AIRFIELD TRAFFIC COMPLEXITY

Tatjana Krstic Simic and Vojin Tosic
Division of Airports and Air Traffic Safety
Faculty of Transport and Traffic Engineering, University of Belgrade
Vojvode Stepe 305, Belgrade 11000, Serbia
tel: +381 (0)11 3091 352, fax: +381 (0)11 2496 476
t.krstic@sf.bg.ac.rs, v.tosic@sf.bg.ac.rs

Abstract

The main objective of this paper is to define the concept and measure of airfield traffic complexity. Complexity has been observed through traffic characteristics, i.e. as a measure of quantity and quality of traffic interactions on an airfield, under certain circumstances. The term Dynamic Complexity is introduced and it is a measure developed as a linear function of traffic density within a system and a number of traffic complexity factors (number of a/c path mergings, number of a/c path crossings, number of runway crossings, etc). In addition, a simulation model is developed and experiments are carried out to obtain the values of airfield traffic complexity for different traffic scenarios and given airport configurations. A comparative analysis of the results for different scenarios in terms of traffic volumes and structure as well as different airport configurations shows that the proposed airfield traffic complexity metric reflects quite satisfactorily the actual state of the system.

Keywords: Traffic Complexity, Airfield, Modeling

I INTRODUCTION

Today, in a time of advanced technology and a high level of automation in all segments of life, humans very often themselves represent the limitation factor to further improvement to the efficiency of some processes. So, better understanding of the particular processes and their influence on the human workload, becomes significant. The same trend occurs in air traffic management.

Large numbers of studies deal with air traffic controller workload. The concept of complexity is introduced, and it should represent “weight” of the traffic situation, i.e. possible impact of the exact traffic situation on air traffic controller workload (Pawlak et al, 1996; Pawlak, 1996; Chaboud et al, 2000; Schaefer, 2001; Masalonis et al, 2003).

Review of the literature from the air traffic control complexity airfield, shows that most research is about complexity of the airspace and airspace traffic complexity areas (abovementioned, Laudeman et al, 1998; Delahaye et al, 2000; Histon et al, 2001; Tosic and Netjasov, 2003; Kopardekar and Magyarits, 2003; Delahaye et al, 2003).

Airport i.e. airfield: runways, taxiways and apron, could represent a complex network with a large number of possible moving paths for departing and arriving aircraft. Such complex, dynamic systems give many possibilities for research and analysis, on different levels of accuracy.

The main objective of this paper, which is a part of a master thesis (Krstic, 2004), is defining the airfield traffic complexity concept, and defining the measure for traffic complexity values determination.

II CONCEPT OF AIRFIELD TRAFFIC COMPLEXITY

The question is: *What are the traffic complexity factors, which are measurable and valid enough for representation of the traffic situation on airport airfields?*

Based on referent literature and taking in account airfield characteristics and aircraft movements characteristics, a measure of airfield traffic complexity is presented.

It should be emphasized that, while most authors who study complexity look from the viewpoint of air traffic controller workload (i.e. through the tasks which different traffic situations implicates for controller), however in this paper complexity will be observed only through traffic characteristics. Namely, complexity will be observed as a measure of quantity and quality of traffic interactions on an airfield, under certain circumstances.

III MEASURE OF AIRFIELD TRAFFIC COMPLEXITY

Complexity could be expressed as structural (static) complexity and dynamic complexity.

$$CPX = SC + DC \quad (1)$$

CPX – Complexity
SC – Structural (static) Complexity
DC – Dynamic Complexity

Structural (static) complexity could be expressed as the weighted sum of different factors:

$$SC = \sum_i Ws_i \times SCF_i \quad (2)$$

SC – Structural (static) Complexity
SCF – Structural Complexity Factor
Ws – Factor Weight

Structural complexity factors could be different structural airport characteristics, fixed in time for particular airport, like following:

- Runway configuration (number, length, mutual position, orientation, crossings),
- Taxiway configuration (number, length, mutual position, crossings),
- Runway and taxiway mutual position,
- Apron configuration,
- Radio-navigation aids.

Structural complexity factors expression, and factors weight values are very interesting, but also pose very complex questions, so these could be the subject of separate study.

Dynamic complexity can be expressed as the sum of different factors:

$$DC = TD + \sum_j \left(Wd_j \times TC_j \right) + WTH + HI \quad (3)$$

DC - Dynamic Complexity
TD - Traffic Density
TC - Traffic Complexity Factor
Wd - Factor Weight

WTH - Weather
HI - Human Factor (controller) Influence

As with the structural complexity factors case, questions of Weather and Human Factors Influence factors expression, and the range of these factor values could be the subject of a separate study.

In this paper, dynamic complexity will be discussed with the assumption of good meteorological conditions (i.e. WTH=0) and no human factor influence (air traffic controller). The equation (3) now looks like:

$$DC = TD + \sum_{j} Wd_j \times TC_j \tag{4}$$

Further, if all traffic complexity factors have even importance and they are equal to Traffic density importance, i.e:

$$Wd_j = 1, \ \forall j$$

the dynamic complexity equation becomes even simplier:

$$DC = TD + \sum_{j} TC_j \tag{5}$$

First, system boundaries should be defined. Aircraft are considered to be in the system:

1) *arriving aircraft* – from the moment when they appear at a given point where they wait for (or immediately get) clearance for a final approach and landing (further in text point FIX – point after which could not appear more then one aircraft in approach), to the moment of arriving on the apron;
2) *departing aircraft* - from the moment a pilot requests push-back and taxi clearance (while the aircraft is in a parking position, on the apron) for taxing to departure waiting position, until a given time after departure.

Complexity factor – Traffic density TD, could be defined in several ways. In this case, traffic density shows the total number of aircraft in the system, either aircraft are already "inside" the system or waiting at the system boundary (described in previous paragraph), at a certain moment in time.

Traffic complexity factors are numerous. In this case, the following traffic characteristics (variables) were chosen for the complexity expression:

- *number of pairs of take-off / landing successive operations* – $N_{t/l}$, where operations are overlaping during a time interval they spend in the system (situations when the controller has in his jurisdiction departing and arriving aircraft at the same time, because that is supposed to be a more complex task, than situations when all aircraft are departing or arriving),
- *number of potential separation violation* – N_{sv}, i.e. number of aircraft pairs whose minimal separation will be violated without controller intervention, either in overreach situations (because the trailing aircraft is faster or leading aircraft is standing), or the separation could be violated in intersections, i.e. in common points for aircraft paths, all refered to airfield movings,
- *number of merging* - N_m, i.e. number of aircraft pairs which will, during their taxing phase, go through the same point and go on by the same path (they will be merged in the same flow),
- *number of crossing* - N_c, i.e. number of aircraft pairs which will, during their taxing phase, go through the same point and go on by different paths.

