Influence of Airport Operations Management on Traffic Complexity and Efficiency

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Abstract*— Different air traffic management tactics (runway scheduling, ground movement management, etc.), for given airport airfield configuration and traffic demand, could result in different traffic complexity and efficiency on the airport. This paper presents research on the relationship between air traffic control (ATC) tactics, airport traffic complexity, time and environmental efficiency. Emphasis is on the evaluation of airport traffic complexity, aircraft fuel consumption and corresponding gas emission and time efficiency for different ATC tactics. Namely, for busy airports during peak hours, arrival queuing delays, taxi-in and taxi-out times and runway queuing delays increase, which induces additional, unnecessary fuel consumption, gas emission and time inefficiency. In order to find a tool which could indicate potential delays "generators", a measure of airport traffic complexity – called Dynamic Complexity is proposed. Using SIMMOD simulation model, experiments were performed for the given airport layout, traffic demand and different ATC tactics. Traffic situations (interactions) were analyzed and delays were measured. The values of airport traffic complexity, fuel consumption and gas emissions were also determined. A comparative analysis of the results shows the following: first, the proposed airport traffic complexity metric quite satisfactorily reflects the influence of traffic "characteristics" upon the "environmental state" of the system, and second, different ATC tactics could imply different airport traffic complexity, and further, different time and environmental efficiency of the system.

Keywords- Air Traffic Management; Airport; Traffic Complexity; Environment

I. Introduction

Over the last few decades, air traffic has increased significantly, and this trend is predicted to continue in the future. Flight demand in Europe is predicted to be 14.4 million movements in 2035, which is the 1.5 times the 2012 volume. This scenario is considered by EUROCONTROL's forecast experts as a "most-likely" growth scenario [1].

Such growth has its positive as well as negative effects on the society and environment. In order to "control" negative effects of the constant growth, concept of sustainability and sustainable development has been introduced in air transportation, like in many other areas. Most current definitions recognize three main categories of sustainable development issues: economic, social and environmental. In this research, emphasis is on the environmental dimension of the air traffic effects, which became a very important issue. Reasons are numerous, e.g. air traffic is responsible for 3.5% of overall European CO_2 emission [2], and this percentage is still growing (it is expected that until 2050 air transport CO_2 emission would grow 3 to 4 times compared to emission level of the year 2000 [3]).

The major air traffic management (ATM) initiatives in Europe - Single European Sky ATM Research (SESAR) [4], and US - Next Generation Air Transportation System (NextGen), set environmental impact reduction targets regarding noise, air quality and climate change, and both identify ATM improvement as a most important element in meeting their overall goals (e.g. to reduce by an average of 10% per flight the ATM CO_2 emitted by aircraft). Also, the Intergovernmental Panel on Climate Change (IPCC) suggests that improvements in ATM could help to improve overall fuel efficiency by 6-12% per flight [5]. In [6] authors show that there is a possibility to reduce fuel consumption through improvement in operational performance, since that operational performance is responsible for up to 10% of airborne fuel consumption.

Due to air traffic growth, number of flights increased significantly, delays have been increased too, as well as aircraft fuel consumption and air pollutant emissions, in all flight phases. Since airports have been recognized as one of the bottle-necks in the air transport system, landing and take-off cycles, with detailed analysis of the ground movement of the aircraft (airfield movement), are chosen for analysis in this research.

Namely, for busy airports during peak hours, arrival queuing delays, taxi-out/in times and runway queuing delays increase, which induces additional, unnecessary fuel consumption and gas emission. By 2035, airport delay will rise from around 1 minute/flight in 2012 to 5-6 minutes in 2035, transforming it from a minor/intermittent to a permanent, major contributor of delay [1]. In order to avoid that, airports have either to be enlarged, or (since enlargement is not possible in most cases), to utilize the existing resources as efficiently as possible [7].

This paper presents research on the relationship between airport traffic complexity and time and environmental airport efficiency, under different air traffic control (ATC) tactics. For that purpose, a measure of traffic complexity (interaction) called *Dynamic Complexity* (DC) was introduced. Additionally, some ATM performance metrics were proposed. Afterwards, for the given airport configuration (airfield layout) and traffic demand, different applied ATC tactics influence were analyzed, from the aspects of traffic complexity, delays and environmental impacts (aircraft fuel consumption and gas emission).

