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ESTIMATION AND REPRESENTATION OF AIR TRAFFIC FLOWS INDICES IN TERMINAL CONTROL AREAS

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Abstract. *The article deals with the analysis of the research conducted in the field of air traffic flow and capacity management. Set of air traffic indices, air traffic flows quantitative estimation, applied techniques and software have been reviewed. Principles of detailed estimation and further analysis of air traffic flows statistics in Terminal control areas have been proposed.*

Keywords: aeronautical system; air traffic flows; air traffic flow and capacity management; air traffic management; capacity; terminal control area; quantitative parameters of air traffic flows; workload of air traffic controller

1. Introduction

The analysis of the European Air Traffic Management (ATM) performance for 2014 shows continuous growth of the major key performance indicators, such as Traffic volumes, Safety and Capacity in most of important domains and regions [1,2]:

– after the decrease between 2011 and 2013, average daily Instrumental Flight Rules (IFR) flights in Europe increased by +1.7 % in 2014 with notable regional variations. For 2015, the STATFOR 7-year forecast (2015) expects European flights to grow by +1.5 % in the baseline scenario (see Fig. 1). However, despite the positive growth in 2014 and the promising outlook, the impact of the economic crisis on the industry is still prominent. At European level, there were almost three million flights less in 2014 than initially predicted before the economic crisis in 2008;

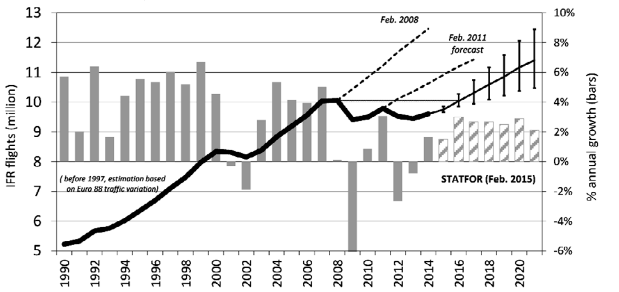

Fig. 1. The statistics of the IFR flights in European region according to the STATFOR 7-year forecast

– overall, safety levels in Europe continue to remain high, yet with scope for further improvements in some areas. Over the past five years, there were only two accidents where Aeronautical system (ANS) was a factor in the causal chain of events;

– after the best year on record in 2013, en-route Air Traffic flow and Capacity Management (ATFCM) delays increased again to 0,61 minutes per flight in 2014.

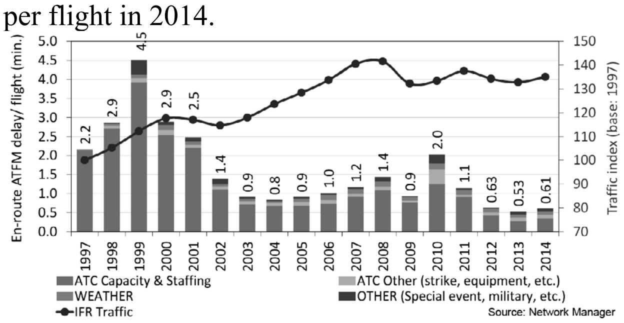

Fig. 2. Average en route ATFCM delay per flight (Eurocontrol area)

The above mentioned tendencies expected to be continued in future, that presses the Air Traffic Services (ATS) processes and Air Traffic Controller (ATCO) performance parameters in typical Terminal Control Areas (TMAs), as one most vulnerable “bottlenecks” of Aeronautical system.

So, the major source of congestion, all around the world, is the saturated airspace around the metropolitan airports (in TMAs), and the future efforts include an enhanced data flow and traffic synchronisation there.

2. TMA air traffic flows indices taxonomy and detailed analysis

Above mentioned statistics and tendencies in the European ATM network confirm the high relevance and importance of research devoted to major aspects of air traffic flows in typical TMAs, such as indices, ATCO workload, zone capacity, performance, delays, cost-efficiency, etc. It's highly important for end-users and researchers to clarify the impact of the uncertainty onto the air traffic flows planning processes (on strategic, pre-tactical and tactical phases) and to propose appropriate solutions applicable to Pan-European level and specific conditions of Ukraine.