Now equation (5) can be expressed in the following way:

$$DC = TD + N_{t/l} + N_{sv} + N_m + N_c \qquad (6)$$

Next, a very important question is the question of time crossings, i.e. in which specific moments the complexity change should be measured. Should it be for a given time interval – at the end or at the beginning of that interval, or complexity should be measured at some events moment, e.g. appearance of new aircraft in system?

In this case it was chosen to “note” every change of the dynamic complexity value (when value of any of mentioned dynamic complexity factors is changed), and that change could appear in the following situations:

- when aircraft appear in the system:
  - in point FIX – for arriving aircraft, or
  - at the apron – request for departure (push-back and taxi clearance),
- when aircraft are leaving the system:
  - at the apron – for arriving aircraft,
  - flying over a specific point after departing – for departing aircraft,
- the beginning of a potential separation violation situation for the taxing aircraft i.e. the situation where, without controller intervention, minimal aircraft separation will be violated,
- when the potential separation violation situation is resolved, i.e. after a certain time for which the trailing aircraft was waiting (aircraft delay) at a specific “important” point (important for separation) to avoid a given situation,
- aircraft arriving in one of the taxiway intersection points or in some taxiway “important” points, if that lead to an aircraft path merging or crossing situation,
- when a merging or crossing situation is finished i.e. after a certain time period and in reference to “important” points,
- aircraft arriving at one of the runways intersection points or at taxiways / runways intersection points (if there is more then one runway on the airport), and occupying the resource (RWY, intersection) for a certain period of time (or, if resource is already occupied, first wait and then occupies resource), and
- when aircraft release an occupied resource, after a certain period of time.

Note: Exact situations when minimal separation is “potentially” violated, when two aircraft are considered to be in merging or crossing situations, when aircraft occupy certain resources and when those situations are resolved (finished) are precisely defined in master thesis (Krstic, 2004), refer to airport configuration and specific defined points, important for separation. All separation values, occupying times and given situational conditions are from the “real life” domain.

When dynamic complexity is expressed as a function of time, (6) became:

$$DC(t) = TD(t) + N_{t/l}(t) + N_{sv}(t) + N_m(t) + N_c(t) \qquad (7)$$

where t is the moment of some of the above mentioned events.

A. *Generic airport configuration – Model 1*

If the simplest airport configuration is observed, with one runway, one taxiway and the apron (since the apron is not the object of this paper, it was assumed that apron capacity is big enough to receive all aircraft for any traffic volume), and if arrivals and departures are on/from the same runway threshold (THR 12) – fig. III-1, intuitively it could be said that, in the case of low traffic density, complexity is also low.

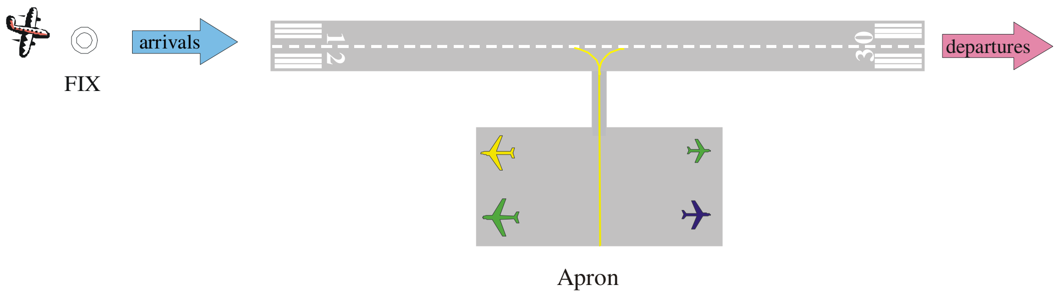

Fig. III-1. Generic airport configuration - Model 1

Arriving aircraft could leave the FIX point, and go to the final approach and landing, only if:

- previous arriving aircraft left the runway, and
- departing aircraft left the runway (if the previous operation was departure).

Departing aircraft could get departure clearance and leave their parking position at the apron, only if:

- previous arriving aircraft left runway and arrive at the apron,
- there is no aircraft in approach (or the arriving aircraft is on the proper distance), and
- previously departing aircraft left the runway.

By applying defined rules, the traffic situation complexity could be "controlled" for a certain amount of traffic. But, if the system became saturated, with an increasing number of aircraft which are appearing in the system, complexity will also increase (more and more aircraft will be in the system, waiting to be served). Since such configuration implies low traffic demand, with the increase of traffic, the saturation problem will be resolved at the strategic level (e.g. introducing a new taxiway which connects the runway and apron, a new taxiway parallel to the runway, etc.)

Dynamic complexity will be, based on (7), equal to:

$$DC(t) = TD(t) + N_{t/l}(t)$$

$$N_{sv} = 0$$
$$N_{m} = 0$$
$$N_{c} = 0$$

B. ***Airport with taxiway parallel to runway - Model 2***

Model 2 represent the complete concept of an airport with one runway – the airport has a taxiway parallel to the runway (B) with runway exits (A, D, and E), a taxiway which connects taxiway B with runway (C) and two taxiways which connect the apron and taxiway B (F and G) – fig. III-2. The assumption regarding apron capacity mentioned in the Model 1 case is also valid for this, and for all other models.

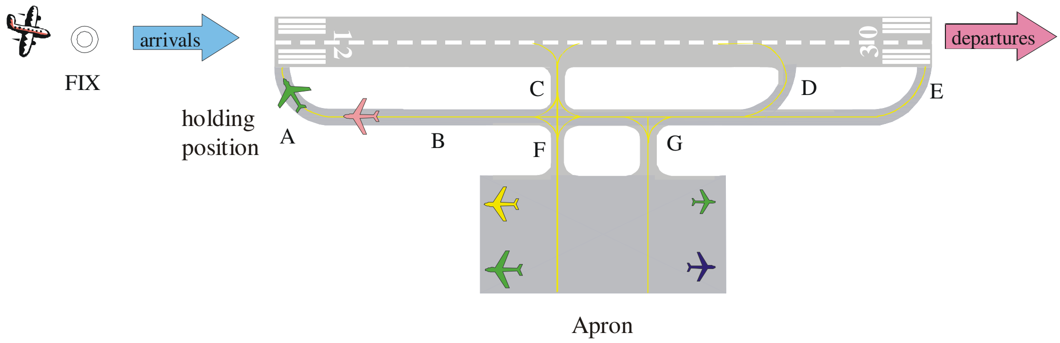

Fig. III-2. Airport with taxiway parallel to runway - Model 2

Intuitively, it could be said that such an airport configuration would reduce the traffic situation complexity for the given traffic volume (for cases with “high” traffic density), comparing to Model 1. But, in the case of high demand, a large number of aircraft could be found on the airfield simultaneously, which could further contribute to a complex traffic situation.