One of the important contributions of this paper is the presented relationship between airport traffic complexity and airport environmental impact. Namely, that interrelation could be embedded in some decision support tools for the airport planners, in order to support them (when trying to reduce airport traffic complexity and environmental impact) to make decisions related to introduction of some changes in ATC tactics used for airport traffic management (on tactical or strategic level) and/or changes of airport airfield infrastructure (on strategic level).

In addition to introductory section, the paper is structured as follows: Section 2 provides a brief literature review on air traffic complexity area as well as airport ground movement problem from different points of view; in Section 3, the concept of airport traffic complexity and a measure for complexity quantitative computation are proposed; in Section 4, some Flight inefficiency metrics are proposed; Section 5 describes different ATC tactics which will be applied in experiments; Section 6 illustrate the proposed traffic complexity and flight inefficiency measures, applied on the given airport layout, and obtained results analysis are presented. Finally, the last section summarizes conclusions and directions for further research.

II. Related Work

The review of the literature in the field of air traffic complexity shows that a large number of studies deal with relationship between complexity and air traffic controller (ATCo) workload. Generally, the concept of complexity is introduced as "weight" of the traffic situation, i.e. possible impact of the existing or expected traffic situation on ATCo's workload.

Reference [8] is one of the first research which dealing with complexity and its influence on the ATCo's workload and it gives the list of all complexity factors previously used in ATC. A new concept called *"Dynamic Density"* (DD) is introduced in [9]; DD includes traffic density, different complexity factors and ATCo's intentions. Afterwards, many researchers deal with DD modelling and its application analysis. The analysis of complexity influence on the level of ATC service is presented in [10]. In [11] it is concluded that measure of complexity will find wide appllication in air traffic management and in new management concepts (like free flight) evaluation. The aim in [12] is to find an indicator of essential traffic complexity, through measure of level of traffic situation entropy. The focus of [13] is to investigate the relationship between ATC complexity, controller's activity measures and subjective workload.

All the above mentioned research refers to air traffic complexity in the en-route environment. Namely, literature review of complexity area shows that air traffic complexity in terminal maneuvering areas (TMA) has received only moderate attention (e.g. [14]-[16]) and airfield traffic complexity almost no attention at all ([17]-[19]). In the first two mentioned research related to TMA complexity, authors propose a generic metric for measuring the complexity of a given terminal airspace (TMA). The metric includes static and dynamic complexity, both consisting of the complexity component for arriving and departing traffic. In [16] the predictive capabilities of complexity metrics are analyzed towards two aspects: ATCo's workload and the level of safety (collision risk). In the study related to airfield complexity - [17], focus is on complexity factors and their incidence, how these contribute to ATCo's job performance and strategies, and information sources used to deal with complexity within ATC Towers. The results show that relative contribution of each of the complexity factors is site-specific (depending on Tower). Even so, high traffic volume and frequency congestion are among the most highly rated factors across all sites. The above mentioned research [18] and [19] will be explained in more detail in the following sections.

The problem of aircraft fuel consumption and gas emission on airports is closely connected to aircraft ground movement. In [20] authors give a comprehensive review of the research related to ground movement problem. Ground movement problem studies which deal with fuel consumption and gas emission are numerous: [21]-[29], etc.

From an optimization point of view, ground movement of aircraft can be considered as one of the most important airside operations at an airport, since it connects several problems together: the runway sequencing problems for arrivals and/or departures, the stand holding problem and the gate assignment problem [7]. Ground movement problem may be considered from different points of view, depending on the aims of an airport. In a recent paper [28], authors summarize a variety of different constraints and objective functions which have been used in the past: such as minimising the total taxi time or multi-objective approaches like weighted linear objective function for simultaneous consideration of total routing time, the delays for arrivals and departures, the number of arrivals and take-offs, the worst routing time and the number of controller interventions, etc. They also observe that there is little coverage of environmental considerations in taxiing within the previous research. Namely, the main focus has been on reducing the total taxi time, with assumption that shorter taxi time means better efficiency of airport operations and reduction of fuel consumption. However, this may not be true in all cases, due to "specific" relationship between fuel consumption and the corresponding speed profile (e.g. smooth speed profiles vs. unnecessary fuel burn due to acceleration and deceleration). The trade-off between the total taxi time and the fuel consumption for the conflict-free routing problem for aircraft on an airport's surface was analyzed too.