Analysis of documentation and literature sources makes possible to compose the classification of air traffic flows indices applicable to use for TMAs researches [3-12]:

1. ***Basic indices*** (the most common examples):
– intensity;
– density;
– regularity (punctuality), etc.

2. ***Combined (integrated) indices*** (generalise several basic level indices in one in order to reflect ANS and ATFCM performance):
– complexity [3];
– variability [2];
– delays (traffic congestion and peak periods);
– workload of ATCO;
– zone capacity, etc.

Let's study in more detail the ***variability*** parameter of air traffic flows in TMAs. If traffic is highly variable, resources may be underutilised, or made available when there is little demand. Variability in traffic demand is therefore likely to have an impact on productivity, cost-efficiency, service quality and predictability of operations.

Variability can be broadly characterised as seasonal variability (difference in traffic level between different times of the year), temporal variability (difference in traffic levels between different times of the day), and spatial variability (variability of demand within a given airspace).

Different types of variability require different types of management practices, processes, and training to ensure that an Air Navigation Service Provider (ANSP) can operate flexibly in the face of variable traffic demand. To a large extent, variability can be statistically predictable, and therefore adequate measures to mitigate the impact of variability could in principle be planned (for example, overtime, flexibility in breaks, and flexibility to extend/reduce shift length).

The ***complexity*** is considered as a composite measure which combines a measure of traffic density (concentration of traffic in space and time) with structural complexity (structure of traffic flows).

The structural complexity is based on the number of potential horizontal, vertical or speed interactions between aircraft in a given volume of airspace (TMA).

Traffic complexity is generally regarded as a factor to be considered when analysing ANS performance (see Fig. 3). The relationship between "traffic complexity" and ATM performance in general, is not straightforward.

High density can lead to a better utilisation of resources but a high structural complexity entails higher ATCO workload and potentially less traffic.

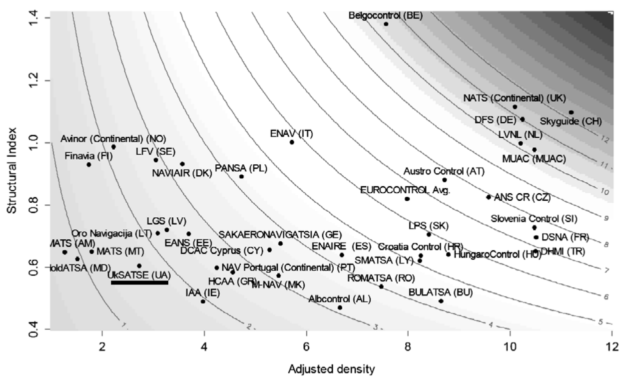

Fig. 3. Complexity index at ANPS level (2014)

Brief analysis of Figure 3, represents the UKSATSe place among the ANSPs with the lowest complexity indices in Europe, that reflects low traffic volumes and relatively simple (and clear) ATS routes network in the Ukrainian Flight Information Regions (FIRs).

Let's study in more detail the ***delays*** parameter of air traffic flows in TMAs. Statistics shows clearly that departure delays at origin airports are the main contributor towards arrival punctuality. Improvements in actual flight time distributions do not automatically result in improved punctuality levels, as the airline schedules for the new season are likely to be reduced by applying the punctuality target to the set of improved flight times (see Fig. 4).

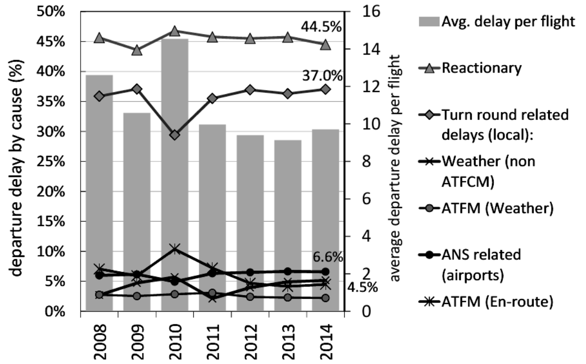

Fig. 4. Delays distribution by reason (2014)

The departure delays can be further categorised into primary (delay cause is directly attributable) and "reactionary" delays (from previous flight legs).