When arrivals and departures are on/from the same runway threshold (THR 12), aircraft could also go to departure from the taxiway C holding position (for smaller aircraft, which need shorter departing length). With the assumption that all aircraft could use taxiways F and G, either they go to departure or they just arrive and taxi to the apron, the dynamic complexity equation will contain all abovementioned traffic complexity factors:

$$DC(t) = TD(t) + N_{t/l}(t) + N_{sv}(t) + N_{m}(t) + N_{c}(t)$$

Merging situation, i.e. a situation where aircraft will, during their taxing phase, go through same point and go on by the same path, could occur in several cases:

- e.g. aircraft which arrived and left the runway on exit D, could be merged in the same flow with aircraft which arrived and left runway on exit E, during taxing on taxiway B;
- when aircraft which arrived and are taxing on taxiway B to taxiway F (and further to the apron), and aircraft which are going to depart, leaving the apron by taxiway G and entry on taxiway B, go to the departure holding position (RWY 12).

Crossing situations could occur in circumstances where aircraft that leave the apron by taxiway G, exit on taxiway B and further taxi to taxiway A i.e. to RWY 12 to departure, since other aircraft, which also go to departure, but to a shortened departure, leave the apron by taxiway F, cross taxiway B and go on taxiway C to the departure holding position.

C. *Airport with two parallel runways – Model 3*

Model 3 represents an airport with two parallel runways with independent operations (minimal distance between runways central lines should be 1035m (ICAO, July 2004)). Introducing a new runway enables a “significant” increase in capacity. So, in high demand situations, large number of aircraft could be found on airport airfields.

In real life, this airport configuration is mostly used in the following way: one runway for arrivals, and another for departures. Such tactics make aircraft flow management simpler (either in phase of arriving or departing or in airfield traffic management). But, because in this paper hypothetical examples were considered, the more complex case is analyzed – a case with the assumption that both, arrivals and departures could use both runways – THR 12R and THR 12L – fig. III-3.

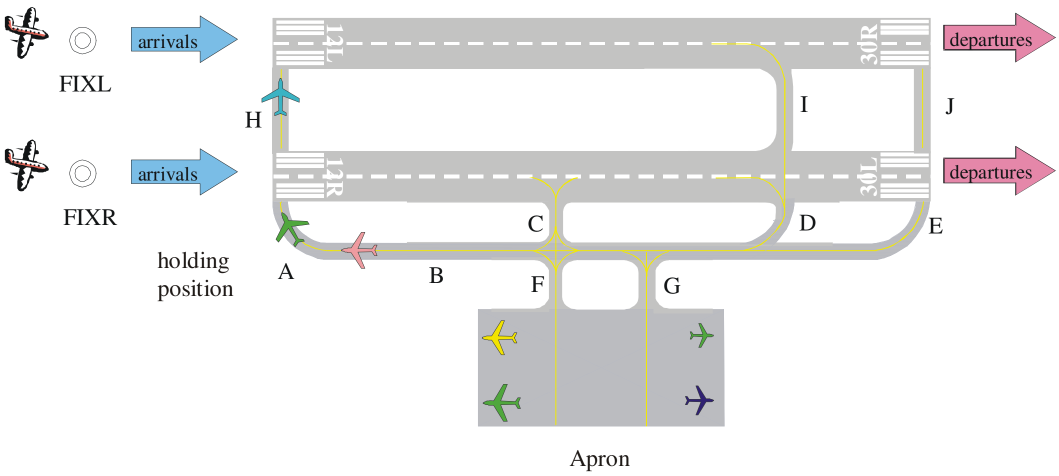

Fig. III-3. Airport with two parallel runways - Model 3

Analysis of traffic flows shows that some aircraft cross runway 12R/30L (RWY1) during their taxing phase. Namely, aircraft which depart from RWY 12L (RWY2), must cross over RWY1 to get to the departure runway (aircraft crosses runway at its end - in threshold 12R zone). Also, aircraft which arrive at threshold 12L, after leaving the runway, cross RWY1 by taxiway I (in the middle of runway), or by runway J (at the end of runway - in threshold 30R zone). So, it was necessary to introduce new complexity factors in order to include those occurrences in the equation for dynamic complexity determination:

- *number of runway crossings, at the end of RWY* - N_{REND}, i.e. number of aircraft which, during taxing, cross the runway at the threshold zone, and
- *number of runway crossings, in the middle of RWY* - N_{RMID}.

Runway crossings in the middle zone have higher significance for complexity from crossings in the runway threshold zone, so some weightings should be assigned to those factors - e.g. γ_1 ($\gamma_1 > 1$) and γ_2 ($\gamma_2 > \gamma_1$), for N_{REND} and N_{RMID} respectively.

The equation for dynamic complexity now has the following form:

$$DC(t) = TD(t) + N_{t/1}(t) + N_{sv}(t) + N_m(t) + N_c(t) + \\ + \gamma_1 N_{REND}(t) + \gamma_2 N_{RMID}(t)$$

D. *Airport with two crossing runways – Model 4*

Model 4 represents an airport with two crossing runways, so arrival and departure operations on / from those runways are interdependent.

In real life, this airport configuration is mostly used, because of the wind, such that one runway is for both, arrival and departure operations. These two runways are practically replacements for each other, so that airport utilization can be maintained at a high level, for different meteorological conditions. In this case, with the objective to consider all possible types of interactions between aircraft, and with the assumption meteorological conditions allows that, both arrival and departure aircraft could use both runways – THR 12 and THR 16 – fig. III-4.