Research presented in this paper analyzes both arrivals and departures, while interactions between aircraft are considered from the moment when aircraft enter the system until aircraft leave the system. So, separations between multiple aircraft were respected in all considered phases of the flight (both airborne and ground). Also, besides delays, fuel consumption and gas emission calculations, which were analyzed in numerous previous research, contribution of this research is reflected in the airport traffic complexity measure which is proposed and analyzed.

III. Airport Traffic Complexity

The concept and measure of airport traffic complexity used in this research were proposed in [18]. Complexity has been observed through traffic characteristics, i.e. as a measure of quantity and quality of traffic interactions on airport airfield and in airport vicinity, under certain circumstances.

The system analyzed in this research contains the airfield part of the airport system as well as airspace in the airport vicinity. So, its boundaries are:

- for *arriving aircraft* – from the final approach point (FAF), to the moment of arriving on the apron;
- for *departing aircraft* - from the moment of push-back or start-up clearance request, until a given time after departure.

The term *Dynamic Complexity* - *DC* is introduced as a measure of airport traffic complexity and is defined as a linear combination of traffic density and a number of proposed traffic complexity factors:

$$\begin{aligned} DC(t) = {} & \alpha TD(t) + \beta_1 N_h(t) + \beta_2 N_{t/l}(t) + \\ & + \beta_3 N_{sv}(t) + \beta_4 N_m(t) + \beta_5 N_c(t) + \\ & + \gamma_1 N_{REND}(t) + \gamma_2 N_{RMID}(t) + \gamma_3 N_{RXR}(t) \end{aligned} \quad (1)$$

where: α, $\beta_1 \ldots \beta_5$ and $\gamma_1 .. \gamma_3$ are specific "weights" of traffic density and the given traffic complexity factors.

TD - traffic density shows the total number of aircraft in the system, either aircraft already "inside" the system or waiting at the system boundary (due to assigned delays), at a certain moment in time.

$\mathbf{N_{t/l}}$ - number of pairs of take-off/landing successive operations, where operations are overlaping during a time interval they spend in the system (situations when ATCo has under his/her 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 departures or arrivals),

$\mathbf{N_{sv}}$ - number of potential separation violation on the ground, i.e. number of aircraft pairs whose minimal separation will be violated without ATCo's intervention, either in catching-up situations (because the trailing aircraft is faster or leading aircraft is standing), or in intersections, i.e. in common points for aircraft paths, all refered to airfield movings,

$\mathbf{N_m}$ - number of mergings, i.e. number of aircraft pairs which will, during their taxiing phase, go through the same point and go on by the same path (during certain time period),

$\mathbf{N_c}$ - number of crossings, i.e. number of aircraft pairs which will, during their taxiing phase, go through the same point and go on by different paths (during certain time period),

$\mathbf{N_h}$ - number of departing aircraft holding at gate,

and for the airports with two or more runways:

$\mathbf{N_{REND}}$ - number of runway crossings, at the end of RWY, i.e. number of aircraft which, during taxiing, cross the runway at the threshold zone (if this may have an impact upon the other traffic, in any way),

$\mathbf{N_{RMID}}$ - number of runway crossings, in the middle of RWY (if this may have an impact upon the other traffic, in any way),

$\mathbf{N_{RXR}}$ - number of runway crossings in two runways crossing point (if this may have an impact upon the other traffic, in any way).

Time *t* is the moment when any change in the system occurs, which further implicates *DC* value change, such as:

- aircraft appearance in the system,
- aircraft leaving the system,
- the beginning and ending of a potential separation violation for the taxiing aircraft,
- aircraft arriving in one of the taxiway intersection points or in some taxiway "important" points, if this leads to an aircraft path merging or crossing situation, and when a merging or crossing situation is finished, etc.

Equation (1) is general, i.e. it covers all types of airport layouts. In [18] it is shown that the proposed measure - *DC* is a good indicator of the system situation changes (traffic structure and volume changes) and the measure "reacts" in the expected way in different airport configurations, under certain circumstances.

IV. Flight Inefficiency Metrics

In an ideal air transportation system, all aircraft would fly their optimal four-dimensional trajectories between airports (the most direct route, at most fuel-efficient altitude and speed profiles), and taxi on the optimal airfield routes (shortest routes with no holds and with optimal speeds). This would lead to lowest fuel burn and gas emissions, lowest noise level and overall effects upon air quality. However, real world constraints (such as required minimum aircraft separation) lead to less efficient aircraft flying and taxiing trajectories and create greater environmental negative effects than ideal.

