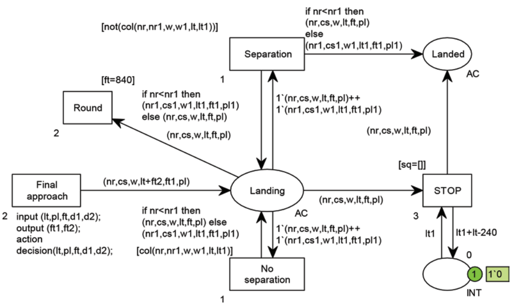

Figure 2. CSPN model for scheduling assessment—separation control.

lr_i—the moment in time when i-th landing sequence has finished,
lt_1—the moment in time when the first aircraft in sequence appeared at the initial point of the scheduling,
ls—the total number of aircraft in the sequence.

As a reference value, an assessment of an actual sequence from Table 1 (without any interference or disturbance) will be determined. All aircraft in this particular sequence belong to the same weight category M (medium). After the scheduling process an actual distances between the airplanes were: 143, 111, 145, 128 and 163 seconds. As one can see, these distances are higher than the minimum separation. This is the result of the scheduling strategy used by the controller, it consists in adding some additional redundant distance.

The average landing time per one aircraft calculated according to the formula (1) is 150 seconds.

3.4 *Assessment of the scheduling process including disturbances*

For an assessment of the quality of the traffic flow management (scheduling) under disturbances the following plan of experiment has been adopted:

1. Aircraft in the sequence are separated by minimum separation according to Table 2 increased by the redundant time distance Z determining the assessed scheduling strategy. This reserve will change from 0 to 180 seconds.
2. Execution of landing operation is planned for 240 seconds, counted from the aircraft's appearance in the initial point of scheduling.
3. The real flight times are random and can differ from the nominal time by a maximum of 30 seconds. This means they are in the range from 210 to 270 seconds.
4. The moment when the FOD has been noticed is random and may occur at any stage of the sequence realization with equal probability.
5. Time to remove the FOD is also random, however our measurements indicate that this time is in the range from 180 to 600 seconds.
6. The runway is closed (landing operation cannot be held) from the moment in time when the FOD is noticed to its complete removal.
7. The aircraft that arrive outside the time range defined in point 6 can land without any disturbances.
8. For the aircraft which planned landing falls into the time range specified in point 6 the following restrictions apply:
   a. if the taxiway closure is going to last more than 120 seconds from the scheduled landing time—the aircraft goes around,
   b. if the taxiway closure is going to last less than 120 seconds, the aircraft is delayed for the necessary amount of time,
9. The execution of the go around procedure takes 14 minutes (840 seconds).

The plan of experiment assumed determination of the impact of an additional time buffer Z, i.e. the increase of the separation between the landing aircraft, on the evaluation of scheduling, in this case—the average time needed to perform the landing operation by a single aircraft $OS\ (Q_i)$ calculated according to formula (1). For each value of the decision variable Z (additional time buffer) 10^5 simulation runs have been performed. The results of the simulations are shown in Table 3 and their graphical representation—in Figure 3.

The simulations performed focused on a situation where a traffic disturbance in the form of detection of a dangerous object on the runway starts affecting the landing schedule at a randomly selected time. As the results demonstrate, when the spacing between aircraft is reduced to a minimum determined by the regulations, the average time needed for one landing operation is high and it exceeds 350 seconds. This is because all aircraft that are affected by the disturbance have to go around, as they are unable to sufficiently delay landing to complete the operation after the FOD is removed from the runway. According to the model (and in line with practice) they have to repeat the approach by performing the appropriate

Table 3. Average time per landing operation $OS\ (Q_i)$ related to additional time buffer Z.