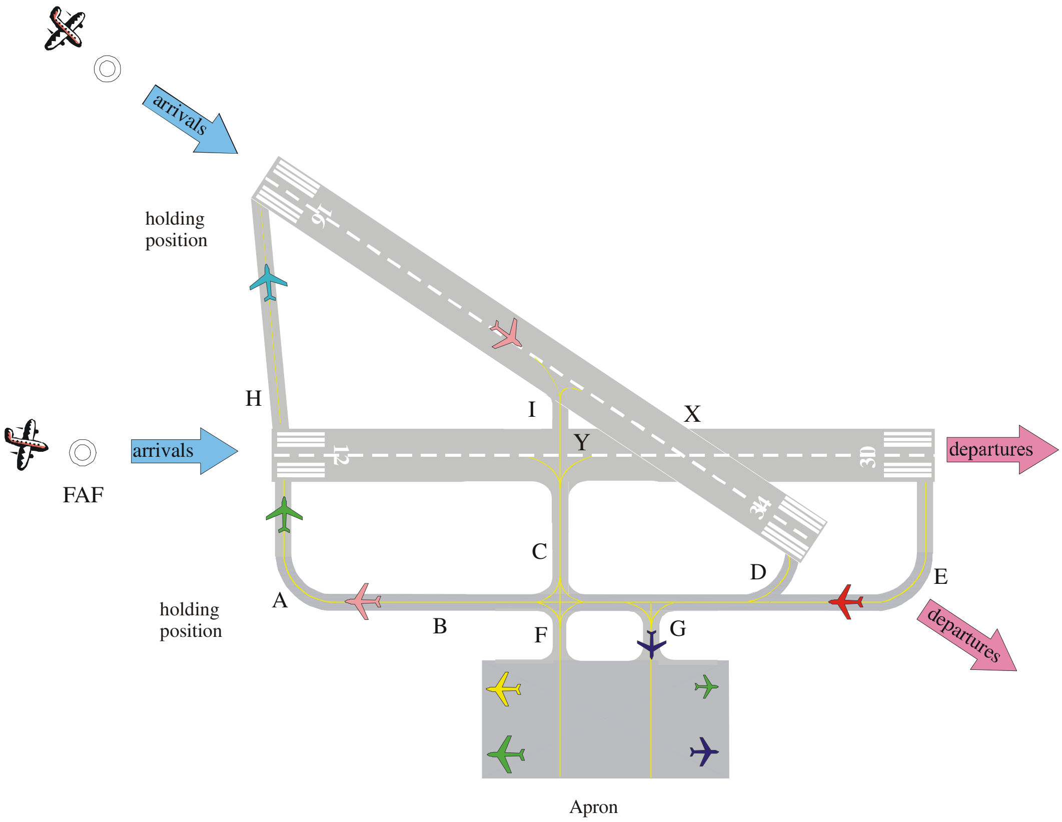

Fig. III-4 Airport with two crossing runways - Model 4

Regarding the Model 3 case, the runway crossing situation could appear in more cases. Namely, each aircraft which departs from RWY 16 (RWY2) will cross RWY1 twice:

- during taxing to threshold 16, an aircraft crosses RWY1 at the end of runway (threshold 12) – adequate complexity factor is "*number of runway crossings, at the end of RWY* - N_{REND}", and
- during departure, in point X where two runways cross each other. This type of cross has a more significant importance to situation complexity than taxiway / runway crossing, so the new complexity factor is introduced - "*number of runway crossings in two runways crossing point* - N_{RXR}".

Aircraft which arrived on threshold 16 (RWY2) crosses RWY1 once:

- in point X where two runways cross each other (N_{RXR}) and the aircraft leaves RWY2 on exit D, or
- at point Y, if an aircraft leaves RWY2 on exit I, where the taxiway crosses the runway in the middle - adequate complexity factor is "*number of runway crossings, in the middle of RWY* - N_{RMID}".

Aircraft which depart from runway 12 (RWY1), cross RWY2 once, in point X.

Aircraft which arrive at RWY1 threshold 12, also cross RWY2 once, in point X. Further, aircraft either leave RWY1 in point X, using RWY2 and exit D, or aircraft taxies to the end of RWY1 and leaves runway on exit E.

As for N_{REND} and N_{RMID} complexity factors, for the newly introduced traffic complexity factor - N_{RXR} specific weight is assigned - γ_3, where $\gamma_3 > \gamma_2 > \gamma_1$ ($\gamma_1 > 1$).

Equation for dynamic complexity now takes the following form:

$$DC(t) = TD(t) + N_{t/l}(t) + N_{sv}(t) + N_m(t) + N_c(t) + \\ + \gamma_1 N_{REND}(t) + \gamma_2 N_{RMID}(t) + \gamma_3 N_{RXR}(t)$$

IV EXPERIMENT

For each of the mentioned airport models, a simulation model based on the Monte Carlo method was developed, and for each model one stochastic experiment was run, for the given traffic sample.

During modeling, many assumptions were introduced, and some with more importance are:

- Aircraft i.e. times of aircraft appearing in the system were generated using random numbers. Actually, the inter-arrival periods between aircraft were generated, for the given distribution, and then times for aircraft appearing were calculated;
- Then, the type of operations (arrivals or departures) and type of aircraft regarding speed (faster or slower), were assigned to previously generated aircraft, also randomly (50/50%). Speed values and taxing times were chosen from the domain of real life values;
- Aircraft occupy resources (runways, taxiways, runway and/or taxiway intersection points) using the “First Come – First Served” principle;
- Dynamic complexity values were calculated with the assumption that all complexity factors have the same importance i.e. $\gamma_1 = \gamma_2 = \gamma_3 = 1$;
- In all experiments, aircraft delays were calculated too. These data were not necessary for complexity determination (by proposed equations), but it was interesting to see how much delays specific airport configurations “produce” for the given traffic volume and complexity. Delays were calculated from the difference between the time that the aircraft spent in the system and time which the aircraft would spent in the same system if it had been alone in the system;
- All simulations and calculations were done for one hour time interval and with the assumption that the system is empty at the beginning of the observed period.

Further, in the text, some of the results obtained will be shown.

A. *Model 1 – R (180s, 360s)*

Aircraft appear in the system by the uniform distribution, for a 3 to 6 minutes (180 to 360 seconds) interval (inter-arrival period). In an observed hour 14 aircraft entered the system and 12 aircraft were served (left system in the given hour), i.e. in this case the airport “flow” was 12 aircraft/h.

In the fig. IV-A1 to IV-A3 values of dynamic complexity components (factors) and values for dynamic complexity itself were shown. For this airport model, the dynamic complexity equation contains two components: traffic density - TD and number of pairs of take-off / landing successive operations - $N_{t/l}$ (Section III-A). It could be seen that a maximum of two aircraft were in the system instantaneously, number of take-off / landing successive operations were 0 or 1 so dynamic complexity values have maximal value 3.

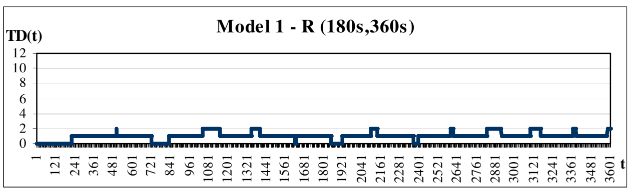

Fig. IV-A1. Traffic density - Model 1, R(180s,360s)

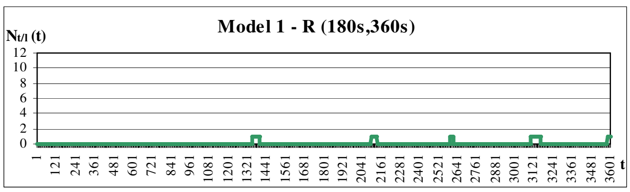

Fig. IV-A2. Successive take-off / landing operations pairs - Model 1, R(180s,360s)

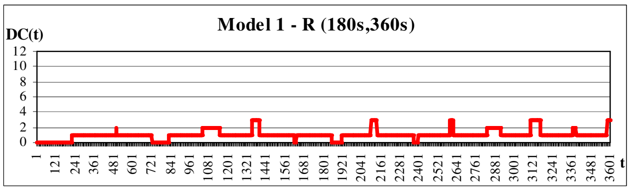

Fig. IV-A3. Dynamic Complexity - Model 1, R(180s,360s)

B. *Model 1 - R(120s,300s)*

Aircraft appear in the system due to uniform distribution, for 2 to 5 minutes (120 to 300 seconds) interval. In a given hour 18 aircraft entered the system, while 13 aircraft were served (left the system), so in this case airport "flow" was 13 aircraft/h.