ATM could have a significant role in reducing the environmental impacts of air transportation. For the purpose of better understanding, one approach is to quantify ATM performance using relevant flight inefficiency metrics, where flight inefficiency is defined as any deviation from optimum flight 4D path, in any of the flight phases. This could enable identification of the levels and sources of inefficiency in the observed system, and recognition of potential possibilities for improvement in the ATM system. "*Inefficiency Metric"(IM)* provides information about the difference between actual and optimal values of the analyzed parameters and the general form is [5]:

$$IM(\%) = ((Actual - Optimal)/Optimal)) \times 100 \quad (2)$$

In this research, relative measure of the time which aircraft spent in the system, fuel consumed and corresponding gas emission (within defined system boundaries) are chosen for analysis. *Inefficiency Metric* refers to *Time, Fuel or Emission Inefficiency,* so *Actual* and *Optimal* values in (2) refer to actual and optimal time spent in the system, actual and optimal fuel consumption and actual and optimal gas emission. Optimal values are the values which aircraft would obtain in case of unimpeded flight, taxiing on the shortest route with no holds (as if it were alone in the system).

A. Fuel consumption and gas emission

In the last decade, numerous studies were dealing with estimating aircraft fuel consumption, usually using Flight Data Recorder (FDR) Archives. Regarding ground movement, the ICAO engine emisssions data base states that the engine power setting for taxi or ground idle is 7%, but it does not distinguish between the different phases of taxiing. Some authors show that levels of around 5% to 6% are more realistic for most engine types, others use four different values for different taxi operation phases: 4% for idle thrust, 5% for taxiing at a constant speed or brake thrust, 7% for perpendicular turn thrust and 9% for breakaway thrust, while others use a certain thrust domain for the given taxiing phase, with different random distribution of the thrust values inside the given domain [28]. In [29] authors try to estimate fuel burn using linear regression, concluding that the total taxi time is the main fuel burn factor, but the number of acceleration events also exerts significant influence.

For this research, it was decided to use “standard” values for fuel consumption and corresponding emission data (for carbon dioxide - CO_2, water vapor, carbon monoxide - CO, hydrocarbons - HC, nitrogen oxides - NO_x, benzene and sulfur oxides - SO_x) in different flight phases, from ICAO Aircraft Engine Emissions Databank [30], and from the data base of EUROCONTROL taken from model AEM3 – Advanced Emission Model (which is based on BADA data base; [31]). Based on those data, the following engine power settings for different phases of flight are assumed:

- Approach and Landing: Approach thrust mode of 30%,
- Take-off: Take-off thrust mode of 100%,
- Climb-out: Climb thrust mode of 85%,
- Taxi-in, taxi-out and holding on airfields: Taxi/Idle thrust mode of 7%.

Those engine thrust regimes further affect fuel consumption and gas emission. Values for fuel consumption and gas emission for arriving aircraft during assigned delays (holdings, speed reductions, vectoring, etc) were taken from AEM3 data base - for aircraft cruising on FL30 (FL30 was chosen due to available data, and for the purpose of the scenario comparison it is acceptable).

Fuel consumption and gas emission of aircraft in considered system boundaries depend on aircraft type, i.e. aircraft engine type, flight phase(s) and on time spent in considered flight phase(s).

Total fuel burned of the flight i for the observed flight phases j is:

$$TF_i = \sum_j FB_{ij} = \sum_j \left(T_{ij} \times N_i \times FBI_{ij}\right) \qquad (3)$$

where: FB_{ij} is the fuel consumption during certain phase j of the flight i, T_{ij} is the time which the given flight spends in the given phase j of the flight i, N_i is the number of engines of the aircraft on the flight i and FBI_{ij} is a single engine fuel consumption index in the given phase j for the certain engine type of the flight i (in kg/s).

Total fuel burned TF_a of all observed flights i (for the observed flight phases j) is:

$$TF_a = \sum_i TF_i \qquad i = 1,\dots n \qquad (4)$$

where n is the total number of flights in the analyzed system during the observed time period.

Total gas emission of all observed pollutants k during flight phases j for the flight i - TE_i is:

$$TE_i = \sum_j \sum_k E_{ijk} = \sum_j \sum_k \left(T_{ij} \times N_i \times EI_{ijk}\right) \qquad (5)$$

where: E_{ijk} is emission of the pollutant k during phase j on the flight i, EI_{ijk} is a single engine emmision of the pollutant k during phase j for the certain engine type of the aircraft on the flight i (in kg/s).