Unsurprisingly, reactionary delay (≈44.5 %), caused by delay which could not be absorbed on subsequent flight legs, is the largest single delay group.

Very interesting to investigate impact of ***uncertainty*** to the air traffic flows indices on the ATFCM phases. Let's represent our research in this field in form of appropriate table 1.

Table 1. Interrelation and impact of uncertainty to the air traffic flows indices on the ATFCM phases

The ATFCM phase	Input data	Internal phase processes and Output data
Strategic phase (SPh)	ATC capacities; Planned ATS route network; Identified bottlenecks	Routing & level capping scenarios; Routes availability document
Uncertainty influence on the SPh	Major Uncertainty Contributors – on level of mid-term traffic forecasts and special events, long-term routes availability, general stability of structure of the Pan-European ATS routes network	
Pre-tactical phase (PTPh)	Previous experience; Ad hoc special events; Data from reference day; Standard sector configuration and capacities for planned day	Identified likely capacities & optimum sector configurations; Identified critical areas; Regulations from ETFMS; AIMs – network news bulletins
Uncertainty influence on the PTPh	Major Uncertainty Contributors – on level of routeing and level capping scenarios, expected traffic demand and capacity, bottleneck areas, updated sector configurations	
Tactical phase (TPh)	ATFCM measures from pre-tactical plan; Flight plan & updates; Updated real time flight plan	CTOTs; Suggested re-routings and level capping
Uncertainty influence on the TPh	Major Uncertainty Contributors – on level of updated real-time sector configurations, updated real-time flight plans and actual implementation of ATFCM measures, peak hours origination	

The ATFCM phases (with uncertainty impact explanation):

– ***strategic phase*** (significant time before operations, month, year, etc.) includes scientific estimations, statistics of flights, season flight distribution, global co-ordination, regional agreements are taken into consideration. The uncertainty on this phase mostly connected with long time periods to expected events and low relevance (lack of statistics) in forecasting models of applied software;

– ***pre-tactical phase*** (week before operation) includes management of the available capacity resources and co-ordination on the implementation of flow measures with airspace users (air navigation service providers). The uncertainty on this phase mostly connected with the vulnerability of declared available capacity of zones to unexpected internal/external disruptors resulting in significant it decrease (up to 25 % of the maximum cap);

– ***tactical phase*** (day of operation) includes solution of current problems, revealing of overloaded areas and undertaking measures. The uncertainty on this phase mostly connected with dynamic nature of all monitored (supervised) processes, which makes all relevant info "old" (obsolete, not actual) at a moment of decision making.

3. Software for automated processing and initial analysis of ATFCM information

There are many software tools (such as CAPAN, SAAM, RAMS+ etc.) designed to improve the automated processing and initial analysis of ATFCM information. Let's demonstrate benefits of automated traffic indices processing on example of SAAM.

SAAM (System for traffic Assignment & Analysis at Macroscopic level) is a European airspace design evaluation tool. It is used to model, analyse & visualise route network and airspace volume developments at local, regional and European-wide levels.

The tool represents to researchers how the sectors traffic entry rate correlates with its corresponding hourly capacity figure, both values can be displayed at the same time in a graph. If there are more aircraft entering during an interval than the capacity allows there is an ***overload***.

Also very important task is to investigate correlation of capacity with workload (CAPAN-like method). This method is the Air Traffic Control (ATC) task oriented. For each flight crossing a sector, a set of basic ATC tasks is recorded, according to the flight profiles, the critical events of the flight through the airspace and the conflicts.

In the model two main elements are taken into consideration (Fig. 5):

1. ***Sector parameters***:

– Supervision and intervention thresholds;

– Maximum number of interventions and supervisions;

– Long flight time and skip flight time.