In fig. IV-B1 to IV-B3 values of dynamic complexity components and values of dynamic complexity itself were shown. For the given traffic distribution, dynamic complexity has a maximal value of 8. The value is significantly higher than in the previous case (Model 1, R(180s,360s)) because of over-saturation of the system in the latter third of the observed hour. Namely, in that period aircraft enter the system but they could not be served. The number of aircraft present in the system, and number of take-offs / landings successive operations $N_{t/l}$ gradually increases, so the traffic situation complexity in the system rises too.

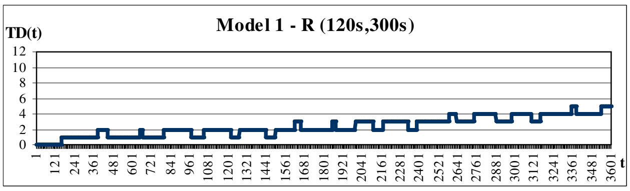

Fig. IV-B1. Traffic density - Model 1, R(120s,300s)

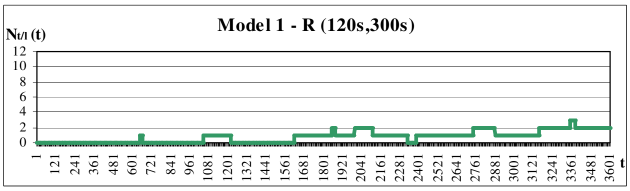

Fig. IV-B2. Successive take-off / landing operations pairs - Model 1, R (120s,300s)

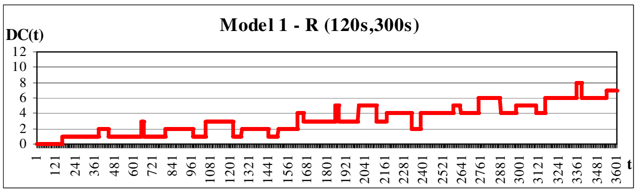

Fig. IV-B3 Dynamic Complexity - Model 1, R(120s,300s)

C. *Model 3 – R(0s,150s)*

With the objective of making the experiment for Model 3 (Section III-C) simpler, it was assumed that all arrivals are on RWY2 threshold 12L, and all departures from RWY 12R.

Aircraft appear in the system due to the uniform distribution, for the 0 to 2.5 minute (0 to 150 seconds) interval. In the observed hour 50 aircraft entered the system, while 45 aircraft were served (left the system).

In fig. IV-C1 to IV-C6 values of dynamic complexity components and values of dynamic complexity itself were shown. For this airport model, the dynamic complexity equation contains the following components: TD, $N_{t/l}$, N_{sv}, N_m, N_c, N_{REND} and N_{RMID}. It should be noticed that, for the given traffic distribution, a maximum of 9 aircraft were in the system instantaneously, the complexity factor $N_{t/l}$ had a maximum value 5, while factors: N_{sv}, N_m, N_c, N_{REND} and N_{RMID} had values 0, 1 or 2, so dynamic complexity had a maximal value 16.

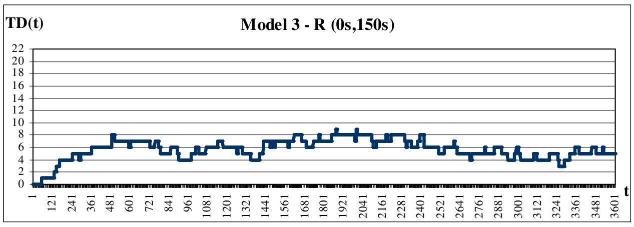

Fig. IV-C1. Traffic density – Model 3, R(0s,150s)

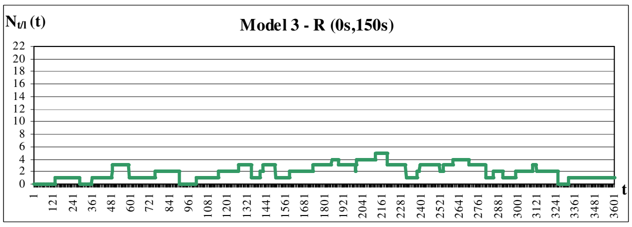

Fig. IV-C2. Successive take-off / landing operations pairs – Model 3, R(0s,150s)

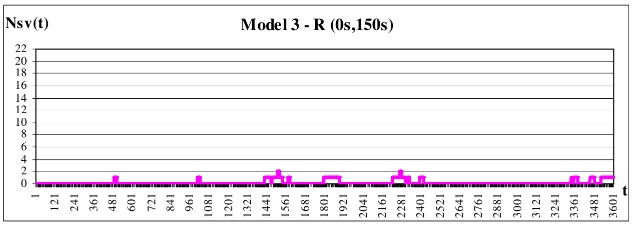

Fig. IV-C3. Potential separation violation – Model 3, R(0s,150s)

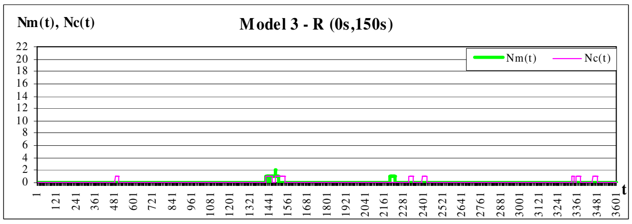

Fig. IV-C4. Number of merging and crossing – Model 3, R(0s,150s)

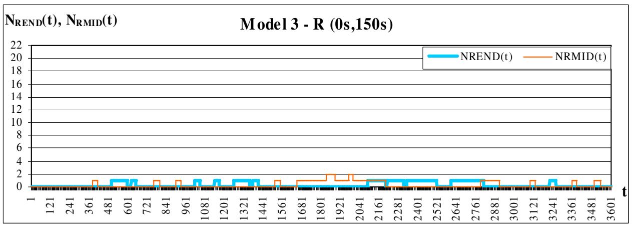

Fig. IV-C5. Runway crossings, at the end of RWY and in the middle of RWY – Model 3, R(0s,150s)

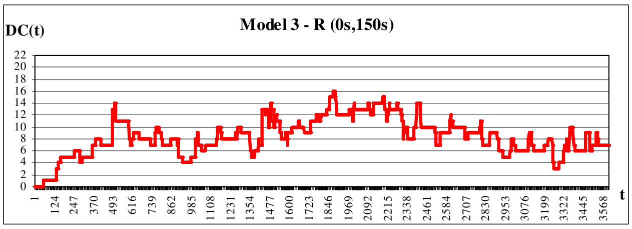

Fig. IV-C6. Dynamic Complexity – Model 3, R(0s,150s)

But, since RWY1 and RWY2 operations, in this case departures and arrivals, are independent in their flying, final approach phase (it was already emphasized in Section III-C), the total dynamic complexity value should be probably observed without the factor "number of pairs of successive take-off / landing operations - $N_{t/l}$" influence (because that influence certainly is not so "strong" like in case when arrivals and departures are both on/from same RWY). In that case dynamic complexity of the traffic situation has a maximum value of 12 – fig. IV-C7. With further analysis these lower values of dynamic complexity will be taken into consideration.