Total gas emission TE_a of all observed flights i (for the observed system) is:

$$TE_a = \sum_i TE_i \qquad i = 1,\dots n \qquad (6)$$

where n is the total number of flights in the analyzed system during the observed time period.

V. ATC TACTICS

ATC tactics for sequencing arrival and departure flows influence both the complexity and inefficiency values. One of the main objectives of the ATC is to manage traffic efficiently. Some ATC management actions could significantly influence system performances, and one of those is system efficiency. Namely, different tactics for airport infrastructure utilization could be applied for a given airport layout. For example, for arriving and departing aircraft different sequencing tactics could be used:

- First come First served – FCFS: where aircraft occupy runway in the sequence regarding time for runway use requested by the aircraft (pilot),

- Arrivals have priority over departures, and departing aircraft could get clearance for take-off only if there is enough space between two arrivals,
- Tactic when each two arrivals have to be separated so as to provide enough time for at least one departure (of course, in the case when there is a departure on the holding position, ready for take-off),
- Certain optimization model could be applied to obtain optimal (or close to optimal) sequence, regarding defined objective function/s, etc.

All the above mentioned sequencing tactics usually have to consider a lot of different constraints like: departures and arrivals slots, some airlines' priority over others, connecting flights, etc.

During taxiing to the gate after landing and during taxiing to holding position for take-off, aircraft could be assigned to different taxiing routes. The related decision could result from some airport rules regarding taxiing traffic, ATCo experience, some decision support tools (e.g. Surface Manager - SMAN), etc, or from the combination of some of the above.

Runway scheduling problem was also very often analyzed in the literature: e.g. [32] - [35], etc. The general conclusion was that FCFS method is robust, and that only sophisticated algorithms can offer a significantly better solution, without concern over the costs of aircraft delays due to changing their position from the one initially obtained by FCFS rule.

Two different tactics were analyzed here:

Arrivals priority sequencing tactic (AP) applied for the runway occupancy. Arrival sequence was determined according to the moments when aircraft appear in the system on the FAF point (FCFS sequence), and departure sequence according to the moments when departing aircraft arrive on the holding position next to the runway threshold (also FCFS sequence). Departure could get the take-off clearance and leave departure queue (if there is any) only if there is enough time (separation) to be inserted between two arrivals. After landing and during taxiing to holding position for take-off, taxiing routes to/from gates were partly assigned to aircraft at random and were partly defined (but only intuitively logical routes).

Arrival-departure sequencing tactic (A/D) for the runway occupancy. Arrival and departure sequences were determined separately, in the same way like in previous case. Arrivals were additionally separated (if there is no enough separation according to assigned moments of appearing in the system) in order to insert a departing aircraft between each two arrivals. So, arrivals will have some additionally assigned delays, while total delay of departures will be less (comparing to previous sequencing tactic). During taxiing phase, taxiing routes were assigned to the aircraft in the same way like in the previous tactic.

VI. Illustration

In order to examine the influence of different ATC tactics on the proposed traffic complexity measure, as well as on system efficiency, some experiments were done.

First, an airport with one runway and taxiway parallel to runway was modeled using SIMMOD simulation model (Version 8.1) – Fig 1. Airport with such airfield configuration was chosen as configuration which enables "high" traffic throughput and for which air traffic controllers have possibilities to organize traffic in different ways on tactical level.

Hereon, some stochastic experiments were performed in order to obtain the range of values for *Dynamic Complexity,* delays of the aircraft - *Time Inefficiency (TI)*, fuel consumption – *Fuel Inefficiency (FI)* and corresponding gas emission – *Emission Inefficiency (EI)*, for the given traffic scenario and different airfield utilization strategy (ATC tactics).