2. ***ATC tasks:***

– Flight data management;

– Co–ordination and radiotelephony (RT) communications;

– Planning conflict search;

– Radar supervisions and interventions;

– Radar handovers.

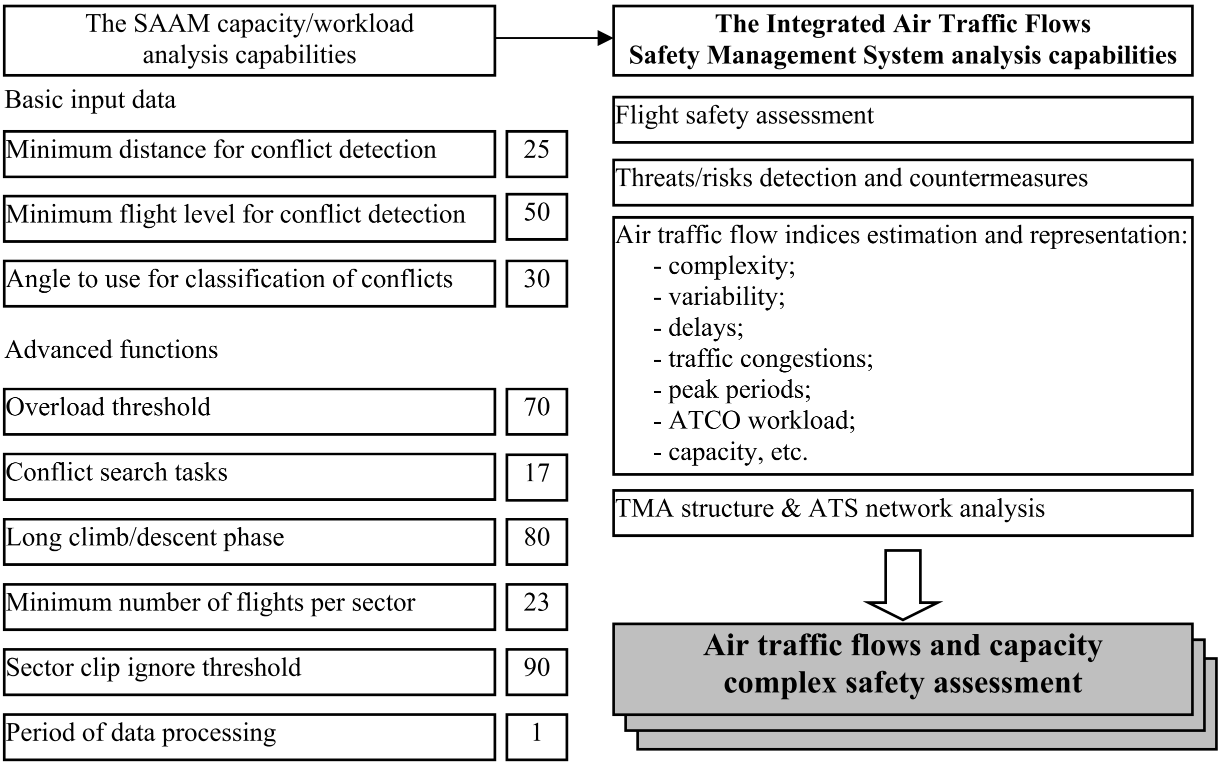

Fig. 5. Advanced parameters for workload and capacity analysis in SAAM

4. The model of complex automated processing and detailed analysis of uncertainty influence to major air traffic flow indices in TMA

The purpose of this section is to review some recent air traffic flow models, which are applicable to TMA and uncertainty research:

– ***queue models*** (determined, network and simulated);

– ***fluid models*** (continuous and discrete);

– ***cellular automata models***.

The review of air traffic models shows their high applicability and relevance to detailed investigation of air traffic flow indices in TMA taking into consideration uncertainty parameter as major contributor in seamless and continuity of the main flow (see Table 2).