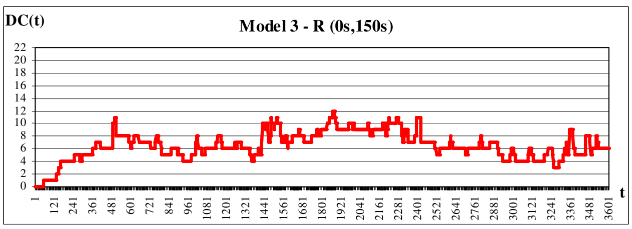

Fig. IV-C7. Dynamic Complexity without $N_{t/l}(t)$ – Model 3, R(0s,150s)

D. *Model 4 – R(0s,150s)*

The same as in the Model 3 case, with the objective of making the experiment for Model 4 (Section III-D) simpler, it was assumed that all arrivals are on the RWY2 threshold 16, and all departures from RWY 12.

Aircraft appear uniformly distributed in the system for the 0 to 2.5 minutes (0 to 150 seconds) interval. In the observed hour 50 aircraft entered the system, while 42 aircraft were served (left the system).

Fig. IV-D1 to IV-D6 shows values of dynamic complexity components and values of dynamic complexity itself. For this airport model, the dynamic complexity equation contains the following components: TD, $N_{t/l}$, N_{sv}, N_m, N_c, N_{RXR} and N_{RMID}. The complexity factor N_{REND} does not appear, because there were no departures from RWY 16 in this experiment (regarding the abovementioned assumption). It should be noticed that, for the given traffic distribution, a maximum of 10 aircraft were in the system instantaneously, the complexity factor $N_{t/l}$ had a maximum value 5, while factors: N_{sv}, N_m, N_c, N_{RXR} and N_{RMID} had values 0, 1 or 2, so the dynamic complexity had maximal value 17.

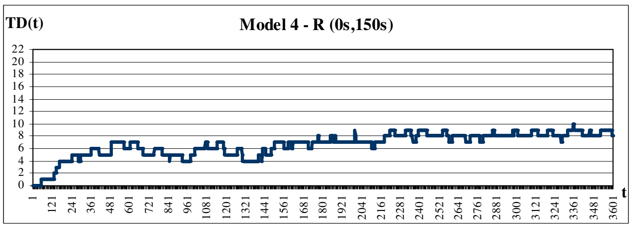

Fig. IV-D1. Traffic density – Model 4, R(0s,150s)

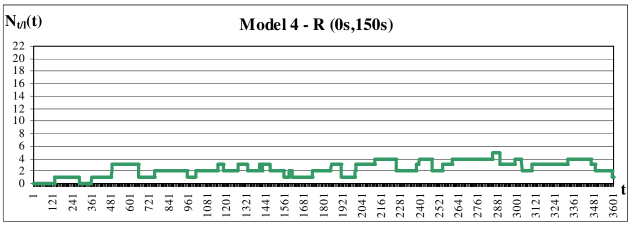

Fig. IV-D2. Successive take-off / landing operations pairs – Model 4, R(0s,150s)

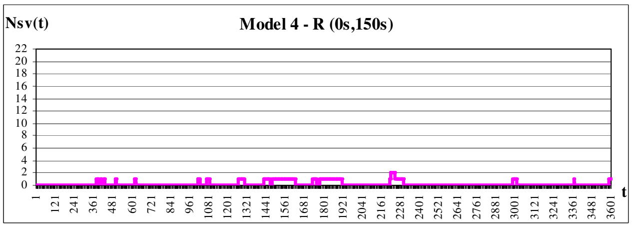

Fig. IV-D3. Potential separation violation – Model 4, R(0s,150s)

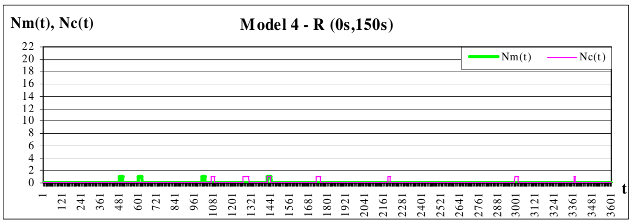

Fig. IV-D4. Number of merging and crossing – Model 4, R(0s,150s)

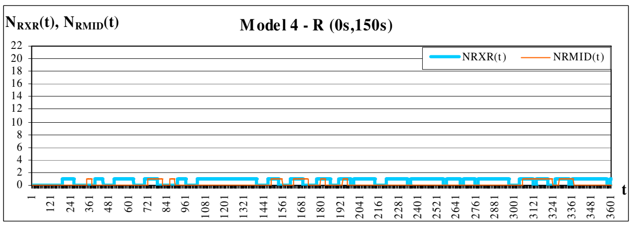

Fig. IV-D5. Two runways crossings and runway crossing in the middle of RWY – Model 4, R(0s,150s)

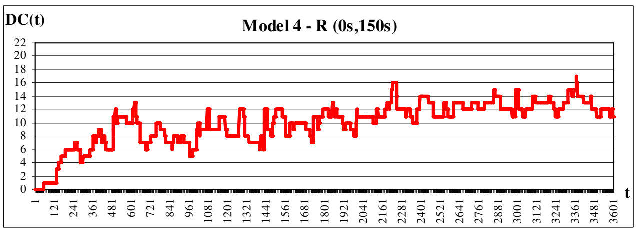

Fig. IV-D6. Dynamic Complexity – Model 4, R(0s,150s)

V COMPARATIVE ANALYSIS

In this section, the comparative view of determined values for the given airport models will be show, and, based on that some conclusions will be made.

It should not be forgotten that dynamic complexity values – DC(t) were calculated as a simple sum of complexity factors, instead of weighted sum. Namely, in Sections III and IV it was mentioned that, with the objective of making the experiments simpler, it was assumed that all complexity factors have even weighting. This assumption implicates such results that traffic density – TD(t) and, for some models the factor "number of pairs of take-off / landing successively operations - $N_{t/l}$" have the greatest effect in the DC(t) total value.

Also, because the purpose of the simulations was just to illustrate the proposed dynamic complexity measure, only one iteration was run for each simulation (by model, for given traffic distribution). For more precise analysis, larger number of iterations should be run for all observed models and traffic distributions, while more different values could be variables in the model:

- moment of aircraft appearance in the system, for the given traffic distribution, and/or
- flying and taxing duration between determined points, or flying and taxing speed, and/or
- choice of taxiway by which aircraft exit or entry the apron (for Models 2, 3 and 4), and/or
- choice of runway exit after arriving (also for Models 2, 3 and 4), and/or
- choice of runway for departure or arrival operation (for Models 3 and 4).