A. Modeling Assumptions

Modeling assumptions were numerous, the most important being:

Aircraft appear in the system randomly, by uniform distribution, when aircraft inter-arrival time is 1 to 3 minutes - R(60s, 180s) for arrivals, as well as for departures;

Type of operations (arrivals or departures) and type of aircraft (heavy or large), were randomly assigned to previously generated aircraft (arrival/departure rate: around 50/50% and heavy/large aircraft rate: around 25/75%). Speed values, separation between two arrivals, two departures or between arrivals and departures, separations on the runway and on the ground during taxiing were chosen from the domain of real life values;

Aircraft occupy taxiways and taxiway intersection points, using the FCFS principle;

For traffic complexity factor: number of pairs of take-off / landing successive operations – $N_{t/l}$; it was chosen to have the following values: value 0 – for time intervals when ATCo has under his jurisdiction (i.e. within the defined system boundaries) only departing or only arriving aircraft at the same time, or value which is equal to: $N_{t/l}$ = number of arrivals between final approach fix and runway exit (after landing) + 1 (for the first aircraft in the departure queue). For the $N_{t/l}$ value determination, arrivals are taken into account only until aircraft leave the RWY, because, afterwards, that aircraft is not considered "interesting" for this traffic complexity factor;

Traffic density and all traffic complexity factors have even importance (equal to 1);

Regarding fuel consumption and gas emission, two types of aircraft were considered for heavy aircraft: B747 (4 engines: type 3GE077) and A310 (2 engines: type 1GE015) - randomly assigned: around 50/50%, and two types for large aircraft:

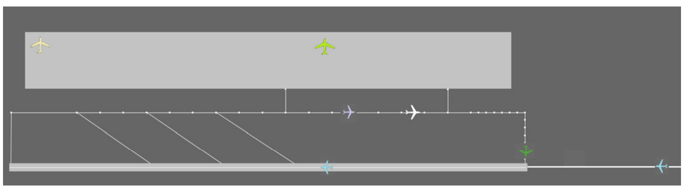

Figure 1. Airport layout with taxiway parallel to runway

B737-700 (2 engines: type 3CM031) and F100 (2 engines: type 3RR031) – also randomly assigned: around 50/50%. Fuel consumption and gas emission of the aircraft were calculated for the following flight phases: aircraft holding in the air (in the approach phase, before FAF point), approach, landing, take-off, climb-out, taxi-in/out and holding on the airfields, in the way described in the Section 4.A;

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;

Since the purpose of the simulations was only to illustrate the proposed concept of dynamic complexity and its interaction with proposed inefficiency indicators, six iterations were run and analyzed for each of the two ATC tactics (with randomly assigned delays to the aircraft by uniform distribution from 0 to 3 minutes, compared to initial traffic sample).

B. Results and Discussions

This section shows a comparative view of determined values for the given airport model, traffic demand and proposed ATC tactics.

Table I gives the values of average total and mean delay (per aircraft), for two different ATC tactics: AP and A/D, obtained from 6 simulation iterations.

Comparison of DC(t) obtained for those tactics is shown in Fig. 2 . Fig. 3 shows the comparative view of DC(t) values and inefficiency metrics obtained for the same cases.

These figures and values presented in the Table I show a significant difference between system performances for two considered cases. Namely, A/D ATC tactic, compared to AP tactic, generally provides much better system efficiency: significantly lower delays for higher throughput of the system, with lower values of *DC* of the traffic situation on the airport (particularly evident in the last two-thirds of the observed time interval; system became saturated for the AP case – Fig. 2) and lower *TI, FI* and *EI*.

It was also interesting to look at the obtained inefficiency values in more detailed. Fig. 3 shows those values separately for arrivals and departures, for different ATC tactics. Differences are significant. First, for AP tactic departures *TI* is very significant and much higher than arrivals *TI* (only few percent of the total *TI* were obtained from arrivals delays). For A/D tactic, departures *TI* are still higher compared to arrivals inefficiency, but the difference is smaller (around 80% of *TI* goes to departures and around 20% to arrivals delays). Such distribution of inefficiency is partially resulting from the total time which departures and arrivals spent in the system (within defined system boundaries). Namely, departures spent in the system (without delays) from 192 to 320 seconds (depends on the gate from which aircraft starts) and arrivals from 295 to 440 seconds (depending on runway exit and destination gate). So, same aircraft delay gives higher value of inefficiency for departures than for arrivals. *FI* and *EI* “distributions” between departures and arrivals are: for AP tactic ratio is around 90% - 10%, and for A/D tactic 45%-55% (so arrivals have little higher inefficiency, since they have higher fuel consumption and emission rate than departures). Still, departures delays are high for both tactics (Table I), which indicates that the given or higher demand could be a trigger for some strategic measure (e.g. planning a new runway and/or taxiways).