A single queuing system, representing an en-route sector can be seen in Figure 6. Aircraft arrive with rate λ (number of aircraft per hour) requiring entry to the sector. The capacity of the sector is μ (number of aircraft per hour). The fact that multiple aircraft are allowed to enter a sector simultaneously through different routes is represented by C routes.

After crossing the sector, a flow with rate Q_{out} leaves it. When the capacity of the sector is attained, a queue of length l forms in front of the system. It is known that airlines cancel flights when the expected delay is too high (represented by more than S aircraft in the queue). This rate is represented by the quantity $\lambda - Q_{in}$.

Table 2. Comparison of traffic flow models

Model title	Purpose	Weaknesses	Uncertainty study
Queue models	Applicable for realistic study of departing/arrival TMA flows, delays analysis	Difficulties with relevant statistical data and real-time dynamic behaviour	Impact of trajectory uncertainties on flow performance; Impact of safety threats and risks assessment on air traffic flows actual parameters
Fluid models	Applicable for study of Approach ATCO control strategies on air traffic flow	Low fidelity of conflict situations and other system interactions, interpolation of flight flan data	Impact of ATCO control strategies and decision making uncertainties on flow strategic management; Fluid models flight safety assessment uncertainties
Cellular automata models	Applicable for study of interactions of adjacent TMA sectors	Generally unrealistic model, which may be used for fundamental researches exclusively	Uncertainties connected with switch between cells of grid (TMA sectors); Uncertainties with cells actual parameters

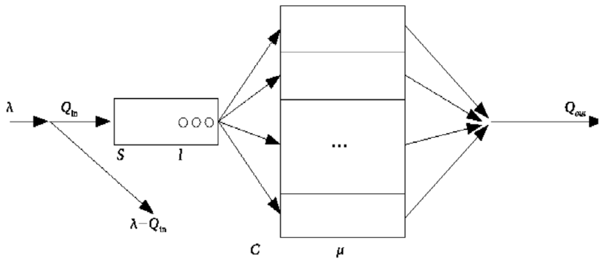

Fig. 6. The single queue for the ATCO sector (TMA)

A simplified mathematical analysis of a stochastic queuing network is as follows: let $n = (n_1, \dots, n_J)$ denote the state of the network, meaning that there are n_i customers at queue i. The state space of the network is $\Omega = \{n : n_i \geq 0, i = 1, \dots, J\}$. Now let $a(n,m)$ be the transition rate from state n to state m, i.e. the number of transitions between the two states per unit time.

The queue parameters and transition probabilities are estimated from past flight data. As performance metric, they define for a centre j the traffic flow efficiency:

$$E(E_j) = 1 - \frac{E(W_{qi})}{E(W_j)} \tag{1}$$

where W_{qj} is the delay inside the centre and $W_j = S_j + W_{qj}$ is the traversal time through the centre, which is the sum of the traversal time under optimal conditions S_j and the delay. $E(X)$ is the expected value of the random variable X. For a route from centre i to centre j, they then define the path efficiency as the average of the traffic flow efficiencies along the path.

One of the first macroscopic flow models is a continuity equation, called the Lighthill-Whitham-Richards (LWR) equation:

$$\frac{\partial \rho(x,t)}{\partial t} + C(\rho)\frac{\partial \rho(x,t)}{\partial x} = 0 \tag{2}$$

The solution to (2) is called a wave, describing the propagation of an initial traffic pattern $\rho(x,0)$ with speed $C(\rho)$. When $C(\rho)$ depends on ρ, different densities propagate with different velocity, implying that the shape of the initial traffic pattern changes over time, but also that discontinuities in the solution $\rho(x,t)$ (so-called shock waves) appear. Note that $C(\rho)$ is the speed of the traffic density and not the speed of the objects (ACFT).

Now, let's consider the fluid dynamical models for en-route air traffic flow. Their aim is to analyse the impact of controller's actions in one sector onto the flow patterns in other sectors. These models are discrete in space and in time. A sector x is a one-dimensional volume, with aircraft entering from the previous sector $x-1$ with rate $J(x-1,t)$ and leaving at its output with rate $J(x,t)$ per unit time (see Fig. 7).