These will enable more statistical analysis (mean values for observed values, standard deviation, etc.), which further enables more reliable conclusions.

A. *Model 1 – comparative view for R(180s,360s) and R(120s,300s)*

As already mentioned in Section IV-B, for the distribution R(120s,300s) system became saturated in the last third of the observed time period. In Table V-AI aircraft delays are shown for both distributions - R(180s,360s) and R(120s,300s). It could be noticed that differences are very significant.

TABLE V-A1. Aircraft delays (in seconds) – Model 1, comparative view

Traffic distribution	Number of served a/c	Total delay for served a/c	Mean delay by served a/c	Number of a/c in the system	Total delay for all a/c in the system	Mean delay by a/c in the system
R(180s,360s)	12	330	27.5	14	418	29.9
R(120s,300s)	13	3005	231.2	18	6856	380.9

Fig. V-A1 shows the cumulative number of aircraft appearing in the system, for both distribution, and respective dynamic complexity values – DC(t), during the observed time period. It could be seen how the DC(t) value is rising during the time for R(120s,300s) distribution, while for R(180s,360s) given value is rather "stabile".

Also, in fig. V-A2, duration of determined DC(t) values during the observed one hour time interval are shown, for both traffic distributions. This kind of result view enables for an easier catch of difference in dynamic complexity values for the given cases, i.e. increases in dynamic complexity with traffic volume increase, for the given airport configuration.

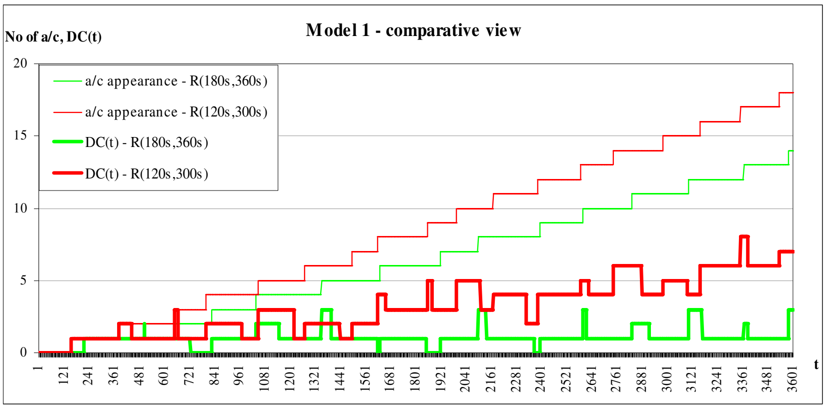

Fig. V-A1 Cumulative number of aircraft and DC(t) – Model 1, comparative view

From the “practical” perspective, this kind of view could enable a supervisory controller to more easily understand how much will be system i.e. air traffic controller load during an observed time period, would he be with a high or low workload, is that load over some defined threshold, etc. Of course, this will be applicable only if dynamic complexity and workload interdependence are already examined, and the limitation for dynamic complexity i.e. workload are reestablished.

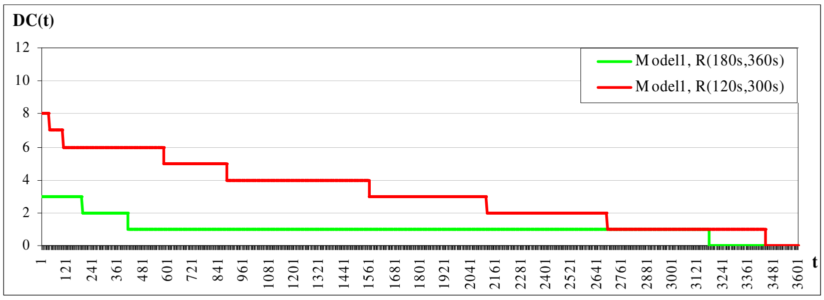

Fig. V-A2 Duration of the DC(t) values – Model 1, comparative view

B. ***Model 1 / Model 2 - comparative view***

A comparative view of DC(t) values for uniform traffic distribution - R(120s,300s), for Models 1 and 2, is shown in fig. V–B1. Also, in fig. V-B2 the comparative view of duration of determined DC(t) values during observed one hour time interval, for both airport models, is shown.

It should be noticed that traffic situation complexity, for R(120s,300s) distribution, is higher for Model 1. The number of served aircraft is 13 for Model 1, and 16 aircraft for Model 2. Values of aircraft delays are also significantly higher for Model 1 compared to Model 2 – Table V-BI.

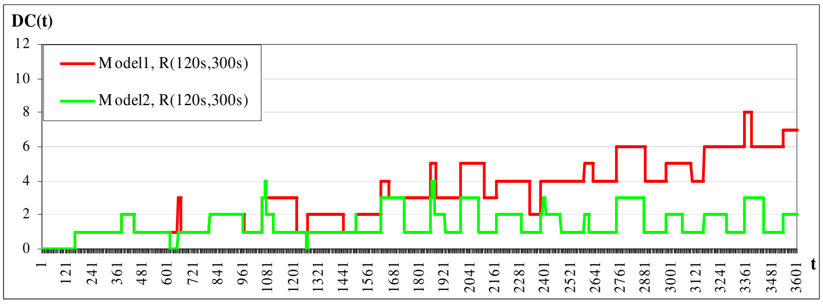

Fig. V-B1 DC(t) – Models 1 and 2, R(120s, 300s)

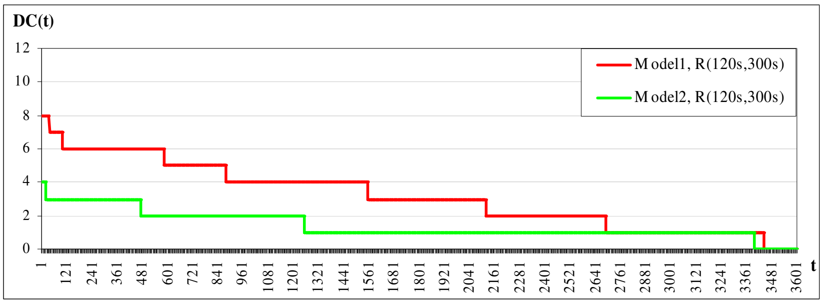

Fig. V-B2 Duration of the DC(t) values – Models 1 and 2, R(120s, 300s)

TABLE V-B1. Aircraft delays (in seconds) – Models 1 and 2, R(120s,300s)

Airport model	Number of served a/c	Total delay for served a/c	Mean delay by served a/c	Number of a/c in the system	Total delay for all a/c in the system	Mean delay by a/c in the system
Model 1	13	3005	231.2	18	6856	380.9
Model 2	16	18	1.1	18	18	1.0

Based on given comparative views, the following could be concluded:

- for the given airport configuration (model), with increase of number of aircraft that appears in the system, traffic situation complexity and aircraft delays rise too,
- for the given traffic distribution, a completely developed concept of an airport (Model 2) enables a bigger airport "flow" while traffic situation complexity and aircraft delays are significantly decreased, regarding Model 1 airport.