Z	0	10	20	30	40	50
$OS\ (Q_i)$	376.4	349.4	322.2	297.1	277.0	266.2
Z	60	70	80	90	100	110
$OS\ (Q_i)$	263.9	263.4	265.6	267.2	268.7	270.0
Z	120	130	140	150	160	170
$OS\ (Q_i)$	271.2	273.5	277.6	284.6	290.9	296.5

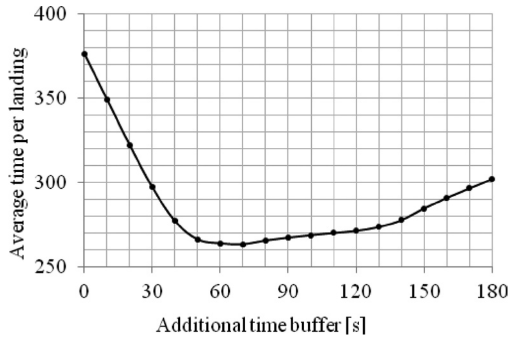

Figure 3. Results of experiment (additional buffer—average time per landing relation).

procedure resulting in returning to the end of the existing schedule.

As shown in Figure 3, increasing the additional time buffer Z results in better traffic flow management quality. The scheduling evaluations, despite the longer distances between the landing aircraft, are better—the average time needed for a single landing operation is reduced. This is due to the improved ability to compensate the impact of the disturbance by a small elongation of the flight time instead of going around. If the additional time buffer is about 70 seconds, the average time necessary for one landing reaches its minimum so the evaluation of the scheduling is the highest possible for the considered scenario. According to the conducted experiment, adoption of 70 seconds of time buffer enables the air traffic controller to achieve the time necessary for one landing operation to be equal to about 260 seconds, which is a very good result compared to the average time per landing equal to 376 seconds in the case of very close spacing.

Of course, if the time buffer Z is too large it does not lead to a better evaluation of the scheduling because a large buffer increases the average time necessary for a landing operation. However, this scheduling strategy has some positive consequences, as it increases the reliability of the sequence. Reliability is defined here as the probability of realization of the planned sequence without any changes. This strategy also increases the safety of air traffic in the analyzed area. Missed approach procedure is a non-typical event and is not planned by the air traffic controller. It fundamentally changes the anticipated traffic situation and is a kind of surprise to the controller. A large buffer Z eliminates, to a great extent, the need to perform this procedure in the case of disturbances. However, it has a negative impact on the airport's throughput and is completely unnecessary in the case of undisturbed traffic.

4 SUMMARY AND CONCLUSIONS

An analysis of the traffic flow management process in the vicinity of the airport and scheduling strategies used by air traffic controllers shows that in practice they add a certain additional time buffer between landing aircraft. In the case of the real-life sequence presented in Table 1 the additional time buffer was, on average, equal to 78 seconds. Taking into account the fact that minimum separation described by the regulations is about 60 seconds one can see that controllers more than double the necessary minimum.

An evaluation of the real traffic of landing aircraft that are subject to the scheduling process indicates that in the event of no or small disturbances, the strategy of high density of aircraft in the sequence is advantageous.

However, the situation is quite different in cases where disturbances are present. Tight packing of aircraft in the landing queue often leads to the risk of loss of separation, which of course must be prevented in advance by the air traffic controller. This may lead to an aircraft being sent to the end of the queue, which increases the carrier's costs, reduces the airport's throughput, and may affect the safety of air traffic.

The results of the experiments make it possible to observe the changes in the evaluation of the scheduling process in relation to the added time buffer, i.e. the extra distance by which the minimum separation is enlarged. An analysis of the values that were observed shows that the evaluation of the scheduling reaches the maximum value for the time buffer equal to about 70 seconds. For this value, the average time needed to perform one landing operation is the shortest.

It must be emphasized that the time buffer at the best evaluation of the scheduling equal to 70 seconds is very close to the average time buffer of 78 seconds added in practice by the air traffic controllers while forming the queues, as determined by way of measurements. On the one hand, this validates our model and, on the other hand, it shows that the intuitive actions are correct in this case.

In their further works, the authors will focus on defining variable scheduling strategies. In good visibility conditions, when no interferences are expected, one can propose a dense scheduling strategy that increases the throughput of the airport. However, if disturbances are expected (for instance due to present or anticipated bad weather, presence of birds in the vicinity of the airport, etc.), one can get ready for the problem by changing the scheduling strategy and adding an extra time buffer between aircraft. Thanks to this, the basic throughput of the airport is reduced, but the airport is ready for the disturbance and can compensate its negative consequences. This is a proactive approach with regard to safety and reliability of implementation of scheduling. The model presented in this article and the computer tool make it possible to determine the proper value of the additional time buffer for each anticipated interference.

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