In both tactics, *EI* is directly dependent on *FI* and both are proportional to *TI* and *DC*. However, *FI* and *EI* values are much lower than for *TI*, since delays are mostly departure delays and the fuel consumption and corresponding emission is not so high during idle phase (like during waiting in the air).

Average total fuel consumption and emission (obtained from six iterations), for both mentioned ATC tactics are shown in Fig. 4 and Fig. 5. Also, values for fuel consumption and emission which would be obtained if aircraft go through the system without any delay (as if aircraft were alone in the system) are shown, as well as values (for both ATC tactics) without departure delays. Namely, for departing aircraft, which have some delay assigned (according to the mentioned sequencing tactic), there is a possibility to wait on the gate (parking position) with engines off, instead on the holding position with running engines, so the unnecessary fuel consumption and gas emissions will be avoided. In practice, it is very hard to enable aircraft to come in a certain point in the exact moment (in this case - on the holding position for take-off). So, the practice is that aircraft come to the holding position approximately 5 minutes before the calculated take-off time, with a tendency to keep the target sequence of the aircraft in the departure queue. Also, it is very important to emphasize that this tactic could be applied only if aircraft can stay at its parking position for some additional time. Since the need for applying this tactic usually “rises” in the peak time periods when apron is highly utilized, aircraft usually must leave parking position within particular time interval. However, the “theoretically

TABLE I. AIRCRAFT DELAYS – DIFFERENT ATC TACTIC

Strategy		Average number of served a/c	Average total delay for served a/c	Mean average delay by served a/c	Average number of a/c in the system	Average total delay for all a/c in the system	Mean average delay by a/c in the system
AP	Total	36.17	341 min	9,43 min	56.33	824 min	14,63 min
	Arrivals	23.17	11 min	0,47 min	28.17	17 min	0,60 min
	Departures	21.33	330 min	15,47 min	28.17	807 min	28,65 min
A/D	Total	44.5	172 min	3,87 min	56.33	281 min	4,99 min
	Arrivals	24.67	47 min	1,91 min	28.17	64 min	2,27 min
	Departures	11.5	125 min	10,87 min	28.17	216 min	7,67 min

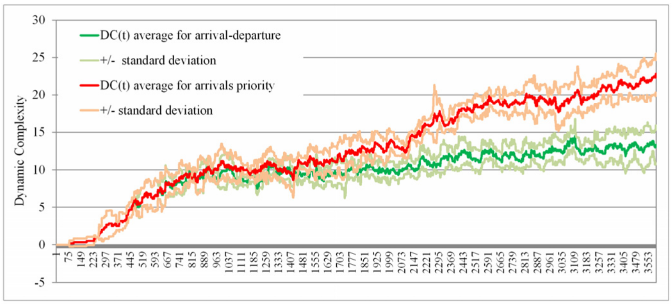

Figure 2. Dynamic Complexity – comparative view for both ATC tactics

possible" benefits from holding departures on their gates (if all the aircraft came to holding position in the exact moment when they can immediately go to take-off) are very obvious for AP tactic, for almost all "components". The biggest decrease is for CO, total HC and benzene emission (over 75%; the emission of those gasses are extremely high during the taxi/idle phases), but there is also a very significant decrease for fuel consumption and CO_2, water vapor and SO_x emission (almost 50% decrease). For A/D tactic, benefits are lower, since the departure delays were much lower, and arrival delays slightly higher.

VII. Conclusions and Further Work

This paper proposes the concept and a measure of airport traffic complexity called *Dynamic Complexity*. Complexity is defined as a measure of quantity and quality of traffic interactions on airport airfields and in airport vicinity, under certain circumstances.

In addition, so as to provide better understanding about the impacts of different ATC tactics on the airport system performances, several flight inefficiency metrics are defined and analyzed. These are Time, Fuel and Emission Inefficiency.

In order to illustrate the proposed concepts some experiments are performed. A comparative analysis of the results for different scenarios in terms of different ATC tactics applied on given airport configuration, shows that the proposed airport traffic complexity metric is "behaving" as expected, i.e. it reflects quite satisfactorily the state of the system (traffic complexity situation and system efficiency). Moreover, the "logical" relationship between Dynamic Complexity and Time, Fuel and Emission Inefficiency is observed.