Results are intuitively "logical", so it could be concluded that obtained values for dynamic complexity of the given traffic situations, calculated using the equation for DC(t) determination, for the case of an airport with a single runway:

$$DC(t) = TD(t) + N_{t/1}(t) + N_{sv}(t) + N_m(t) + N_c(t)$$

are good indicators of the traffic situation in the system, i.e. obtained values are a good reflection of traffic structure and volume change for the given airport configuration, and also the proposed complexity measure "reacts" in the expected way for the different airport configurations.

C. *Model 2 / Model 3 / Model 4 – comparative view*

Comparative view of DC(t) values for a uniform traffic distribution - R(0s,150s), for Models 2, 3 and 4 is shown on fig. V–C1. Also, on fig. V-C2, comparative view of the duration of determined DC(t) values during observed one hour time intervals for those three airport models, is shown.

It should be noticed that traffic situation complexity (i.e. DC(t) values), for the R(0s,150s) distribution, is the lowest for Model 3, a little higher for Model 4 and the highest for Model 2. The main reason for that is a large number of instantaneously present aircraft in the system. Values of aircraft delays are also lowest for Model 3, although the number of served aircraft is the biggest for that model – Table V-CI.

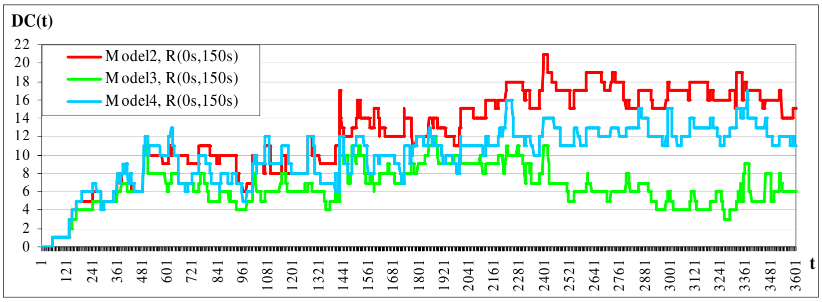

Fig. V-C1 DC(t) – Models 2, 3 and 4, R(0s, 150s)

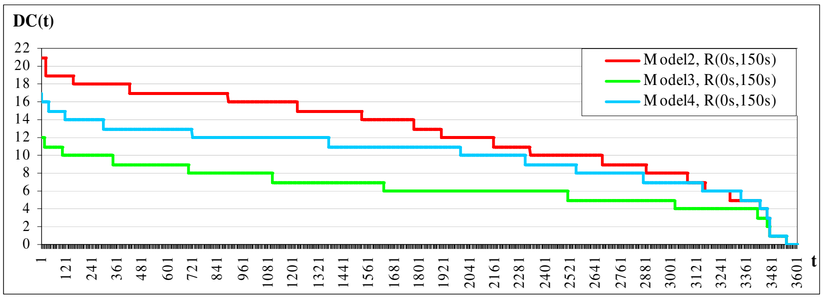

Fig. V-C2 Duration of the DC(t) values – Models 2, 3 and 4, R(0s, 150s)

TABLE V-C1. Aircraft delays (in seconds) – Models 2, 3 and 4, R(0s,150s)

Airport model	Number of served a/c	Total delay for served a/c	Mean delay by served a/c	Number of a/c in the system	Total delay for all a/c in the system	Mean delay by a/c in the system
Model 2	39	255.2	6.5	50	381.1	7.6
Model 3	45	89.9	2.0	50	97.0	1.9
Model 4	42	169.1	4.0	50	212.7	4.2

Based on given comparative views, the following could be concluded:

- the airport configuration shown as Model 3, i.e. introducing of the new parallel runway enables “flow” increase, while traffic situation complexity and aircraft delays are significantly decreased, compared to Model 2 (airport model with single runway);
- for the airport configuration shown as Model 4 – airport with two crossing runways, complexity and aircraft delays are increased compared to Model 3. Also, regarding Model 2 (airport with single runway), airport “flow” is increased, while complexity and delays are decreased.

It is very important to emphasises the assumption that all traffic complexity factors have an even importance for dynamic complexity values. Complexity factors such as: N_{sv}, N_m, N_c, N_{REND}, N_{RMID}, N_{RXR}, should be weighted and have different impact on DC(t) values. That will be “more correct”, because those events have larger weighting (in most cases) than events such as, for example, aircraft appearance in the system.

As in previous case, results are intuitively “logical“, so it could be concluded that obtained values for dynamic complexity of the given traffic situations, calculated using the equation for DC(t) determination, for the case of an airport with two runways:

$$DC(t) = TD(t) + N_{t/l}(t) + N_{sv}(t) + N_m(t) + N_c(t) + N_{REND}(t) + N_{RMID}(t) + N_{RXR}(t)$$

are good indicators of the traffic situation in the system, i.e. obtained values are a good reflection of traffic structure and volume change for the given airport configuration, and also the proposed complexity measure “reacts” in the expected way for the different airport configurations.

VI CONCLUSION

The concept of airfield traffic complexity is defined, and measures for traffic complexity computation for different airport configurations are proposed. Complexity was observed like a measure of quantity and quality of traffic interactions on airport airfields.

Sets of results of numerical examples for some of airport models, and comparative analysis for different traffic structure and for different airport models were performed. Based on this analysis, some conclusions were obtained.

It was shown that the proposed measures for dynamic complexity values determination, for different airport configurations, are good indicators of the system situation changes (traffic structure and volume changes). Also, proposed complexity measures “react” in the expected way on the different airport configurations, under certain circumstances.

Possible directions for further research were noticed. One of the interesting directions would be to include the human factor in complexity determination, for example by interviewing air traffic controllers about their subjective evaluation of the importance of the particular complexity factors i.e. about weightings of those factors, and their subjective evaluation for the particular traffic situations.

By including human factors, the quality of the proposed dynamic complexity measure could be improved, so that obtained dynamic complexity values could better represent the real system state and system state changes.

Information about complexity in particular traffic situations in observed system, could help supervisory controllers in certain situations (on strategic, pre-tactical or tactical level), to better perceive the given traffic situation impact on controller workload. Of course, dynamic complexity and workload interdependence should be previously examined, and the limitation for dynamic complexity i.e. workload should be reestablished. Good controller workload evaluation is very important to improve traffic safety and Air Traffic Control system efficiency (for example, to avoid controller overload situations, i.e. situations were controller could not respond to system demand).

Those abovementioned effects of knowledge of traffic complexity states (values) are important for an airport, but also for airlines (higher safety, potential decrease of aircraft delays, etc).

Based on all the abovementioned, it is considered that these research results could be important for further research in the air traffic complexity area.

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