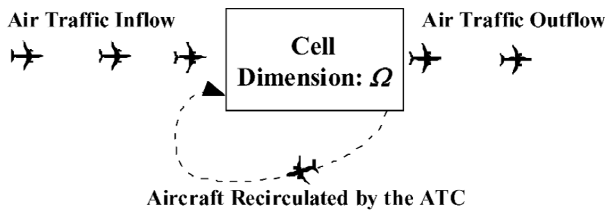

Fig. 7. The one-dimensional air traffic flow in TMA

Air traffic controllers modulate the outflow by varying the speeds or by stretching the paths of some aircraft inside the sector. This mechanism will remove a number u_r of aircraft from the outflow. It is modelled as a loop and is called 're-circulated aircraft'. Mathematically the model can be written as:

$$\rho(x,t+1) = \rho(x,t) + J(x-1,t) - J_r(x,t) \tag{3}$$

where $\rho(x,t)$ is the number of aircraft in sector x and time interval t and $J_r(x,t) = J(x,t) - u_r(x,t)$ represents the outflow adjusted by the number of re-circulated aircraft.

The basic idea of Cellular Automata in flow modelling is simple: divide the airspace into cells of equal size and let each cell i either be occupied by an aircraft with speed v_i or be empty. Aircraft follow their flight plan, and in each time-step they move forward v_i cells if the destination cell is free, or they adjust their speed or route by some (stochastic) rule if the cell is occupied.

Since the state of a cellular automaton depends only on its previous state, the mathematical analysis of stochastic cellular automata is based on Markov

Chains, similar to the queuing networks discussed above: a cell is in state $\boldsymbol{n}$ in time interval $t+\Delta t$ either when it has been in state $\boldsymbol{n}$ in interval $\boldsymbol{t}$ and no transition out of the state occurred, or if a transition from another state into state $\boldsymbol{n}$ occurred in time interval $\boldsymbol{t}$.

5. Conclusions

The specific automated systems (such as the Integrated Air Traffic Flows Safety Management System) are necessary to completely (adequately) research and integrate the air traffic indices in TMA and determine complex parameters of the air traffic flows safety in TMA.

Further scientific work will be connected with improvement of the models, which are applicable to study of the TMA air traffic flows structure taking into account uncertainty parameter.

The obtained final model will show us how the uncertainty, transforming air traffic flows, significantly changes flow indices, affects capacity and ATCO workload in TMA.

Additional attention (with practical implementation in TMAs) shall be paid to countermeasures against the uncertainty origins/outcomes and other adverse effects on the safety of air traffic flows.

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У статті проаналізовано дослідження щодо організації потоків повітряного руху та пропускної здатності. Розглянуто питання щодо сукупності показників повітряного руху, кількісної оцінки потоків повітряного руху, прикладних методик та відповідного програмного забезпечення. Запропоновано принципи детальної оцінки та аналізу статистичних даних щодо потоків повітряного руху в термінальних диспетчерських районах.

Ключові слова: аеронавігаційна система; завантаженість авіадиспетчера; кількісні показники потоків повітряного руху; організація потоків повітряного руху та пропускної здатності; організація повітряного руху; потоки повітряного руху; пропускна здатність; термінальний диспетчерський район

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В статье проанализированы исследования в области организации потоков воздушного движения. Рассмотрены вопросы в отношении совокупности показателей воздушного движения, количественной оценки потоков воздушного движения, прикладных методик и соответствующего программного обеспечения. Предложены принципы детальной оценки и анализа статистических данных по потокам воздушного движения в терминальных диспетчерских районах.

Ключевые слова: аэронавигационная система; загруженность авиадиспетчера; количественные показатели потоков воздушного движения; потоки воздушного движения; организация воздушного движения; организация потоков воздушного движения и пропускной способности; пропускная способность; терминальный диспетчерский район

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