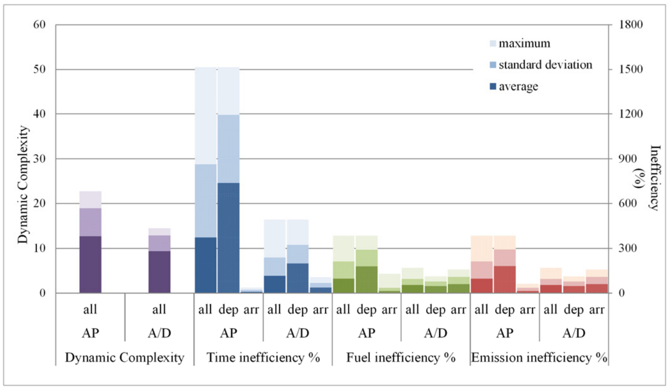

Figure 3. DC and Inefficiency values – comparative view for both ATC tactics

Through observed numerical examples it was also shown how some improvements of the system efficiency could be achieved by ATC tactics changes, while in some cases, result indicates that strategic measures (such as airport airfield infrastructure changes by building new elements) are necessary, in order to obtain satisfactory system efficiency (primarily "acceptable" delays, which further imply corresponding fuel and gas emission efficiency).

The established mutual relationship between airport traffic complexity, time efficiency and airport environmental impact represents a significant contribution of this paper. Namely, that interrelation could serve as very useful information for airport planners and support them to evaluate effects of traffic increase, or some changes in ATC tactics applied for airport traffic management and/or changes of airport infrastructure (e.g. building of new taxiway(s) and/or runway(s)) on airport traffic complexity, time efficiency and environmental impact.

Possible directions for further research are observed. With regard to traffic complexity measure, one of the interesting directions would be to include human factor in complexity determination, for example by interviewing ATCOs about their subjective evaluation of the importance of particular complexity factors i.e. about weightings of those factors, and their subjective evaluation for particular traffic situations.

In addition, it would be very interesting to conduct all mentioned analysis for more complex airport configurations (with more runways and especially with more taxiways) and higher traffic intensity, where larger number of different aircraft interactions is quite possible. New ATC tactics could be

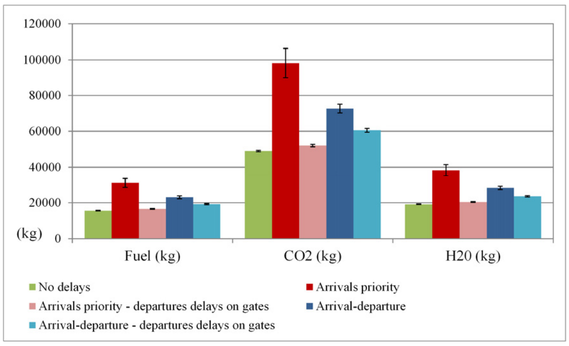

Figure 4. Total (average) fuel consumption and emission

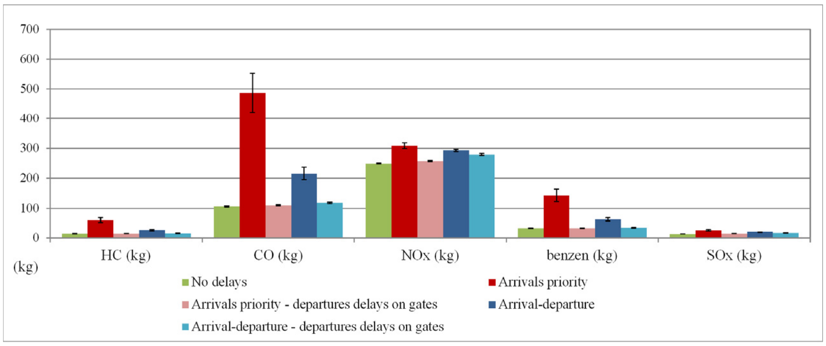

Figure 5. Total (average) emission for different ATC tactics

analyzed, as well. Finally, in order to "create more stochastic conditions" (which is closer to real life conditions) of traffic situation and to enable more statistical analysis, larger number of simulation iterations should be run.

All the above mentioned conducted and future research could enable development of a decision support tool for the airport planners, which could help them to evaluate implementation of some ATC tactical and/or strategic measures (i.e. introducing a new ATC tactic on the existing airfield infrastructure and/or some airport infrastructure upgrade), from the efficiency and environment point of view, by "simple" *Dynamic Complexity* and *Time, Fuel and Emission Inefficiency* computation and analysis.

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